The contribution of divided attention to tripping while walking

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Abstract

Falls in older adults has long been recognised as a significant public health problem requiring urgent intervention. Tripping while walking is one of the most commonly cited reasons for falls, however, little research has focused so far on foot motion characteristics and their contribution to the likelihood of tripping while walking. Even fewer studies have examined tripping on unseen obstacles while obstacle negotiation (i.e. tripping on seen obstacles) has received more attention. The primary aim of this research was to examine foot motion during long-term (e.g., 30 minutes) continuous treadmill walking by measuring minimum toe clearance (MTC), the very small distance the foot clears the ground during swing phase of gait. Examining MTC of each stride allowed an estimation of the likelihood of an individual tripping on unseen obstacles while walking. Since cognitive decline and reduced ability to multitask (reduced divided attention capacity) has been observed in older adults and has been linked to falls risk, this research also examines foot kinematics during distracted walking conditions. Foot motion was analysed during undistracted and distracted walking using various short (turning the head to identify objects to the left and then the right; reacting to a visual stimulus by pressing a hand-held button; reaching into a waist pouch to retrieve a handkerchief; and a cough) and prolonged distractions (counting backwards by threes; and watching a video) that could be encountered in normal everyday life. This enabled an evaluation of the types of distractions and situations that might increase the risk of tripping in healthy elderly females.

This research, therefore: (1) focused on healthy elderly females (n = 18, mean age 71.3 years, SD = 3.6 years) and healthy young females (n = 18, mean age 21.8 years, SD = 3.6 years); (2) utilised a 2D model of the foot to using shoe dimension to calculate MTC at midswing; (3) calculated probability of tripping for each subject based on individual MTC distributions; and (4) examined MTC descriptive statistics during undistracted walking at a self-selected comfortable walking speed on the treadmill for ~20 minutes and during various everyday distractions (short and prolonged) for 10 minutes.

Descriptive statistics of individual MTC distributions, which included between 906 to 1253 strides per subject, were examined. For undistracted walking, the elderly adults had lower measures of all variables in the lower end of the MTC distribution, namely minimum (min_{MTC}) (1.08cm vs. 1.42cm, $p<.05$), first percentile ($PC1_{MTC}$) (1.35cm vs. 1.68cm, $p<.05$), fifth percentile ($PC5_{MTC}$) (1.50cm vs. 1.81cm, $p<.05$), and first quartile ($Q1_{MTC}$) (1.80cm vs. 2.00cm, $p<.05$). The higher skewness of MTC distributions (0.60 vs. 0.33, $p<.05$) in the elderly, however, suggests some attempt was made to reduce the frequency of MTC in the lower portion of the distribution. It was discovered that an individual's calculated frequency of tripping was approximately once every second stride when MTC was approximately equal to the individual's MTC distribution central tendency (median). Elderly subjects had greater calculated probability of tripping (PT) between MTC(y) = 0.9cm – 2.0cm ($p<.05$). The elderly also had higher intra-individual variability in MTC as measured by interquartile range (IQR_{MTC}) (0.44cm vs. 0.28cm, $p<.01$). For normal undistracted walking, the elderly are at an increased risk of tripping on unseen obstacles given the smaller MTC and greater variability in MTC.

For the distracted walking conditions, the elderly had significantly lower $median_{MTC}$ compared with the young for most distraction tasks ($p<.05$). The elderly also typically had lower min_{MTC} and higher IQR_{MTC} compared with the young. The lower MTC and higher intra-individual variability due to distractions places the elderly at an increased risk of tripping on small unseen obstacles compared with the young. The distraction eliciting the smallest MTC was a prolonged task (60 seconds) and involved structural interference where vision was focused on the task as well as maintaining posture and balance (*video* task). Distractions such as observing the scenery while walking therefore could increase the likelihood of tripping. The largest MTC was during the *head turn* task, where subjects turned the head to identify objects to the left and right. This large MTC could have been an attempt to reduce the likelihood of tripping.

Student Declaration

"I, Lisa Dell'Oro, declare that the PhD thesis entitled "The contribution of divided attention to tripping while walking" is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature Date

Table of Contents

List of Appendices

List of Tables

List of Figures

List of Equations

List of Abbreviations

ABS	Australian Bureau of Statistics
ADL	Activity of daily living
AGS	American Geriatrics Society
AIHW	Australian Institute of Health and Welfare
AP	Anterio-posterior
BBS	Berg balance scale
COM	Centre of mass
COP	Centre of pressure
CPD	Computerised dynamic posturography
DT	Dual task
ESU	Event synchronisation unit
IQR	Interquartile range
IRT	Inhibition reaction time task
JOLO	Judgement of Line Orientation
K	Kurtosis
LED	Light emitting diode
MFC	Minimum foot clearance
MTC	Minimum toe clearance
MTT	Multiple Tasks Test
NIPAC	National Injury Prevention Advisory Council
RTP	Reaction time probe
S	Skew
SD	Standard deviation

SRT	Simple reaction time task
ST	Single task
TCG	Time code generator
TUG	Timed Up & Go

Chapter 1: Introduction

Falls in elderly adults constitute a serious public health problem. Approximately one third of community-dwelling elderly adults aged 65 years and over, and approximately half of those aged 80 years and over, will fall at least once a year (Kreisfeld *et al.*, 2004; Cripps and Carman, 2001; Dolinis *et al.*, 1997; Winter, 1995; Lord *et al.*, 1993). This high falls incidence is associated with elevated morbidity and mortality rates, and other human and economic costs. Elderly individuals, aged 65 years and over, represent a large and increasing proportion of Australia's population (ABS, 2005). The increase in the proportion of elderly, coupled with the high rate of falls in this group, requires urgent and effective intervention. This can be achieved by identifying risk factors contributing to falls, then identifying and predicting individuals at risk and finally, implementing preventative strategies.

The aetiology of falls includes a multiplicity of factors. The falls risk increases with the number of risk factors present. These risk factors have broadly been categorized as intrinsic or pathological (i.e. decline or deficiency pertaining to the individual) and extrinsic or environmental (i.e. pertaining to factors in the environment largely uncontrolled by the individual). Strong evidence has been accumulated for intrinsic risk factors predisposing to falls (e.g. Lord *et al.*, 2002b; NIPAC, 1999a; 1999b; Owings *et al.*, 1999; Snow, 1999; Kerrigan *et al.*, 1998; Maki, 1997; O'Loughlin *et al.*, 1993; Whittle, 1993; Campbell *et al.*, 1989; Blake *et al.*, 1988; Tinetti *et al.*, 1988; Prudham and Evans, 1981). The evidence for extrinsic factors predisposing individuals to falls (e.g. home environmental hazards) is not as persuasive due to a lack of studies

that have explored these factors (Lord *et al.*, 2002b; Hill *et al.*, 1999; NIPAC, 1999a). In most instances of falls it is recognized that intrinsic and extrinsic factors interact to varying degrees (Tinetti and Speechley, 1989). Irrespective of the precise combination of risk factors, it has been found that tripping is responsible for more than one third of falls during locomotion (Kreisfeld *et al.*, 2004; Cripps and Carman, 2001; Hill *et al.*, 1999; Sattin *et al.*, 1998; Lord *et al.*, 1993; Campbell *et al.*, 1990; Tinetti and Speechley, 1989; Overstall *et al.*, 1977).

The injury rates due to falls increases with the number of co-morbid diseases diagnosed, coupled with age-related decline. Falls related injury and death rates, however, are not limited to frail elderly (AGS, 2001). It has been found that even in apparently healthy elderly, falls can result in significant injury from which full recovery does not eventuate, and can ultimately result in death (Prince *et al.*, 1997; Harper and Lyles, 1988; Oreskovich *et al.*, 1984). Older adults with one or more identified risk factors are clearly at risk of falls and are subsequently targeted for intervention programs. As Hill *et al.* (1999) highlights, healthy older adults without any obvious balance impairments or other risk factors can still fall. Given the high injury and death rates, it is critical to prevent the first fall since it is possible one fall can result in serious injury or even death in a previously healthy older individual (Hill *et al.*, 1999).

The challenge for researchers is to prevent falls in healthy older adults with no obvious balance impairment or other obvious risk factors. Indeed, the AGS guidelines (2001) highlight the need to direct prevention programs toward healthy older adults. Current research includes many studies on falls prevention but a paucity of studies on falls prediction. The lack of studies attempting to predict falls may be due in part to the

complex nature of falls aetiology. There is currently no quantitative measure for the probability of an individual tripping on unseen obstacles while walking. If an obstacle is seen, alterations to the gait pattern will be initiated to prevent a trip. When an obstacle is not seen, however, the likelihood of tripping on the obstacle increases. Given the high contribution of tripping to falls rates, and that tripping frequency is a strong predictor of falls (Pavol *et al.*, 1999), a method of predicting probability of tripping would be very useful for a falls prevention program.

Although all individuals, young and old, have the propensity to trip from time to time, the consequences of trip induced falls are clearly more serious for older adults. During locomotion, foot clearance plays a critical role in the successful negotiation of obstacles and uneven ground. Foot clearance is typically quantified as minimum toe clearance (MTC). During normal unobstructed gait, MTC is typically reported to be approximately 1.3 cm (Winter, 1991). This small MTC and variability in MTC has the potential of causing irregular tripping, where typically the lead foot contacts the ground or unseen object.

Although seldom performed, most gait analysis in the area of falls due to tripping focuses on MTC during the swing phase of either unobstructed or obstructed walking (e.g. Patla and Rietdyk, 1993; Winter, 1991a). These studies have generally defined MTC as the distance between the ground and the toe marker during midswing. More recently, however, alternative methods of estimating MTC have been employed, such as utilising a virtual point on the inferior most distal portion on the sole of the shoe (Begg *et al.*, 2007; Best *et al.*, 1999; Startzell and Cavanagh, 1999). These methods

give a more accurate representation of MTC during gait by accounting for the influence of footwear on foot clearance.

Gait analysis studies typically report mean values as an average representation, or central tendency measure, of selected parameters for a group or individual. Similarly, standard deviation is typically reported as a measure of variability for a group or individual (e.g. Winter, 1991a). It has never been shown that MTC data is normally distributed and, therefore, if mean and standard deviation calculations (or statistics) are an appropriate representation of central tendency and variability.

The type of descriptive measures employed and the size of the data sets examined are important methodological factors to consider when obtaining an accurate analysis of gait. In gait analysis studies, generally only a limited number of trials are used per individual, with the assumption that these trials form a normal distribution and represent typical gait characteristics. Intra-subject variability in gait patterns can vary greatly with fluctuations being higher for trials collected days apart compared with minutes apart (Winter, 1991a). It is important to determine how many trials are required to obtain a stabilised gait parameter for an individual to further ensure the reliability of the data used for analysis and when drawing statistical conclusions (Best *et al.*, 2000). Collecting a large number of consecutive strides allows a more comprehensive examination of the intent and accuracy of the locomotor system in implementing the critical event of MTC over a longer, more realistic walking time.

Older adults typically undergo some age-related decline in cognitive and perceptual motor abilities. Associated with these declines is a reduced capability to divide

attention between multiple concurrent tasks. There is now sufficient evidence to suggest that elderly individuals have more difficulty dividing attention between multiple tasks compared with younger individuals (e.g. Sparrow *et al.*, 2002b; Brown *et al.*, 1999; Hartley and Little, 1999; Chen *et al.*, 1996; Lajoie *et al.*, 1996; Ponds *et al.*, 1988; McDowd, 1986). Moreover, this decreased ability to divide attention has been linked to a reduced ability to maintain postural control and an increased risk of falling (e.g. Woollacott and Shumway-Cook, 2002; Campbell *et al.*, 1989; Stelmach and Worringham, 1985).

Most studies examining postural control under divided attention conditions have concentrated on a static standing position (e.g. Redfern *et al.*, 2001; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000) but some have attempted to relate divided attention ability to dynamic stability, such as during walking (e.g. Sparrow *et al.*, 2006; Sparrow *et al.*, 2002a; Lundin-Olsson *et al.*, 1998; Chen *et al.*, 1996). Moreover, it has been observed that the elderly are more affected than the young by divided attention positions and that postural control was more affected in situations of reduced sensory input and particularly conditions of conflicting sensory information (e.g. Pellecchia, 2003; Redfern *et al.*, 2001; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000). These studies are particularly useful since many everyday situations involve either conflicting or reduced sensory information. For example, turning the head to scan for cars whilst crossing the road. Despite recognising impaired divided attention ability as a falls risk factor in the elderly, there are to date no studies examining the types of distractions most likely to induce a trip. Moreover, there is an identified need to include more 'real-life' tasks in these studies (Abernethy, 1988).

In summary, falls in the elderly is a serious public health problem, which involves enormous physical, psychological and economic costs to the individual and the community. Tripping is a frequent cause of falls the declined ability to attend to more than one task might increase the risk of tripping and falling whilst walking. With the ageing of the population, the implementation of effective preventative strategies is vital. This research will contribute to the area of falls prevention by:

1. Exploring age-related biomechanical differences in MTC during treadmill walking in healthy female subjects.

2. Examining MTC during longer walking trials (i.e. approximately 1,000 strides over a 20 minute period) to enable a more comprehensive understanding of gait control and function.

3. Presenting a quantitative method of predicting the probability of tripping on unseen obstacles while walking.

4. Examining divided attention ability during treadmill walking using a number of short and prolonged 'distraction' tasks, which can be related to normal, everyday experiences. Changes to MTC during these distracted periods are examined in an effort to determine age-effects and the type of distraction most likely to lead to tripping while walking.

Chapter 2: Literature review

This chapter reviews the scientific literature pertaining to the topic being investigated in three major sections:

1. falling behaviour (incidence, aetiology, prevention and prediction);
2. biomechanics of normal gait; and
3. tripping and obstacle avoidance research.

Sub-sections with detailed examination of literature relating to pertinent areas of this research, including control of balance during gait, divided attention and methodological issues important for this research, are also included. Each section concludes with a summary and critical assessment of the current literature. Areas not thoroughly researched are identified and, therefore, support the need for this research.

2.1 Falling behaviour in elderly populations

2.1.1 Falls incidence and outcomes

Falls in elderly populations are a serious concern due to its high incidence, associated mortality and other human and economic costs. Australian studies involving community-dwelling elderly adults have shown that approximately 30% of people aged 65 years or more, and approximately half of those aged 80 years or more, sustain a fall at least once a year (Kreisfeld *et al.*, 2004; Cripps and Carman, 2001; Dolinis *et al.*,

1997; Lord *et al.*, 1993). Moreover, a study by Hill *et al.* (1999) identified similar fall rates (i.e. approximately 50%) in subjects aged 70 years or more. Many further studies use retrospective reporting of falls (e.g. Dolinis *et al.*, 1997; Lord *et al.*, 1993) which could underestimate true falls rates by 15 to 20% (Tinetti *et al.*, 1988).

Although the high falls incidence is a major concern, the greater susceptibility to serious injury in the elderly further increases the seriousness of the situation. The most recent Australian Government report on falls in Australian elderly individuals for the Australian Institute of Health and Welfare (AIHW) (Cripps and Carman, 2001) states that hospitalisation due to falls (n = 45,069 or 1,995 per 100,000 population) accounts for approximately 54% of all hospitalisations (n = 82,724) for the elderly aged 65 to 85 years. The report by Cripps and Carman (2001) examines and summarises hospital records reporting injuries and deaths in the elderly due to falls during 1998. The report provides a particularly useful graphical representation of hospitalisation rates due to falls by age and gender (refer Figure 2.1). It can be seen in Figure 2.1 that fall rates increase exponentially for both males and females, with an approximately 9-fold increase between 65 years and 85 years and over. Figure 2.1 also shows that hospitalisation rates are significantly greater in older females compared with males and this gender difference increases with advancing age (Cripps and Carman, 2001; Dolinis *et al.*, 1997). Additionally, elderly females are more likely to sustain fall-related injuries than males. For example, Cripps and Carman (2001) found females were 2.8 times more likely to sustain a fracture due to falls compared with males (105.0 v. 37.6 per 100,000 population) while Fildes (1994) reported a likelihood of sustaining a fall-related injury approximately double in elderly females compared with males.

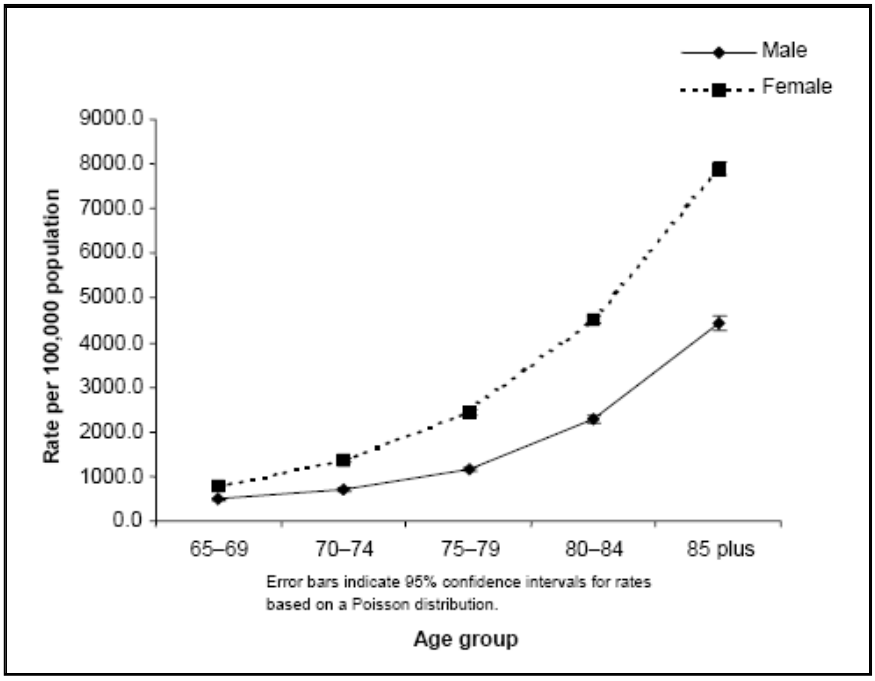


Figure 2.1: Age-specific rates of hospitalisation due to accidental falls in people aged 65 years and above (Taken from Cripps and Carman (2001), p.2).

Figure 2.2 displays data by the Australian Government AIHW report on hospital records of injury deaths in Australia during 2002 (Kreisfeld *et al.*, 2004). As seen in Figure 2.2, accompanied by high fall-related morbidity is a high mortality rate due to falls, which is clearly concentrated in the older age groups. Chart a) shows death rates due to unintentional fall injury for all ages (n = 1,517) and it can be seen that the elderly group aged 60 years and over comprise the majority of deaths (n = 1,352 or 89%). Chart b) focuses on the elderly group and shows greater detail by dividing the elderly group into smaller intervals. It can clearly be seen that fall death rates due to falls increase with age. Furthermore, deaths due to falls in the 85 years and over group account for over half (~59%) the deaths in the elderly aged 60 years and over.

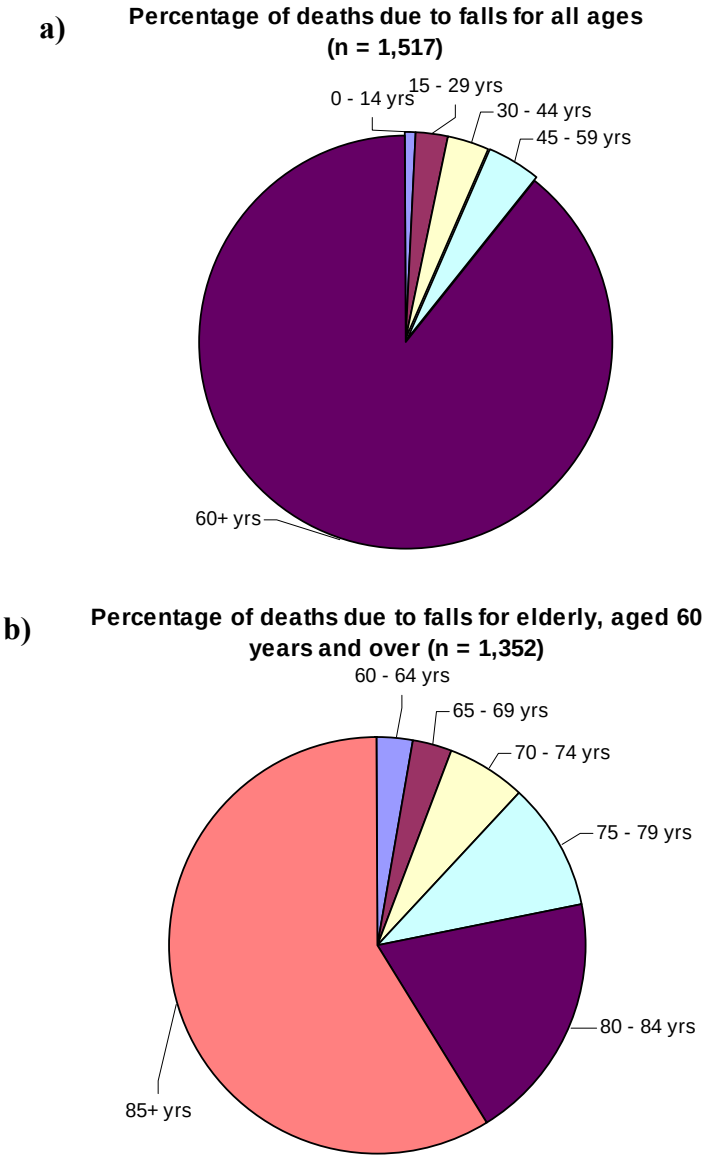


Figure 2.2: Death rates due to unintentional fall injury by age (from data reported by Kreisfeld *et al.* (2004)).

In the reported data for critical falls resulting in death in the elderly, females account for approximately 61% of the cases while elderly males make up the remaining 39%. For example, Cripps and Carman (2001) reported 1,014 deaths due to accidental falls in people aged 65 years and above in 1998, with 61% being female (n = 617 or 48.1 per 100,00 population) and 39% being males (n = 397 or 39.7 per 100,000 population).

Similarly, the report by Kreisfled *et al.* (2004) for 2002 revealed of the 1,314 fall-related deaths in the elderly, 61% were females (n = 799) whilst 39% were males (n = 515). Figure 2.3 shows death rates from accidental falls in the elderly using 1998 data reported by Cripps and Carman (2001). It can be seen that more than half of these deaths (n = 576 or 256.8 per 100,000 of population) occur in the oldest old aged 85 years and over (approximately 270 per 1000,000 for males (n = 186 deaths) and 250 per 100,000 for females (n = 390 deaths) in the 85 years plus age group). These rates are consistent with the Australian Government's AIHW report on injury deaths in Australia for 2002, which found falls death rates are concentrated in the older age groups and are particularly high over 85 years (~300 deaths per 100,000 population) for both males and females (Kreisfeld *et al.*, 2004).

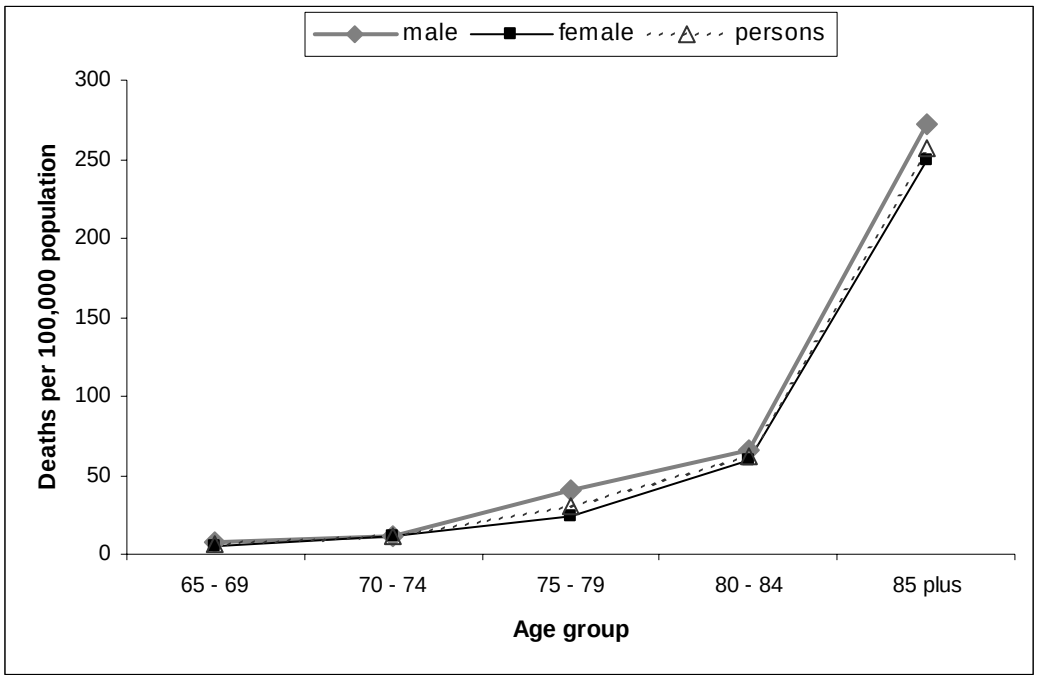


Figure 2.3: Deaths from accidental falls in people aged 65 years and above by age and gender (adapted from data reported by Cripps and Carman (2001), p. 27).

As highlighted in the American Geriatrics Society (AGS) guideline for falls prevention (AGS, 2001), the susceptibility to fall-related injury is related to high prevalence of co-morbid diseases (e.g. osteoporosis) and age-related physiological decline (e.g. slower reflexes). Even in apparently healthy elderly adults, a fall may result in serious complications or death due to physiologic changes caused by the prolonged bed rest required to manage an injury (AGS, 2001; Harper and Lyles, 1988). Almost 90% of older persons admitted to hospital due to a fall will not return to their previous level of independence (Oreskovich *et al.*, 1984) and of those who sustain fractures to the hip, 50% are subsequently admitted to a long-term facility (Prince *et al.*, 1997).

Falls in older adults frequently result in the development of a fear of further falls. This 'fear of falling', also called post-fall anxiety syndrome, has recently been recognised as a serious consequence of falls and, therefore, it has been given more attention by researchers (e.g. Herman *et al.*, 2005; Jorstad *et al.*, 2005; Cumming *et al.*, 2000; Salkeld *et al.*, 2000; Hill *et al.*, 1999). A fear of falling typically results in self-imposed isolation due to a lack of confidence to ambulate safely, particularly outdoors. This often leads to a need for additional help with activities of daily living or, ultimately, an inability to live independently. The resulting loss of independence has a substantial impact on quality of life in older persons (Salkeld *et al.*, 2000).

In addition to the psycho-social cost of falls, the total financial cost in Australia, which has been examined both in terms of the lifetime cost of the injury per year and total cost to the health system per year, is estimated to be between $1 and $2 billion annually (Mathers and Penm, 1999; Watson and Ozanne-Smith, 1997; Fildes, 1994).

These figures all show that the elderly are overrepresented in falls incidence rates, a situation which is reported worldwide. Additionally, Australian Bureau of Statistics (ABS, 2005) projections show that by 2051, the proportion of persons aged 65 years and over in Australia could potentially reach 38%, almost treble the 13% proportion in 2004, and decrease slightly by 2101 to 31%. Moreover, according to these ABS projections the proportion of the population in the 85 and older age group has the potential to rise more than 5-fold to 8% by 2051 and more than 6-fold to 10% by 2101 compared with the 1.5% proportion in 2004. Given the high incidence of falls and the associated morbidity, mortality and other costs, combined with the ageing of the population, the incidence of falls in the elderly and the associated costs are expected to rise unless effective preventative techniques are implemented. In a report to the Commonwealth Department of Health and Ageing, Moller (2005) states that by 2051, the total health cost attributable to fall related injury is expected to increase almost three-fold to $1,375 million per annum. Additionally, there will be 886,000 additional hospital bed days per annum and 3,320 nursing home places required unless effective preventative strategies are implemented.

2.1.2 Falls risk factors

2.1.2.1 An overview of risk factors

Epidemiological studies have consistently stated that falling in older populations is a multifactorial phenomenon. While there are many documented risk factors likely to contribute to falling behaviour, they are often not universally demonstrated. Similarly, the exact role of each risk factor, and their interaction, has not yet been determined (NIPAC, 1999a). As with many geriatric syndromes, falls are most often due to an accumulation of deficits in multiple areas rather than an isolated pathology (Tinetti *et al.*, 1996). Due to their multifactorial aetiology, there appears to be no uniform classification of falls. However, researchers have generally categorised falls into a) intrinsic or pathological falls; and b) extrinsic, environment-related or accidental falls. In most instances of falls, intrinsic and extrinsic factors interact to varying degrees (Tinetti and Speechley, 1989).

There is some strong evidence for certain intrinsic risk factors predisposing an older individual to falling behaviour. These risk factors include cognitive impairment (including decreased ability to divide attention between more than one task), poor balance and inability to correct for the unexpected loss of balance which may result from any of/or some combination of decreased reaction time, diminished central nervous integration, decreased muscular strength, impairments in visual, vestibular or proprioceptive sense, loss of joint mobility, real or perceived reductions in limits of stability, or capacity for sway without taking a step (Lord *et al.*, 2002b; NIPAC, 1999a; 1999b; Owings *et al.*, 1999; Snow, 1999; Kerrigan *et al.*, 1998; Maki, 1997;

O'Loughlin *et al.*, 1993; Whittle, 1993; Campbell *et al.*, 1989; Blake *et al.*, 1988; Tinetti *et al.*, 1988; Prudham and Evans, 1981). Chronic health conditions such as stroke, Parkinson's disease and arthritis, as well as acute health problems, such as delirium or urinary tract infection for example, are recognized as important intrinsic falls risk factors. In some cases, the presence of certain intrinsic factors results in the use of prescription medication, some of which are also linked with falls incidence (Lord *et al.*, 2002b; NIPAC, 1999a; Whittle, 1993; Blake *et al.*, 1988; Tinetti *et al.*, 1988). Moreover, the presence of intrinsic factors is often a predictor for recurrent falls (Wolf and Gregor, 1999; Graafmans *et al.*, 1996; Craik, 1989; Blake *et al.*, 1988).

Whilst the evidence for extrinsic risk factors is not as strong, extrinsic risk factors reported include environmental hazards such as uneven surfaces, poor lighting, poor steps and stairway design and repair or other hazards around the home (including for example, slippery floors, furniture, unsecured mats and rugs and lack of non-skid surfaces in bathtubs and bathrooms), and self-imposed restriction due to a fear of falling (Lord *et al.*, 2002b; Hill *et al.*, 1999; NIPAC, 1999a). There have been no comprehensive, large-scale studies finding a significant and specific association between home environment hazards and the risk of falling, and due to this, these factors have been implicated mainly by self-report (NIPAC, 1999a; Campbell *et al.*, 1990; Tinetti *et al.*, 1988). The presence of extrinsic factors creates the opportunity for a fall, particularly for individuals already impaired by a combination of intrinsic factors. Indeed, Lord *et al.* (2002b) highlight the fact that although some environmental factors may not be directly related to a fall, they do have an influence on other important intrinsic risk factors. For example, high-heeled shoes reduce balance and bifocal lenses impair depth perception and contrast sensitivity.

Since intrinsic falls-risk factors have been more closely related to falls, most prevention programs have focused on reducing these factors. Despite intrinsic falls-risk factors being described as more closely linked with falls, current Australian Institute of Health and Welfare (AIHW) reports on falls in the elderly (Cripps and Carman, 2001) and Australian injury and death rates (Cripps and Carman, 2001) show that external causes were in fact cited as causes for approximately 54% of falls resulting in hospital admissions. As shown in Figure 2.4, 39.1% of falls resulting from external causes were associated with slips, trips and stumbles. However, these data are reported without consideration of the interaction of any intrinsic factors contributing to a fall. As noted by Braun (1998), the elderly typically place greater emphasis on external factors as the cause of falls and neglect the contribution of intrinsic factors, particularly for themselves. Although elderly might ascribe external factors as the cause of a fall, this is often not the major cause once intrinsic factors are examined more closely.

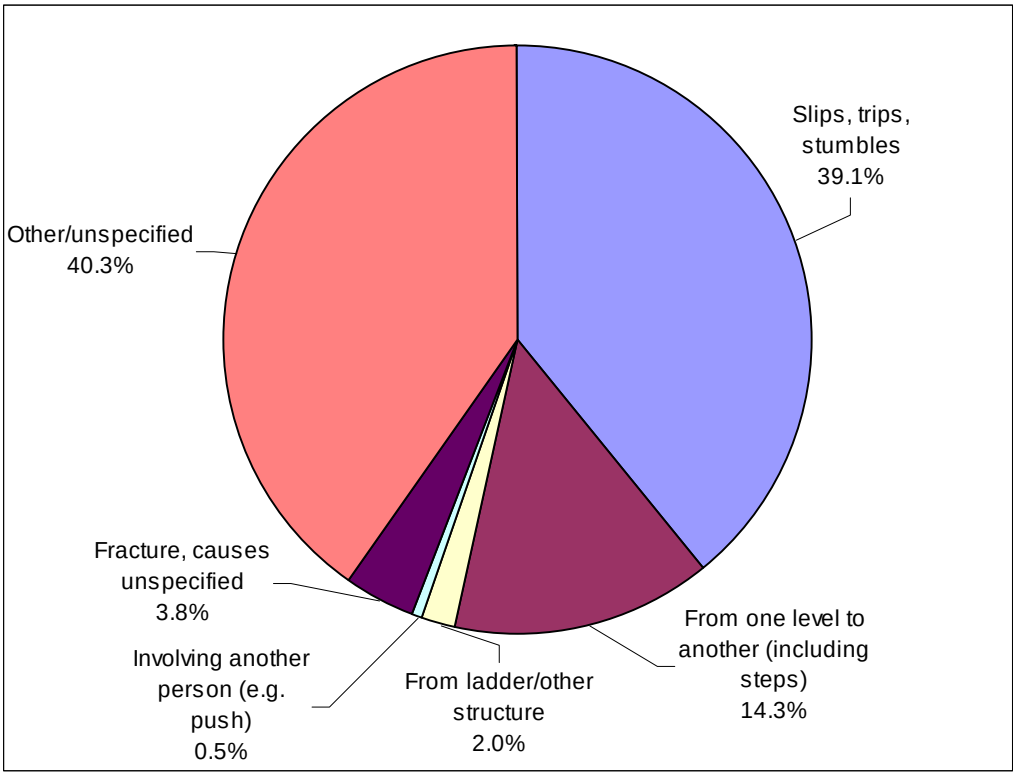


Figure 2.4: External causes of hospitalisation due to falls in the elderly (adapted from data reported by Cripps and Carman (2001)).

The risk of falls increases with the number of risk factors present (Cwikel *et al.*, 1998). Since older people may experience deficits in multiple areas, compensatory mechanisms may be hampered increasing the likelihood of falling in response to a postural perturbation. For example, a failure in one system (e.g. instability) may ordinarily be compensated for by another (e.g. visual feedback), which may also be failing (Graafmans *et al.*, 1996).

A person sustaining a fall often experiences anxieties or fears of a subsequent fall. This often results in a reduction of activity and self-imposed isolation due to a fear of falling whilst performing activities they had previously done safely before the fall (e.g. Hill *et al.*, 1999). This reduction in activity can result in a decline in muscular strength and general fitness, culminating in a downward spiral further predisposing the person to falls. This 'fear of falling' or 'post-fall anxiety syndrome' has been linked to falling behaviour (Lord *et al.*, 2002b; Cumming *et al.*, 2000; Hill *et al.*, 1999; Maki, 1997).

2.1.2.2 The role of vision and other sensory control (vestibular and proprioceptive input) in balance and gait

Vision, together with other sensorimotor mechanisms (i.e. reaction time, neuromuscular control, muscular strength, proprioception and vestibular sense), plays a vital role in the regulation of safe walking over both even and uneven terrain. This section involves a brief discussion of the role of vision in negotiating a safe walking terrain, followed by visual input for maintaining balance. The other two sensory systems for the control of balance, namely vestibular and proprioceptive systems, are also discussed since they

are inextricably linked and each has an important role in providing a stable posture for walking.

Vision as a means of seeing the travel path and hazards obstructing the path is the most obvious role of vision. Visual function plays a vital role in the ability to see hazards and, thus, proactively avoid a trip. Vision in this sense has often been termed 'exteroceptive', or providing information about the environment and external objects (Lee and Lishman, 1977), and 'exproprioceptive', proprioceptive information picked up in the external environment by the visual system (Anderson *et al.*, 1998). As Patla (1997) describes, vision provides almost simultaneous information about near and far environment, which is used to regulate locomotion on a local level (step by step basis) and a global level (route planning). Pavol *et al.* (1999) concluded in their study that trip-related falls were predominately due to tripping frequency rather than a reduced ability to recover. Vision therefore plays a vital role in the prevention of tripping through the ability to see and proactively avoid physical hazards.

Degeneration in visual function has frequently been cited as a risk factor for falls and, in particular, recurrent falls (Ivers *et al.*, 1998; Klein *et al.*, 1998; Lord *et al.*, 1993; Perry, 1982) and hip fracture (Ivers *et al.*, 2000; Felson *et al.*, 1989). These degenerations typically include decline in visual acuity, contrast sensitivity, glare sensitivity, dark adaptation and depth perception (Lord *et al.*, 2002b). Degenerations in visual function present in elderly adults may be the result of normal age-related declines or certain diseases and conditions, such as diabetes and cataracts. Indeed, Jack *et al.* (1995) concluded that screening elderly fallers for vision impairment may be

beneficial in the prevention of subsequent falls since some visual impairments are reversible or correctable.

There are several dimensions of visual function, each of which plays an important role and undergoes some age-related decline. It is not within the scope of this research to discuss each aspect in detail, however, a brief description is included here since declining visual function has been associated with an increased risk of falls and researchers have therefore attempted to determine which aspects of visual function are correlated with falling behaviour. Cross-sectional studies with retrospective reporting of falls have identified visual acuity (clearness or sharpness of vision), reduced visual field (particularly peripheral rather than central), impaired contrast sensitivity (the size of detail and its contrast), impaired depth perception and the presence of cataracts as risk factors for falls (Lord, 2006; Lord *et al.*, 2002a; Lord *et al.*, 2002b; Ivers *et al.*, 1998; Klein *et al.*, 1998; Lord *et al.*, 1993; Nevitt *et al.*, 1989; Tinetti *et al.*, 1988; Owen, 1985; Marron and Bailey, 1982). The nature of falls is multifactorial and a combination of intrinsic (i.e. impaired vision) and extrinsic (environmental) factors is a better predictor of falls. Indeed, some investigations have found a stronger correlation with falls when aspects of vision are combined with other risk factors such as inactivity, subjective fall risk and other aspects of vision (e.g. Ivers *et al.*, 1998; Kuyk *et al.*, 1998; Berg *et al.*, 1997; Jack *et al.*, 1995; Lord *et al.*, 1993; Owen, 1985; Marron and Bailey, 1982).

Visual acuity, the most frequently examined aspect of vision in falls-related studies, is typically used as an overall measurement of visual function. A lack of clear, sharp vision results in a reduced ability to detect objects on the walking terrain. Reduced

peripheral visual field reduces the ability to detect hazards out of direct view (e.g. moving object, such as a ball or animal, at ground (tripping) level approaching). Impaired contrast sensitivity increases the difficulty in distinguishing borders of objects in poor lighting conditions, detecting raised or uneven sections of footpath, and observing the edges of tree roots or steps. Given that some aspects of vision have been linked to an increased falls risk, vision tests (visual acuity and edge contrast sensitivity) have been included in the screening for healthy elderly subjects for this research.

The second important task of vision is its central role in the control of balance and posture and has been described as the most efficient source of proprioceptive information for balance control (Lee and Lishman, 1977). As Winter (1995) describes, human balance and posture is controlled by three major sensory systems: 1) visual system for sensing position and location of the body in space; 2) vestibular system, which Winter describes as a 'gyro' which senses movement and stabilises the body with respect to gravity; and 3) the proprioceptive system which senses movement and orientation of all body segments, and their contact with the ground and external objects. The effectiveness of these three systems generally undergo decline with age (Lord *et al.*, 2002b).

Vision and head stabilisation plays a vital role during walking for providing a stable reference to co-ordinate body motion (Mulavara *et al.*, 2002). Menz *et al.* (2003) concluded maintenance of head control, or minimising head movement, was one of the primary objectives of the postural control system, and that the stepping pattern on irregular surfaces may be altered to ensure the head remains stable. Indeed, Koceja *et al.* (1999) found increased postural sway in standing by approximately 42% ($p<.05$) in

response to a volitional head movement by turning the head to the left and right in elderly subjects but no change in young subjects. When vision is directed elsewhere, and not solely allocated to maintaining heading or postural control, the contributions of the proprioceptive and vestibular systems become more important and it appears that the elderly have more difficulty maintaining posture in these situations.

A brief review of the literature regarding sensory control of posture and balance assists in providing an integrated understanding of posture and balance control, including during walking. Researchers have shown that these three sensory systems (i.e. vision, proprioception and vestibular) are particularly challenged in the elderly under distracted conditions, and declines in these systems have been linked with falling behaviour (e.g. Redfern *et al.*, 2001; Shumway-Cook and Woollacott, 2000; Brown *et al.*, 1999; Chen *et al.*, 1996). Researchers have examined the relative contribution of the vestibular, visual and proprioceptive systems to the control of balance by manipulating the availability of these systems and measuring balance recovery responses (e.g. Ducic *et al.*, 2004; Menz *et al.*, 2004; Redfern *et al.*, 2001; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000; Simoneau *et al.*, 1999; Shumway-Cook *et al.*, 1997b; Anacker and Di Fabio, 1992; Ray *et al.*). Several studies have shown that when proprioception or visual input are reduced, older people have significantly more trouble controlling posture than young subjects (Ducic *et al.*, 2004; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000; Manchester *et al.*, 1989). There is evidence to suggest the elderly, particularly those with balance-impairments, typically place most emphasis on visual cues for the control of balance (e.g. Poulain and Giraudet, 2008; Williams *et al.*, 1997).

The study by Simoneau *et al.* (1999) examined postural adjustments of elderly and young subjects under conditions of conflicting sensory input, namely the opening of an elevator door. The motivation for conducting this study was after using continuous video surveillance to record falls by elderly in an assisted living environment that 75% of falls occurred near an elevator. The study is interesting since it is a simulation of a realistic situation (Holliday *et al.*, 1990). While waiting for the elevator, the individual focuses on the doors as a 'visual anchor' to spatially orient themselves in order to maintain balance. It was postulated that opening elevator doors requires a switch of visual anchor from nearby (the doors) to a new anchor further away (the far wall of the elevator cage) (Simoneau *et al.*, 1999). This switch of visual anchor requires recalibration of the body in space and, in the process, produces a destabilising postural response.

The results of Simoneau *et al.*'s study showed that elderly subjects responded with increased COP displacement compared with the younger subjects in response to simulating the opening of an elevator door and that the subjects did not perceive these increased displacements. Judge *et al.* (1995) also suggested that the sensory deficit in failure to detect COP excursion, or centre of mass (COM) displacement, increase the risk for falls if inappropriate responses to the perturbation are made (e.g. due to either muscle weakness or a deficit in the pattern of motor response). In everyday life, individuals are continually required to adapt to changing walking terrains (e.g. flat, bumpy, slippery etc) and adjust to various visually distracting or potentially postural destabilising conditions (e.g. walking in crowded shops, turning the head to scan for cars while crossing a road or simply walking as cars pass by). Each of these situations

has the potential to disturb balance if correct adjustments are not made, particularly if the COM displacement is detected late or not at all.

Researchers have also tested the reliance of visual input on postural control. It has been found that despite impaired vision and/or deficiency in the visual system to adequately control posture, the elderly typically rely on visual information for the control of balance and posture (e.g. Poulain and Giraudet, 2008; Choy *et al.*, 2003; Anderson *et al.*, 1998; Patla, 1997; Sundermier *et al.*, 1996; Chen *et al.*, 1994b; Patla, 1993; Tobis *et al.*, 1985; Marron and Bailey, 1982). Further, the elderly typically require longer periods of visual information to orient themselves and modulate step length in order to avoid obstacles. The relatively greater dependence on visual sources in the elderly is thought to be in response to impaired feedback on posture and gait from the proprioceptive and vestibular systems as a result of age and chronic health problems (Tobis *et al.*, 1985). Given that balance-impaired elderly individuals typically rely more heavily on visual input for balance, they are clearly more at risk of falling in situations where something unexpected occurs in the generally motion-rich nature of today's environment (Anderson *et al.*, 1998; Sundermier *et al.*, 1996).

2.1.2.3 Impaired cognition and divided attention ability

Cognition, or cognitive function, includes memory, association, comparison, abstract reasoning, spatial ability and manipulation and synthesis. The processes of cognitive function, including attention, working memory, information processing speed, psychomotor ability and perception, support cognitive functions (Spirduso, 1995). Impaired cognition may be the result of certain disease processes but is typically

observed with increasing age and has been associated with an increased risk for falls (e.g. Giladi, 2007; Snijders *et al.*, 2007; Yogev-Seligmann *et al.*, 2007; Tinetti *et al.*, 1988). Associated with the declines in perceptual-motor and cognitive abilities typically seen in the elderly is the ability to divide attention. It is consistently reported that the elderly, compared with younger adults, have more difficulty dividing attention between multiple tasks (Jamet *et al.*, 2007; Brauer *et al.*, 2002; Sparrow *et al.*, 2002a; Brown *et al.*, 1999; Hartley and Little, 1999; Chen *et al.*, 1996; Lajoie *et al.*, 1996; Ponds *et al.*, 1988; McDowd, 1986). This difference in divided attention ability appears to remain unchanged regardless of the amount of practice given (McDowd, 1986). Moreover, the reduced ability of older adults to divide attention has been cited as a risk factor for falls (e.g. Springer *et al.*, 2006; Woollacott and Shumway-Cook, 2002; Campbell *et al.*, 1989; Stelmach and Worringham, 1985).

Dual-task (divided attention) paradigms are frequently utilised in cognitive psychology to gain an understanding of the processes that produce skilled performance (Abernethy, 1988). In recent years, however, dual-task applications have been employed in the area of motor control behaviour problems, such as postural control during standing and walking (Dubost *et al.*, 2008; e.g. van Iersel *et al.*, 2007; Toulotte *et al.*, 2006; Broglio *et al.*, 2005; Schrodt *et al.*, 2004; Brauer and Burns, 2002; Sparrow *et al.*, 2002a). Dual-task, or divided attention, methodology simply implies that more than one task are performed concurrently. The task for which the attentional demands are of interest is termed the 'primary task'. A 'secondary' task is performed under two conditions, 'single-task' (performed alone with no other distractions) and 'dual-task' (a second task performed concurrently with the primary task). Performance changes in the secondary

task during dual-task compared with single-task conditions are noted allowing conclusions to be drawn regarding the attentional demands of the primary task.

The basic assumption underlying the use of these methodologies is an individual has limited central processing capacity and part of this processing capacity is required for performing a task. Performing two tasks concurrently requires the processing capacity to be shared, therefore disturbing performance on one or both tasks if the limited processing capacity is exceeded (Lajoie *et al.*, 1993). In other words, the more demanding the primary task, the more attentional resources will be required to maintain the level of performance of that task. Therefore, poor secondary task performance equates to high primary task demands whilst good secondary task performance is interpreted as the primary task requiring little attentional capacity (Abernethy, 1988).

Postural control has traditionally been viewed as an automatic response that requires minimal attentional resources. However, research has revealed that postural control requires significant attentional resources and that this increases with age and the difficulty of the task, for example, quiet standing compared with walking (e.g. Marsh and Geel, 2000; Brown *et al.*, 1999; Lajoie *et al.*, 1993; Kerr *et al.*, 1985). It has been consistently found in the research that the declines in postural control and balance typically observed with advancing age contribute to an increased falls risk (e.g. Springer *et al.*, 2006; Woollacott and Shumway-Cook, 2002; Stelmach and Worringham, 1985).

Since declines in postural control and reduced ability to divide attention are contributing factors for falls, researchers have investigated the interaction of these

factors. These studies have explored the relationship between attention and postural control in static (Jamet *et al.*, 2007; Sparrow *et al.*, 2006; Sparrow *et al.*, 2002a; Redfern *et al.*, 2001; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000) and dynamic conditions (Dubost *et al.*, 2008; van Iersel *et al.*, 2007; Sparrow *et al.*, 2006; Schrodt *et al.*, 2004; Brauer *et al.*, 2002; Sparrow *et al.*, 2002a; Lundin-Olsson *et al.*, 1998; Chen *et al.*, 1996) by utilising various cognitive (Toulotte *et al.*, 2006; Lundin-Olsson *et al.*, 1998) and manual (Sparrow *et al.*, 2006; Sparrow *et al.*, 2002a; e.g. Woollacott and Shumway-Cook, 2002; Shumway-Cook and Woollacott, 2000; Chen *et al.*, 1996) secondary tasks. Many dual-task studies have found significant differences between healthy old and young subjects (e.g. Toulotte *et al.*, 2006; Brauer *et al.*, 2002; Shumway-Cook and Woollacott, 2000; Shumway-Cook *et al.*, 1997b), and healthy older adults and older adults with pathology or a history of imbalance or falls (Shumway-Cook *et al.*, 1997b) thus suggesting the elderly, particularly those with pathology or falls history, are at a greater risk of falls in situations where attention is divided. In fact, relatively simple cognitive tasks are sufficient to induce an increased challenge to balance when postural stability is already impaired (e.g. Shumway-Cook *et al.*, 1997b).

It has been postulated that the increased attentional resources required for posture and balance in older adults may be accounted for by the typical age-related decline in the three sensory systems which control balance, namely visual, vestibular and proprioceptive systems (e.g. Pellecchia, 2003; Redfern *et al.*, 2001; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000). Researchers have, therefore, examined the contribution of these sensory losses to the ability to maintain posture and balance. Whilst some of these studies investigate the primary task as one condition, e.g. postural

control in static standing, others investigate the primary task under a number of situations of progressively more challenging positions (e.g. static standing on a compliant (foam) surface). Researchers can manipulate the difficulty of the primary task of postural control by reducing or providing conflicting sensory input from the visual, vestibular and proprioceptive systems in single- and dual-task conditions (e.g. Pellecchia, 2003; Redfern *et al.*, 2001; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000). These studies all concluded that the elderly are more affected than the young and that postural control was more affected in situations of reduced sensory input and particularly conditions of conflicting sensory information.

A description of the study by Redfern *et al.* (2001) is helpful in explaining the methodologies typically employed to manipulate the amount of sensory feedback for postural control. Redfern *et al.*'s study explored the contribution of all three sensory systems, namely the visual, vestibular and proprioceptive systems, to postural control. Figure 2.5 shows experimental set-up to measure postural control using Computerised Dynamic Posturography (CDP) (Equitest, NeuroCom Int. Inc.). As seen in parts b) and c), this system provides rotation of the floor surface (sway-referenced surface) and visual surround (sway-referenced visual scene). Sway-referencing measures centre of pressure (COP) excursion via the in-built force platform and uses this to estimate body sway in the anterio-posterior (AP) direction. Body sway is then used to control the AP rotation of the floor surface and visual scene as follows:

1. Sway-referenced floor condition - the tilt of the floor surface (AP ankle rotation) is proportional to the amount of AP body sway. This procedure

reduces the effectiveness of the proprioceptive system via the rotating floor surface.

2. Sway-referenced visual scene - the amount of AP rotation of the visual surround is proportional to the amount of AP body sway. This procedure reduces the effectiveness of the visual system via the moving visual surround.

3. Sway-referenced floor condition and visual scene combined - the amount of AP body sway controls the tilt of the standing surface and visual surround to ensure ankle angle relative to the visual surround remains constant and, therefore, visual scene stabilised. This procedure reduces the effectiveness of the visual system via the moving visual surround and the proprioceptive system via the rotating floor surface, thereby placing greater emphasis on the vestibular system.

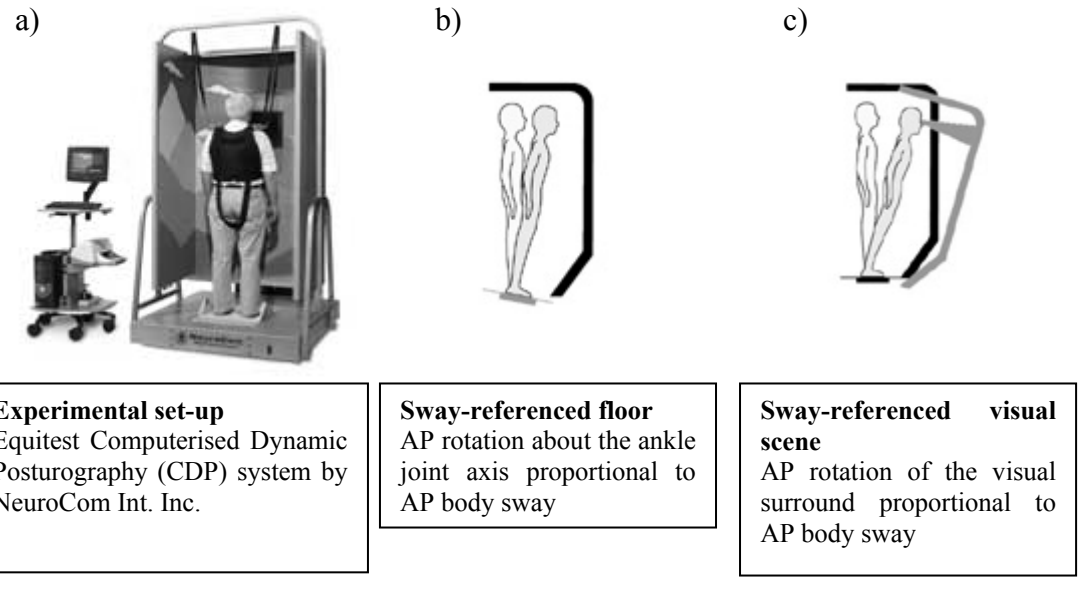


Figure 2.5: Experimental set-up as used by Redfern *et al.* (2001).

a) shows experimental set-up with subject wearing protective harness; b) shows the rotating force platform. Rotation about the ankle joint is proportional to the anterio-posterior (AP) body sway thereby reducing proprioceptive input to the control of balance and placing greater emphasis on the visual and vestibular systems; c) shows sway-referenced visual scene where AP movement of the visual surround is proportional to the AP body sway as measured by COP excursion via the force plate thereby altering visual input to the control of balance and placing greater emphasis on the vestibular and proprioceptive systems.

Using the sway-referencing methods, the researcher can manipulate the effectiveness of specific sensory input and provide conflicting sensory information. For example, during the sway-referenced visual scene the effectiveness of the visual system for maintaining balance is challenged since conflicting sensory information is received. The moving visual scene increases the difficulty of the visual system determining an accurate reference frame with respect to the environment and, therefore, contribution of vestibular and proprioceptive input is relied upon to compensate for the lack of effective visual input.

While Equitest by NeuroCom (refer Figure 2.5) is an effective and useful method of evaluating sensory contribution to balance, the equipment is expensive and other researchers have successfully employed alternative, inexpensive methods. For example, the Clinical Test of Sensory Interaction and Balance (CTSIB), described by Shumway-Cook and Horak (1986), require only a foam standing surface and a visual conflict dome, which is placed over the subject's head to provide conflicting visual feedback. The CTSIB is a timed test and was developed for systematically evaluating the contribution of visual, proprioceptive and vestibular input on standing balance. There are six conditions in the CTSIB:

1. Standing on floor with eyes open
2. Standing on floor with eyes closed
3. Standing on floor and wearing visual conflict dome
4. Standing on foam surface with eyes open
5. Standing on foam surface with eyes closed
6. Standing on foam surface wearing visual conflict dome

The foam standing surface is used instead of the rotating surface of the Equitest to reduce proprioceptive input and the dome provides a sensory conflict by depriving the subject of peripheral vision and introducing a sway-referenced image. The CTSIB has been used described as an effective screening tool for measuring standing balance (e.g. Madureira *et al.*, 2007; Whitney and Wrisley, 2004; Wrisley and Whitney, 2004; Boulgarides *et al.*, 2003; Allum *et al.*, 2001) and has often been in studies evaluating aspects of balance (e.g. Shumway-Cook and Woollacott, 2000). Another alternative has been using a moving vertical line in the lateral direction, placed in front of the subject, which provides incorrect feedback from the visual system in stead of the moving visual surround (Shumway-Cook and Woollacott, 2000).

In the study by Redfern *et al.* (2001), challenge to postural control in healthy young (n = 18) and older (n = 18) subjects was manipulated by providing different conditions:

1) seated;
2) standing on fixed floor with a stable visual environment;
3) standing on sway-referenced floor with a fixed visual scene;
4) standing on sway-referenced floor with a sway-referenced visual scene.

The different information processing tasks were:

1) none;
2) a visual simple reaction time (SRT) task (subjects responded to a visual probe (green light-emitting diode (LED)) at eye level on the visual surround) by pressing a hand-held button);

3) an auditory SRT task (subjects responded to an auditory probe (1000 Hz tone presented for 1s through a set of headphones) as quickly as possible by pressing a hand-held button); and
4) an inhibition reaction time task (IRT) (subjects responded to the visual probe (green LED) unless they heard an instruction to stop through the headphones.

Reaction times were measured for all three tasks. The results showed postural sway was significantly greater in older adults ($p<.001$) across all information processing tasks. Within-group analysis of postural condition and information processing task on postural sway revealed older subjects were significantly affected by postural condition ($p<.001$) and information processing task ($p<.01$) and their interaction ($p<.007$) while young subjects were affected by postural condition only ($p<.002$). Postural sway of young subjects was not affected by concurrent information processing task and was only affected by postural task ($p<.001$). Further analysis revealed older subjects were significantly influenced by information processing task in postural condition 4 (sway-referenced floor and sway-referenced scene) ($p<.002$) only, but this was not seen in young subjects.

Studies investigating ability to maintain posture under dual-task conditions have all found that the elderly have more difficulty maintaining postural stability than young subjects in all postural conditions. These studies have contributed much to the area of divided attention ability and falls by revealing that the elderly are particularly affected under conditions of multiple sensory conflict. Given that many instances of either reduced or conflicting sensory input are encountered during normal everyday walking,

these studies have been useful by examining the responses of elderly individuals in these situations.

The findings of these investigations have resulted in some important recommendations for falls prevention and identification of those at risk. For example, Brauer *et al.* (2002) concluded balance recovery (i.e. stepping) with attention focused on another task would be a useful addition to balance training for elderly adults to reduce the likelihood of falls. Shumway-Cook *et al.* (1997a) suggested balance retraining should include general stability training under dual-task conditions. Since the elderly have difficulty maintaining postural control, balance and balance recovery under situations of divided attention, it is important to improve performance in these conditions to reduce the risk of falling. Bloem *et al.* (2001) proposed a new balance test incorporating a dual-task challenge to posture and cognition, the Multiple Tasks Test (MTT). This study is one of only a few that included real-life situations as opposed to those performed in a controlled laboratory setting. The MTT test is based on simultaneous assessment of multiple postural components, represents everyday situations, and can be applied by clinicians. The MTT test (Bloem *et al.*, 2001) required healthy young (n = 50) and healthy elderly (n = 13) to complete a series of eight tasks comprised of 11 separate components (refer Table 2.1).

Table 2.1: Components of the Multiple Tasks Test (MTT), Bloem *et al.* (2001).

Components	Task							
	One	**Two**	**Three**	**Four**	**Five**	**Six**	**Seven**	**Eight**
1. Standing up	+	+	+	+	+	+	+	+
2. Undisturbed walking	+	+	+	+	+	+	+	+
3. Turning around	+	+	+	+	+	+	+	+
4. Sitting down	+	+	+	+	+	+	+	+
5. Answering questions		+	+	+	+	+	+	+
6. Avoiding obstacles			+	+	+	+	+	+
7. Carrying empty tray				+	+	+	+	+
8. Carrying loaded tray					+	+	+	+
9. Slippery shoes						+	+	+
10. Bending to touch the floor							+	+
11. Reduced illumination								+

Components selected for MTT are listed in the first column, the eight tasks are shown in the top row. '+' indicates components used during each of the eight consecutive, progressively more difficult, tasks. For example, in task one, subjects were required to stand up (component 1.), walk undisturbed 8m (component 2.), turn around 180 deg (component 3.) and sit down (component 4.). These four components were repeated seven times (tasks two to eight), but each time including one extra task (components 5. through to 11.). The shaded areas indicate components that were scored (i.e. 'normal' – rapid performance of all components within the task; 'hesitation' – obvious slowing in one or more components within the task; or 'block' – complete stop or inability to perform one or more components within the task). From Bloem *et al.* (2001), p194.

Each task was progressively more difficult by including more components that were to be completed. The components were chosen after review of the literature to identify specific risk factors for falls that could be adapted to become a functional test. As listed in Table 2.1, the different components included a cognitive component of a continuous mental task (answering questions, component 5.), components that challenged the motor system (components 1. to 4., 7. and 10.), some of which required specific attention (components 6. and 8.). The third component challenged the visual system by reducing illumination in the room (component 11.) and the final component was wearing shoes with slippery soles (component 9.).

Subjects were scored on performance of the tasks, indicated by the shaded areas in Table 2.1. This involved subjective assessment by the researcher as 'normal' – rapid performance of all components within the task; 'hesitation' – obvious slowing in one or more components within the task; and 'block' – complete stop or inability to perform one or more components within the task. Some items were not able to be scored but were included to complicate the task and facilitate a greater rate of errors in the task. These included carrying the unloaded or loaded tray, wearing slippery shoes and reduced illumination. Results of the study showed that motor errors increased significantly as the complexity of the task increased ($p<.05$) and the elderly made more overall errors compared with the young subjects (52% of young subjects made errors vs. 92% of elderly, $p<.01$). These results were consistent with those of Southard *et al.* (2005), who found the MTT is a promising predictor of falls even in high-functioning elderly.

The studies by Bloem *et al.* (2001) and Southard *et al.* (2005) are significant since they are amongst only a few to include real-life situations in dual-task methodologies. The first study to examine real-life situations found elderly subjects who stopped walking when talking had an increased risk of falling (Lundin-Olsson *et al.*, 1997). The authors postulated that the divided attention task of walking whilst talking was so attentionally demanding in some elderly subjects that they stopped walking in order to talk. The authors then used a manual task of carrying a glass of water during performance of the Timed Up & Go (TUG_{manual}) test vs. TUG without carrying the glass (Lundin-Olsson *et al.*, 1998). The TUG test (Podsiadlo and Richardson, 1991) is a test of functional mobility requiring subjects to stand from a chair, walk 3 meters, turn around, walk back and sit down as quickly as possible (refer methods chapter). The Lundin-Olsson *et al.*

(1998) study found elderly subjects with a greater time to complete TUG_{manual} compared with TUG also had significantly poorer scores on other tests of known risk factors such as dementia, vision, hearing, activities of daily living (ADLs), dynamic balance, cognitive function and visual perception ($p<.007$ to $p<.04$). A recent study explored the use of MTT with high-functioning older adults to see whether performance was correlated with the Berg Balance Scale (BBS), a widely accepted test for measuring falls risk (Southard *et al.*, 2005). Results showed significant correlations between BBS and MTT ranging from -.765 to -.79 ($p<.01$).

Despite the increasing number of studies of divided attention ability, the dual-task paradigm is not without controversy. These controversies generally involve deviation from the strict methodological criteria of traditional dual task paradigms. One of these methodological issues is 'attentional switching' between the primary and secondary task. As Abernethy (1988) highlighted in his paper detailing dual-task applications and constraints, performance on the primary task must be held constant in order for meaningful interpretation of the effects of the secondary task to be made. For example, where the attentional demands of postural control are being assessed there should be no change in postural control as measured by centre of pressure excursions during the dual task conditions. For this reason it is recommended that subjects be given clear instructions including ensuring full attention is allocated to the primary task. Abernethy (1988) states where primary task performance is not held constant, there is confusion in interpreting the performance decrements on the secondary task as a consequence of attentional resources required for the primary task or due to attentional switching between the two.

More recently, researchers have purposefully included attentional switching in dual-task studies of postural control in elderly individuals by examining performance on both the primary and secondary tasks (e.g. Jamet *et al.*, 2007; van Iersel *et al.*, 2007; Toulotte *et al.*, 2006; Schrodt *et al.*, 2004; Redfern *et al.*, 2001; Shumway-Cook *et al.*, 1997b). Shumway-Cook *et al.* (1997b) measured postural stability under two conditions (static standing on firm and compliant surface to manipulate proprioceptive input) by measuring centre of pressure excursion with different cognitive tasks:

1. Sentence completion task – language processing task. Required subjects to create a four-word sentence by filling in four blank lines, some of which were preceded by a letter indicating the word must begin with that letter.

2. Judgement of Line Orientation (JOLO) – a perceptual matching visual task. Required subjects to identify the two single lines which best describe the orientation of an array of lines presented. This well established test evaluates visuo-spatial ability, a known falls risk factor.

Changes to the primary task (postural stability via COP excursion) and performance on the secondary cognitive tasks were measured. In older adults with a falls history postural stability was significantly affected by surface ($p<.001$) and both cognitive tasks (JOLO, $p<.03$; sentence completion, $p<.0001$) compared with healthy young and healthy old adults. Their results also revealed a high correlation between performance on clinical measures of balance and mobility and COP excursion in dual-task conditions ($r = -.419$ to $-.835$, $p<.0001$).

In a review article, Woollacott and Shumway-Cook (2002) defended the usefulness of studies examining performance on both the primary and secondary tasks in showing attentional demands of postural control. They did, however, acknowledge their limitation in clarifying the exact attentional demands due to the interaction of the two tasks, as described by Abernethy (1988). Indeed, studies examining the influence of various distractions on postural control are very important for determining how individuals react when subjected to divided attention conditions. Once this is understood it is then possible to predict situations in which falls risk is increased.

Whilst the emerging trend for dual-task studies of postural control using this methodology do not quantify the change in secondary task performance during dual- compared with single-task performance, they are very useful in examining the effect of attentionally demanding tasks on postural control. In order to compensate for any possible learning effect, researchers using this method have conducted the secondary task prior to the testing session to allow for practice and in order to determine how many trials are required to obtain stable values (e.g. Pellecchia, 2003; Redfern *et al.*, 2001; Shumway-Cook and Woollacott, 2000).

Researchers have examined how individuals prioritise tasks in divided attention situations and the circumstances in which the allocation of attention for maintaining posture is affected. It is thought that a 'posture first' strategy exists where maintaining posture takes precedence over any concurrent task and is therefore related to the issue of attentional switching. The increasing number of studies examining both postural control measures as primary task and various secondary task assume performance decrements will occur on the primary task by selecting them as outcome measures. In a

posture first strategy, minimal change to postural control measures (e.g. COP excursion) is expected since attentional resources would be allocated to maintaining posture. This theory has not been supported in all studies, however, and some have found posture first was more likely to apply to young subjects (e.g. Shumway-Cook and Woollacott, 2000; Stelmach *et al.*, 1990).

The findings for theories of posture first strategy and allocation of attention during more complex tasks are not clear. However, the effects of manual tasks and cognitive tasks in particular on postural control are receiving more attention in the literature. It is possible the lack of support for the posture first strategy is due to the tasks used being relatively simple and not sufficient to pose a considerable challenge to available attentional resources and postural control. Therefore, a modification to the posture first attentional hierarchy has been proposed (e.g. Bloem *et al.*, 2001; Shumway-Cook *et al.*, 1997b). It has been suggested that the allocation of attention is complex and depends on the nature of the cognitive and postural task, the goal of the subject, and the instructions given. In a controlled laboratory setting where the subject wears a safety harness and/or has a researcher close by in order to 'catch' them, the threat of injury is not great. Therefore, in situations where the postural task is perceived as hazardous, the posture first theory is more likely to apply. Further research is required to determine the responses of young and elderly, and those with falls history and/or other pathology, in these situations.

Abernethy (1988) highlighted the need to avoid 'structural interference', where both the primary and secondary tasks share a common sensory or response modality. Typically, in studies examining the dual-task effect on postural control, structural

interference occurs when the visual system is required for the secondary task (e.g. reaction time to a visual probe) whilst also being required to maintain postural control. However, it is not yet known whether visual processing for postural control and a secondary visual information-processing task utilise the same pathways. Some studies have attempted to eliminate structural interference in order to more accurately evaluate the attentional demands of the primary task. For example, Marsh and Geel (2000) hypothesised that since vision is involved in maintaining balance, a verbal reaction time task to an auditory rather than visual stimulus would be better to minimise structural interference. Other studies, however, have purposefully included such structural interference since it is a situation that does occur in normal everyday life, such as the use of vision to maintain posture whilst walking with conflicting visual input as cars pass by on busy roads (e.g. Jamet *et al.*, 2007; Bloem *et al.*, 2001; Shumway-Cook *et al.*, 1997b). It is important to include real life divided attention situations in studies in order to gain a more comprehensive understanding of the situations in which the elderly are more likely to fall.

Divided attention while walking, and its relative contribution to the likelihood of tripping is scarce in the literature. However, divided attention and the ability to avoid obstacles while walking is receiving more attention (e.g. Schrodt *et al.*, 2004; Weerdesteyn *et al.*, 2003; Chen *et al.*, 1996). Schrodt *et al.* (2004) measured centre of pressure excursions (COP) of the trail limb at obstacle crossing and several gait variables, including foot clearance, step length, horizontal toe-obstacle distance (HTO), horizontal heel-obstacle distance (HHO), overall gait speed and obstacle crossing speed in healthy elderly adults (n = 21). Subjects walked at their fastest speed without distraction and stepped over an obstacle (wooden block, 0.91cm in width, 0.15m in

depth and 0.02m in height) (single-task) and in conjunction with a cognitive task of reciting numbers (dual-task). The authors hypothesised that fast walking posed a greater challenge than self-selected walking and speed and therefore could be useful in examining the effect of dual-task activities on gait performance. Significant differences between single- and dual-task were only found for HTO (0.291cm vs. 0.315cm, $p \leq 0.001$) and HHO (0.188cm vs. 0.038cm, $p \leq 0.009$). Additionally, performance decrements were observed on the secondary task of reciting numbers (single-task = 98.2% vs. dual-task = 92.7% accuracy, $p \leq 0.007$).

Chen *et al.* (1996) were the first to examine obstacle avoidance performance during overground walking at a self-selected comfortable walking speed in young (n = 16) and elderly adults (n = 16) while attention is divided. The study measured rates of success (RS) in avoiding a band of light (virtual obstacle) that was suddenly projected across the gait path. The virtual obstacle appeared at the predicted next-footfall locations to give either 350ms or 450ms available response time (ART) to successfully avoid the obstacle. A secondary cognitive task of responding vocally to a visual red light emitting diode (LED) stimulus as quickly as possible was performed concurrently with the task of obstacle avoidance. Two secondary reaction time tasks were used: synchronised reaction time (SRT) – when only red LEDs were lit at the end of the walkway at intervals synchronised with the appearance of the obstacle; and unsynchronised reaction time (URT) – when green or yellow LEDs in addition to the red LEDs were presented with intervals not synchronised with the appearance of the obstacles. Subjects were to respond to the red LED only and reaction time was measured under conditions of no attention division (RT task only), SRT division and URT division.

The results showed smaller ART and increased task complexity (i.e. URT task) was responsible for reduced obstacle avoidance performance, particularly in the elderly. With a smaller ART of 350ms, RS of obstacle avoidance in young subjects decreased by 14.7% during the SRT task and 19.9% for URT task. The decrease in performance was significantly greater in older adults (SRT, $p<.033$; URT, $p<.015$) with decreases of 32.0% and 35.7% in SRT and URT task, respectively. In the SRT trials, young subjects avoided obstacles approximately 75% of the time but elderly successfully avoided obstacles in less than half of the trials ($p<.001$). Chen *et al.* (1996) concluded that divided attention significantly decreased successful obstacle avoidance in young and old subjects, but significantly more in the older subjects and particularly under time critical conditions (i.e. reduced ART).

Several methodological criticisms could be made of the study by Chen *et al.*(1996). First, it is possible that subjects anticipated the appearance of the obstacle and therefore altered their gait pattern accordingly. It has been found that anticipatory movements to compensate for a predictable perturbation are made in order to place the body in a more stable position (McIlroy and Maki, 1995). Further, it has been found that subject responses to perturbations on the first instance (e.g. on a novel travel terrain) differ fundamentally to subsequent responses (Patla *et al.*, 1996; McIlroy and Maki, 1995). Lythgo (2003) suggested future research should examine the first compensatory response to a novel path or disturbance. The second methodological limitation involves the use of structural interference by using the same input system (visual system) for maintenance of posture, detection of the virtual obstacle and observing and responding to the visual stimuli. Chen *et al.* (1996), however, suggest that structural interference

and distractions whilst walking are to be expected in normal, everyday life, and even fit and healthy older adults are at a greater risk of tripping over obstacles that suddenly appear in the field of view.

2.1.3 Falls prevention and prediction

Given the frequency and seriousness of falls in older populations, there has been considerable effort dedicated to devising effective preventative interventions. As Lord *et al.* (2002b) highlight, the initial step to effective falls prevention is identifying risk factors that are amenable to modification. Some techniques may be more effective than others and since the aetiology of falls is regarded as multifactorial, a combination of preventative measures may be required. Further, since each individual varies considerably with regard to deficits, programs that are tailored to the individual appear to be more effective (NARI, 2004). Most falls prevention research focuses on preventing the fall itself, however, there is an identified need for further research investigating the effectiveness of interventions to reduce the severity of injuries, such as fractures, related to falls (NARI, 2004; Gillespie *et al.*, 2003; Gardner *et al.*, 2000).

Some systematic reviews and meta-analyses, including a Cochrane Collaboration systematic review, of interventions for falls prevention in the elderly have been conducted (Chang *et al.*, 2004; Gillespie *et al.*, 2003; Lyons *et al.*, 2003; Gardner *et al.*, 2000). In general, the strongest evidence has been found for multidisciplinary interventions combined with multifactorial risk assessments for unselected population of older people, with risk ratio (RR – the probability of a fall occurring by observing the number of subjects who fell relative to the total sample) 0.73, 95% CI 0.63-0.85

(Gillespie *et al.*, 2003) and RR 0.82, 95% CI 0.72-0.94 (Chang *et al.*, 2004), and elderly with a falls history RR 0.86, 95% CI 0.76-0.98.

Exercise appears to be the next most effective preventative strategy with RR 0.86, 95% CI 0.73-1.01 (Chang *et al.*, 2004), however, Chang *et al.* grouped balance, endurance, flexibility and strength and found no differences between type of exercise. The precise components of exercise programs most effective in reducing falls and/or injurious falls are still unclear (Gardner *et al.*, 2000). The Cochrane Collaboration systematic review (Gillespie *et al.*, 2003) found a program of strength and balance retraining, individually prescribed at home by a trained health professional was effective with RR 0.80, 95% CI 0.66-0.98. The Gillespie *et al.* (2003) review also concluded home hazard assessment and modification that is professionally prescribed for elderly with falls history (RR 0.66, 95% CI 0.54-0.81), withdrawal of psychotropic medication (RR 0.34, 95% CI 0.16-0.74) and 15-week Tai Chi group exercise intervention (RR 0.51, 95%CI 0.36-0.73) were interventions likely to be beneficial. As described by Gillespie *et al.* (2003), it appears that the most effective exercise is tailored to the individual, is professionally prescribed and includes elements of balance and strength training.

Given the focus of this thesis is on tripping, it is pertinent to explore preventative techniques specifically aimed at risk factors relating to tripping. Whilst most studies of improved measure the effect on falls outcome (number of falls) in general, Lamoureux *et al.* (2003) studied the effect of improved lower body strength on obstacle negotiation. Improved obstacle negotiation strategy, thereby reducing the risk of tripping, clearly is an important contribution to falls prevention research. Community-dwelling elderly adults were randomised into control (n = 16) or experimental group (n

= 29). The experimental group undertook 24 weeks of progressive resistance training aimed at strengthening the muscles of the lower body. Significant strength improvements were reported at the conclusion of the 24 weeks programme ($p<.05$) and these were associated with significantly improved functional gait and safe obstacle negotiation strategy. These findings suggest that improved muscular strength, with associated improvements in obstacle negotiation, is likely to result in decreased falls risk.

As outlined in section 2.1.2.2, vision plays a very important role in safe walking and prevention of tripping. McGwinn *et al.* (2006) examined the effect of cataract surgery, and the resulting improvement in visual acuity and contrast sensitivity, on falls and mobility in community-dwelling elderly adults. The study examined older adults with cataracts who elected to have surgery (n = 122) compared with those who did not have surgery (n = 92). Baseline data including recalled number of falls in the previous 12 months, visual acuity and contrast sensitivity were recorded. Subjects were retested for visual acuity and contrast sensitivity and to recall falls at follow-up, which was at least 12 months after surgery. The study reported improved levels of visual acuity and contrast sensitivity post surgery, however, there was no difference in fall rate between the surgery and no-surgery groups. The authors note that further study is required and it may be that other pathologies prevented an improvement in fall rate.

Harwood *et al.* (2005) also examined the effect of cataract surgery on vision, health outcomes and falls. The study examined elderly females with cataracts (n = 306) who were randomised into expedited (approximately 4 weeks wait) and routine (12 months wait) surgery. Falls were recorded in a diary and follow-up occurred every 3 months.

Rate of falling was reduced by 34% in the operated group (rate ratio 0.66, 95% confidence interval 0.45 to 0.96, $p = 0.03$). Furthermore, activity, anxiety, depression, confidence, visual disability, and handicap all improved in the operated group compared with the control group.

Whilst most falls prevention research is targeted at identified intrinsic factors (e.g. through exercise programs), extrinsic factors have been studied less. Extrinsic factors, typically combined with intrinsic factors, are responsible for tripping during locomotion. Since tripping is a frequent cause of falls during locomotion (Pavol *et al.*, 1999) and tripping frequency has been cited as a risk factor for falls (NZNHC, 1997), reducing the likelihood of tripping is likely to be an effective falls prevention approach. No studies have attempted to predict individuals at risk of tripping.

Given the seriousness and frequency of falls in the elderly, the ability to predict those at risk would enable suitable interventions to be implemented and tailored to the individual. Despite its importance in preventing falls, literature on falls prediction is scarce. As one would expect, the number of falls increase with the number of fall risk factors present, however, older people with no identified risk factors still fall (e.g. AGS, 2001; Hill *et al.*, 1999). The critical need to predict a first-time faller, typically with no apparent falls risk factors, has been identified (e.g. Gabell and Nayak, 1984).

In general, studies exploring predictive techniques have used certain identified risk factors in predictive models to distinguish fallers from non-fallers (Maki, 1997; Gabell and Nayak, 1984). Since changes in gait typically seen in the elderly have been linked with a risk of falling, and the fact that falls are commonly reported during locomotion,

researchers have attempted to use gait variables in predictor models. For example, intra-individual stride-stride variability has been identified as a strong predictor of falls (e.g. Dingwell and Marin, 2006; Dingwell *et al.*, 2001). The major limitation with most studies of intra-individual variability and falls risk is the failure to examine consecutive strides. Additionally, these studies typically examine small numbers of strides of up to 10 non-consecutive strides. Examination of consecutive strides over a longer period allows a more comprehensive understanding of the control and function of gait. While some studies have explored the use of intra-individual variability in gait over consecutive strides (e.g. Woollacott and Shumway-Cook, 2002), examination of intra-individual variability of the important gait parameter of MFC has received little attention. Adequate foot clearance is vital for safe walking and it is important to understand how intra-individual variability influences an individual's risk of tripping.

2.1.4 Summary

The high incidence of falls combined with a high prevalence of injury and death rates in elderly populations is a serious concern. Indeed, even when death does not occur, the human costs of falls are enormous in terms of the associated morbidity and the impact on quality of life including loss of independence through possible admittance to care-facility, loss of confidence, fear of falling and social isolation.

The seriousness of falls in the elderly has resulted in a plethora of studies examining various aspects of falls risk. These investigations have contributed to the knowledge of falls aetiology but have primarily focused on intrinsic factors. It has been recognised that there is an important interaction between intrinsic and extrinsic risk factors.

Moreover, extrinsic (environmental) factors, often combined with intrinsic factors, are involved in tripping incidence, a major cause of falls during locomotion. It has also been found that tripping frequency is a strong predictor for falls. Despite this, there are few studies examining the foot kinematics during walking and no studies have used such information to evaluate the risk of tripping.

Declines in cognition, including divided attention ability, are typically observed with ageing and have been recognised as falls risk factors. Research has consistently shown the elderly perform more poorly than the young under conditions of divided attention regardless of the amount of practice given. Dual-task, or divided attention, experiments have been employed to examine the attentional demands of one task while performing a second concurrent task. Dual-task experiments are not without controversy with several methodological issues being debated. These issues have centred on observing performance decrements in the secondary task whilst the primary task is kept consistent. However, it has been argued that observing changes in the primary task (e.g. postural control measured by COP excursion) makes a useful and important contribution to falls research (Woollacott and Shumway-Cook, 2002). Strict criteria are traditionally followed to ensure there is no conflict in the sensory modalities utilised. However, it is also argued that these studies represent real-life situations and also contribute important information to falls research.

There is a lack of dual-task research examining 'real-life' situations despite the identified need for such research. Moreover, there is a lack of research on divided attention ability under conditions of dynamic stability, such as walking. Studies examining postural stability have mainly been limited to static standing (e.g. Redfern *et*

al., 2001; Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000). Divided attention and the ability to avoid obstacles while walking has been investigated in two studies (Weerdesteyn *et al.*, 2003; Chen *et al.*, 1996). However, divided attention while walking, and its relative contribution to the likelihood of tripping has not yet been investigated. Moreover, the types of distractions most likely to disrupt walking and increase tripping risk have not been examined. This research addresses some of the gaps in the literature by examining the likelihood of healthy elderly females tripping on unseen obstacles whilst walking under undistracted and distracted conditions.

2.2 Biomechanics of normal human gait

2.2.1 Overview of the gait cycle

Walking, or gait, is one of the most common and necessary activities humans undertake, affording independence and quality of life via a means of interacting with the environment. Whilst the ability to walk may be taken for granted, it has been described as one of the most complex and totally integrated movements (Winter, 1991a). In elderly populations, falls are frequently associated with degenerations in the control of walking (Sudarsky, 1990). Additionally, tripping is the most commonly cited reason for falling whilst walking (Kreisfeld *et al.*, 2004; Cripps and Carman, 2001; Hill *et al.*, 1999; Sattin *et al.*, 1998; Lord *et al.*, 1993; Campbell *et al.*, 1990; Tinetti and Speechley, 1989; Overstall *et al.*, 1977). An understanding of the biomechanics of gait allows an appreciation of the inherently unstable nature of the body while walking and how easily tripping can occur.

The gait cycle is generally defined as the time interval between two successive heel contact events of one foot. Figure 2.6 depicts one gait cycle from heel contact events of the right foot, or one stride. It is characterised by a stance phase (60% of the total gait cycle), where at least one foot is in contact with the ground, and a swing phase (40% of the total gait cycle), where one limb swings through to the next heel contact (Whittle, 1993) (Winter *et al.*, 1991).

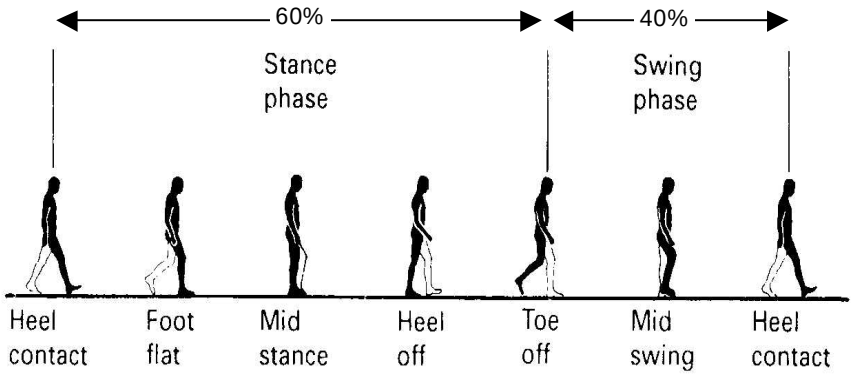


Figure 2.6: Positions of the legs during a single gait cycle from right heel contact to right heel contact (adapted from Whittle, 1993).

Figure 2.7 depicts the contribution of the right and left legs to one gait cycle. It can be seen that the stance phase (total of 60% of the gait cycle) is comprised of two episodes of double support (a total of 20%) and single support (40%). The body is, therefore, supported by one leg approximately 80% of the time during one entire gait cycle (Winter *et al.*, 1991).

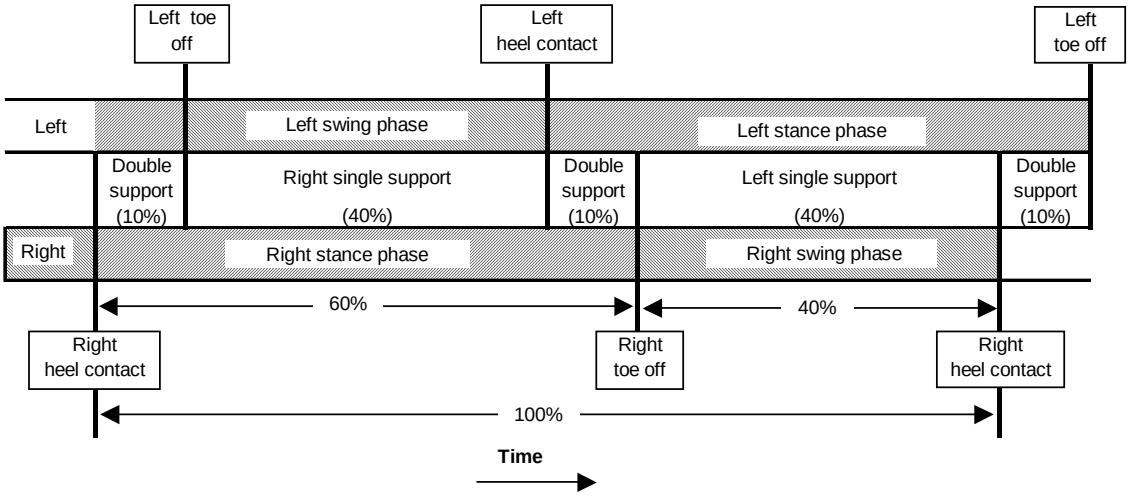


Figure 2.7: Contribution of the right and left legs to one gait cycle (adapted from Whittle, 1993).

Walking has been described as an extremely complex motor control problem (Winter *et al.*, 1991). First, the task requires the integration of the central system with peripheral sensory systems to control the muscles acting on a highly mobile skeletal system. Second, the human mechanical system operates in a gravitational environment on two small bases of support (the feet) with a centre of mass located a considerable distance from the ground (approximately two thirds of body height from the ground). With the body's large forward momentum, and with single support about 80% of the time, a state of continuous imbalance exists. A further challenge on this critically balanced condition is the need to achieve a safe foot trajectory, which involves adequate clearance of the ground and a gentle heel contact. In addition, a safe gait pattern requires no collapse, loss of balance or tripping. The regulation of such a system requires neural control that has well defined total limb synergies, but is also flexible enough to respond to a wide variety of dangerous perturbations, and adaptable enough to anticipate changes sufficiently well in advance (Winter *et al.*, 1991).

2.2.2 Swing phase of gait and minimum toe clearance

The swing phase constitutes 40% of the gait cycle and is initiated as the toes leave the support surface and continues until heel contact of the ipsilateral limb (refer Figure 2.6 and Figure 2.7). It can be seen that swing phase occurs with single support of the contralateral limb. During the early part of swing, the thigh moves anteriorly while the knee flexes and the ankle begins to dorsiflex to accomplish foot clearance. Momentum from the thigh segment and supplemental action of the biceps femoris short head are the primary knee flexion forces during this interval.

Mid swing continues the task of limb advancement and foot clearance through knee extension and ankle dorsiflexion. Most of the elevation of the leg required to achieve a safe foot clearance comes from flexion of the knee but the ankle also needs to move from its position of plantarflexion, at the end of the stance phase, to an approximately neutral position to help with foot clearance. This movement requires contraction of the anterior tibial muscles (Whittle, 1993). During mid swing, the swinging limb passes the stance limb and clears the ground by a small distance. This critical event, termed minimum toe clearance (MTC) in this research, is vital for safe locomotion.

Certain dysfunctions may hamper the attainment of adequate MTC. For example, pathologies limiting hip flexion, knee flexion, or ankle dorsiflexion may result in the toe dragging on the ground and, hence, a greater propensity to trip. As a crucial event for safe locomotion, humans at risk of tripping on the ground make compensatory adaptations to improve the likelihood of achieving adequate toe clearance. To compensate for diminished knee flexion, gait deviations to ensure toe clearance is achieved include hip hiking (ipsilateral elevation of the iliac crest) and vaulting (contralateral plantar flexion). Reduced dorsiflexion strength, and thus excessive plantarflexion at midswing, is accommodated by increased proximal joint motion, resulting in excessive hip and knee flexion to achieve toe clearance (Adams and Perry, 1994). It has also been shown that individuals with impaired vision increase MTC to compensate for a lack of visual information of tripping hazards in order to reduce the likelihood of tripping (Patla, 1997).

The timing of the critical event of MTC during the gait cycle differs within the literature. Sutherland *et al.* (1994) report MTC occurs at 75% of stride while Winter *et*

*al.(*1991a*)* suggest 80%. However, it should be noted that normative data is based on studies of normal adults and, given the individual differences in gait parameters, slight differences may be found in the relative time spent in swing and stance periods (Adams and Perry, 1994). Regardless of the precise timing, MTC occurs during mid swing (refer Figure 2.6) whilst supported by the contralateral limb.

The normal toe clearance during mid swing is very precise, clearing the ground by a very small distance. In fact, Winter (1991) highlights that a relatively small change in the hip, knee and ankle motion can strongly influence the end-point trajectory of the toe, thus resulting in large changes in toe clearance. Despite the identified need for comprehensive reports of the toe trajectory (e.g. Winter, 1991a) given the high proportion of falls related to trips, research is lacking in this vital area.

Although seldom reported in the literature, researchers have employed differing methods of calculating MTC. Traditionally, MTC is reported as the distance the toe clears the ground during mid swing (refer Figure 2.8). The reference point for clearance of the ground is, therefore, assumed to be the toe. Proponents of this method calculate MTC as the vertical displacement between the ground reference and the toe marker (e.g. Karst *et al.*, 1999; Patla and Rietdyk, 1993; Winter, 1992). This method is straightforward and relatively simple to administer. However, the major limitation with this method is it neglects the part on the outsole of the shoe that is closest to the ground at mid swing and, therefore, the toe marker overestimates MTC (see methods section 4.4.3).

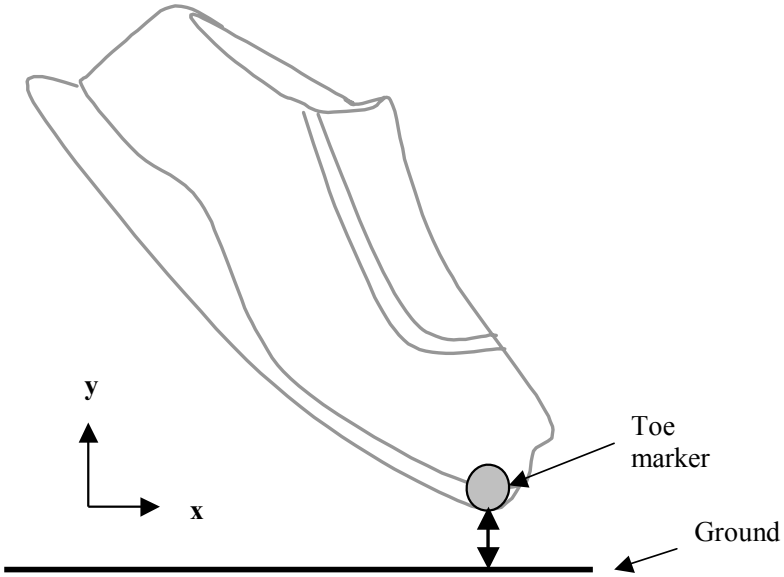


Figure 2.8: Traditional 2-dimensional method of calculating MTC.
MTC is calculated as vertical displacement between Ground and Toe marker.

Researchers have proposed alternative methods of calculating MTC based on geometric modelling, such as utilising virtual points on the outsole of the shoe (Begg *et al.*, 2007; Best *et al.*, 1999; Startzell and Cavanagh, 1999). These methods offer a more accurate representation of MTC since the inferior and most distal portion of the shoe, which is closest to the ground during mid swing, is predicted using modelling techniques. The use of the predicted or virtual point on the inferior and most distal portion of the shoe is necessary since clearly a marker cannot be placed at this location whilst walking. Startzell and Cavanagh (1999) presented a 3-dimensional method of calculating MTC by utilising virtual points along the length of the shoe outsole and describing shoe dimensions with respect to the ground reference. They found this method to be accurate to within +/-2mm (refer Figure 2.9). These trials were performed under static and simulated trials of swing phase, however, no actual walking trials were conducted.

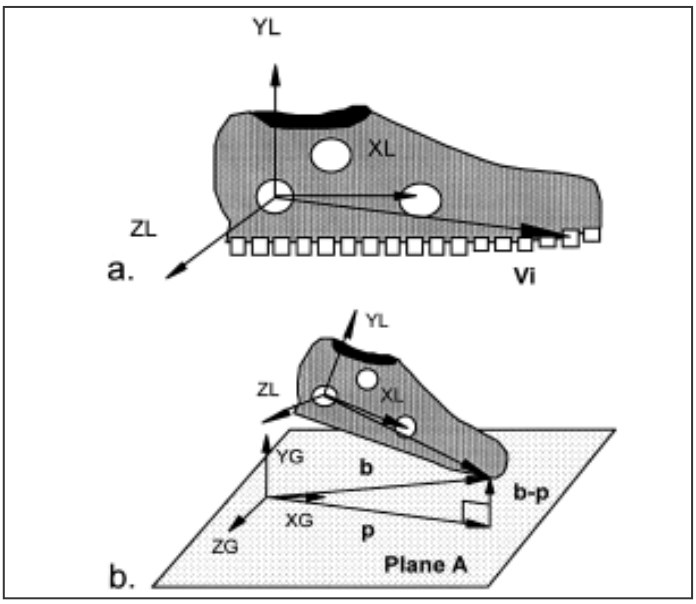


Figure 2.9: Schematic of the method of determining MTC used by Startzell and Cavanagh (1999). a. the locations of virtual markers on the outsole of the shoe, V_i, were defined in local coordinates during calibration; b. the minimum clearance between the plane *A* and all virtual points was calculated and the overall minimum clearance, [$(b - p)$], was determined. (taken from Startzell and Cavanagh, 1999, p. 607).

In contrast to the method conducted during static and simulated trials proposed by Startzell and Cavanagh (1999), the method described by Best *et al.* (1999) was conducted during self-selected comfortable walking trials using 2-dimensional procedures (refer Figure 2.10). Best *et al.* (1999) also used an estimate of a single point on the outsole defined as the inferior most distal point on the shoe that would strike the ground in the event of a trip.

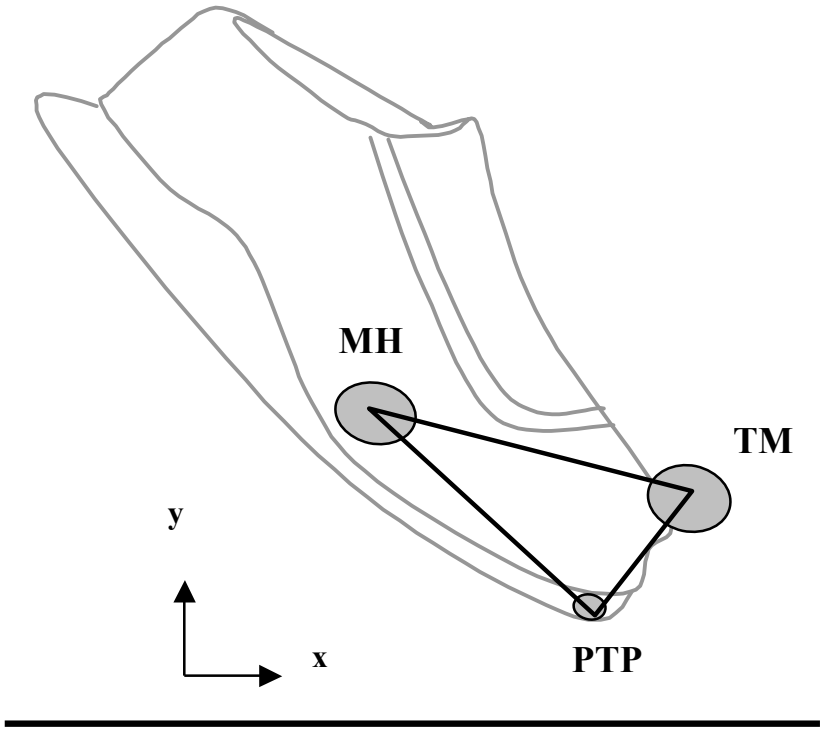


Figure 2.10: Schematic of the method proposed by Best *et al.* (1999).

MH = metatarsal head marker; TM = toe marker; PTP = predicted toe point, the inferior, most distal portion of the shoe.

As shown in Figure 2.10, markers were placed at the 5th metatarsal head (MH) and great toe (TM). The inferior, most distal portion of the shoe (PTP – predicted toe point), where it would strike the ground in the event of a trip, was estimated. MH and TM markers were automatically digitised. Next, with the manually digitised PTP, a 2-dimensional model of the foot was created. This model was then applied to the entire walking trial to calculate PTP with respect to the ground and, therefore, MTC for each gait cycle. A thorough description of this method can be found in the methods chapter, section 4.4.

There are several assumptions underlying the use of these methods. First, for methods utilising modelling in order to calculate MTC, it is assumed there is no shoe distortion.

Startzell and Cavanagh (1999) recognised this limitation and concede that shoe distortion was minor in swing phase. They did find, however, that shoe distortion was more significant when loaded during stance, particularly at toe-off. For this reason, they suggest modelling the shoe as two or more rigid bodies. However, Best *et al.* (1999) described a model that incorporated the forefoot only (i.e. markers placed on the great toe and 5th metatarsal head) and therefore the impact of shoe distortion on the results obtained during the swing phase is lessened. Moreover, the point of interest occurs repeatedly at around mid swing where the shoe distortion is minimal and, at the very least, is consistent.

There are inferred assumptions with techniques for 2-dimensional calculation of MTC (e.g. Best *et al.*, 1999; Dingwell *et al.*, 1999; Winter, 1992; Winter *et al.*, 1990). Typically, there are two types of errors inherent in 2-dimensional kinematic analysis. Perspective error, which is small in the sagittal plane compared with the frontal plane (Whittle, 1993), can be minimised by ensuring the optical lens of the camera is perpendicular to the plane of motion and that the distance between the camera and point of interest is maximised. Parallax errors are encountered when there is movement away from the optical axis of the camera lens. It is assumed in 2-dimensional analysis that negligible movement occurs in the frontal and transverse planes.

Although seldom reported, similar mean MTC have been reported in the literature using the traditional method of utilising the toe marker as the reference point and, therefore, calculating toe clearance as the vertical distance from the ground to the toe marker. For example, Karst *et al.* (1999), Winter *et al.* (1991a) and Winter *et al.* (1990) report mean toe clearance of approximately 1.29cm while Whittle (1993)

reports mean toe clearance of about 1.4cm. Foot clearance between and within individuals can vary considerably and values as low as 0.55cm have been reported (refer Figure 2.11).

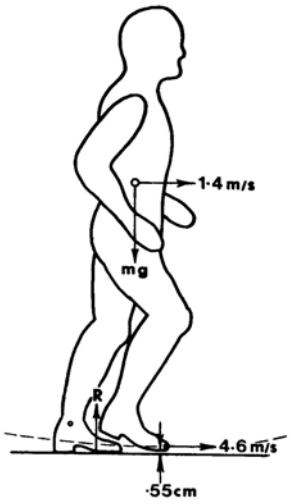


Figure 2.11: Minimum Toe Clearance (adapted from Winter, 1991).

Note that the horizontal velocity (v_h) of the foot is 4.6m/s, more than three times greater than the v_h of the centre of mass (COM). Note also that the body's COM is anterior to the stance foot. mg represents the body's COM vector; R represents the ground reaction force vector.

MTC shown here is very low (0.55cm), typically lower than mean values reported in the literature (e.g. 1.29cm by Winter, 1991).

The critical event of MTC occurs concurrently with maximal horizontal (forward) velocity of the toe of approximately 4.6 m/s (refer Figure 2.11), as reported by Winter (1991a). Any degeneration in the fine motor control of the foot may result in problems of tripping and stumbling (Winter *et al.*, 1990).

Figure 2.11 shows the small toe clearance while the foot moves forward at its maximum velocity. The velocity of the foot is considerably greater than the forward velocity of the body's centre of mass (COM). Figure 2.12 shows displacement and

velocity of the toe for one stride using ensemble averages (Winter, 1991a). It is assumed the toe marker is the part of the foot closest to the ground during mid swing and that MTC occurs at approximately 80% of the gait cycle (Winter, 1991a). Note that the horizontal velocity is at its peak as vertical displacement of the toe reaches a minimum. At the point of MTC, where the foot is moving forward close to its maximum velocity, the COM has also progressed forward of the stance foot. In the event of a trip, the stance foot is unable to assist in the recovery. To prevent a fall following a trip, the individual must react in sufficient time by moving the swing foot. All of these characteristics make MTC a critical event of the gait cycle.

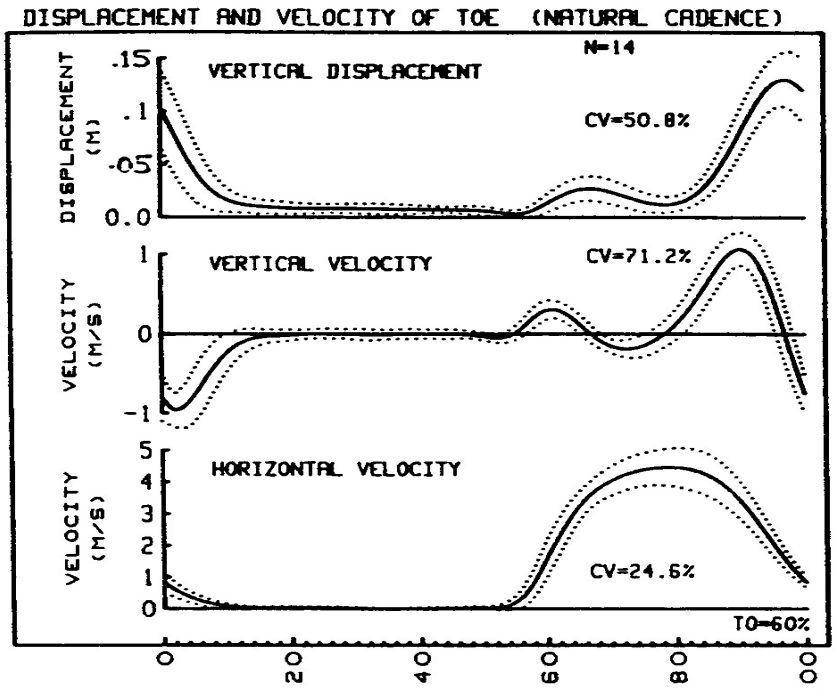


Figure 2.12: Displacement and Velocity of the Toe During One Stride using ensemble averages (adapted from Winter, 1991)

Control of the foot trajectory is clearly an important consideration for safe walking since a lack of control could increase the chance of tripping on overground obstacles.

In spite of this, and given that tripping is often cited as a reason for a fall, there is a paucity of studies examining MTC and MTC variability and their relationship to tripping in elderly populations.

2.2.2.1 Age-related changes to gait

Normal gait is dependent on the integrity of multiple systems, namely, the neurologic, musculoskeletal and cardiovascular systems. Elderly individuals are more at risk of developing dysfunctions of these systems (e.g. stroke, arthritis, vestibular disorders) that predisposes them to degenerations in gait independent of normal age-related decline (Judge *et al.*, 1996b). Gait patterns of elderly individuals exhibit characteristic differences when compared with young adults. Gait characteristics of young and elderly have therefore been examined in an effort to identify risk factors for falls and predict individuals at risk.

The most prominent differences in elderly gait are slower velocity, shorter steps, reduced cadence, an increase in step width and increased time spent in stance and double support compared with their younger counterparts. For example, healthy older adults (n = 26) compared with healthy young adults (n = 32) exhibited velocity 11% slower (young = 1.15m/s vs. elderly = 1.03m/s; $p<.001$), step length proportional to leg length 12% shorter (young = 0.74/leg length vs. elderly = 0.65/leg length; $p<.001$) and single support time 8% less (young = 40% vs. elderly = 37%; $p<.001$) (Judge *et al.*, 1996a). Similar results have been reported in other studies (e.g. McGibbon and Krebs, 2001; Ostrosky *et al.*, 1994; Winter, 1991a; Murray *et al.*, 1969).

The reduced gait velocity typically observed in elderly individuals has been attributed to shorter step length, which is approximately 12 – 18% shorter (Judge *et al.*, 1996a; Nigg *et al.*, 1994; Winter, 1991a; Campbell *et al.*, 1989; Hageman and Blanke, 1986). Whilst some studies have found a direct relationship between gait velocity and physical fitness, particularly in men (e.g. Cunningham *et al.*, 1982), others have concluded this slowness is not entirely an inability to walk faster but rather that a slower gait affords a sense of security in preventing a fall (e.g. Winter, 1991a).

Intuitively, slower walking speeds are viewed as contributing to a safer gait but walking slowly also has some negative implications. From a functional view, for example, walking too slowly may not allow enough time to cross the road at pedestrian lights. Additionally, it has been found that falls at slower walking speeds generally result in impact on the hip, predisposing to hip fracture (Smeesters *et al.*, 2001; 1999). Van den Bogert *et al.* (2002) recommended caution in suggesting slower walking speeds in elderly as a safer gait modification. Van den Bogert *et al.* (2002) concluded that improved reaction time, rather than slower walking, is more important in determining successful recovery from a trip. Despite the general finding of slower walking velocity in the elderly, there is disagreement in relating this to a safer or more risky gait pattern.

Toe clearance is a seldom reported spatial kinematic parameter and of those who do report it, examination of age-related differences is rare. As discussed in section 2.2.2, ground clearance of the foot at mid swing can be defined as the toe-ground clearance by using a marker on the toe (e.g. Winter, 1991a) or by modelling the foot by, for example, using two markers (great toe and 5th metatarsal head) or more and predicting

the inferior most distal part of the shoe (Begg *et al.*, 2007; e.g. Best *et al.*, 1999; James, 1999; Startzell and Cavanagh, 1999). Winter (1991a), using the former method, found toe clearance of the ground to be 13% lower in a group of healthy elderly subjects (1.12cm, n = 18) compared with healthy young subjects (1.29cm, n = 11) but this difference was not statistically significant. James (1999) also found foot clearance was 16% lower in a group of healthy elderly females (0.78cm, n = 6) compared with healthy young females (0.92cm, n = 6), but this was again not statistically significant. The elderly population studied was fit and healthy which might explain the lack of significant difference in these studies.

Horizontal heel contact velocity of Winter's (1991a) elderly subjects was also approximately 32% higher in the elderly subjects compared with the young (elderly = 1.15m/s vs. young = 0.87m/s; $p<.01$). The greater heel contact velocity in the elderly was despite their slower walking velocity (elderly = 1.27m/s vs. young = 1.44m/s; not statistically significant). The study by Winter analysed a minimum of eight separate strides over an hour and, while limited by a small sample size, the study by James examined continuous strides over a minimum of 30 minutes. Although not significantly smaller, the lower foot clearance in the elderly can potentially increase the likelihood of tripping, while higher heel contact velocity increases the likelihood of a slip-induced fall, particularly on slippery surfaces.

Foot clearance during midswing involves a compromise between safely clearing the ground without tripping and expending minimal energy. Higher foot clearance would reduce the likelihood of tripping on obstacles on the walking terrain, such as an uneven footpath, but would also increase energy expenditure. Some attempts have been made

by researchers to examine the differences in energy expenditure during gait between young and elderly subjects. Some of these include studies examining EMG and kinetic parameters (e.g. muscle force and powers generated) and joint angle profiles (Judge *et al.*, 1996a; Eng and Winter, 1995; Winter, 1991a). Another approach is to observe the trajectory of the centre of mass (COM) during gait and relate this to energy expenditure. For example, Murray *et al.* (1969) found vertical elevation of the head and, therefore, centre of mass (COM) during early stance phase was less in elderly men compared with young adults. Higher vertical displacement of the COM increases the potential energy of the body, which is then converted to kinetic energy at push-off. The lower elevations found by Murray *et al.* therefore suggests less development of potential energy at early stance and could be explained as a mechanism to conserve energy and not simply as a result of walking slower.

Kinetic studies have found lower peak plantarflexor moment and power at push-off. For example, Judge *et al.* (1996a) found peak ankle plantarflexor power was 17% less in elderly subjects (elderly = 2.9W/kg, n = 26 vs. young = 2.9 W/kg, n = 32; p=.007). Winter (1991a) measured work done by the ankle, knee and hip at various stages of the gait cycle. He found push-off was 35% lower in the elderly (young = 0.293 J/kg, n = 11 vs. elderly = 0.190 J/kg, n = 18; p<.01) and absorption of energy by the knee was 89% greater in the elderly (young = -0.047 J/kg, n = 11 vs. elderly = -0.089 J/kg, n = 18; p<.01).

Other age-related kinematic differences in gait have been summarised by Judge *et al.* (1996b). Compared with younger subjects, in the sagittal plane the elderly display greater anterior pelvic tilt (APT) (young = 10 deg. vs. elderly = 14 deg; p<.001), are

slightly more flexed at the hip due to the increased APT, and show reduced hip extension. Additionally, pelvic range of motion is reduced in the frontal (young = 9 deg vs. elderly = 6 deg, $p<.001$) and transverse planes (young = 9 deg vs. elderly = 7 deg, $p=.002$). Also in the frontal plane, external rotation of the foot (toeing out) during stance is greater in the elderly (elderly = 16 deg vs. young = 11 deg, $p<.001$).

Whilst vision typically undergoes age-related decline, there is evidence to suggest the elderly, particularly those with balance-impairments, typically place most emphasis on visual cues for the control of balance (e.g. Williams *et al.*, 1997) and to regulate gait velocity (Anderson *et al.*, 1998). The role of vision for maintenance of posture and negotiating a safe walking terrain has been highlighted and is described in section 2.1.2.2 (e.g. Anderson *et al.*, 1998; Patla, 1997; Patla and Vickers, 1997; Patla *et al.*, 1996; Winter, 1995; Patla *et al.*, 1991; Lee and Lishman, 1977), however, ageing effects are discussed here.

One method of evaluating the efficiency of the balance control systems, including vision, is to examine the ability to provide a stable visual platform achieved through minimising A/P head accelerations. For example, amongst the various kinematic, kinetic and EMG measures comparing young (n = 11) and elderly (n = 18) gait, Winter (1991a), also quantified horizontal accelerations of the head and measured these relative to horizontal accelerations of the hip. As Winter explains, the significantly larger head accelerations in the elderly (young = 0.475m/s^2, n = 11 vs. elderly = 0.621m/s^2, n = 18; $p<.05$) could be explained by degenerations in the vestibular system which requires larger acceleration input in order to adequately monitor A/P head accelerations. Winter also suggests maintenance of a stable platform for the visual

system requires strongly attenuated head accelerations. The elderly had reduced hip accelerations compared with young subjects (elderly = 1.54 m/s^2, n = 18 vs. young = 1.91 m/s^2, n = 11, p<.01) but greater head accelerations (elderly = 0.62 m/s^2, n = 18 vs. young = 0.48 m/s^2, n = 11, p<.05), suggesting they might be experiencing early signs of degeneration of the trunk balance control system. As Winter (1991a) explains, the ratio of head to hip acceleration measures damping of pelvic acceleration by the spinal column. The young were able to reduce pelvic acceleration by the spinal column relative to head acceleration to 23% of that of the pelvis, while the elderly were only able to achieve a reduction of 42% of that of the pelvis (p<.02).

Intra-individual variability in various gait parameters, typically spatial and temporal parameters of step kinematics such as step length, step width, stride frequency and step/stride time, stance and swing phase time have been reported for young and elderly subjects (e.g. Hausdorff *et al.*, 2001; Hausdorff *et al.*, 1997; Maki, 1997; Winter, 1991a; Gabell and Nayak, 1984; Guimaraes and Isaacs, 1980). Greater variability is typically found in elderly subjects but the theories surrounding these differences and their functional applications are inconsistent in the literature.

Intra-individual variability of basic spatial and temporal gait parameters has been reported, but only a few have examined the sensitive measure of MTC. Intra-individual variability in MTC for young and elderly have been reported by Winter (1991a) and James (1999). In Winter's (1991a) healthy elderly subjects, intra-individual variability in toe clearance was 22% less than the young group (young = 0.45cm, n = 11, vs. elderly = 0.35cm, n = 18) but not significant. Standard deviation of toe clearance for each individual over eight separate strides was selected as the measure for intra-

individual variability. James (1999) found intra-individual variability as measured by standard deviation was 19% greater in the elderly group compared with the young group (elderly = 0.32cm, n = 6 vs. young = 0.27cm, n = 6, not significant).

These two studies differed in method of collecting foot clearance data. Winter (1991a) collected a minimum of 8 separate overground strides over a period of one hour, however, the exact stride numbers are not stated. In contrast, James (1999) analysed a minimum of 30 minutes of continuous strides on a treadmill, which was a median of over 1,200 strides for both young and elderly groups. Traditionally, greater variability in the elderly is thought to be indicative of impaired adaptive control and is a risk factor for tripping and, indeed, falls (e.g. Patla, 1997). The higher variability in the elderly group could be attributed to impaired locomotor control resulting in more errors in implementing a consistent MTC. More recently, however, several theories of variability have been proposed and conclude, contrary to the traditional belief, that lower variability is indicative of higher risk of falling since it is an indication of a lack of ability to adapt to the changing nature of the walking terrain. The reader is directed to section 2.2.3.1 for a detailed description of variability.

Whilst some of the gait characteristics typically observed as different in older adults have been linked with falling behaviour (e.g. Maki, 1997; Patla, 1997; Judge *et al.*, 1996a; Lord *et al.*, 1993; Guimaraes and Isaacs, 1980), others have suggested these characteristics are associated with a decreased risk of falling and may be adaptations towards a safer and more stable gait (e.g. Pavol *et al.*, 1999; Winter, 1991a; Gabell and Nayak, 1984). The relationship between age-related changes in gait pattern and falls therefore remains unclear.

This research examines some of the areas raised in this section, namely the effect of age on minimum toe clearance (MTC) during undistracted and distracted walking. The role of vision is important since some distractions pose an increased challenge to posture by placing additional demand on the visual system by attending to the distraction task while maintaining posture and regulating walking.

2.2.3 Methodological issues in biomechanics research

2.2.3.1 Variability in gait and sample sizes required for an accurate representation of gait

Variability, or the spread or dispersion of a set of data, is typically measured by range, interquartile range, standard deviation and coefficient of variance (Vincent, 1999). Inter-individual variability, or between-group variability, is typically used as a measure of group homogeneity by reporting, for example, group mean and standard deviations. Intra-individual variability is also an important parameter that, in the case of gait kinematics, gives an indication of locomotor control and dynamic stability. Intra-individual variability is less often reported and has traditionally been examined by measuring fluctuations in certain gait parameters including temporal and spatial kinematics, kinetics and electromyography. Researchers have attempted to correlate variability of these parameters with control and consistency of the locomotor system, and with falling behaviour. This section discusses variability as:

1. importance of intra- versus inter-individual variability;

2. findings of measures of intra-individual variability and their relationship with falls; and
3. sample size required for accurate representation of intra-individual variability and selection of appropriate measure of intra-individual variability.

The major focus of this research is on intra-individual as opposed to inter-individual variability and, therefore, variability will be referred to as either intra- or inter-individual variability throughout the thesis to easily distinguish between the two.

Increased intra-individual variability of various walking parameters has been equated with instability of the locomotor system and has been characterised as a predictor for falling by several researchers (e.g. Hausdorff *et al.*, 2001; Hausdorff *et al.*, 1997; Maki, 1997; Winter, 1991a; Gabell and Nayak, 1984; Guimaraes and Isaacs, 1980). Given the association with falling behaviour, several researchers have examined intra-individual variability of gait parameters in various elderly population groups and have attempted to explain any differences in relation to falls risk. Intra-individual variability in gait parameters, typically spatial and temporal parameters of step kinematics such as step length, step width, stride frequency and step/stride time, stance and swing phase time, has been reported for young subjects and elderly with and without a history of falls (Buzzi *et al.*, 2003; Danion *et al.*, 2003; Hausdorff *et al.*, 2001; Guimaraes and Isaacs, 1980) or neuropathic elderly (Richardson *et al.*, 2005; Dingwell and Cavanagh, 2001; Dingwell and Cusumano, 2000).

In general, the elderly compared with young have shown greater intra-individual variability in most, but not all, measured gait parameters (refer section 2.2.2.1). It has

been suggested that the increased intra-individual variability in elderly populations may be due to the reduced walking velocity and not to some pathological cause (e.g. Dingwell and Marin, 2006; Dingwell and Cavanagh, 2001; Dingwell and Cusumano, 2000) but not all researchers have found this (e.g. Owings and Grabiner, 2004b). These studies did, however, have some methodological differences. For example, Owings and Grabiner (2004b) examined treadmill walking during a subject-determined comfortable walking speed (normal) and then imposed a slower walking speed calculated as 90% of normal for slow walking speed. Dingwell and Cusumano (2000) collected overground walking data at a subject-determined comfortable walking speed and attempted to associate subjects' different walking speeds with intra-individual variability for each individual. These studies show that important parameters such as walking speed need to be probed further in order to examine the influence on measures such as intra-individual variability.

Whilst many studies examining intra-individual variability in various temporal and spatial kinematic variables can be found, examination of the important variable of MTC is seldom reported. Given the need for a precise foot trajectory to prevent tripping, MTC could be described as a more sensitive measure than basic gait parameters such as step width, step length and time spent in stance and swing phase. As discussed in section 2.2.2.1, few studies have examined intra-individual variability of the foot trajectory (e.g. James, 1999; Winter, 1991a). The methodological approach utilised by James (1999) was, however, fundamentally different to that of the study by Winter (1991a). James (1999) analysed consecutive strides over a period of at least 30 minutes while Winter (1991a) analysed less than 10 non-consecutive strides. While neither study found significant age effects, the elderly in Winter's study tended to have smaller

intra-individual variability compared with the young, while the elderly in James' study tended to have greater intra-individual variability compared with young. There is a paucity of studies examining intra-individual variability in MTC and there is no clear definition of intra-individual variability in this sense. There is clearly a need for examination of intra-individual variability in the critical measure of foot clearance during continuous strides.

Intra-individual variability in locomotor patterns has traditionally been explained as solely noise in the system. For example, as Newell and Corcos (1993) assert, random intra-individual variability is inherent in all biological systems and the challenge for researchers is to "understand how order and regularity arise in the co-ordination and control of movement with noise (random fluctuations) as an inherent component to the system" (Newell and Corcos, 1993, p.4). However, the notion of 'random' variability proposed by Newell and Corcos has not been supported by all researchers. For example, Dingwell and Cusumano (2000) and Buzzi *et al.* (2003) proposed the stride-to-stride variability in human gait was not random but instead displayed a deterministic behaviour. They stated these fluctuations appeared to be chaotic and may be partly controlled by deterministic central nervous system processes. Further, Dingwell and Cusumano (2000) concluded that long-term and short-term patterns often underpin variability in long-term gait. Further research is warranted to determine the nature and origin of stride-to-stride variability.

An important consideration when examining intra-individual variability is the sample size studied. Most methods of examining intra-individual variability include a few strides that can be averaged to generate mean ensemble curves and in the process some

of the intra-individual variability in gait patterns is difficult to identify (Buzzi *et al.*, 2003). As Owings and Grabiner (2004b) recognised, the accuracy of intra-individual variability estimates is proportional to the amount of data collected. Other studies have acknowledged this consideration and utilised larger sample sizes. For example, Hausdorff *et al.* (2001) used 6 minutes of overground walking data while Owings and Grabiner (2003) analysed 10 minutes of treadmill walking data. These studies identified greater intra-individual variability in some gait measures for elderly vs. young (Owings and Grabiner, 2004b; 2004a) and elderly fallers vs. non-fallers (Hausdorff *et al.*, 2001). Owings and Grabiner (2004b) compared spatial and temporal step kinematics, namely step length, step width and step time, between healthy young and elderly subjects. While variability was greater in the elderly compared with young on all measures, significant difference was only found for step width variability (young = 2.1cm, n = 18 vs. elderly = 2.5, n = 12, p=.037). In the study by Hausdorff *et al.* (2001), increased variability in stride time and swing time was observed in elderly fallers compared with elderly non-fallers. Stride time variability for elderly fallers was 106ms (n = 20) vs. 49ms for elderly non-fallers (n = 32), p=.04.

Owings and Grabiner (2004b; 2004a; 2003) and Hausdorff *et al.* (2001) also deleted points defined as greater than 3.77 standard deviations from the mean (Owings and Grabiner, 2004b; 2004a; 2003) and 3 standard deviations from the median (Hausdorff *et al.*, 2001) due to the fact they were deemed to be 'extreme'. The study by Hausdorff *et al.* was the first to employ this method, while Owings and Grabiner based their method on Hausdorff *et al.*'s work. Hausdorff *et al.* (2001) excluded the first 10 seconds of data from each data set to minimise any start-up effect. Next, they deleted data points ±3 standard deviations from the median. The only other information

supplied stated each subject typically had several hundred strides. Owings and Grabiner (2004b; 2004a; 2003) sequentially sorted the data to obtain mean and standard deviation of the middle 90% of data. Next, any data from the original, unsorted series (i.e. 100% of the data) that was ±3.77 standard deviations, described as a conservative estimate of 3 standard deviations of 100% of the data points, was removed. Since each subject would vary in number of steps due to differing step frequency and the number of steps eliminated, each subject's data set was truncated to match the subject with the least number of steps. No further information was provided on deleted data points and it is therefore not known how many and from which subjects data was deleted. It is also not known how many steps were analysed for each subject. The intra-individual variability measured may therefore have been underestimated and deleting extreme points may misrepresent the differences between the groups.

Owings and Grabiner (2003) examined the validity of measuring intra-individual variability in various gait parameters with respect to the size of the data set. They found that a minimum of 400 strides was required in order to obtain an accurate estimation of step kinematic intra-individual variability. It is important to know how many strides are necessary for accurate calculation of intra-individual variability data. One extreme point can substantially increase the intra-individual variability in the measured gait parameters, particularly in small data sets. A representation of the intra-individual variability in MTC descriptive statistics can be gained by observing the 'stability' of each statistic throughout the gait cycle. Stability of MTC descriptive statistics is derived by plotting each statistic with the addition of each new MTC data point. Recent research using this method has shown that MTC outliers can

substantially influence the stability of MTC descriptive statistics (Best *et al.*, 2000; James, 1999).

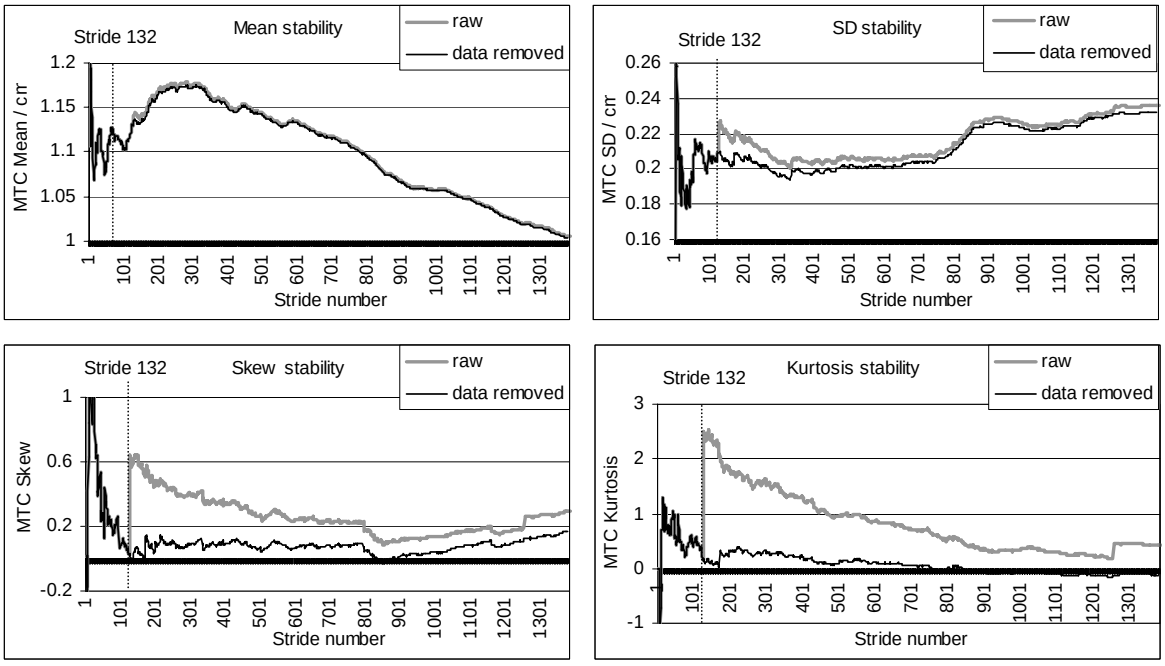


Figure 2.13: Stability of descriptive statistics.

Data shown for one young female subject during 1382 consecutive strides of a 30 minute treadmill walking period. Descriptive statistics for each data set: a) data removed series (1382 strides) - M = 1.00cm, SD = 0.23cm, S = 0.17, K = -0.12; and b) raw series (1385 strides) - M = 1.00cm, SD = 0.24cm, S = 0.30, K = 0.43.

The largest MTC in the data series (2.15cm) occurred at stride number 132.

Adapted from James (1999)

Figure 2.13 gives a representation of the stability of four MTC descriptive statistics, namely mean (M), standard deviation (SD), skew (S) and kurtosis (K), for 1382 strides for one healthy young female during a 30 minute treadmill walking period (James, 1999). Descriptive statistics of the data removed series for this subject for M, SD, S and K were 1.00cm, 0.23cm, 0.17 and –0.12, respectively. It can be seen in Figure 2.13 that a large MTC occurred at stride 132 and was in fact the largest MTC for the entire data set at 2.15cm, an increase of 1.14cm or 114% from the mean MTC of 1.00cm.

The large MTC at stride 132 caused increases of M, SD, S and K of 0.7% (1.13 to 1.14cm), 8.5% (0.21 to 0.23cm), 1677% (0.04 to 0.65) and 1315% (0.18 to 2.52), respectively. These figures demonstrate that one extreme outlier substantially influences descriptive statistics and therefore support the need for large data sets in order to obtain data representative for the individual.

Best *et al.* (2000) used this method of examining stability of descriptive statistics for 2,766 strides for one healthy young male adult during a 60-minute treadmill walking period. An unusual block of 12 strides was identified and, on closer examination, it was discovered that this unusual block contained 12 of the 20 most extreme data points in the MTC distribution. It was thought that the subject might have been distracted during this short period. The influence of this 'distracted' block, which occurred at stride 824, approximately one third of the way through the walking trial, resulted in increases in SD of 12% and K of 50%. Additionally, a single MTC value of 2.55cm which occurred at stride 1751, slightly over half way through the walking trial, caused increases in M, SD, S and K of 0.1%, 1%, 10% and 20% respectively. It took K a further 250 strides to re-stabilise after this single extreme outlier.

The walking trial analysed by Best *et al.* (2000) did not intentionally include distractions, however, it is expected that an individual would be distracted at times for many different reasons and the data shows that such distractions have a substantial impact on MTC. The extreme MTC achieved during the distracted period might indicate areas of increased tripping risk or could be the individual's response to prevent a tripping incident during distracted attention. These findings indicate a need for closer examination of the effect of distracted walking. Consistent with the data presented in

Figure 2.13, the study by Best *et al.* (1999) highlights the important finding that extreme MTC have a substantial influence on descriptive statistics and support the need for larger data sets for accurate analysis.

Studies examining only a few strides (e.g. Winter, 1991a) make the assumption that these trials form a normal distribution and represent typical gait characteristics. Table 2.2 and Figure 2.14 present the range of MTC descriptive statistics obtained by dividing a 60-minute walking period (3,318 strides) for one healthy young adult female into different time intervals (James, 1999). For example, M, SD, S, and K were calculated for 332 x 10 strides, 120 x 30s intervals of the 60 minutes of data, 60 x 1 minute intervals, 30 x 2 minute intervals, 12 x 5 minute intervals, 6 x 10 minute intervals, 4 x 15 minute intervals, 3 x 20 minute intervals, 2 x 30 minute intervals and 1 x 60 minute interval. The median values of each set of intervals are shown together with the range of values for each set of time/stride interval. Minimum and maximum values are shown in Figure 2.14.

Table 2.2: Range of MTC descriptive statistics in different time intervals, n = 3318 continuous strides for one healthy young female (adapted from James, 1999).

Time/stride interval	Strides/ interval	mean		median		sd		s		k	
		med	range	med	range	med	range	med	range	med	range
332x10strides	10	0.96	1.09	0.94	1.12	0.21	0.38	0.25	5.50	0.03	10.72
120 x 30s	28	0.95	0.86	0.94	0.87	0.23	0.25	0.39	3.26	0.09	10.38
60 x 1min	55	0.94	0.73	0.95	0.73	0.24	0.16	0.36	2.01	0.21	6.56
30 x 2min	111	0.95	0.57	0.94	0.58	0.25	0.09	0.40	1.36	0.30	4.66
12x5min	277	0.94	0.39	0.93	0.43	0.27	0.08	0.34	0.72	0.33	2.75
6x10min	553	0.94	0.28	0.93	0.29	0.27	0.04	0.41	0.66	0.34	2.12
4x15min	830	0.93	0.30	0.92	0.32	0.27	0.03	0.35	0.52	0.35	1.63
3x20min	1106	0.94	0.23	0.93	0.23	0.27	0.01	0.42	0.15	0.30	0.81
2x30min	1659	0.96	0.20	0.95	0.20	0.27	0.02	0.39	0.25	0.39	0.66
1x60min	*3318*	*0.96*		*0.94*		*0.29*		*0.36*		*0.15*	

Note: descriptive statistics given are for MTC in various time/stride intervals (sd = standard deviation, s = skew, k = kurtosis). Median (med) and range of the 5 descriptive statistics are shown. Actual value for mean, median, sd, s and k are shown for 1 x 60 minute interval.

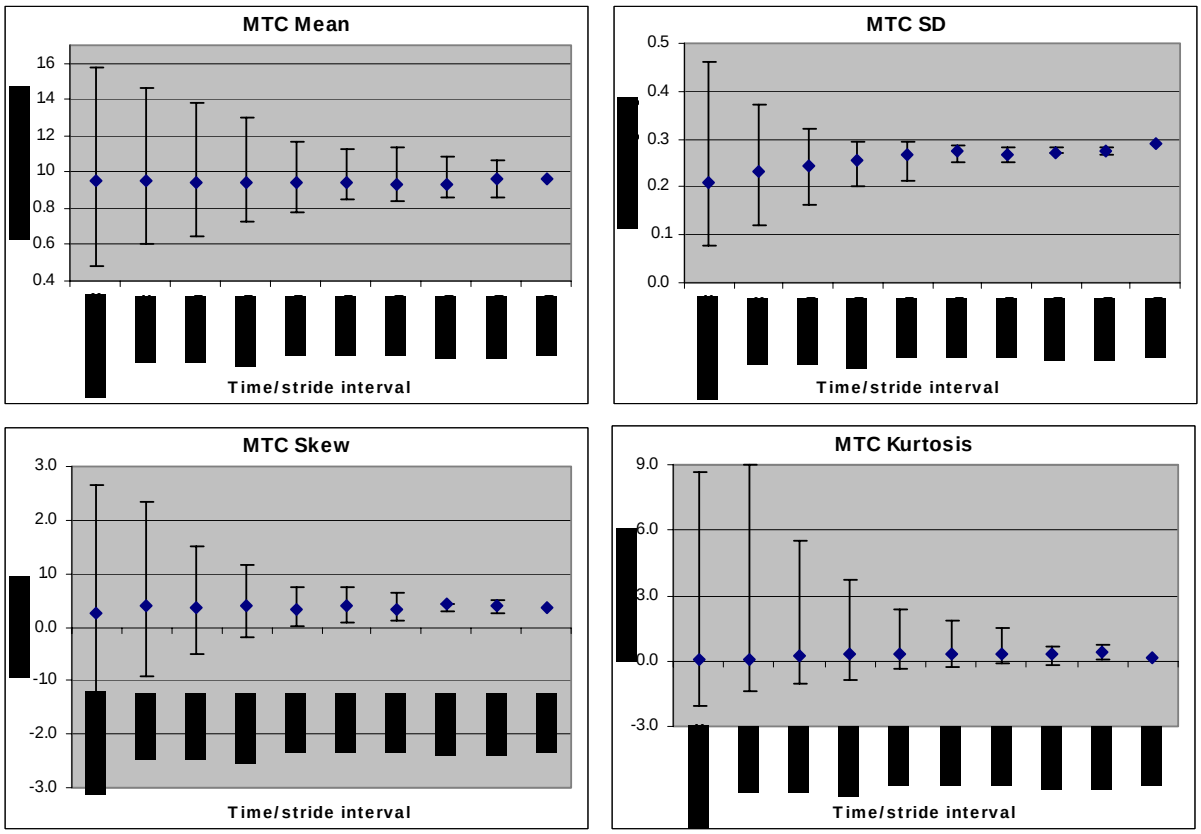


Figure 2.14: Comparison of median, minimum and maximum descriptive statistic values (mean, SD, skew and kurtosis) for various time/stride intervals (adapted from James, 1999).

Descriptive statistics for the entire 60-minute walking period were M = 0.96cm, SD = 0.29cm, S = 0.36 and K = 0.15. As Table 2.2 shows, the range of values is substantially greater in the smaller intervals, particularly the 10-stride intervals. In general, range of values becomes progressively smaller as the time intervals increase to include greater number of strides (i.e. inter-interval intra-individual variability in descriptive statistics decreases). The two largest time intervals, i.e. 3 x 20 minute intervals and 2 x 30 minute intervals, have the smallest range of values for each of the five descriptive statistics.

Figure 2.14 and Table 2.2 clearly shows the greater range of each descriptive statistic is within the smallest time intervals, i.e. 232 x 10 strides and 120 x 30 seconds.

Conversely, it can be seen that the range of each descriptive statistic decreases as the time interval increases. This demonstrates that inter-interval variability in descriptive statistics is substantially greater in small sample sizes. Small sample sizes, therefore, may not be sufficient to achieve stable values and may not be representative of the gait for the individual.

The greater range of values within each time/stride interval in the smaller set of intervals, i.e. the 332 x 10 strides and 120 x 30 second intervals, also has implications for the normality of each data set within the set of intervals. For example, S during the 332 x 10 stride intervals range from –2.84 to 2.66 and K ranges from –2.06 to 8.66 while ranges for M and SD are 0.48 to 1.48cm and 0.08 to 0.46cm, respectively. Given that S and K for a normal distribution are zero, small data sets with greater inter-interval variability have the potential for greater deviation from the assumptions of a normal distribution. In data sets that are not normally distributed, measures of standard deviation, and indeed mean as a measure of central tendency, may not be appropriate.

2.2.3.2 Generalising treadmill walking to overground walking

Gait kinematics, such as basic temporal and spatial parameters, including joint angles, stride length and time spent in stance and swing and more sensitive measures such as MTC, can be analysed during overground walking or on a treadmill. An advantage of using a treadmill is that it is a controlled environment where multiple consecutive gait cycles can be analysed. Since the treadmill has been recognised as a useful tool in obtaining data over multiple strides, researchers have examined the reliability of data collected on the treadmill compared with overground walking.

Researchers have examined variables including kinematics (e.g. Wass *et al.*, 2005; Vogt *et al.*, 2002; Schache *et al.*, 2001; Alton *et al.*, 1998; Siler *et al.*, 1997), heart rate response (e.g. Greig *et al.*, 1993) and electromyography (e.g. Hwang *et al.*, 2003) during treadmill walking (e.g. Hwang *et al.*, 2003; Vogt *et al.*, 2002; Alton *et al.*, 1998; Siler *et al.*, 1997; Stolze *et al.*, 1997) and treadmill running (e.g. Schache *et al.*, 2001). Most kinematic variables are examined in the sagittal plane, which are the most commonly studied, best understood, and reported to be most accurately reproduced (Sutherland *et al.*, 1994). These studies have generally focused on 'normal' unimpaired subjects and only a few have concentrated on elderly adults (e.g. Wass *et al.*, 2005; Greig *et al.*, 1993).

Whilst some studies have concluded that treadmill walking provides reliable information with minimal or no difference to overground walking (e.g. Matsas *et al.*, 2000; Murray *et al.*, 1985) others identified significant differences in some of their measured parameters (e.g. Wass *et al.*, 2005; Alton *et al.*, 1998; Stolze *et al.*, 1997). In general the treadmill appears to produce temporal and spatial kinematic parameters of increased swing time and cadence, and decreased step length and stance time. For example, Stolze *et al.* (1997) reported a significant increase ($p<.05$) of approximately 3% in swing time on the treadmill (approximately 42% of stride) compared with overground (approximately 39% of stride) at the same walking speed in the 12 healthy young adults studied. Significantly reduced stance time on the treadmill compared with overground walking were recorded with a 3% decrease compared with overground walking (overground = 61% vs. treadmill = 58%, $p<.001$). Additionally, Stolze *et al.* (1997) concluded cadence was greater during treadmill walking compared with

overground walking with cadence of 113 and 121 steps/min, respectively, (p<.05). Whilst some studies examined elements related to the swing phase such as time spent in swing phase, none have compared measures of the critical event of MTC.

It is proposed here that walking on the treadmill, like walking overground on a tiled indoor surface (such as in a shopping centre), a footpath outdoors, on gravel paths, grassed areas, carpeted surfaces etc. all represent specific and different terrains. In this sense it seems a valid assumption that all terrains should be treated as separate terrains that may or may not differ from one another.

As a different terrain, it is reasonable to suggest the treadmill also has a different 'comfortable' or 'normal' walking speed, as would be the case for different overground terrains. Most studies examining differences in treadmill and overground walking have estimated overground walking speed and set this on the treadmill. As noted by Alton *et al.* (1998), all subjects in their study commented that the treadmill speed, despite being the same as overground speed, felt too fast. Alton *et al.* (1998) recommended future research should incorporate subjective feelings of the subjects in order to obtain a more accurate representation of comfortable walking speed on the treadmill. This methodological consideration was recently employed by Dingwell and Marin (2006).

Another major methodological issue with studies of overground and treadmill walking is the failure to examine continuous strides. Most studies typically examine one overground stride during a number of trials and averaged these results (e.g. Hwang *et al.*, 2003; Vogt *et al.*, 2002; Alton *et al.*, 1998). For accurate comparison of the two walking terrains it is important that they are examined in the same way, e.g. as

continuous strides or both using discontinuous strides. As highlighted by Dingwell and Cusumano (2000) and Buzzi *et al.* (2003), previous studies ignored the dynamic nature of locomotion and any information on how the neuromuscular system controls locomotion on a stride-stride basis is lost.

Treadmill familiarisation, or habituation, is also an important methodological consideration. It is important to know how much practice and what period of time is sufficient in order to obtain stable and reliable kinematics during treadmill locomotion. As Matsas *et al.* (2000) emphasised, the studies that found significant differences have generally neglected familiarisation. Some studies have examined the amount of familiarisation required in order to obtain reliable results, however, these have generally been with young subjects. For example, Matsas *et al.* (2000) concluded that reliable knee kinematics that can be generalised to overground walking after four minutes and reliable temporal and distance parameters (e.g. cadence, stride time and step length) could be obtained after six minutes of treadmill familiarisation. In contrast, Wass *et al.* (2005) studied the amount of treadmill familiarisation required to obtain reliable sagittal plane gait kinematics in unimpaired older people. They concluded that older adults had not familiarised to the treadmill within the 15-minute test period. However, nine of the 15 subjects examined walked while holding the treadmill rails. The only other study examining differences between treadmill and overground walking in older adults found an increased heart rate and decreased cadence after two 6-minute practice sessions (Greig *et al.*, 1993). However, all subjects held the rails on the treadmill and it is possible that the elderly may have gripped the rails more tightly, thus increasing energy cost and elevating heart rate.

Researchers are divided in the validity of the treadmill in obtaining reliable kinematic results. However, it is proposed that walking on any terrain, whether it be treadmill, tiled indoor surfaces or outdoor paved, gravel or grassed surfaces, should be considered as a specific and different terrain. Indeed, the treadmill offers the only realistic and reliable way of collecting multiple consecutive strides necessary for examining elements of control exhibited by the locomotor system on a stride-stride basis.

2.2.4 Summary

The critical event of MTC occurs at midswing while the body is supported by one leg and with the body's centre of mass forward of the stance foot. Tripping at the point of midswing results in difficulty regaining balance since the stance limb is unable to assist in the recovery and, therefore, the swing limb must be moved forward quickly (Winter, 1991a).

Despite a need to examine trip-related falls given the high frequency, there are few studies focusing on MTC. Studies that have examined this critical event have employed differing methods. Traditionally, MTC is calculated as the vertical distance from the toe marker to the ground (e.g. Karst *et al.*, 1999; Patla and Rietdyk, 1993; Winter, 1992). More recently, however, points on the shoe outsole have been used to model the foot and predict the inferior most distal portion of the shoe near the toe, where it would strike the ground in the event of a trip (e.g. Begg *et al.*, 2007; Best *et al.*, 1999; Startzell and Cavanagh, 1999). These studies have found greater accuracy in calculating MTC. This research contributes to the knowledge base through the strong focus on MTC using foot modelling techniques and relating this to risk of tripping.

This research examines consecutive strides over at least 30 minutes (i.e. over 1,000 strides) while gait analysis traditionally analyses up to 10 non-consecutive overground strides (e.g. Winter, 1991a). Large sample sizes are important in order to examine intra-individual variability in MTC, which gives an indication of the extent of variation in the locomotor system in implementing MTC. Elderly populations typically show higher intra-individual variability in gait parameters, however, these have been limited mainly to basic or more general parameters such as stride length and stride width (e.g. Hausdorff *et al.*, 2001; 1997; Maki, 1997; Winter, 1991a). Only two studies to date have examined intra-individual variability in the more sensitive, critical measure of MTC (James, 1999; Winter, 1991a). Winter's study, however, examined non-consecutive strides resulting in important stride-to-stride information being lost.

2.3 Tripping and obstacle avoidance research

Tripping in the elderly has been identified as a frequent cause of falls during locomotion (Kreisfeld *et al.*, 2004; Cripps and Carman, 2001; Hill *et al.*, 1999; Sattin *et al.*, 1998; Lord *et al.*, 1993; Campbell *et al.*, 1990; Tinetti and Speechley, 1989; Overstall *et al.*, 1977). Despite this, few studies have specifically examined control of the foot trajectory and MTC while walking. Studies examining control of the foot trajectory have been limited primarily to obstacle negotiation. When confronted with some walking terrains, an individual must make adjustments to gait in order to go over the obstacle without tripping (e.g. a raised portion of footpath or a curb) or go around the obstacle (e.g. a pothole or a small obstacle on the ground).

Obstacle negotiation studies have typically examined spatial and temporal parameters of gait while negotiating various obstacles (e.g. Weerdesteyn *et al.*, 2003; Chou *et al.*, 2001; Pijnappels *et al.*, 2001; Begg and Sparrow, 2000; Austin *et al.*, 1999; Pavol *et al.*, 1999; Chou and Draganich, 1997; Chen *et al.*, 1996; 1994a; 1994b; 1991; Patla and Rietdyk, 1993). Tripping with the lead limb is considered a greater risk for falling since the COM is anterior to the stance limb and due to this, the lead limb is most commonly investigated. The trailing limb, although less risky in terms of falling, is still responsible for some trips but is least often studied. Ageing effects reported in obstacle negotiation studies have generally included elderly taking shorter steps to cross the obstacle and elderly crossing the obstacle significantly slower than the young. For example, Chen *et al.* (1991) identified significantly slower crossing speed in the elderly group (young range = 1.23m/s – 1.24m/s, n =24 vs. elderly range 1.12m/s –

1.15m/s, n = 24; $p<.0001$) and took shorter steps to cross the obstacle ($p<.0001$) compared with young subjects. A limitation with many of these studies is the use of a predetermined limb to cross obstacles, a situation which does not occur in real life, and may be a confounding variable in the obtained results. Some studies, however, have allowed subjects to select lead limb during obstacle avoidance (Chou *et al.*, 2001; 1997).

Gait studies have revealed important information regarding the role of vision in negotiating obstacles. For example, gait variables, such as step length and width, can be regulated in the same step cycle to go over low obstacles but steering control (e.g. turning or going around an obstacle) must be planned at least in the previous step (Patla *et al.*, 1991). Winter *et al.* (1991) reported that changes in gait pattern to ensure obstacles of different heights are cleared occurred as early as 50% of the gait cycle, more than 300ms before toe clearance was needed. The authors concluded such control is clearly anticipatory and is initiated by vision (Winter *et al.*, 1991).

During normal everyday walking, an individual is constantly confronted with situations requiring visual input, such as scanning for cars, as well as allocating visual resources to maintaining balance and safely negotiating the walking terrain. Sparrow *et al.* (2002a) evaluated the attention demands of walking in young (n = 12) and elderly subjects (n = 12) under dual-task conditions using a reaction time (secondary) task. Subjects were required to respond to a visual stimulus together with walking (condition 1) and walking with specific foot placement (condition 2). Reaction times to an auditory, visual and auditory/visual stimulus were measured at baseline (no walking), while walking (condition 1) and during targeting (condition 2), where one foot was to

be placed within a target area on the ground. Sparrow *et al.* (2002a) discovered that while there were no age differences in reaction times under single-task conditions (baseline with no-walking) elderly adults were significantly slower in visual and auditory/visual reaction time tasks while walking, particularly when specific foot placement is required (targeting) (p<.01). As the authors noted, the results revealed that the elderly group have difficulty under dual-task conditions when vision is to be directed elsewhere concurrently with attending to negotiating the walking terrain. The results have implications for the safety of elderly adults during road crossing, for example, where at the same time as walking there is a requirement to attend to oncoming vehicles, pedestrians and any other potential hazards. It is reasonable to suggest that during demanding gait tasks, the competing visual information associated with a secondary task could affect gait task performance and increase the risk of a fall. Alternatively, if increased attentional resources are allocated to the gait task, it is possible that time to respond to a hazard will be reduced.

Chou *et al.* (1997) examined minimum energy requirements of the lead leg when stepping over obstacles of different heights. The study examined healthy young subjects only (n = 8) while stepping over obstacles of 5.1cm, 10.2cm, 15.3cm and 20.4cm and during level unobstructed walking. Toe-obstacle clearance ranged from 14 – 15.5cm, slightly higher than the results reported by Patla and Rietdyk (1993) and Chen *et al.* (1991). The high obstacle clearance resulted in a significant increase in mechanical work (p=.022) required to elevate the foot sufficiently to clear the obstacle with a safety margin between the toe and the obstacle. Chou *et al.* (1997) concluded that higher priority is allocated to optimisation of neural control of lower extremity

muscles in an attempt to minimise the risk of tripping whilst crossing obstacles than minimising energy expenditure.

Several studies have examined obstacle avoidance under time critical conditions and whilst attention was divided (Weerdesteyn *et al.*, 2003; Ashton-Miller, 1999; Chou *et al.*, 1997; Chen *et al.*, 1996; 1994b). In general, these studies show that rates of successful obstacle avoidance decrease when attention is divided and when available response times (ART) are reduced. Chen *et al.* (1996; 1994b) measured rates of success (RS) in avoiding a band of light projected transversely onto the walkway at predicted next-footfall to give varying amounts of ART. Additionally, Chen *et al.*'s (1996) study required subjects to respond verbally to simple and choice visual reaction time probes (previously described in section 2.1.2.3). The results showed that with a smaller ART of 350ms, RS of obstacle avoidance in elderly subjects was significantly poorer ($p<.033$ - $p<.015$) with decreases of 32.0% - 35.7% during the two different secondary tasks. Chen *et al.* (1996) concluded that divided attention significantly decreased successful obstacle avoidance in young and old subjects, but significantly more in the older subjects and particularly under time critical conditions (i.e. reduced ART).

In another study, Weerdesteyn *et al.* (2003) examined rates of success in obstacle avoidance of healthy young subjects whilst responding verbally to an auditory stimulus. The auditory stimulus was chosen to eliminate the structural interference (i.e. when the same sensory modality is required placing extra demands on that sensory system – described in divided attention section 2.1.2.3) involved in presenting a visual cue while the visual system is also required for identifying the appearance of the obstacle. In

contrast to walking overground in Chen *et al.*'s studies, subjects in Weerdesteyn *et al.*'s study walked on a treadmill at an imposed speed of 4km/hr. A wooden obstacle containing a piece of iron (length = 40cm, width = 30cm, height = 1.5cm) suspended by a magnet was mounted on a small bridge at the front of the treadmill. Dropping of the obstacle onto the treadmill belt was timed to co-incide with ipsilateral midswing (i.e. short ART), ipsilateral midstance (i.e. long ART), and late stance of the ipsilateral limb. Appearance of the obstacle at late stance involved two possible avoidance strategies: long stride strategy (LSS – i.e. take a longer crossing step) or short stride strategy (SSS – i.e. shorten normal step length). The secondary task required subjects to listen to the words "high" and "low", spoken at either a high or low tone so that the meaning of the word may or may not be in conflict with the pitch of the tone spoken. Subjects had to identify and say the pitch of the words spoken (i.e. high or low). Subjects performed 30 trials (15 minutes) each of single- (ST) and dual-task (DT). Results showed that rates of success were lower when available response time was less (i.e. with short ART of 120 – 480ms, obstacle avoidance failure rates were 10.8% greater during dual- compared with single-task condition, $p<.05$). This appears comparable to the results of Chen *et al.* (1996) where failure rates of young adults increased between 12.6% and 17.1% during divided attention when ART was shortened to 350ms.

These studies of the foot trajectory have contributed valuable information to the area of tripping and falling research, however, they have been limited mainly to obstructed walking. Examination of unobstructed walking over a longer period of walking allows an understanding of the control of gait. Dual-task studies during gait have shown

important performance decrements in older subjects, however, none have used 'real-life' distractions and focused on MTC during unobstructed walking.

2.3.1 Calculation of the probability of tripping

A key feature of this research is predicting the probability of an individual tripping on an unseen obstacle that occurs at the point of MTC using each individual's MTC data set for the 20-minute undistracted walking. Given that the frequency of tripping has been identified as a risk factor for falling (Pavol *et al.*, 1999), the ability to predict the likelihood of tripping would be advantageous for falls prevention. This section outlines the calculation of the probability of tripping as described by Best and Begg (2002).

The true probability of tripping over an unseen ycm obstacle that occurs at MTC ($TPT_{MTC}(y)$) for a given terrain is given by:

$$TPT_{MFC}(y) = \left[PT_{MFC}(y) \times P_{MFC}(y)\right] \qquad \textbf{Equation 2.3.1}$$

where $PT_{MTC}(y)$ is the probability of tripping over an unseen y centimetre (ycm) obstacle that occurs at MTC, and $P_{MTC}(y)$ is the probability of a ycm obstacle occurring at MTC on that terrain (Best and Begg, 2002).

All probabilities vary between 0 and 1. $P_{MTC}(y)$ is entirely a function of the walking terrain. $P_{MTC}(y) = 1$ represents a ycm obstacle always occurring at MTC, and $P_{MTC}(y) = 0$ represents a ycm obstacle never occurring at MTC. $PT_{MTC}(y)$ is individual specific,

specific to the terrain, and may be specific to many other factors (e.g. type of shoe, lighting, level of distractedness or type of distraction).

For treadmill walking, $P_{MTC}(y>0cm) = 0$ and, therefore, $TPT_{MTC}(y>0cm) = 0$. This does not mean the $PT_{MTC}(y)$ calculated during treadmill walking, as in this research, is irrelevant but rather that $PT_{MTC}(y)$ for treadmill walking represents a terrain where the person is not expecting an obstacle to occur. It could be argued that there are many similar terrains (e.g. in the home where an unseen object is lying on a known walkway, a corridor at work or a shopping centre floor).

The treadmill terrain is currently the only terrain on which the method of calculating the probability of a person tripping (PT) has been applied. PT is calculated for all values of MTC (y) in 0.1cm increments from 0cm to 6cm. Calculated PT using this method are presented in the results and discussion chapter and extracts are shown in Table 2.3 to assist with explanation of the PT method. Here, the group median values are shown for the young and elderly groups and the frequency of tripping (number of strides per trip) and probability of tripping ($PT_{MTC}(y)$) ranging from 0 to 1. For example, at MTC(y) 2.0cm, the young subjects had a PT_{MTC} of 0.24, that is, the median young individual will hit an unseen 2cm obstacle approximately 24% of the time, or once in every 4.18 strides. Notice from MTC(y) 0 – 0.5cm, both young and elderly groups appear to have equal PT. PT at these small heights are, in fact, not equal but the PT are so small that calculation is not possible. From MTC(y) 0.8cm to 2.5cm, the elderly have greater PT than the young subjects and from MTC(y) 3.0 to 6.0cm, both groups have similar or equal PT. This data shows that the elderly are at a greater risk

of tripping on small unseen obstacles and as the height of the object increases, both young and elderly are equally likely to trip if it is unseen.

Table 2.3: Probabilities of tripping.

MTC (y) / cm	Young		Elderly	
	Frequency	PT	Frequency	PT
0.0	10,000,000	0.00000010	10,000,000	0.00000010
0.5	10,000,000	0.00000010	10,000,000	0.00000010
0.8	10,000,000	0.00000010	8,387,510	0.00000012
0.9	10,000,000	0.00000010	268,502	0.000007
1.0	10,000,000	0.00000010	17,187	0.00006
1.1	3,657,330	0.0000003	1,552	0.0006
1.2	244,887	0.000004	368	0.003
1.3	26,230	0.00004	139	0.008
1.4	3,757	0.0003	47	0.02
1.5	717	0.001	22	0.05
2.0	4.18	0.24	2.09	0.48
2.5	1.16	0.86	1.11	0.90
3.0	1.01	0.99	1.01	0.99
4.0	1.00	1.00	1.00	1.00
5.0	1.00	1.00	1.00	1.00
6.0	1.00	1.00	1.00	1.00

Reworking the data presented in Table 2.3 to plot a graph of $PT_{MTC} = f(y)$, results in the profiles shown in Figure 2.15. Much useful PT data is presented in Figure 2.15 and there are many ways to use the PT data to define parameters, from both a group and individual perspective. This information can be in the form, for example, $PT_{MTC}(2.0cm) = 0.24$ (i.e. the individual will hit an unseen 2cm obstacle once in every 4.18 strides). An alternative way of presenting the data is in the form 'the unseen obstacle height at which PT is 1 in 100,000 strides, etc (ie. PT_{100000}, PT_{10000}, PT_{1000}, PT_{100}, etc). For the young subjects using median values, these parameters work out to be $PT_{100000} = 1.3cm$, $PT_{10000} = 1.4cm$, $PT_{1000} = 1.5cm$, $PT_{100} = 1.7cm$, $PT_{10} = 1.9cm$, $PT_5 = 2.0cm$, $PT_2 = 2.2cm$.

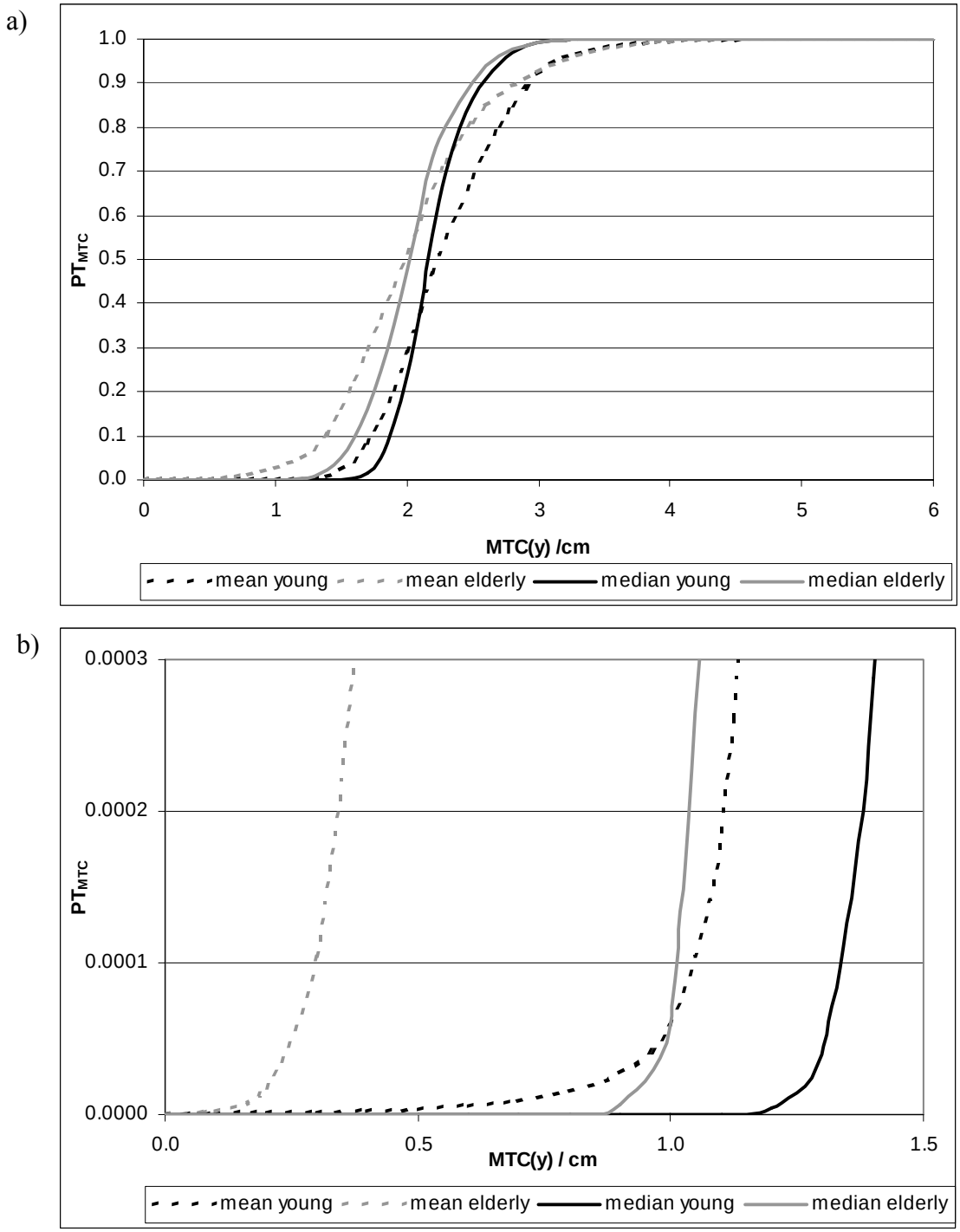


Figure 2.15: Probability of tripping plot of graph PT_{MTC} vs. obstacle height (y): a) varying from 0 to 6cm; b) y varying from 0 to 1.5cm.

Figure 2.15 shows profiles for group median (solid line) and mean (dotted line) PT_{MTC} at given obstacle heights, MTC(y), for young and elderly. Profile a) shows $PT_{MTC}(y)$

with MTC varying from 0 to 6cm whilst profile b) shows MTC varying from 0 – 1.5cm and highlights PT for the data in the range from 0 to 0.0003. It can be seen that the elderly have greater $PT_{(MTC)}$ for all values of MTC(y).

The $PT_{MTC}(y)$ technique (Best and Begg, 2002) was applied to the treadmill terrain, which is currently the only method of obtaining the large number of MTC required for accurately calculating PT. Being able to measure $PT_{MTC}(y)$ on different terrains would be a useful addition to tripping research.

During 'normal walking' on a terrain which includes obstacles it is reasonable to assume people see obstacles some of the time. To account for this fact, $TPT_{MTC}(y)$ for unseen objects is given by:

$$TPT_{MFC}(y) = \left[PT_{MFC}(y) \times P_{MFC}(y) \times \left\{1 - P_{VOB}(y)\right\}\right] \qquad \textbf{Equation 2.3.2}$$

where $P_{VOB}(y)$ is the probability of seeing the ycm obstacle, P_{VOB} varies from 0 - 1.

A person seeing the obstacle all the time results in $P_{VOB}(y) = 1$ and, according to Equation 2.3.2, $TPT_{MTC}(y) = 0$. In rare circumstances, a trip may occur even when an obstacle is seen. This can be modelled by splitting Equation 2.3.2 into 'seen' and 'unseen' components, viz:

$$TPT_{MFC}(y) = \left[PT_{MFC(UNSEEN)}(y) \times P_{MFC}(y) \times \{1 - P_{VOB}(y)\}\right] + \left[PT_{MFC(SEEN)}(y) \times P_{MFC}(y) \times P_{VOB}(y)\right]$$

Equation 2.3.3

where the left side of Equation 2.3.3 represents the case of an unseen obstacle and the right side represents the case of a seen obstacle.

For the treadmill research of Best and Begg (2002), the probability of the foot hitting the ground was calculated and it was found that $PT_{MTC(SEEN)}(y=0cm) = 3.8x10^{-6}$ (ie. 1 in every 266,305 strides). In contrast, group median values for both young and elderly in this research shows that $PT_{MTC(SEEN)}$ $(y=0cm) < 1x10^{-7}$ (i.e., <1 in every 10,000,000 strides). For treadmill walking, it can be assumed the walker sees and is aware that the height of the obstacle (ground) is always 0cm, so $P_{VOB}(0cm) = 1$, and since the ground is always there, $P_{MTC}(0cm) = 1$. Hence, the left side of Equation 2.3.3 is zero (ie. the ground is never regarded as unseen) and, using the median young and elderly data, $TPT_{MTC}(0cm) = PT_{MTC(SEEN)}(0cm) = 1x10^{-7}$.

As described by Best and Begg (2002), the true probability of tripping (TPT(y)) on a ycm obstacle can be calculated for the entire flight phase of the foot. This involves integrating $PT_{SEEN}(y)$ and $PT_{UNSEEN}(y)$ for the whole of the flight phase of the foot, and replacing $P_{MTC}(y)$ with $P_{OB}(y)$; ie. the probability of a ycm obstacle occurring at some point during the flight phase of the foot on that terrain; viz

$$TPT(y) = \left[\left\{ \int_{TO=0}^{FS=1} PT_{UNSEEN}(y).dt_{normalised} \right\} \times P_{OB}(y) \times \{1 - P_{VOB}(y)\} \right] + \left[\left\{ \int_{TO=0}^{FS=1} PT_{SEEN}(y).dt_{normalised} \right\} \times P_{OB}(y) \times P_{VOB}(y) \right]$$

Equation 2.3.4

where $t_{normalised}$ is the normalised time of the flight phase of the foot; ie. between toe-off (TO = 0) and foot strike (FS = 1), thus ensuring that TPT(y) varies between 0 and 1.

Equation 2.3.4 assumes that an obstacle is just as likely to occur at any point between toe-off (TO) and footstrike (FS) irrespective of whether it is seen or not. While this is true for the case of the unseen obstacle, for an obstacle that is seen (with plenty of time to adjust to the obstacle) it can be argued that the instant of foot clearance is the only point of interest, irrespective of where the obstacle appears between TO and FS in the swing phase, and;

$$TPT(y) = \left[\left\{ \int_{TO=0}^{FS=1} PT_{UNSEEN}(y).dt_{normalised} \right\} \times P_{OB}(y) \times \{1 - P_{VOB}(y)\} \right] + \left[PT_{MFC(SEEN)}(y) \times P_{OB}(y) \times P_{VOB}(y) \right]$$

Equation 2.3.5

The function $PT_{UNSEEN}(y) = f(t_{normalised})$, $PT_{MTC(SEEN)}(y)$ and the function $PT_{SEEN}(y) = f(t_{normalised})$ (if applicable) have never been calculated previously but a number of facts are known about these functions. For example, at toe-off ($t_{normalised} = 0$), if the toe is in contact with the ground, $PT_{UNSEEN}(y>0cm) = PT_{SEEN}(y>0cm) = 1$. Also, for a 'normal' walking gait where the toe is always below 20cm off the ground,

$$\int_{TO=0}^{FS=1} PT_{UNSEEN}(y > 20cm).dt_{normalised} = 1$$

ie. for a walking gait where the toe remains below a height of 20cm, it doesn't matter where the >20cm obstacle appears in the gait cycle, it will cause a trip 100% of the time if it is not seen.

Figure 2.16 presents the relationship between PT_{UNSEEN} and $t_{normalised}$ for a variety of obstacle heights (or MTC values). The area under this graph is equivalent to the PT_{UNSEEN} integral referred to in Equation 2.3.4.

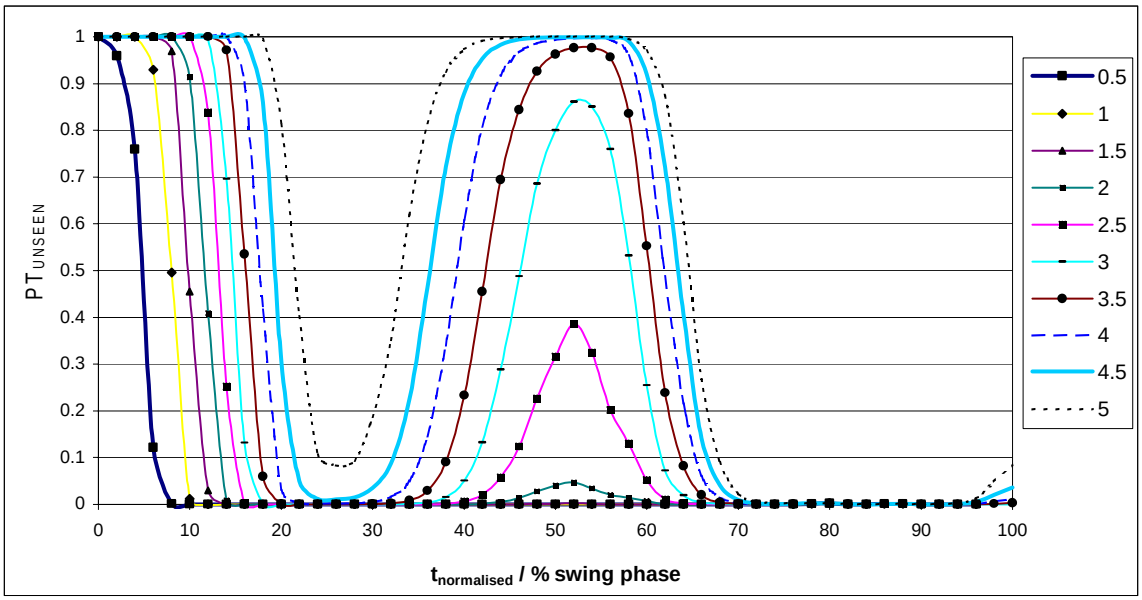


Figure 2.16: Graph of PT_{UNSEEN} vs $t_{normalised}$ for various obstacle heights (y).

A separate $PT_{SEEN}(y)$ and $PT_{UNSEEN}(y) = f(t_{normalised})$ could be measured for each part of the shoe/foot. The heel of the shoe will have a different $PT_{SEEN}(y)$ and $PT_{UNSEEN}(y) = f(t_{normalised})$ profile compared to the tip of the shoe. Also, the heel (and other parts of the foot/shoe) is sometimes at a lower position than the toe/tip of the shoe (e.g. at foot strike). All these factors are easily incorporated into variations of Equation 2.3.4.

Even when an obstacle is seen with plenty of time to accommodate it, elderly subjects tend to be less successful in obstacle avoidance (e.g. Chen *et al.*, 1996). Moreover, when available response time is reduced, and/or attention is divided, the difference in successful obstacle avoidance is significantly less in the elderly (Chen *et al.*, 1996; 1994a; 1994b). For example, Chen *et al.* (1994b) found the elderly adjusted step pattern one step earlier than young adults and tend to take short steps to accommodate the obstacle and had more difficulty taking long steps when available response time was reduced. If it is important to know the probability of tripping at different points in the swing phase for seen objects then the $PT_{SEEN}(y) = f(t_{normalised})$ relationship between TO and FS is required. In this case it should be noted that the probability of an obstacle occurring at different points in the swing phase is not constant, and this should be taken into account. However, in practical terms and for most applications, Equation 2.3.5 adequately incorporates variability within the swing phase and variability between subjects, and provides a good overall assessment of the probability of a person tripping.

If an obstacle is seen early enough, the individual has time to alter the gait path to either go around or adjust the stride in order to go over an obstacle (e.g. Patla *et al.*, 1991). An obstacle seen late is a hazardous situation and more likely to lead to a trip and fall, particularly in older adults where reaction and response times are typically reduced (e.g. van den Bogert *et al.*, 2002; Chen *et al.*, 1996). Moreover, Begg and Sparrow (2000) concluded that approach to an obstacle is a critical determinant for older adults to successfully negotiating an obstacle. When an obstacle is contacted very late in the gait cycle, the body's centre of mass is already anterior to the stance foot. Therefore, it is possible due to reduced reaction and response times that if an

obstacle is seen late and tripped on, an older adult may have difficulty in recovering, leading to a fall.

If an obstacle is seen so late that it is too late to adjust gait then it is effectively 'unseen' and the left side of Equation 2.3.4 (and Equation 2.3.5) applies. When an obstacle is seen late, i.e., at the last minute, it is often the case that the foot strike that precedes the obstacle negotiation has already occurred and late adjustments are made to try and negotiate the obstacle. In this instance, $PT_{MTC(SEEN)}(y)$ from Equation 2.3.5 becomes $PT_{MTC(SEENEARLY)}(y)$, the obstacle is equally likely to occur at any point in the swing phase (since the preceding foot strike has already occurred) and a third part to Equation 2.3.5 is required to incorporate the new parameter, $PT_{MTC(SEENLATE)}(y)$, viz;

$$TPT(y) = \left[\left\{ \int_{TO=0}^{FS=1} PT_{UNSEEN}(y).dt_{normalised} \right\} \times P_{OB}(y) \times \{1 - P_{VOB}(y)\} \right] +$$

$$\left[PT_{MFC(SEENEARLY)}(y) \times P_{OB}(y) \times P_{VOBE}(y) \right] +$$

$$\left[\left\{ \int_{TO=0}^{FS=1} PT_{SEENLATE}(y).dt_{normalised} \right\} \times P_{OB}(y) \times P_{VOBL}(y) \right]$$

Equation 2.3.6

where $P_{VOBE}(y)$ = the probability of seeing the obstacle early and $P_{VOBL}(y)$ = the probability of seeing the obstacle late (ie. $P_{VOBL}(y) + P_{VOBE}(y) = P_{VOB}(y)$ = the probability of seeing the obstacle).

2.3.2 Summary

Tripping while walking has been recognised as a frequent cause of falling. Most research investigating tripping has concentrated on obstacle negotiation (i.e. tripping on or negotiating seen objects). These studies have highlighted that elderly adults are at a greater risk of tripping on obstacles, particularly under conditions of divided attention requiring vision to be directed to a secondary task. It has also been shown that vision plays a vital role in the successful negotiation of the walking terrain. In obstacle negotiation studies, ageing effects in obstacle avoidance and stepping strategies employed have been found, particularly under time critical conditions. The major limitation with these studies, however, is that the subject is aware an obstacle will appear and therefore will anticipate its appearance regardless of its timing (i.e. early or late in the stride). In reality, individuals are constantly confronted with situations of divided attention while walking and may not see an obstacle in their path and, therefore, the option of pre-planning gait adjustments to accommodate an obstacle is not possible.

There is a need to examine foot motion over unobstructed walking and the biomechanical patterns contributing to tripping on unseen obstacles. Additionally, whilst current studies have focused on various temporal and spatial gait kinematics, more attention should be directed specifically towards sensitive measures such as MTC and any ageing effects. There is clearly a need to examine the foot trajectory while walking on level ground in order to gain an insight into how some individuals might be at a greater risk of tripping on unseen obstacles. There is also a need to examine the effect of various distractions on the foot trajectory and its contribution to tripping.

When an obstacle is seen, some attempts will be made in order to avoid tripping on it. In reality, however, small obstacles are often not seen and this is likely the case in the high tripping frequency reported in community-dwelling elderly. Whilst all individuals experience tripping from time to time, the consequences of falling due to tripping are clearly more serious in older populations. Since tripping frequency is a predictor of falling, the ability to reduce tripping frequency and identify those at risk of tripping would be an important contribution to falls research. There is, therefore, a need to examine MTC during unobstructed walking in order to estimate the likelihood of tripping on unseen obstacles.

Chapter 3: Objectives of investigation

3.1 General aims

The purpose of this research is to investigate minimum toe clearance (MTC) distributions in healthy, young and elderly females during treadmill walking both without distractions and whilst attention is divided. The data obtained will be used to identify age-related degeneration in gait control, which may be related to increased risk of tripping on unseen obstacles while walking.

The effect of different distractions, which can be related to 'everyday' activities, on MTC while walking will be examined. Changes to MTC descriptive statistics will assist in determining which type of distractions elicit the greatest disruption to gait control and, therefore, are more likely to lead to tripping on unseen obstacles.

3.2 Specific aims

1) To determine the effect of age (young or old) and walking condition (distracted or undistracted) on major descriptive statistics of the MTC distribution and identify strategies employed in implementing MTC. Major descriptive statistics examined include: (i) mean; (ii) median; (iii) standard deviation; (iv) interquartile range (IQR); (v) skew; and (vi) kurtosis.

2) To determine the effect of age (young or old) on the predicted probability of tripping.

3.2.1 Hypotheses

Aim 1: Null Hypothesis

1. No significant effect of age upon major descriptive statistics of the MTC distribution.
2. No significant effect of walking condition upon major descriptive statistics of the MTC distribution.

Aim 2: Null Hypothesis

1. No significant effect of age upon the predicted probability of tripping.

Chapter 4: Methods

4.1 Subjects

4.1.1 Population studied

The population studied comprised of 24 healthy young female subjects aged 18.3 to 32.5 years (mean age 21.7, SD = 3.4 years) and 24 healthy elderly community-dwelling females aged 65.1 to 80.6 years (mean age 71.9, SD = 4.2 years). All subjects were free of conditions that might impair normal locomotion (e.g. joint replacements, arthritis or other musculoskeletal conditions) or compromise safety (e.g. balance disorders, cardiovascular conditions). A full description of inclusion and exclusion criteria is detailed in section 4.1.2.

Only female subjects were chosen in this study because only a small sample was achievable within the timeline. For example, data collection, digitising and parameter extraction for one subject took a minimum of 50 hours per subject, which is equal to a minimum of 2,400 hours for all 48 subjects. Estimating a workload of 8 hours a day, 60 weeks alone would be required from data collection to parameter extraction. Several more hours per subject were required, in addition to the estimated 50 hours, for data analysis for the undistracted and each of the six distraction conditions. Eliminating gender effects by examining females only was also seen as an important methodological consideration. Furthermore, research has shown that women are more

prone to falls and injurious falls. Older females have fall rates and fall injury rates that are approximately 1.5 – 2 times higher than those of older males (Schultz *et al.*, 1997).

4.1.2 Recruitment

Young subjects were recruited from the academic community of Victoria University. Elderly subjects were recruited through advertisements in newsletters and local newspapers, contacting subjects who had previously participated in studies at Victoria University, and through visits to walking clubs, exercise groups and gymnasiums running programs for older adults.

Inclusion criteria for young subjects were gender (female) and age (18 – 35 years). Additionally, subjects had to declare themselves as being relatively fit and active, which was defined as regular participation in some form of physical activity and capable of walking for at least 30 minutes. Exclusion criteria were any musculoskeletal or other conditions that might impair normal locomotion (e.g. sprains, strains and other injuries to the lower limb, back pain, advanced pregnancy etc) and any medical condition that might compromise safety. Each of the young subjects had prior treadmill experience while some were regular treadmill users and all participated in physical activity on a regular basis. All young subjects rated themselves in good physical health, none were pregnant and all were free of any acute or chronic injuries or other musculoskeletal or medical conditions that might present a safety risk or influence normal walking.

Recruitment of elderly subjects was a more complex process and was completed in three stages:

1. preliminary screening to ensure potential subjects satisfied basic inclusion criteria;
2. obtaining approval from their own General Practitioner to ensure no health risks were present and that they were capable of at least 36 minutes of continuous treadmill walking (6 minutes familiarisation immediately followed by 30 minutes data collection); and
3. final screening tests including physical performance, visual function, cognitive state and level of fear of falling (described in section 4.1.2.3).

4.1.2.1 Preliminary screening of elderly subjects

Preliminary screening was conducted via telephone conversation, the point of initial contact with the subject expressing their wish to participate in the study. During the telephone conversation, subjects were verbally screened to ensure they were within the target population sought for the study. The inclusion criteria selected were based on review of the literature (refer section 2.1) to ensure there were no known conditions that might compromise safety and affect normal gait. Table 4.1 details preliminary screening for basic inclusion and exclusion criteria.

Table 4.1: Basic inclusion and exclusion criteria for elderly subjects.

Inclusion	Exclusion
➢ Female ➢ Aged between 65 and 85 years ➢ Self-perceived relatively fit and active ➢ Live independently in the community ➢ Regularly go outdoors ➢ Usually walk for exercise ➢ Walk without the use of a gait aid	➢ History of falls in the past 12 months ➢ Recent limb or spinal fracture ➢ Other orthopaedic or musculoskeletal conditions (e.g. joint replacement, arthritis, chronic back pain) ➢ Significant past head trauma ➢ Neurological disease (including vertigo, light-headedness, dizziness or unsteadiness) ➢ Ophthalmic disease (e.g. glaucoma) ➢ Visual impairment not correctable with glasses ➢ Cardiovascular disorders ➢ Any painful foot problems (e.g. ulcers, bunions, spurs) ➢ History of cerebral vascular accident or Parkinson's Disease

4.1.2.2 General Practitioner approval

Once potential subjects were identified and preliminary screening successfully completed, subjects were asked to visit their General Practitioner to obtain medical clearance in order to ensure subjects were 'healthy'. At this stage, subjects were mailed an information pack which outlined the procedures involved with obtaining medical clearance, details about testing protocol and testing venue and confirmation of inclusion and exclusion criteria for the study. An information sheet about the study and testing protocol was included as well as the information subjects were to take to their General Practitioner (refer Appendix A). The information for the General Practitioner included an information sheet regarding the objectives and procedures of the study and a sheet that required the General Practitioner to indicate whether the subject was safe to participate in the study. Subjects were asked to retain the signed General Practitioner approval sheet and to contact the researcher once approval was obtained.

4.1.2.3 Final screening tests for elderly subjects

After General Practitioner approval was received, a time was arranged for elderly subjects to attend the biomechanics laboratory for additional screening and testing. Screening tests, to determine whether the subject satisfied further inclusion criteria, included tests of mobility (Step Test and Timed Up & Go Test), vision (visual acuity using logMAR chart and edge contrast sensitivity using Melbourne Edge Test), cognitive state (Mini-Mental State Examination) and level of fear of falling (Modified Falls Efficacy Scale). These screening tests, and justification for their use in this study, are described in detail in this section. Subjects within established 'normal' limits of these screening tests (refer Table 4.2) were included in the study and were tested on the same day. Informed consent was obtained prior to conducting final screening tests (refer Appendix B).

Table 4.2: Screening tests conducted on elderly subjects.

Parameter Measured	Test	Exclusion
Mobility	Step Test	Unable to perform unassisted or completes less than 17 steps
Mobility	Timed Up & Go Test	Longer than 8.5s to complete
Visual acuity	Bailey-Lovie LogMAR chart	6/12 (logMAR 0.30) or more
Edge contrast sensitivity	Melbourne Edge Test	16dB or less
Cognitive state	Mini-Mental State Examination	Score of 23 or less
Level of fear of falling	Modified Falls Efficacy Scale	Mean score of less than 7.7

There are now several identified risk factors for falls with strong supporting evidence. Thus, several clinical tests have been devised to evaluate the falls risk of patients and

subjects for research studies. Since this research examines healthy elderly females, some established tests were conducted to ensure subjects included in the study were within 'normal' limits. Subjects deemed unsuitable were identified in the early stages, that is, through verbal screening over the telephone, and were not included in the final stage of participating in screening tests. All subjects attending the laboratory for screening tests satisfied inclusion criteria (refer Table 4.2) and were included in the study. In summary, the tests conducted were to evaluate mobility (Step Test and Timed Up & Go Test (TUG)), vision (visual acuity using Bailey-Lovie logMAR chart, and edge contrast sensitivity using Melbourne Edge Test), cognitive state (Mini-Mental State Examination) and level of fear of falling (Modified Falls Efficacy Scale).

4.1.2.3.1 Mobility tests

4.1.2.3.1.1 Step Test

The Step Test is a commonly used physical performance test that evaluates the speed at which dynamic single leg stance can be performed during self-perturbation. The test is sensitive to mild levels of balance dysfunction (Hill, 1997) and poor scores are indicative of a higher risk for falls.

The subject stands with feet parallel, shoes removed, with a 7.5cm tall wooden step placed 5cm in front. The tester places one foot on the far side of the step to steady it in case it is displaced by the subject's foot. Without support, the subject is instructed to place the foot fully onto the step and then return it completely to the floor. This is

repeated as quickly and safely as possible. Subjects are advised which leg to use and to ensure the supporting foot stays firmly on the ground. The subject has 15 seconds to complete this task. Test score is the number of times the foot touches the block and returns to the floor in the 15 second testing period. One step is where the foot is placed completely on the step and then down off the block onto the floor. The test is to be completed without the physical assistance of the tester. Should the subject require support due to unsteadiness, the test is stopped at the number of steps completed and this is recorded as the test score.

The tester gave a verbal explanation of the test and then demonstrated. Subjects were allowed several practice steps prior to testing to familiarise themselves with the test. Testing commenced on the command "go" and finished on the command "stop". This procedure was then repeated for the other leg. In a group of healthy older people (mean age 73 years), a mean of 17 steps was completed in 15 seconds (Hill *et al.*, 1996). A mean step rate of 1.13Hz is therefore expected as normal for healthy older people.

4.1.2.3.1.2 Timed Up & Go Test

The Timed Up & Go Test (TUG) is a physical performance test commonly used to examine functional mobility in community dwelling, frail older adults. Functional mobility is defined as balance and gait manoeuvres used in everyday life such as walking, turning and rising from a chair (Podsiadlo and Richardson, 1991). This test is a modified version of the Get-Up-and-Go test (GUGT) described by Mathias *et al.* (1986). In the GUGT, subjects rise from a chair, walk three metres to a wall, turn

around, walk back to the chair and sit down. The task is video-recorded and balance function, as observed by the rater, is scored on a five-point scale in terms of the 'normality' of gait. Normal (or a score of one) was defined as no perceived risk of a fall, whilst severely abnormal (or a score of five) meant the subject appeared to be at risk of falling. The intermediate scores (two to four) relate to hesitancy or slowness of gait, abnormal trunk or upper-limbs movements, staggering. These were defined as indicators of a risk of falling in less favourable circumstances (Mathias *et al.*, 1986).

As Podsiadlo and Richardson (1991) highlighted, the extreme of the scale (one and five) were easy to score but the intermediate scores (two to four) were less clear and tended to produce variation in scores between different observers. Whilst they conceded it was a useful test, they added a timed component to the same task and deleted the subjective scoring of the patient's perceived risk of falling. Podsiadlo and Richardson concluded the TUG test appears to have good inter-rater and intra-rater reliability (ICC 0.99) in medically stable day hospital patients.

Podsiadlo and Richardson (1991) reported significant correlations of the TUG with measures of balance (Berg Balance Scale) (r=-0.81), gait speed (r=-0.61) and functional capacity (Barthel Index of ADL (r=-0.78). Shumway-Cook *et al.* (2000) concluded that the TUG was a valuable tool for predicting falls in community-dwelling older adults with specificity and sensitivity of 87%. In their study, the TUG test was used to predict falls in community-dwelling older adults under dual-task and single-task conditions. They found that both single- and dual-task TUG were equivalent in their accuracy of predicting falls in this group.

For the TUG, the subject wears their own comfortable shoes and is seated on a standard chair (seat height 45cm and arm height 63cm) with their back against the back of the chair and arms resting on the chair arms. On the command "go", the subject is to stand up from the chair, using their arms if they wish. The subject then walks three metres to a line on the ground at their preferred, comfortable walking speed, turns around, walks back to the chair, turns and sits down ensuring their back is again resting on the back of the chair.

Timing begins on the command "go" and finishes when the subject is seated with their back resting against the back of the chair. No physical assistance is given during the test. Subjects are allowed to walk through the test once prior to being timed in order to familiarise themselves with the test. The test score is the time (in seconds) taken to complete the task.

In the study by Podsiadlo and Richardson (1991), healthy elderly control subjects (n = 10), who ambulated without the use of an aid, had mean TUG scores of 8.5 seconds (range 7 – 10 seconds). Shumway-Cook *et al.* (2000) reported similar mean scores of 9 seconds (range 6.4 – 13.4 seconds) in a group of healthy elderly walking without an assistive device (n = 15).

4.1.2.3.2 Vision

4.1.2.3.2.1 Bailey-Lovie logMAR chart for visual acuity

As discussed in the literature review, impaired vision has been linked with increased risk of falls in the elderly. Visual acuity, or distance vision, is one measure commonly assessed in the clinical and research setting when screening for falls risks. The Bailey-Lovie logMAR chart for visual acuity (Bailey and Lovie, 1976) has addressed some of the deficiencies identified with the original Snellen ototypes chart introduced in 1862. The logMAR (logarithm of the minimum angle of resolution) test differs from previous letter charts by utilising letter sizes that follow a geometric progression of 0.1 log unit. Additionally, the test has been standardised by controlling letter and row spacing and using letters of equal legibility. The test chart consists of 14 rows of letters, with 5 letters in each row. The size of the letters is largest at the top row and becomes progressively smaller with each line. Scores are given in both traditional Snellen notation and logMAR scale along the sides of the chart, corresponding with each row of letters read.

The subject stands at a distance of 3m from the test chart with both eyes open. If the subject generally wears spectacles for distance vision, then these are worn for the test. The subject then reads the letters on the chart beginning from the top row, reading from left to right. The test finishes when the subject is unable, or incorrectly reads, the letters on the chart. The score corresponding with the last row correctly read is taken as the subject's test score for visual acuity. High logMAR scores are indicative of

impaired visual acuity. Test scores of logMAR 0.4 (Snellen imperial equivalent 6/15 or metric equivalent 20/50) or more are rated as poor (Lord *et al.*, 1991). More conservatively, the Framington and Beaver Dam Eye Studies, two large-scale studies investigating vision and its relationship to falls in elderly populations, rated logMAR scores of 0.3 (Snellen imperial equivalent 6/12 or metric equivalent 20/40) or worse as indicating impaired vision (Klein *et al.*, 1998; Felson *et al.*, 1989). Other studies have used the same criteria as the Framington and Beaver Dam studies (Wang *et al.*, 1999).

4.1.2.3.2.2 Contrast sensitivity function (Melbourne Edge Test – MET)

As outlined in the literature review, poor contrast sensitivity is predictive of poor orientation and mobility and has been stated as a risk factor for trips and falls. The Melbourne Edge Test (MET) was designed by Verbaken and Johnston (1986) to enable a quick and reliable assessment of contrast sensitivity function. The test consists of 20 circular patches, each with a diameter of 25mm, displayed in four rows of five circular patches on a light box to illuminate the patches (refer Figure 4.1). The circular patches have a series of edges, or lines, with gradually declining contrast and variable orientation (horizontal, vertical, 45 deg right and 45 deg left).

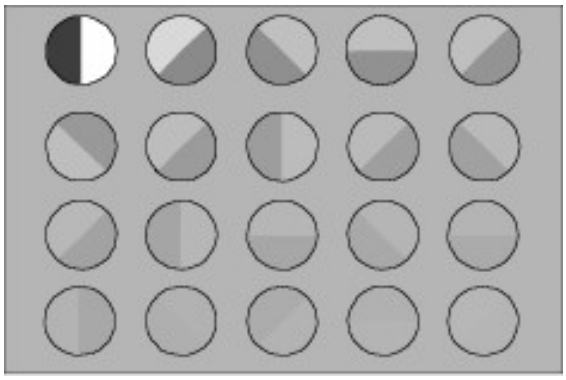


Figure 4.1: The Melbourne Edge Test (MET) by Verbaken and Johnston (1986).

A response key card with a circular cut-out corresponding with size of the circular test patch is placed over each patch, beginning from the top left patch, to isolate the patch being tested. Thus, the subject can easily identify the test patch in question through the circular cut-out, without being distracted by adjacent test patches. The four possible choices are printed around the cut-out for subject selection. The response key card is then moved to reveal each test patch until the subject answers incorrectly. The last patch correctly identified indicates the subject's edge contrast sensitivity. The test is therefore a four-alternative, forced-choice test. The number under each test patch indicates the score, or contrast sensitivity of the edge, measured in decibels (dB = -10 log). Low MET scores are indicative of impaired edge contrast sensitivity. Scores equal to or less than 16dB are considered as poor edge contrast sensitivity (Lord *et al.*, 1991).

4.1.2.3.3 Cognitive state (Mini-Mental State Examination - MMSE)

Since diminished cognition is a well-established risk factor for falls, there have been several methods established for determining level of cognition. One commonly used tool for evaluating cognitive state for both clinical and research purposes is the Mini-Mental State Examination (MMSE) (Folstein, 1975). The test requires subjects to answer questions relating to orientation, registration, attention and calculation, recall, language and spatial orientation (see Appendix C). The maximum possible test score is 30. Subjects with scores equal to or below 23 are generally considered to be of poor cognitive state and are at a greater risk of falls (Lord and Clark, 1996; Murden *et al.*, 1991).

4.1.2.3.4 Level of fear of falling (Modified Falls Efficacy Scale – MFES)

The Modified Falls Efficacy Scale (MFES) (Hill *et al.*, 1996) is an expanded version of the Falls Efficacy Scale (FES) designed by Tinetti *et al.* (1990). The FES requires subjects to rate on a 10-point scale how fearful they were of falling whilst performing 10 different common daily activities. This test proved to be a very valuable advance in the clinical evaluation of balance impairment and was significantly correlated with several measures of balance, gait and anxiety levels (Tinetti *et al.*, 1990). As identified by Hill *et al.*, more difficult outdoor activities were not addressed in the FES. It is these outdoor activities which elderly adults fearful of falling are most likely to avoid due to a fear of falling. Hill *et al.* (1996) included more difficult outdoor items, thus making the test more sensitive to identifying healthy elderly adults with mild levels of

fear of falling. The authors added four more items to the scale, all being normal everyday outdoors activities. Their test is, therefore, more sensitive in identifying elderly adults who have not yet fallen but are at a high risk of doing so.

Based on their preliminary findings, Hill *et al.* (1996) concluded that the MFES is a reliable and valid clinical test for evaluating the early stages of fear of falling in community-dwelling active older adults. Further, they stated that the MFES is a useful addition to the assessment of older adults with a history of falls or balance disturbances.

Subjects are asked to rate on a scale of zero to ten how confident they are at performing each of the fourteen listed common everyday activities without falling (see Appendix D). Zero indicates the subject is not confident at all whilst ten indicates the subject is completely confident in completing the task without falling. In the study by Hill *et al.* (1996), mean score in a sample of normal active elderly adults with no history of falls (n = 111), was 9.76, sd = 0.32.

4.2 Instrumentation and procedure

4.2.1 Information and instructions given to subjects

The type of footwear worn was an important consideration. In order to obtain each subject's 'normal' walking pattern subjects were requested to wear their own flat, comfortable shoes that they would normally wear whilst walking. It was also requested that subjects wear 'closed-toe' shoes in order to attach markers to the shoe (described later in section 4.3.3). Using similar shoe types (i.e. flat shoes) for all participants minimises variation in the data due to differences in gait pattern caused by different shoe heights. Subjects were also asked to wear trousers, shorts or tracksuit pants (i.e. no skirts) in order to adequately fit a safety harness. Test procedures, as outlined below, were explained to the subjects followed by an opportunity to ask questions about the procedures. Subjects were informed that they may stop at any time during testing should they wish to.

Age, height and body mass were recorded for all subjects and used to determine whether homogeneity amongst the subjects existed. Height measurements were also used to examine correlation between walking speed and stature. Additionally, level of regular activity for all subjects was recorded (type, duration and frequency) to determine whether subjects were homogeneous with respect to activity level.

4.3 Experimental procedure

4.3.1 Experimental set-up

This research employs a 2-dimensional method of kinematic analysis of the foot trajectory. Typically, there are two types of errors inherent in this type of analysis. Perspective error, which is small in the sagittal plane compared with the frontal plane (Whittle, 1993), can be minimised by ensuring the optical lens of the camera is perpendicular to the plane of motion and that the distance between the camera and point of interest is maximised. The camera position in the horizontal plane was determined by using three tape measures in order to construct a right-angled triangle as shown in Figure 4.2. Pythagoras' theorem states that in a right-angled triangle the square of the hypotenuse is equal to the sum of the square of the sides, i.e., $A^2 = B^2 + C^2$. A '3, 4, 5' right-angled triangle was used, i.e. $5^2 = 4^2 + 3^2$ to ensure a right-angled triangle was obtained and, therefore, the camera is positioned perpendicularly to the plane of motion. Once achieved, a line was extrapolated to maximise the distance from the optical lens of the camera and the plane of action (the treadmill). In this study, the camera was placed at a distance of 10m from the treadmill.

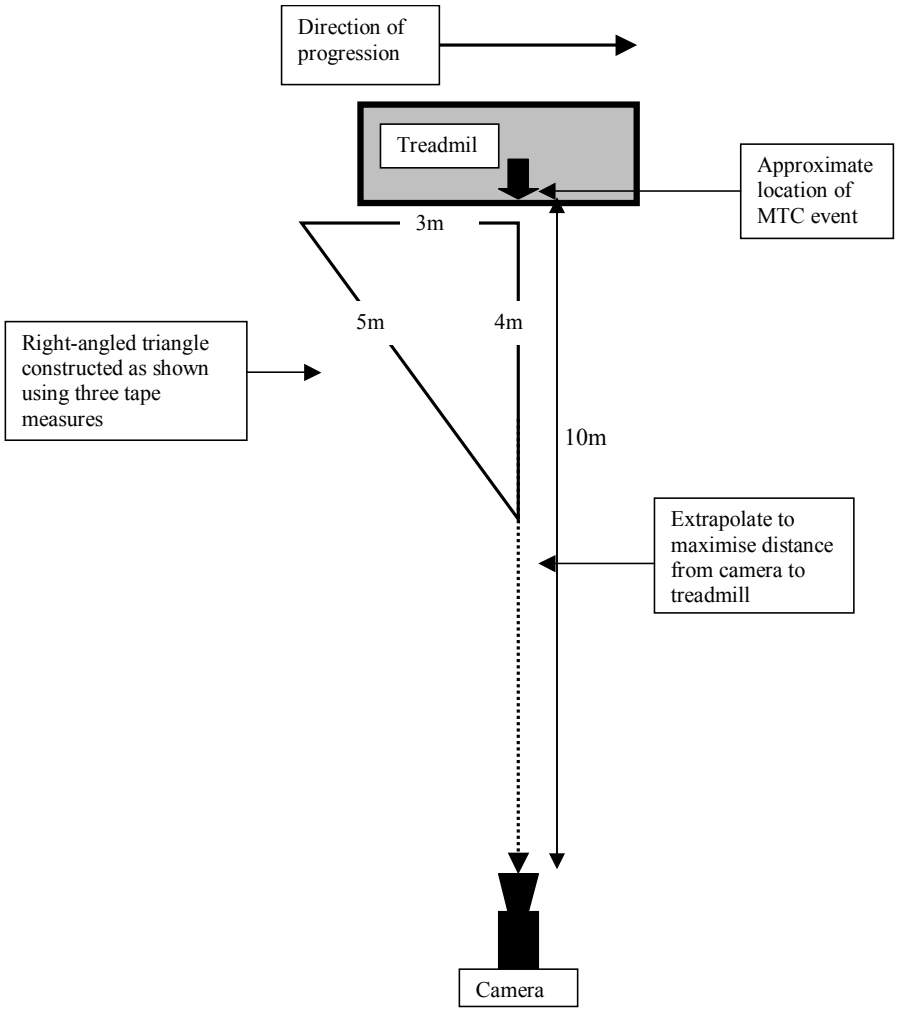


Figure 4.2: Verification of camera placement perpendicular to plane of motion in the horizontal plane.

Camera position in the vertical plane could then be determined by ensuring the optical axis of the camera is at the same vertical height from the ground as the approximate location of the MTC event. This was achieved by lowering the camera on the tripod to the correct level, as shown in Figure 4.3.

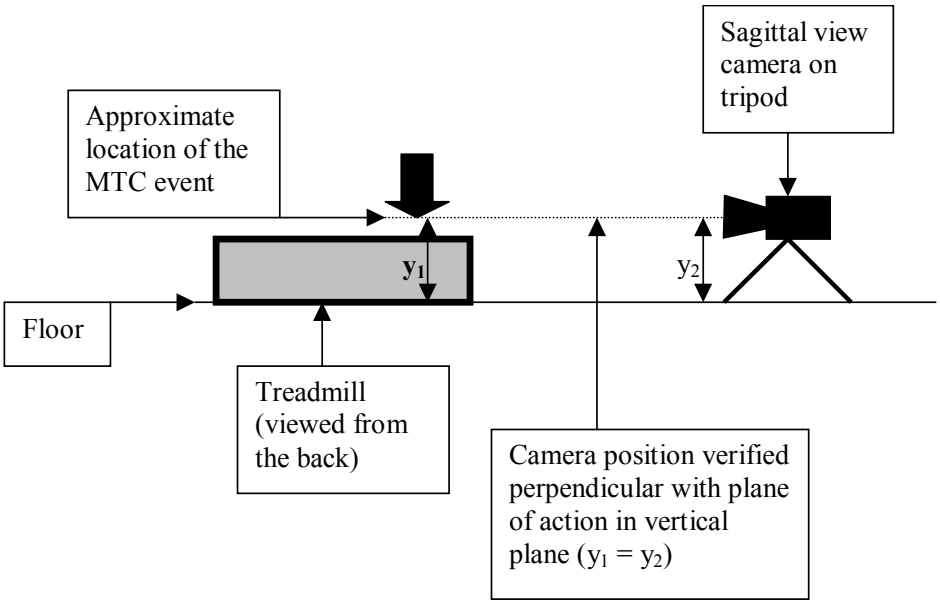


Figure 4.3: Verification of camera placement perpendicular to plane of motion in the vertical plane. y_1 = vertical displacement between ground and approximate location of MTC; y_2 = vertical displacement between ground and optical axis of the camera lens.

The steps illustrated in Figure 4.2 and Figure 4.3 verify the position of the sagittal view camera is perpendicular to the plane of motion (the treadmill) in both the vertical and horizontal directions and, therefore, minimise perspective error.

In addition to perspective error, the other type of error inherent in 2-dimensional kinematic analysis is parallax error. Parallax errors are encountered when there is movement away from the optical axis of the camera lens. Some studies examining foot trajectory in the sagittal plane have assumed that motion of the foot in the coronal and transverse planes to be negligible (e.g. Best *et al.*, 1999; Dingwell *et al.*, 1999; Winter *et al.*, 1990)

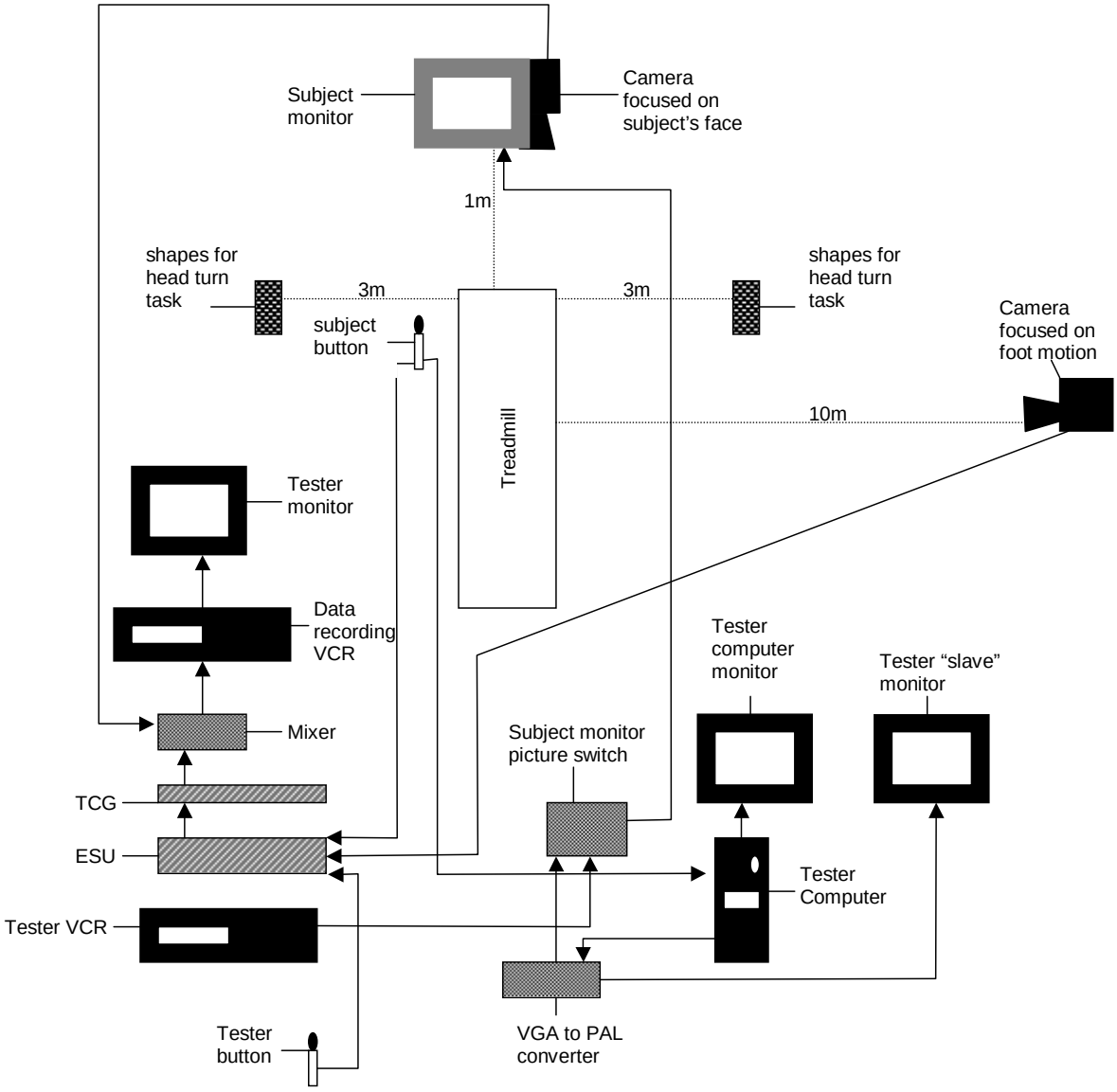


Figure 4.4: Experimental set-up. TCG = Time Code Generator; ESU = Event Synchronisation Unit; Tester 'slave' monitor used to display exact picture displayed on subject monitor.

Experimental set-up is shown in Figure 4.4. The sagittal view camera, which videoed motion of the foot, was connected to the event synchronisation unit (ESU), then, via the time code generator (TCG) to the video mixer for recording onto videotape on the data recording VCR. A camera arranged in the frontal plane was focused on the face of the subject in order to observe where subjects' eyes were directed. This view was edited onto the top left side of the video of foot motion in the sagittal plane using the video

mixer's 'picture-in-picture' function. Pilot testing and a previous study (James, 1999) revealed that the ability to observe sagittal view walking from the waist down concurrently with observing the subject's face would be useful in helping explain any unusual foot motion. The frontal camera was arranged in a position that was as unobtrusive as possible to the subject to ensure it did not pose a distraction, i.e., just beside the subject monitor.

The tester monitor set up near the researcher was used to view real-time video recording of the treadmill walking with the subject's face in the top left corner. This monitor was connected to the video mixing board and depicted the precise picture that would be recorded on the data recording VCR. In conjunction with the treadmill walking, the tester monitor also displayed the time code generated by the TCG. This assisted in the timing of presentation of tasks during testing. It also assisted in examining parts of the videotape after testing was completed by manually cueing the videotape to view certain aspects of the walking where the timing was known. The tester hand-held button was connected to the ESU, then to the TCG and into the mixer to be recorded on to the data recording VCR. The hand-held button was used to manually signal the commencement of each distraction task by displaying a small white square, which was generated by the ESU, on the top right hand side of the screen. The small white square would remain on the tester VCR, and data recording VCR tape, for the duration of the task, and until the researcher pushed the button again to signal the end of the task.

The distraction tasks performed concurrently with walking during 10 minutes of the analysed 30 minute treadmill walking are described later in section 4.3.4.2. For two of

these tasks (*video* and reaction time probe (*RTP*)), a subject monitor was required and was set up in front of the subject, one metre from the front of the treadmill. The subject monitor sat on a stand approximately 1.5m in height and was connected by cable to a switch located near the researcher. The switch controlled the picture displayed on the subject's monitor: 1) the visual "R" stimulus for the *RTP* task and 2) the video for the prolonged distraction *video* task. For the *video* task, the tester VCR was connected directly to the switch, which then displayed the picture (wildlife video) on the subject monitor. For the *RTP* task, the tester computer was connected to the VGA to PAL converter. The visual "R" stimulus was relayed to the subject monitor via VGA to PAL converter then the subject monitor picture switch. The same picture was displayed on the tester 'slave' monitor directly from the VGA to PAL converter. The subject's hand-held button, used for the *RTP* task, was connected to the tester computer to measure reaction time and was also connected to the ESU to signal the end of the RTP task on tester monitor and videoed on data recording VCR via the mixer.

A minimum of 36 minutes of steady state, unobstructed treadmill ambulation was recorded in the sagittal plane via 50Hz video with a camera shutter speed of 1/1000s.

4.3.2 Calculation of individual preferred walking speed (PWS) and treadmill familiarisation

The subjects, with respect to treadmill familiarity, were not homogeneous. All young subjects had at least been on a treadmill and most were proficient, regular treadmill users. It was necessary to ensure subjects were given ample instructions and practice on the treadmill. A self-selected walking speed is thought to best represent overall

walking performance (Kerrigan *et al.*, 1998) and is the most common clinically evaluated aspect of walking (Alexander, 1996). Therefore, a self-selected 'normal and comfortable' preferred walking speed (PWS) on the treadmill was determined for each subject.

All subjects were briefed on the use of the treadmill as a safety precaution and, for the elderly subjects, to reduce any anxieties they may have about it. Subjects were first given a demonstration of how to walk on the treadmill. It was stated that subjects should maintain a tall upright position and take steps to keep up with the belt, rather than trying to 'push' the belt whilst in a forward leaning position. It was stressed that a comfortable, strolling pace was required and not to 'power-walk' or walk as quickly as possible as they might during an exercise session. Subjects were reminded that they would be required to gradually release their grip on the rails and walk using a normal arm-swing motion. As found by Marks (1997), the absence of contra-lateral upper and lower limb motion during walking results in higher variability of the trajectories generated and differences in other kinematic parameters. Thus, arm swing motion was important to ensure a 'normal' walking pattern on the treadmill was achieved. The location of the emergency stop button was also pointed out, along with a reassurance that the safety harness would successfully arrest a fall, should one occur.

The treadmill demonstration was provided for all elderly subjects regardless of their treadmill experience. Following the demonstration, subjects stepped onto the stationary treadmill belt and the safety harness was fastened. The design of the safety harness enabled subjects to walk freely without interference. The harness was a light-weight climbing harness with fasteners and adjustments at the chest and the front of the

leg straps. The length of the harness was also adjustable in order to accommodate subjects of different stature. An attachment at the upper back of the harness allowed attachment to an anchor point in the ceiling.

Subjects were asked to hold the rail at the front of the treadmill and stand on the treadmill belt while it started at 0.8km/hr. The speed was then gradually increased to a user-selected 'comfortable' setting. The comfortable setting was determined by asking subjects if the walking pace felt 'comfortable', "like taking a stroll in the park". If the set walking speed felt comfortable the speed was increased slightly and subjects were asked if the current speed felt more comfortable than the previous one. This procedure was repeated until the subject identified the previous speed as more comfortable, in which case, the speed was reduced to the previous setting. The subject was once again asked if they were satisfied with the treadmill speed as a 'comfortable' preferred walking speed (PWS). If so, walking practice was given until the subject felt comfortable and confident with walking on the treadmill. Since the group of elderly subjects were fit and active, and some were regular treadmill users, the practice sessions were sometimes relatively brief and lasted between 5 – 10 minutes. Some of the common patterns that needed addressing were taking quick, small steps, landing on toes at foot strike and attempting to 'push' the belt by leaning forward. All of these common errors were successfully corrected with feedback and practice.

The commonly used protocol for determining a self-selected comfortable walking pace on the treadmill is to time several trials of comfortable walking overground. The average is taken and this velocity is selected as the subject's self-selected comfortable walking pace. This walking velocity is then set on the treadmill. However, as outlined

in the literature review, some researchers have reported problems with this method. Despite the treadmill speed being set to the same overground velocity, subjects commented that the treadmill walking felt faster (Alton *et al.*, 1998). A more recent study recognised this and employed a method of determining PWS that considered subjects' opinion of the selected walking speed (Dingwell and Marin, 2006). The pilot study for this research also found subjects commented on the treadmill speed being faster and not comfortable using the commonly used method. PWS on the treadmill was a mean of 0.4m/s, or 27.5% slower than comfortable walking speed measured overground (n = 7, $p<.001$). It was shown in pilot testing that the difference in walking speed was significantly slower for elderly subjects (young = 0.3m/s or 22.5% slower, n = 4 vs. elderly = 0.4m/s or 32.5% slower, n = 3; $p=.006$). Therefore, this method was discarded and the alternate method of determining PWS actually on the treadmill, described above, was performed in this study.

Although demonstration was considered unnecessary for most of the young subjects given their familiarity and experience on the treadmill, it was still offered. For consistency and safety, young subjects also wore the safety harness.

4.3.3 Placement of LED markers for analysis of foot motion

Two light-emitting diodes (LEDs) were attached to each subject's right shoe at the 5th metatarsal head (MH) and the great toe (TM) (refer Figure 4.5). These markers were used in a 2D foot model for analysing the motion of the foot during swing phase, described in section 4.4.3. The battery used to power the LEDs was enclosed in a small pouch made of soft polar fleece fabric and attached around the ankle with Velcro

fasteners. This ensured the battery was both securely fastened and did not interfere with the subject's walking pattern.

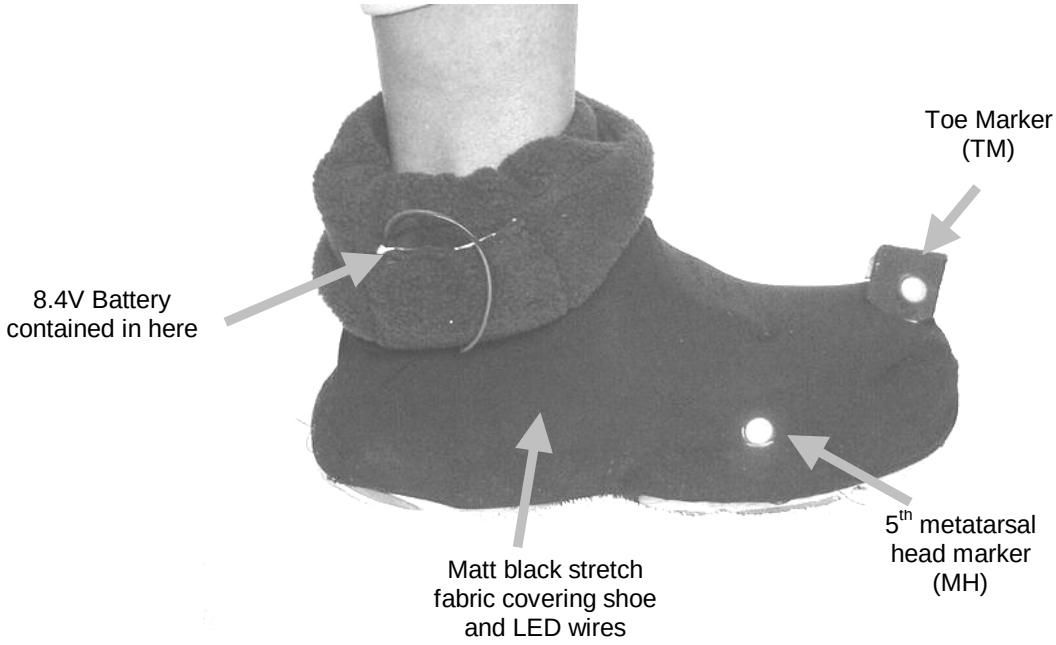


Figure 4.5: Placement of LED markers on the right foot.

It was found during pilot testing that some reflection, generally from the LEDs, periodically appeared on some shoes and on the metallic surface of the treadmill. Problems were then encountered during the automatic digitising process of the Peak Motus motion analysis system. Often these reflections were within the set threshold values and were mistaken as the LED marker resulting in incorrect co-ordinates. To eliminate any reflection on the shoe surface, the shoe and the wires of the LEDs were covered with a matt black stretch fabric and fastened to the shoe's outer edge using Velcro. Small openings in the fabric at the 5th metatarsal head and great toe allowed the LED markers attached to the shoe to be inserted through. The upper horizontal edge of the treadmill, adjacent to the belt, was also covered in a matt black fabric. The simple method of covering the shoe and the side of the treadmill eliminated this

problem entirely without interfering with the subject's walking pattern or compromising safety.

4.3.4 Treadmill walking task

Subjects walked continuously on a motorised treadmill (Trimline 7600 One) for 36 minutes at a self-selected comfortable walking speed. This was considered an achievable task for all subjects given their physical status. Additionally, elderly subjects in a previous study managed this task well without incident (James, 1999). Smaller data sets, such as ten strides, are typically utilised in gait studies and are more easily collected. However, the longer period of walking was necessary in this research since it enabled differences in variability and stability of MTC in a large set of foot motion data to be determined. As outlined in the literature review, reliable kinematics can be obtained after six minutes of treadmill walking. Therefore, in this study the first six minutes of walking was discarded and the remaining 30 minutes was analysed.

The continuous treadmill-walking task was divided into two sections: 1) walking without distractions (20 minutes), and 2) distracted walking (ten minutes). Distracted walking included six different distractions to the subject whilst walking and these were classified as either instantaneous/short distractions (reacting to a visual stimulus by pressing a hand-held button as quickly as possible, reaction time probe (*RTP)* task; turning the head to identify the number of objects displayed on boards to the left and right, *head turn* task; retrieving an item from a waist pouch, *pouch* task; coughing, *cough* task) or prolonged distractions (subtraction from 100 by threes for one minute,

3s task; and observing a video set up in front of the subject for one minute, *video* task). Distracted walking tasks are described more fully in section 4.3.4.2.

The order of presentation of tasks was randomised at two levels. First, the order of walking without distractions (20 minutes) and distracted walking (ten minutes) was alternated for each subject. That is, half of the subjects (n = 24) completed distracted walking (ten minutes) followed by walking without distractions (20 minutes) whilst the other half received the reverse order. Second, the order of presentation of the six distractions tasks was randomised for each subject within the ten-minute block of distracted walking. There was approximately one minute between the presentation of distraction tasks to enable subjects to recover their normal stride if there was a disturbance, and to examine any changes to stability of descriptive statistics due to each individual distraction task.

For data analysis, it was imperative to distinguish the timing of each distraction task within the collected foot motion video recording. All distraction tasks completed during the treadmill walking were timed using a hand-held button (tester button on Figure 4.4) connected to the Peak ESU (Event Synchronisation Unit) with the exception of the *RTP* task, which had its own automatic timing system. The button was pressed by the researcher at the commencement of the distraction task and released on its completion. This procedure ensured the timing of each distraction task could be determined and the duration calculated by encoding a small white square at the top right corner of the screen for the duration of the task. The small white square appeared when the tester button was pressed and remained on the screen until the tester button was pressed again to signal the completion of the task. Additionally, a time code,

located at the bottom of the screen, was generated by the time code generator (TCG). This enabled timing to be calculated from the onset of the white square until its disappearance. Figure 4.6 shows the small white square at the top right hand side of the monitor (generated by the ESU) and the time code at the bottom of the screen (generated by the TCG). This information enabled the foot motion for each distraction task to be easily identified and examined during playback of the tape. The time code also assisted in keeping track of the timing of presentation of the distraction tasks during testing. A monitor showing the time code concurrently with the subject walking on the treadmill set up near the researcher was used for this purpose. This monitor depicted the picture obtained via the video-recording.

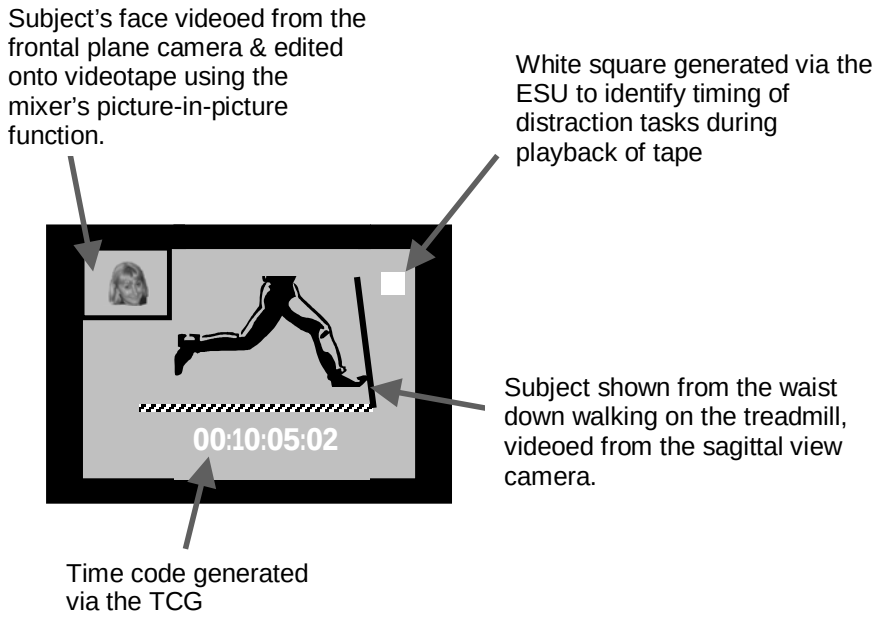


Figure 4.6: Monitor depicting TCG generated time-code and ESU generated white square. Both were used to determine timing and duration of distraction tasks.

The researcher was set up towards the rear of the treadmill, out of view of the subject. During pilot testing the researcher was set up towards the front and to the right of the

treadmill, well within view of the subject on the treadmill. It was found that all subjects were distracted to some degree by watching the researcher organising and recording distraction tasks. This resulted in subjects looking to the right and slightly down as they walked. Being set up out of the subjects' view enabled the researcher to observe the subject, conduct the testing and still be close enough to give verbal instructions. Figure 4.7 depicts the location of the researcher with respect to the subject walking on the treadmill.

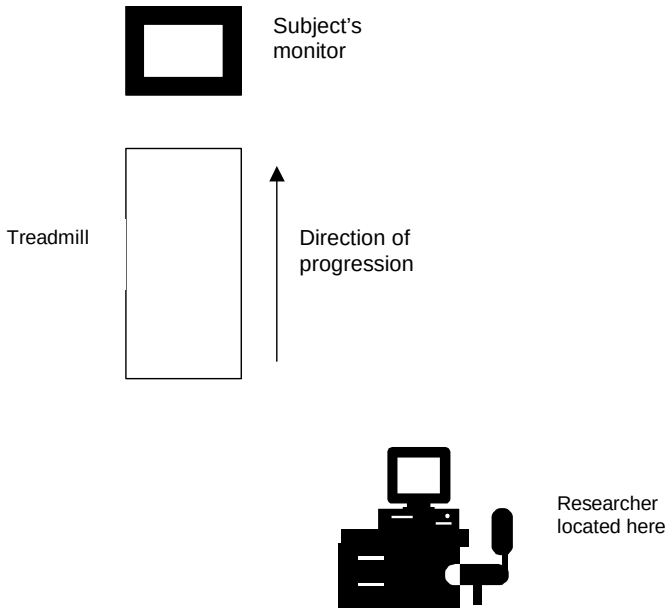


Figure 4.7: Location of the researcher with respect to subjects on the treadmill.

4.3.4.1 Walking without distractions

Obtaining data for comfortable treadmill walking without distractions enabled baseline data for young and elderly subjects to be established. This allowed a comparison of MTC and the associated descriptive statistics (mean, standard deviation (SD), skew (S) and kurtosis (K)) between young and elderly and with distracted walking data.

Talking or turning around during testing was considered a distraction and avoided. Subjects were asked to refrain from talking or turning around during testing and to attempt to maintain an 'eyes-up' position where they look straight ahead rather than at their feet while walking. To reduce anxieties about performance, subjects were reassured that there was no pass/fail evaluation but rather it was their normal, comfortable walking pattern that was required.

4.3.4.2 Distracted walking

Subjects were informed that the treadmill walking would be continuous, i.e., there would be no break between the walking without distractions and distracted walking. Subjects were also instructed to strive for accuracy rather than speed of completing the task, with the exception of the reaction time probe (*RTP)* task. It was thought that taking ample time to complete a task to the best of their ability would present different attentional demands compared with completing the task as quickly as possible. This would also ensure subjects attend to the tasks with the same goals in mind. Instructions prior to each distraction task were consistent for each subject and each task, i.e. "when I say "go" I would like you to…., ready, go". As each task was completed subjects were instructed to continue walking and looking straight ahead. All distraction tasks were explained to subjects prior to treadmill testing to ensure smooth transitions between each task as prompted.

As described in the literature review, the use of dual-task experiments to assess the attentional demands of dynamic posture and motor control is becoming more widespread. Abernethy (1988), however, expressed the need for more 'real-world'

actions to be included in such studies. The distraction tasks chosen for this study may more closely resemble 'real-world' situations that people may experience during normal everyday walking.

As outlined in the literature review, dual-task experiments require the subject to perform two tasks simultaneously. The two tasks consist of a primary task, for which the attentional demands are measured, and the secondary task, from which changes in performances are measured and conclusions drawn regarding the attentional demands of the primary task (Abernethy, 1988). In this study, the walking as measured by MTC is the primary task and separate distraction tasks are the secondary tasks.

Traditional methodology for dual-task experiments suggest criteria be met in order to accurately interpret the data. Some of these criteria include randomising presentation of single- (ST) and dual-task (DT) and repeating the test several times in each task to control for learning effect. The current study does not follow these criteria for several reasons. First, the primary aim of imposing distraction tasks on the subject was to determine the influence it had on MTC. Thus, it was considered important to present the distractions first during the treadmill walking. The need for research examining the first response to a novel task has been recognised (e.g. Lythgo, 2003; McIlroy and Maki, 1995). Second, it was seen as important to present an instantaneous distraction, which may represent a real life situation such as observing a physical distraction while walking. As stated in the literature review, the need for 'real-life' dual-task experiments has been raised (Abernethy, 1988). Therefore, although examining differences in performance of distraction tasks (i.e. for *RTP* and *3s* task) between ST and DT conditions may give an estimate of attentional demands of the primary task

(walking), the researcher is aware of being cautious in drawing conclusions of this nature based on this data.

4.3.4.2.1 Instantaneous/short distractions

4.3.4.2.1.1 Reaction time probe *(RTP)* task

The *RTP* task required the subject to react to a visual stimulus by pressing a hand-held button (subject button in Figure 4.4). Subjects were requested to pick up the hand-held button, which was located in a holder on the left side of the treadmill control panel, approximately 15 seconds prior to the *RTP* task being activated by the researcher. This was done to ensure subjects had time to regain their normal stride before the reaction time stimulus was given. Subjects were informed they may hold the rails only whilst they picked up the button and that they may hold their finger or thumb on the button in anticipation of pressing it. Once the subject was walking comfortably with the button in their hand, the instruction "when the red "R" appears on the screen, press the button as quickly as possible. Ready…". At this stage, the researcher activated the reaction time system by pressing "Enter" on the keyboard. The presentation of the red "R" on the monitor in front of the subject was randomised between 0 and 5000ms as part of the reaction time software. One trial only was performed, and once completed, the subject was instructed to return the button to its holder and continue walking. This task was repeated five times in a static standing position on the treadmill after the conclusion of the treadmill walking to obtain a baseline reaction time. A simple reaction time test,

such as the one used in this research, is a commonly used test of divided attention, or dual-task ability (Abernethy, 1988).

The equipment for this task consisted of software designed by technical staff at Victoria University, a Pentium I computer, 3 monitors (one for the tester's computer, one for the subject's monitor set up in front of the treadmill and one 'slave', named since it depicts precisely the picture on the subject's monitor, namely the red "R"). The slave monitor was located near the researcher while the monitor set up in front of the subject was used for two separate tasks, the *RTP* task and the prolonged *video* task (described later in section 4.3.4.2.2). A cable connected the subject's monitor to a switch located near the researcher. The switch had two options; 1) to enable the visual "R" stimulus to appear on the subject's monitor, and 2) to allow the video to appear for a separate task (*video* task). The researcher's computer and slave monitor were connected to the switch via a VGA to PAL converter. For this distraction task the researcher turned the switch to the setting indicating the *RTP* task.

A consistent delay of 5ms between the activation of the timer and the actual presentation of the visual stimulus on the monitor existed. This delay was related to the processing speed of the computer. Actual reaction times for each subject were, therefore, 5ms longer than their recorded reaction time. All reaction times obtained have, therefore, been adjusted to account for the consistent 5ms delay.

4.3.4.2.1.2 *Head turn* task

Subjects followed a two-stage command which consisted of turning the head first to the left to identify the number of triangles on a board, and then turned to the right to identify the number of squares in a similar arrangement (refer Figure 4.8). The instructions were given prior to the task, which was completed as a continuous movement at the subject's own pace. The boards where A3 size laminated cards printed with overlapping squares, circles and triangles of various solid colours (see Appendix E). These were attached to a stand at a height of 2m from the ground and were placed at a distance of 3m from the control panel at the front of the treadmill. Accuracy and time taken to complete the task were recorded in order to examine any ageing effects between the young and elderly groups. Although there are no similar tasks to be found in the literature, a task such as this may replicate the real-life situation of, for example, crossing the road and watching for cars, or scanning for objects of interest while passing a shop window.

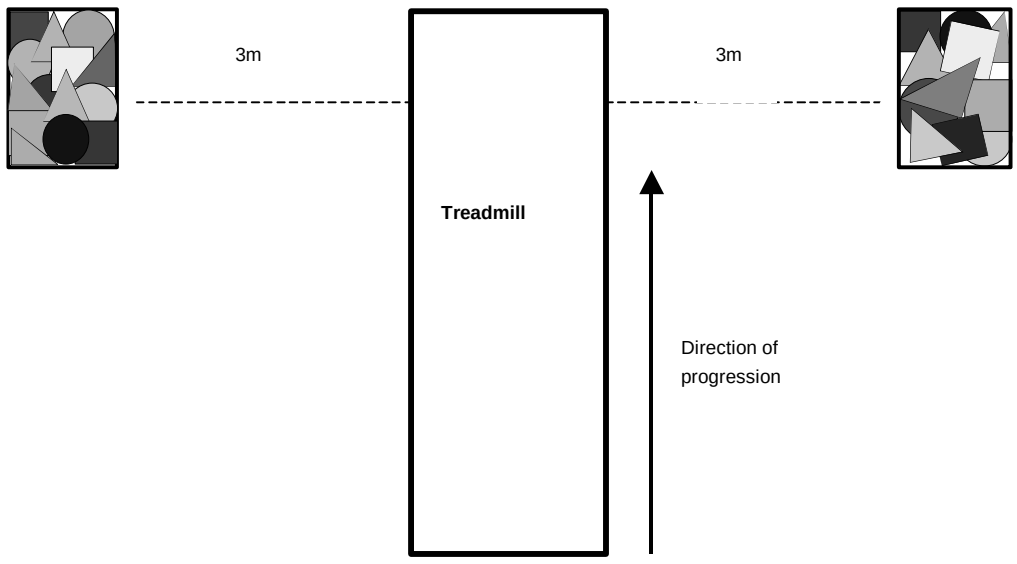


Figure 4.8: Set up of '*head turn*' task.

4.3.4.2.1.3 *Pouch* task

Subjects reached into an open waist-pouch worn posteriorly at approximately sacral level and retrieved the designated item (a handkerchief). The waist pouch contained a set of keys, a small cloth purse and the handkerchief. The subjects retrieved the handkerchief, held it up and then returned it to the pouch. It is thought a task such as this may be similar to finding a bus ticket in a handbag, or searching for another item whilst walking. The waist pouch, as opposed to a similar item such as a handbag, was chosen since it allowed the subject to walk on the treadmill without interference.

For safety reasons, the waist pouch was worn posteriorly and the handkerchief was chosen as the item to retrieve. During pilot testing, it was found that an item falling in front of the subject constitutes a major disturbance to gait and could pose a safety risk. The rear opening of the pouch decreases the likelihood of objects falling in front of the subject. The handkerchief was chosen because it is easy to handle and, if dropped, would easily pass to the back of the treadmill belt without compromising the safety of the subject. All subjects successfully completed this task without dropping the handkerchief.

4.3.4.2.1.4 *Cough* task

During this task, subjects brought their hands to their mouths and coughed twice. Although there are no other studies that have examined the effect of coughing, this task may be similar to the real-life situation of coughing or sneezing while walking.

4.3.4.2.2 Prolonged distractions

4.3.4.2.2.1 *3s* task

Subjects were timed for 60 seconds whilst performing a backward counting task, subtracting by threes. The researcher recorded each subtraction in order to calculate the subject's accuracy and the number of subtractions completed. Although subjects were given instructions regarding this task prior to testing, they were not informed of which number to begin subtracting from until immediately prior to the actual task. This was done to prevent subjects practising and not concentrating on treadmill walking. Subjects were asked to continue counting backwards in threes from the given number until told to stop by the researcher at the conclusion of the 60 second period. It was also stressed that accuracy should be the primary aim.

As outlined in the literature review (see section 2.1.2.3), backward counting is a commonly used test in studies examining divided attention ability. It is thought that concentrating on a cognitive task such as this whilst walking may replicate, for

example, walking and remembering a shopping list, or mentally calculating the cost of a few groceries.

The *3s* task was repeated in a static standing position on the treadmill following the completion of the 30 minute treadmill walking. The subject counted backwards by threes, beginning from a different number, and continued to do so as accurately as possible until told to stop by the researcher at the conclusion of the 60 second period. As previously stated, dual-task methodology generally utilises random presentation of the single- (ST) and dual-task (DT) conditions within groups. For this task, the DT condition is backward counting whilst walking and the ST condition is backward counting whilst static standing on the treadmill. The theory is that the attentional demands of the walking task can be determined by examining any decrease in performance during the DT condition. For this study it was seen as important to present the distractions first in order to examine the associated MTC during this period. The researcher is aware of using caution in drawing conclusions regarding differences between the ST and DT of backward counting by threes.

4.3.4.2.2.2 *Video* task

Subjects watched a video displayed on a monitor set up in front of the treadmill for one minute, timed by the researcher with a stopwatch. The monitor rested on a stand placed one metre from the front of the treadmill, or approximately two metres from the subject as they walked on the treadmill. The height of the stand was approximately 1.5 metres from the ground, therefore placing the monitor approximately at eye level of the subject as they walked on the treadmill. The video, played without sound, was a wildlife production depicting the South African Meerkats, chosen since it was thought it might appeal to most subjects. It was thought that a video of uninteresting content might result in subjects not paying attention to the video. Subjects were asked to concentrate on the video for 60 seconds and were told they would be asked some questions at its conclusion. The questions themselves were irrelevant but it was thought that the 'threat' of questions would encourage the subject to be vigilant in concentrating on the video.

As described earlier, a switch located near the researcher was used to ensure the video was displayed on the subject's monitor. The switch (see Figure 4.4) was turned to indicate the *video* task be displayed on the subject's monitor.

4.4 Data analysis

4.4.1 Digitising using the Peak Motus system

Foot motion data collected on videotape was analysed using the Peak Motus Motion Analysis System (Vicon Motus, Oxford, U.K.). Analysis was performed in two steps: 1) pre-analysis (digital conversion (digitising) and defining the 2D foot model, which will enable calculation of MTC for each stride); and 2) analysis of trial data (digitising the location of the two LED markers on the foot (TM and MH markers) and calculation of the 2D trajectories of the markers as a function of time).

4.4.1.1 Calibration

Prior to digitising, two-dimensional calibration procedures were performed using two reflective markers placed 1m apart horizontally on the treadmill. These two markers were each manually digitised in the Peak Motus system, which calculates the mean vertical and horizontal coordinates of the two points. This calibration procedure, which is later used to convert screen coordinates to real distances, is part of the Peak Motus system. These coordinates are then used as the calibration for the entire trial and the procedure is repeated for each subject.

4.4.1.2 Digital filtering

Raw data was digitally filtered using optimal cut-off frequency, which used a low-pass fourth order Butterworth filter with cut-off frequencies ranging from 4 – 8Hz. This procedure is a part of the Peak Motus system.

4.4.2 Pre-analysis

The purpose of pre-analysis was to define the foot model that will be used to calculate MTC for each stride of the trial data. As discussed in the literature review, some studies have calculated MTC as the vertical distance between the toe marker and the ground whilst, more recently, others have utilised a point on the sole of the shoe. A major limitation with studies that use the toe marker to calculate MTC is they fail to utilise the part of the shoe closest to the ground at midswing and, therefore, overestimate MTC. Marker placement on the sole of the shoe is not possible during locomotion. The inferior most distal point of the shoe (predicted toe point or PTP), therefore, is predicted using a 2D geometric model. Defining the model of the foot enables PTP to be calculated and the model can then be applied to the digitised trial data. Separate foot models were defined for each subject based on their individual TM and MH markers and estimated PTP.

A clear outline of the right shoe was required for the foot modelling procedure. At the conclusion of the walking task, subjects were requested to stand on the stationary treadmill belt with their right foot elevated and resting on a small wooden step. The box was placed on the treadmill belt so that the foot resting on it was in the centre of

the line of view from the optical axis of the camera lens. Camera aperture was increased and external lighting using spotlights was employed in order to adequately illuminate the foot. The tester video monitor was checked to ensure the outline of the shoe, and specifically the bottom edge of the shoe, was clearly visible.

TM and MH markers were automatically digitised and the inferior and most distal part of the shoe, at the toe where it would strike the ground in the event of a trip, was manually digitised using 0.5 seconds of videotape (approximately 25 video fields) while the foot was stationary and resting on the box on the treadmill belt. Individual walking patterns, including the position of the foot during swing as it passes the ground, influences the accuracy of the PTP estimate. Three different points on the edge of the shoe near the toe were separately chosen in order to determine the most accurate estimate of PTP. Figure 4.9 shows examples of the three estimates of PTP on the sole of the shoe. Each PTP(y) value is used in separate analyses using the foot modelling procedure described in section 4.4.3. The PTP estimate deemed to be most correct yields the lowest MTC for each stride after foot modelling procedure and is then used in all subsequent analysis. The PTP estimate yielding the lowest MTC is, therefore, closest to the ground at midswing, making it more likely to be the point to strike the ground in the event of a trip.

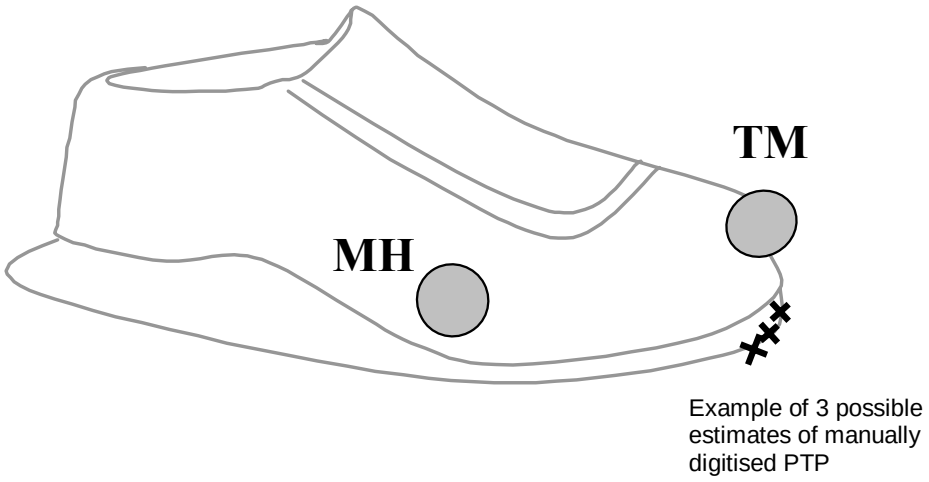


Figure 4.9: Example of three possible estimates of manually digitised PTP.

The Peak Motus system then calculated the mean horizontal and vertical coordinates of each digitised point (TM, MH, PTP). The information gained from this procedure was used to construct the foot model, described in section 4.4.3.

4.4.3 2D geometric model of the foot

Filtered and scaled Peak Motus pre-analysis data were exported to a Microsoft (MS) Excel spreadsheet. This data included horizontal (x) and vertical (y) co-ordinates of the three digitised points (automatically digitised TM and MH markers and manually digitised PTP). These co-ordinates were used to create the 2D geometric model of the foot, which was used to calculate vertical (y) coordinate of PTP for each frame of trial data and, thus, calculate minimum toe clearance (MTC) for each stride. Figure 4.10 shows a diagram of the foot model.

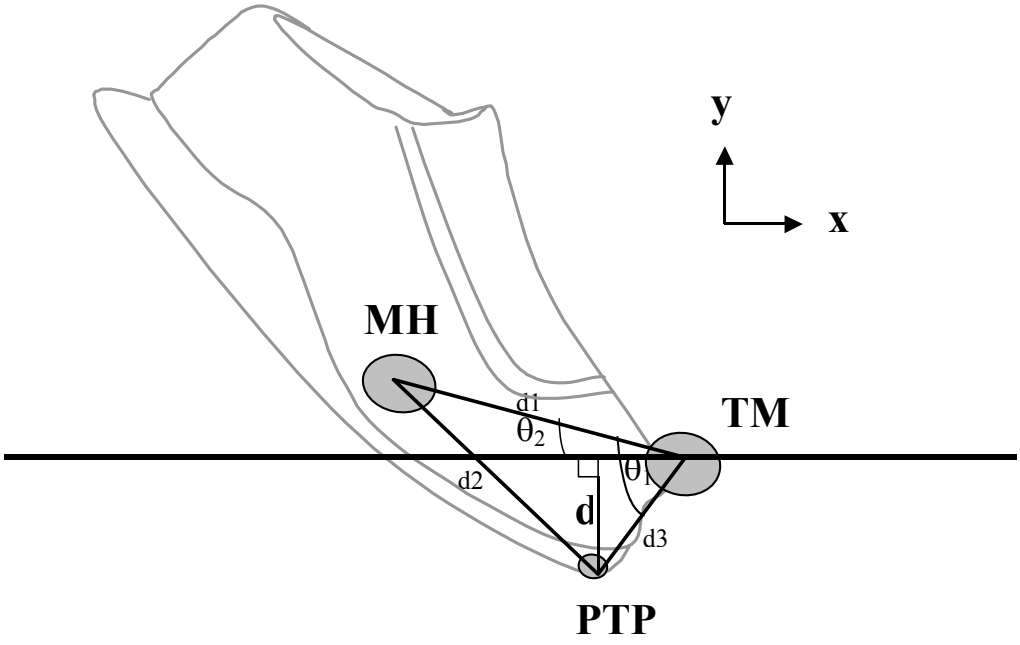


Figure 4.10: 2D geometric model of the foot.
TM marker (x_1, y_1); MH marker (x_2, y_2); PTP (x_3, y_3).

Mean distances for each side of the triangle, d_1, d_2 and d_3, (refer Figure 4.10, Equation 4.4.1 – Equation 4.4.3) were calculated via Pythagoras Theorem using toe (TM) and fifth metatarsal head (MH) marker coordinates and manually digitised PTP virtual coordinate.

$$d_1 = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$ **Equation 4.4.1**

$$d_2 = \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2}$$ **Equation 4.4.2**

$$d_3 = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2}$$ **Equation 4.4.3**

The value of θ_1 remains constant during mid-swing and is calculated using the cosine rule (constant triangle geometry; Equation 4.4.4 and Equation 4.4.5);

$$d_2^2 = d_1^2 + d_3^2 - 2.d_1.d_3 \cos\theta_1$$ **Equation 4.4.4**

and,

$$\theta_1 = \cos^{-1}\left[\frac{\left(d_1^2 + d_3^2 - d_2^2\right)}{\left(2.d_1.d_3\right)}\right]$$ **Equation 4.4.5**

4.4.4 Analysis of trial data

Once the foot model was defined, the foot trajectory could be modelled and, therefore, calculation of MTC for each stride of trial data could be completed. The values of d_1, d_2, d_3, θ_1 (refer Equation 4.4.1 - Equation 4.4.5), as calculated in MS Excel, were input into a Qbasic program. This program was run with each trial data file containing coordinates of TM and MH markers. Angle θ_2 (refer Equation 4.4.6) was calculated and then d via Pythagoras (refer Equation 4.4.7). Finally, the vertical coordinate of PTP for each frame and, thus, MTC for each stride (refer Equation 4.4.8 and Equation 4.4.9) could be calculated.

Angle θ_2 varies with the motion of the foot, and depends on TM and MH marker coordinates such that:

$$\theta_2 = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right)$$ **Equation 4.4.6**

Vertical distance, d (Equation 4.4.1), varies with the motion of the foot such that:

$$d = d_3 . \sin(\theta_1 - \theta_2)$$ **Equation 4.4.7**

The vertical coordinate of the predicted toe position, PTP can now be calculated as:

$$y(PTP) = y(TM) - d$$ **Equation 4.4.8**

During the foot's flight phase, the vertical position of PTP, y(PTP), reaches a minimum value ($y(PTP)_{min}$ or PTP_{min}; Figure 4.12) and, hence, minimum toe clearance (MTC) data can be calculated for each gait cycle:

$$MTC = y(PTP)_{min} - y_g$$ **Equation 4.4.9**

where y_g is the ground reference, determined as the minimum vertical coordinate of the virtual PTP point, designating the toe-off event.

Syntax for the Qbasic program used to determine MTC can be found in Appendix F. The method, using PTP trajectory data, is briefly described here. Figure 4.11 shows a graph of two strides for one healthy young female subject with toe-off (TO) and MTC events identified. The respective frame numbers at which the TO and MTC events occurred are also identified. The lower graph is a magnified version of the first MTC event, which occurred at frame 10. It includes the three frames preceding and three frames following MTC.

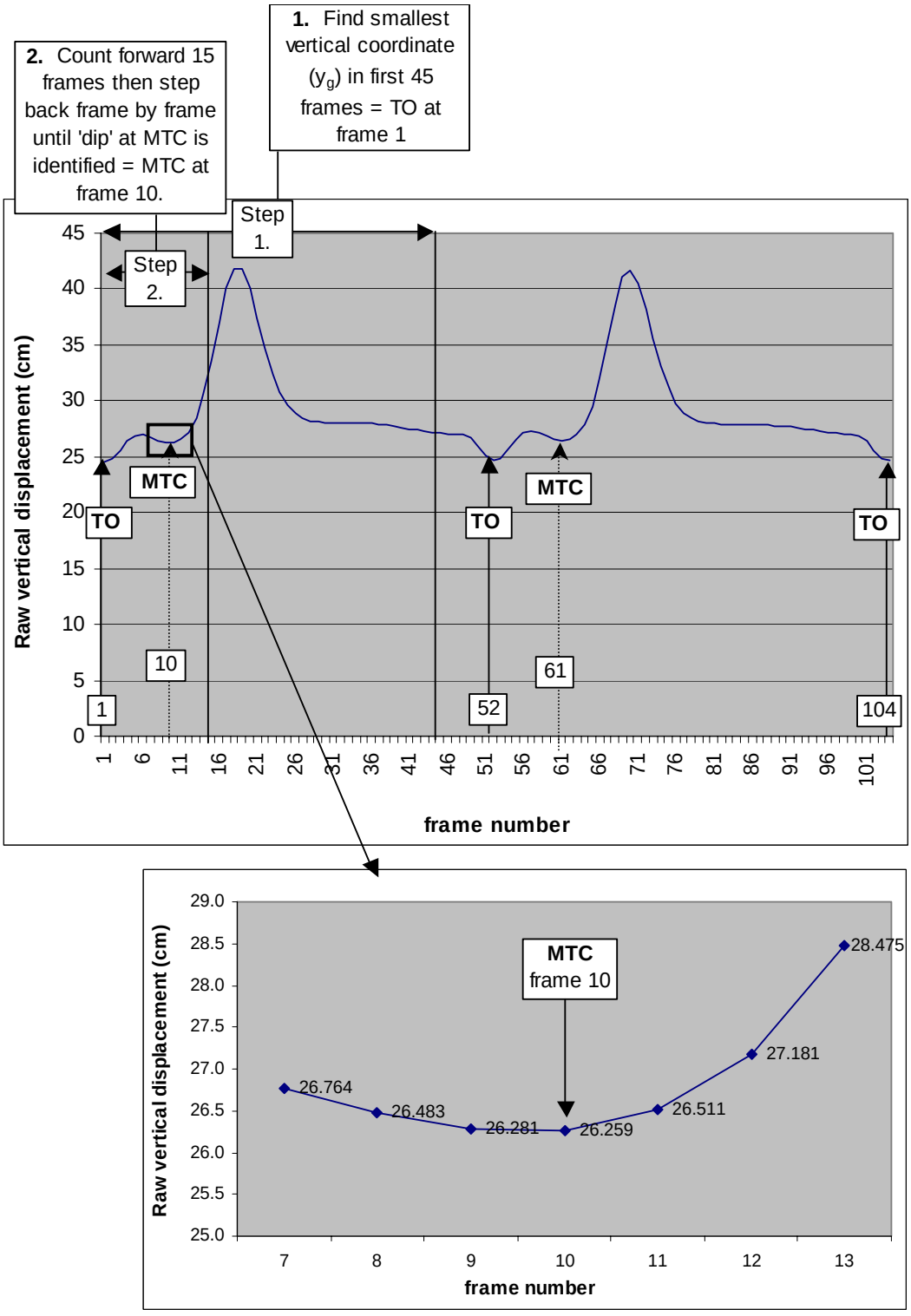


Figure 4.11: Determination of MTC via Qbasic program

TO and MTC events and their frame numbers at which they occurred are identified in the upper graph. The lower graph zooms in on the first MTC event (frame 10) and shows the MTC has a characteristic 'dip' which is used to identify MTC via the Qbasic program.

As shown in Figure 4.11, the first task of the Qbasic program was to identify the TO event (y_g) (step 1.). This was achieved by finding the smallest vertical coordinate of PTP within the first 45 frames. The next step (step 2.) was to count forward 15 frames and then count back until the characteristic 'dip' of MTC was identified. This can be seen easily in the lower graph where the raw value of MTC (26.259cm) is lower than the points either side of it (i.e. 26.281cm and 26.511cm). The figures used in step 1. and 2. (i.e. 45 and 15) were found to accommodate each subject without error. These figures can be changed in the Qbasic program, if necessary, for various walking speeds.

Since there were three estimates of PTP, three separate foot models were run with the trial data. The co-ordinates producing the lowest mean MTC was chosen as the most accurate representation of PTP, and hence calculated MTC. Additionally, accurate estimates of PTP produced little error in detecting MTC, if any (refer section 4.4.5). Thus, the most accurate estimate of PTP, and the associated values of d_1, d_2, d_3, θ_1, were used for subsequent analysis.

Figure 4.12 shows the raw vertical displacement of the TM marker and the predicted PTP (calculated via the geometric model of the foot) during one stride of treadmill walking. TM vertical displacement is greater than that of PTP, emphasising that PTP is a more accurate representation of the end-point of the foot and, therefore, a more precise calculation of MTC.

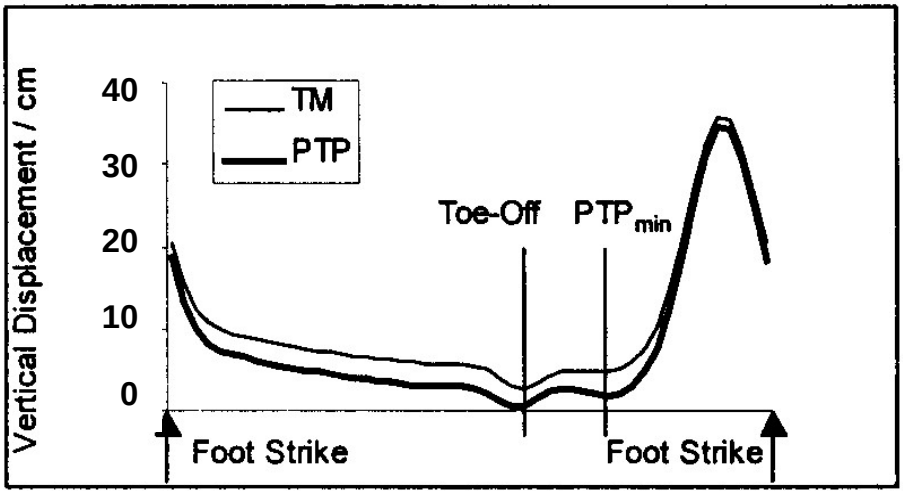
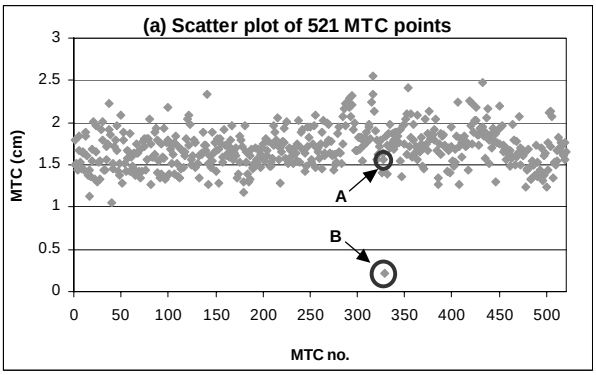
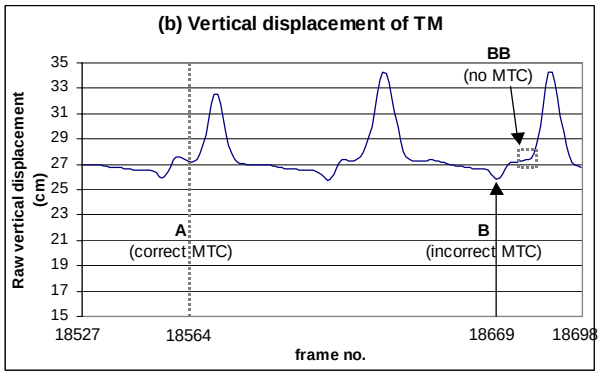


Figure 4.12: Vertical displacement of TM and PTP markers.

4.4.5 Screening data to verifying accuracy of the identified MTC points

MTC data calculated using the foot model in the Qbasic program was transferred to a MS Excel spreadsheet for further analysis. All calculated MTC points were presented as a scatter plot and carefully checked to ensure accurate data was obtained. The vertical displacement of the toe marker (TM), obtained for each frame of digitised trial data, and concurrent PTP, calculated using the foot model in the Qbasic program, were presented as a simple line graph to show their trajectories for the entire walking trial. Figure 4.13 shows an example of the MTC scatter plot (graph (a) and corresponding data in table (a)), and an extract of two strides from the line graph of the TM and PTP trajectories (graph (b) and corresponding data in table (b)).





(a) Output of Qbasic MTC calculation

Stride no.	Frame	Raw MTC	MTC
320	18105	27.53	1.91
321	18163	27.19	1.57
322	18220	27.42	1.80
323	18274	27.25	1.62
324	18333	27.34	1.71
325	18391	27.40	1.77
326	18447	27.42	1.79
327	18506	27.04	1.41
A → ***328***	***18564***	***27.19***	***1.57***
329	18619	27.27	1.64
B → ***330***	***18669***	***25.84***	***0.22***
331	18735	27.47	1.84
332	18795	27.02	1.40
333	18852	27.36	1.73
334	18909	27.49	1.86
335	18969	27.61	1.98
336	19026	27.33	1.70
337	19083	27.38	1.75
338	19141	27.50	1.87
339	19197	27.42	1.79
340	19256	27.32	1.69

(b) Output of Qbasic y coordinates for trial data

Frame	(y)PTP	
18561	27.47239	
18562	27.34841	
18563	27.24286	
18564	***27.19155***	→ correct MTC point **A**
18565	27.23186	
18566	27.40697	
18567	27.77214	
…	…	
18666	26.50046	
18667	26.28796	
18668	26.01662	
18669	***25.84477***	→ incorrect MTC point **B**
18670	25.92513	
18671	26.26744	
18672	26.69735	
18673	27.00945	
18674	27.14858	
18675	27.1829	
18676	27.19391	
18677	27.22693	
18678	27.28072	
18679	**27.32736**	**BB** MTC should occur around here
18680	**27.37158**	
18681	**27.49506**	
18682	**27.85001**	
18683	**28.61522**	
18684	29.89789	
18685	31.58182	
18686	33.23457	

Figure 4.13: Example of verification of MTC points.

Graph (a) shows a scatter plot of MTC in MS Excel with one typical correct point (A) and one typical incorrect point (B). Table (a) is an extract of the output obtained from the Qbasic program that identifies MTC. Graph (b) shows the line graph of the vertical displacement of PTP. An extract of the related data for this can be found in table (b).

Figure 4.13 shows an example of the procedure involved in verifying MTC data points. The example shown is a ten-minute section of treadmill walking for one elderly

subject. Graph (a) is a scatter plot of the 521 MTC points obtained during a ten-minute period. Table (a) is an extract of the output used to construct graph (a). In Table (a) the MTC stride number is identified in the first column whilst the frame number at which it occurs is found in the second column. The third column in Table (a) shows the raw MTC while column 4 shows the MTC value calculated using the foot model.

Graph (b) is an extract of three strides (approximately 171 frames) of the raw vertical displacement of PTP. Table (b) is an extract of the data corresponding with graph (b). The first column in the table refers to the frame number, the second column shows the corresponding raw y coordinates (raw vertical displacements) of PTP. Graphs (a) and (b) and their corresponding data presented in tables (a) and (b) were used to verify the accuracy of the calculated MTC points. To gain an understanding of the verification procedure involved, a typical correct MTC and typical incorrect MTC point are highlighted and discussed.

The initial step in verifying accurate data was to examine the scatter plot of calculated MTC points. An example of a correct MTC point is shown in Figure 4.13, graph (a), circled and labelled "A". This point does not appear unusual since it falls within the cluster of MTC points around the mean of 1.7cm (range 0.22 – 2.55cm). The location of this MTC point A can be seen as it occurs in the trajectory of PTP in graph (b). The timing of this point is found by first identifying the MTC point number in graph (a), and then finding it in the data table (a) (refer to highlighted line labelled "A" in table (a)). It can be seen that the corresponding frame number for this MTC (stride 328) is 18564 and that it has a value of 1.57cm using the foot model. By examining the data related to the PTP trajectory in table (b), it can be seen that there is a small but gradual

decrease in vertical displacement from frame 18561 until the point of MTC (point A) at 18564, and a gradual increase thereafter. It is this 'dip' in vertical displacement the Qbasic program identifies as MTC. The program first locates the minimum vertical displacement at the toe-off event and then proceeds 15 frames and counts back one frame at a time until the next minimum vertical coordinate of PTP (at the timing of MTC) is identified.

A typical inaccurate calculation of MTC is shown as circled point "B" in graph (a). Note that this point is much smaller than the majority of the points. Although it is not unusual for such a small MTC to occur given the high intra-individual variability in gait, points such as this are checked to determine whether they are incorrect or due to variability in MTC. The data from table (a) shows that this unusual point B (point number 330) occurs at frame 18669. Examining the graph (b) easily reveals that this point occurs at the point of toe-off and therefore is incorrect. As demonstrated in Figure 4.12, MTC should occur as the next minimum vertical displacement after toe-off, that is, around the region "BB", labelled in graph (b). Upon closer examination of the data in table (b), it can be seen that there was no MTC in this region. No dip in PTP trajectory exists but, rather, vertical displacement tends to constantly increase. Trajectory of the toe and foot generally follow a predictable path, as demonstrated in Figure 4.12 and Figure 4.13 for correct MTC point A. The Qbasic program to calculate MTC identifies the ground in the toe-off event as the point of MTC since, because there is no MTC, the dip at TO is the first minimum PTP vertical coordinate to be identified. These incorrect points occurred with some subjects. Points such as this were clearly incorrect and reported a much lower value of MTC than the actual foot clearance at the

region where MTC would have been. These points were deemed to be incorrect and deleted from the data set.

Of a total of 75,193 strides (and MTC data points) collected for all subjects (n = 24), 8,814 MTC points were deleted from the data set (11.7%). The number of MTC points deleted varied from 0% to 87% for one subject. Due to this unexpected phenomenon where no MTC occurred, only subjects with 90% or more of their original MTC points were retained for further analysis. Subjects with a larger proportion of MTC points deleted (greater than 10% of the data sets, n = 6 young and n = 6 elderly) were omitted from the statistical analysis. For these 12 subjects there were a total of 18,633 strides with 7,921 strides deleted (42.5%).

Data sets with no identifiable MTC were deemed unusual since the foot trajectory typically follows a predictable path, which includes the 'dip' at mid-swing, making identification of MTC a simple task (e.g. Whittle, 1993; Winter, 1991a). It is not known what caused this unusual foot trajectory and there does not appear to be any other studies reporting such findings. Since the key feature of this thesis is the examination of the MTC event, it is therefore not possible to examine subjects with no identifiable MTC. A proposed method of dealing with the subjects with large numbers of strides having no identifiable MTC is discussed in section 6.3.4, however, no statistical analysis was performed on these data. It is possible that the six elderly subjects excluded from the study might have other gait characteristics that increase the likelihood of tripping. Future research should examine the reasons the unusual gait occurred and develop methods of examining the likelihood of tripping.

4.5 Describing the data

4.5.1 Descriptive statistics of the MTC distribution.

4.5.1.1 Undistracted walking.

Using the screened MTC data, descriptive statistics of the MTC distribution for each individual were calculated in a MS Excel spreadsheet. Descriptive statistics calculated include measures of central tendency, variability, dispersion, symmetry and distribution. These are detailed in Table 4.3, Figure 4.14 and Figure 4.15. The data shown in Figure 4.14 and Figure 4.15 are for one elderly subject (e14). This subject was chosen since descriptive values are similar to group descriptive statistics, particularly the positive skew (S_{MTC}) and kurtosis (K_{MTC}), which is typical of the MTC data in this research. Descriptive measures are examined both on an individual and group basis to determine any relationships and identify any strategies in implementing MTC between the groups.

Table 4.3: Descriptive statistics of MTC distribution examined.

Central tendency measures

Variable	Description
$mean_{MTC}$ (cm)	Mean of minimum toe clearance (MTC) distribution.
$median_{MTC}$ (cm)	Median of MTC distribution.
$mode_{MTC}$ (cm)	Mode of MTC distribution.

Variability measures

Variable	Description
SD_{MTC} (cm)	Standard deviation of MTC distribution.
IQR_{MTC} (cm)	Inter-quartile range (75th - 25th percentiles or $Q3_{MTC}$ - $Q1_{MTC}$).
CV'_{MTC} (%)	Modified coefficient of variance of the MTC distribution ($IQR_{MTC}/Q2_{MTC}*100$).
$range_{MTC}$ (cm)	Range of values in the MTC distribution.
UQR_{MTC} (cm)	Upper quartile range (max_{MTC} - $Q3_{MTC}$) of the MTC distribution.
LQR_{MTC} (cm)	Lower quartile range ($Q1_{MTC}$ - min_{MTC}) of the MTC distribution.
98% rge_{MTC}	MTC distribution range within lower and upper 1% trimmed ($PC99_{MTC}$ - $PC1_{MTC}$).
90% rge_{MTC}	MTC distribution range within lower and upper 5% trimmed ($PC95_{MTC}$ - $PC5_{MTC}$).

Dispersion measures

Variable	Description
min_{MTC} (cm)	Minimum MTC in the distribution.
max_{MTC} (cm)	Maximum MTC in the distribution.
$Q1_{MTC}$ (cm)	25th percentile of the MTC distribution.
$Q3_{MTC}$ (cm)	75th percentile of the MTC distribution.
$PC1_{MTC}$ (cm)	1st percentile of the MTC distribution.
$PC5_{MTC}$ (cm)	5th percentile of the MTC distribution.
$PC99_{MTC}$ (cm)	99th percentile of the MTC distribution.
$PC95_{MTC}$ (cm)	95th percentile of the MTC distribution.

Symmetry measure

Variable	Description
S_{MTC}	Skew of the MTC distribution.

Distribution measure

Variable	Description
K_{MTC}	Kurtosis of the MTC distribution.

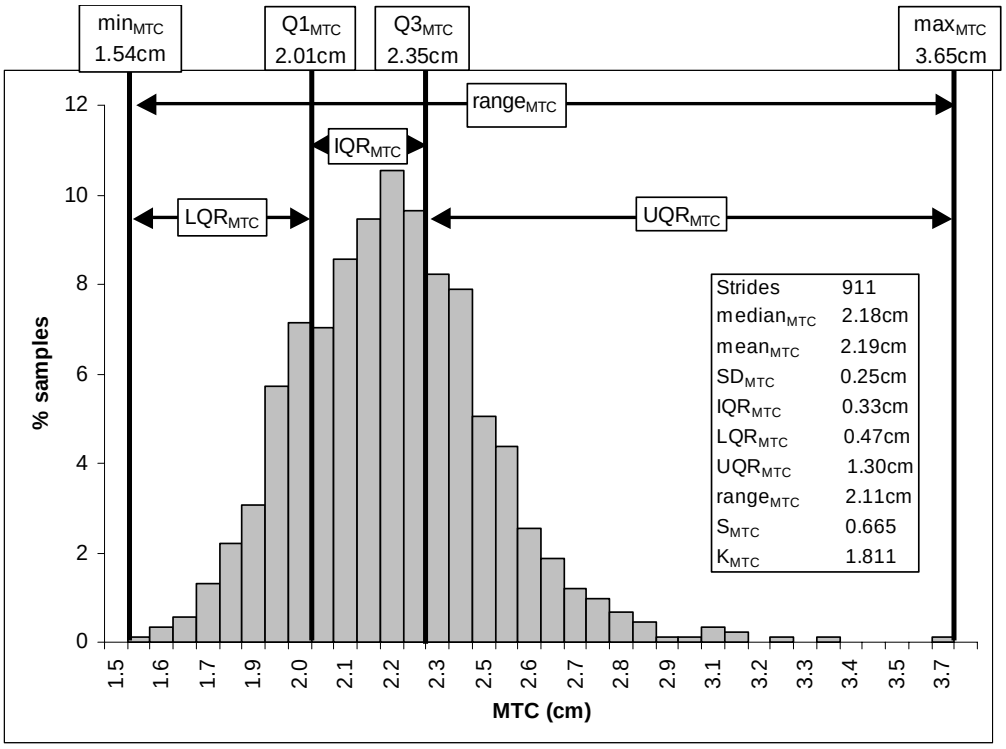


Figure 4.14: MTC distribution for one typical elderly subject (e14) showing min_{MTC}, max_{MTC}, $Q1_{MTC}$ $Q3_{MTC}$, $range_{MTC}$, LQR_{MTC}, UQR_{MTC} and IQR_{MTC}.

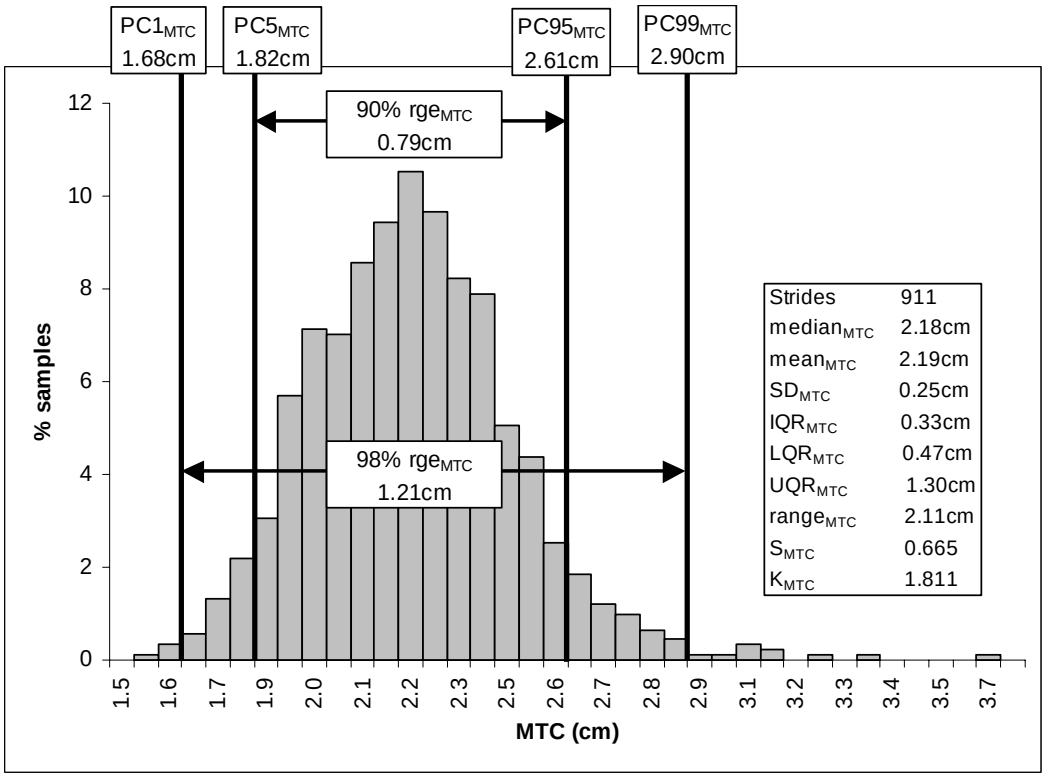


Figure 4.15: MTC distribution for one elderly subject (e14) showing $PC1_{MTC}$, $PC5_{MTC}$, $PC95_{MTC}$, $PC99_{MTC}$, 98% rge_{MTC} and 90% rge_{MTC}.

4.5.1.2 Distracted walking.

Not all the descriptive statistics of the MTC distribution, as detailed in Table 4.3, Figure 4.14 and Figure 4.15, could be calculated for the six distracted conditions. The distracted walking conditions were comprised of less strides compared with the normal undistracted walking condition and, therefore, some descriptive statistics could either not be calculated or were meaningless. Comparison of the group median stride numbers for each walking condition are shown in Table 4.4

Table 4.4: Group median number of strides for normal undistracted and distracted walking conditions for young and elderly groups.

Walking condition	Elderly	Young
normal	1011	1038
3s	52	54
video	51	54
head turn	14	10
pouch	10	9
RTP&delay	4	4
cough	3	3

It can be seen in Table 4.4 that the walking conditions vary considerably in the numbers of strides. $Median_{MTC}$ was calculated for each distraction task since this measure will yield central tendency regardless of the number of strides used and it allows comparison of intention of the locomotor system in implementing MTC to be compared across walking conditions.

Although min_{MTC} is a one-off event and may vary depending on the number of data points (strides) analysed, this was calculated since lower MTC are of particular interest and it allowed comparison of all walking conditions on low MTC. Calculation of $PC1_{MTC}$ and $PC5_{MTC}$ were useful during the normal undistracted walking condition due

to the large size of the data sets. $PC1_{MTC}$ is the MTC value at which 1% of the MTC points are smaller. Likewise, $PC5_{MTC}$ examines the MTC value at which 5% of the MTC points are smaller. Calculation of this point in the data set for the distraction tasks does not produce a meaningful result due to the small numbers of strides. For example, on average there were approximately 10 strides in the lowest one percent of the MTC distribution for the young and elderly groups in the normal undistracted walking condition. For the two prolonged tasks there was approximately half a stride in the lowest one percent of the distribution rendering the use of $PC1_{MTC}$ and $PC5_{MTC}$ meaningless.

Table 4.5 shows the number of strides included in the lowest five percent of the distributions for normal undistracted walking and during the two prolonged tasks of pre-determined 60 second duration, *video* and *3s* tasks.

Table 4.5: Group mean number of strides included in the lowest 5% of each distribution.

Walking condition	No. Strides	
	Young	Elderly
Norm	51	52
Video	3	3
3s	3	3

It can be seen in Table 4.5 that, with a median number of three strides in the lowest 5% of the distribution in the two prolonged distraction tasks, namely *video* and *3s* tasks, $PC5_{MTC}$ is able to be calculated. $PC5_{MTC}$ was, therefore, only calculated for the two prolonged tasks with a pre-determined 60 second duration, namely *video* and *3s* distractions, together with the normal undistracted walking condition for comparison.

A measure of variability for the distracted walking conditions is useful in comparing the precision of the locomotor system in implementing MTC between the undistracted and distracted walking conditions. As shown in Table 4.4, the different walking conditions varied considerably in number of strides included. *Cough* and *RTP&delay*, tasks had low numbers of strides but are comparable to other studies of foot clearance, where anything up to 10 strides are examined (see Table 4.6).

Table 4.6: Number of strides analysed during various MTC studies of unobstructed and obstructed gait.

Author	Procedure	Number of strides analysed
(Osaki *et al.*, 2007)	Unobstructed treadmill walking; consecutive strides	3 trials x 5 – 10 strides (3 trials x 10s of data)
(Osaki *et al.*, 2007; Moosabhoy and Gard, 2006)	Unobstructed overground walking; non-consecutive strides	5 trials x 1 stride
(Lu *et al.*, 2006)	Unobstructed overground walking; non-consecutive strides	6 trials x 1 stride
(Mills and Barrett, 2001)	Unobstructed overground walking; non-consecutive strides	5 trials x 1 stride
(Austin *et al.*, 1999)	Obstacle clearance; non-consecutive strides	3 trials (x 4 conditions)
(Winter, 1992)	Unobstructed overground walking; non-consecutive strides	10 trials x 1 stride
(Winter, 1991a)	Unobstructed overground walking; non-consecutive strides	Minimum of 8 trials x 1

While stride numbers did vary across walking conditions, IQR_{MTC} was also calculated for all distraction tasks since a measure of variability is important to give a representation of the precision of the locomotor system in producing MTC.

As described in the methods section 4.3.4.2.1.1, the reaction time probe task (*RTP*) was under one-second duration and therefore included only one stride. The presentation of the visual stimulus was preceded by a delay period, randomised up to 500ms.

Statistical analysis for *RTP* task therefore included the randomised delay period, which increased the number of strides examined (*RTP&delay*).

4.5.2 Probability of Tripping

The ability to predict the likelihood of an individual tripping would be an extremely useful tool in implementing specific interventions to prevent tripping and, ultimately, falls. The probability tripping on the ground or unseen obstacle of various heights was calculated based on each individual's MTC distribution. The probability of tripping (PT) in this study refers to PTP (virtual predicted toe position) contacting the ground or obstacle at the precise timing of MTC, i.e. during midswing. Each MTC distribution in this study was non-normal, with skew and kurtosis values greater than zero for all subjects with the exception of one. In order to accurately calculate PT, the MTC distribution must first be transformed to a normal distribution by modelling both skewness and kurtosis. This section describes the procedures involved in calculating each subject's probability of tripping on the ground or an unseen obstacle at the timing of MTC while walking. The mathematics involved in the modelling of the MTC distribution and calculation of PT, as described in this section, is credited to Russell Best (Best and Begg, 2002) .

4.5.2.1 Modelling sample distribution

Skew and kurtosis are measures of non-normality of a sample distribution. A score of 0 for skewness indicates symmetry in the MTC distribution. Outliers to the right of the mean may cause positive skew, or skew to the right. Outliers to the left of the mean

may cause negative skew, or skew to the left. Figure 4.16 shows a sample MTC distribution with slight skew to the right, which was typical in this research. The example shown is for 906 strides for one young subject with a $mean_{MTC}$ of 2.06cm. The range of values was 1.17cm to 3.45cm. Note $mean_{MTC}$ (2.06cm) is greater than $median_{MTC}$ (2.05cm) due to the positive skew (S_{MTC}).

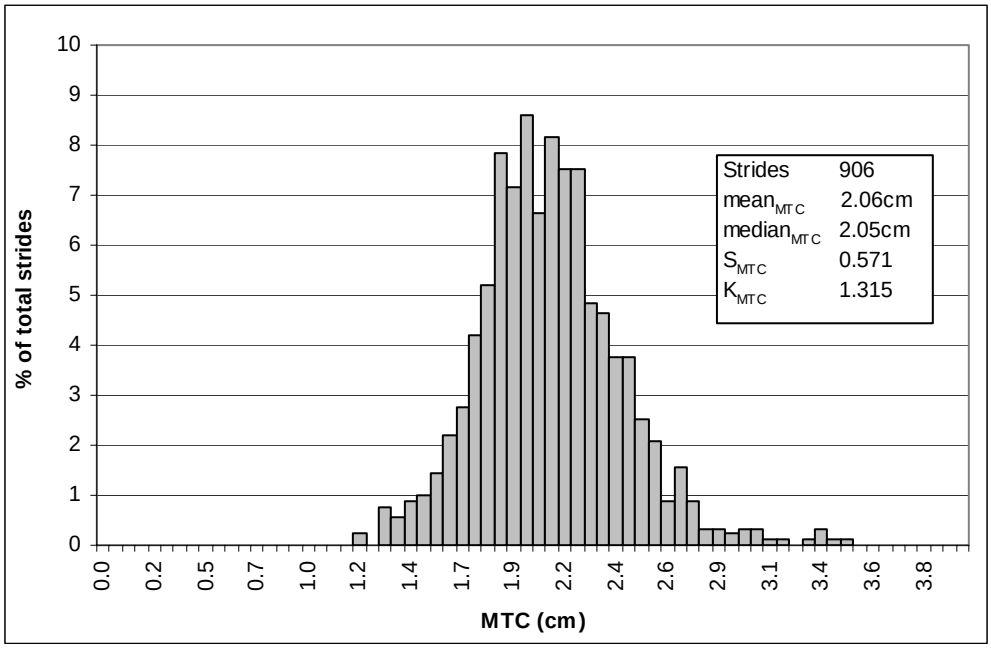


Figure 4.16: A sample distribution with skew to the right (positive skew). Actual skew value was 0.571.

A score of 0 for kurtosis (mesokurtic distribution) indicates no kurtosis (ie. no deviation from a Gaussian curve). When kurtosis is greater than 0, the curve is leptokurtic (more peaked than normal), and when kurtosis is less than 0, the curve is platykurtic (more flat than normal). Figure 4.17 shows an example of these distributions.

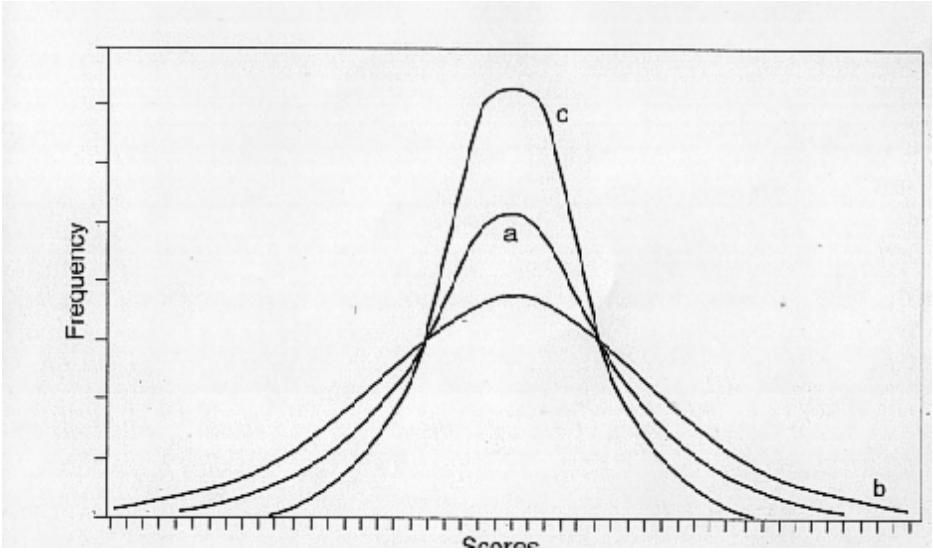


Figure 4.17: (a) Mesokuritc (bell-shaped, Normal or Gaussian), (b) platykurtic, and (c) leptokurtic curves (adapted from Vincent, 1999).

4.5.2.2 Skew modelling

Modelling skewness, or asymmetry, in a sample distribution is generally a straightforward process. The most commonly used procedure is to transform the data using a power function viz:

$$x = y^w$$

where y is the raw data and x is the transformed data.

The power (w) can be varied until a value is found that corresponds to a skewness value (S) of zero for the transformed (x) data. In this study, the value of the power, w, was found using the optimisation algorithm of Davies, Swann and Campey (DSC), first presented by Box *et al*. (1969), and software code adapted from Best (1996), as presented in Best *et al*. (1999). The function minimised in this case was |S|, which

reached a minimum at a value of |S| = 0. The algorithm's results were checked against manual derivations of the power, w.

4.5.2.3 Kurtosis modelling

The mathematical basis for kurtosis modelling was taken from Box and Tiao (1973). The standardised normal distribution equation can be written as:

$$p(x) = k.\exp(-\tfrac{1}{2}.|x|^{q}) \qquad \text{where } q = 2$$

By allowing q to vary, the set of distributions known as the exponential power distributions are formed that include normal, leptokurtic and platykurtic distributions, such that:

$$p(x \mid \bar{x}, \sigma, \beta) = \frac{\omega(\beta)}{\sigma}.\exp\left[-c(\beta).\left|\frac{(x-\bar{x})}{\sigma}\right|^{2/(1+\beta)}\right] \qquad \textbf{Equation 4.5.1}$$

where

$$c(\beta) = \left\{\frac{\Gamma.\left[\tfrac{3}{2}.(1+\beta)\right]}{\Gamma.\left[\tfrac{1}{2}.(1+\beta)\right]}\right\}^{1/(1+\beta)}$$

and

$$\omega(\beta) = \frac{\left\{\Gamma.\left[\tfrac{3}{2}.(1+\beta)\right]\right\}^{1/2}}{(1+\beta).\left\{\Gamma.\left[\tfrac{1}{2}.(1+\beta)\right]\right\}^{3/2}}$$

The parameters $\bar{x}$ and σ, for the purposes of this study, are the mean and standard deviation of the skew-transformed population respectively. For accurate modelling of this study's MTC distributions, exponential power distribution modelling has to be applied to the symmetrical distributions that, in this study, correspond to the skew-transformed data. The parameter β is a measure of kurtosis representing the extent of 'non-Normality' in the symmetrical distribution (Box and Tiao, 1973). The usual measure of kurtosis, k (used throughout this study), is related to β viz:

$$k = \frac{\Gamma.\left[\tfrac{5}{2}.(1+\beta)\right]\Gamma.\left[\tfrac{1}{2}.(1+\beta)\right]}{\left\{\Gamma.\left[\tfrac{3}{2}.(1+\beta)\right]\right\}^2} - 3$$

Equation 4.5.2

The value of β varies between –1, the extreme platykurtic distribution (a square wave or rectangular distribution), and 1, the extreme leptokurtic distribution (a double exponential distribution). A value of $\beta = 0$ is the Normal (Gaussian) distribution. Two distributions and their associated β values are detailed in Figure 4.18.

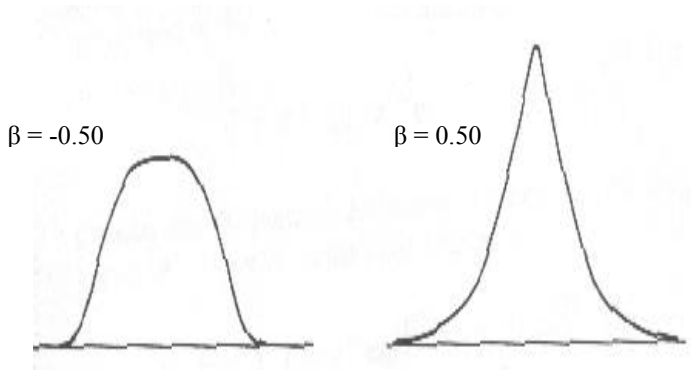


Figure 4.18: Example of non-normal distributions and their associated β values (adapted from Box and Tiao, 1973).

Once the standard kurtosis value, k, is recalculated for the skew-transformed data, β is found through optimisation by varying β until the right hand side of Equation 4.5.2 equals the skew-transformed kurtosis value, k. Once again, the DSC optimisation procedure (Best, 1996; Box *et al.*, 1969) was used for this purpose and checked using the known values of β and k presented in Box and Tiao (1973). The function minimised in this case was:

$$\left| \frac{\Gamma.\left[\tfrac{5}{2}.(1+\beta)\right]\Gamma.\left[\tfrac{1}{2}.(1+\beta)\right]}{\left\{\Gamma.\left[\tfrac{3}{2}.(1+\beta)\right]\right\}^2} - 3 - \mathrm{k} \right|$$

which reached a minimum at a value of zero.

4.5.2.4 Calculating the probability of tripping (PT)

With the raw data transformed to a symmetrical distribution and the skew-transformed β value known, the probability of tripping (PT) is found by integrating the exponential power distribution presented in Equation 4.5.1. The equation must be numerically integrated because the negative exponential (ie. -c(β) in Equation 4.5.1) eliminates the possibility of mathematical integration.

The probability of an MTC of ycm occurring for an individual is given by:

$$\int_{-\infty}^{x} \frac{\omega(\beta)}{\sigma}.\exp\left[-c(\beta).\left|\frac{(x-\overline{x})}{\sigma}\right|^{2/(1+\beta)}\right] \; dx \qquad \textbf{Equation 4.5.3}$$

where, as for Equation 4.5.1, x is the skew-transformed data.

Note that the integral between $\overline{x}$ and $-\infty$ equals 0.5 (50% probability). Thus, when $x < \overline{x}$, Equation 4.5.3 is equivalent to:

$$0.5 - \int_{x}^{\overline{x}} \frac{\omega(\beta)}{\sigma}.\exp\left[-c(\beta).\left|\frac{(x-\overline{x})}{\sigma}\right|^{2/(1+\beta)}\right] \; dx \qquad \textbf{Equation 4.5.4}$$

which obviates the need to integrate to $-\infty$.

Similarly, when $x > \overline{x}$, Equation 4.5.3 is equivalent to:

$$0.5 + \int_{\overline{x}}^{x} \frac{\omega(\beta)}{\sigma}.\exp\left[-c(\beta).\left|\frac{(x-\overline{x})}{\sigma}\right|^{2/(1+\beta)}\right] \; dx \qquad \textbf{Equation 4.5.5}$$

The numerical integration employed was a simple trapezium rule calculation and the step size for the integrations/trapeziums was set at:

$$\frac{|(\bar{x} - x)|}{10000}$$

The figure of 10000 is nominal and was chosen through trial and error. The integration process was checked by comparing the program's probability results with those calculated from the same data using the z-score method outlined by Vincent (1999) and adapted for this application by Best *et al*. (1999). The trapezium rule, though basic, appears to be adequate for this process.

4.6 Statistical analysis

All statistics were calculated by SPSS (version 11.0).

4.6.1 Exploratory data analysis and descriptive statistics

Exploratory data analysis was performed on each data set prior to performing further statistical tests and descriptive statistics examined to determine normality of the data. Shapiro-Wilks statistic was chosen as a measure of normality (within SPSS) since the number of cases (n) was less than 50 (Coakes and Steed, 1999). Several non-normal data sets were identified and further examination revealed these data sets all had non-zero skew and kurtosis.

Data sets of a non-normal distribution were further examined in order to determine the actual nature of the distribution. SPSS program has the option of performing a number of descriptive, exploratory measures for this purpose. One of these is the normal probability (termed Normal Q-Q plots in SPSS) and detrended normal Q-Q plot, generated as part of SPSS (Inc.) statistical software.

In the normal probability (Normal Q-Q plot - expected normal value as a function of observed value) each observed value is paired with its expected value from the normal distribution. The cases form an approximately straight line in a normal distribution. The detrended normal plot shows the actual deviations of the points from a straight line. No pattern to the clustering of points should be evident in a normal distribution

(Coakes and Steed, 1999). Examining the normal Q-Q plots allows a clear insight into the nature of the distribution. It was found that some distributions could be normalised by transformation (e.g. logarithmic) whilst others were approximately linear on the normal Q-Q plots, suggesting the data were normal except for one outlier. For example, Figure 4.19 shows an example of normal Q-Q plot for max_{MTC} (the maximum MTC in the MTC distribution) for young and elderly groups.

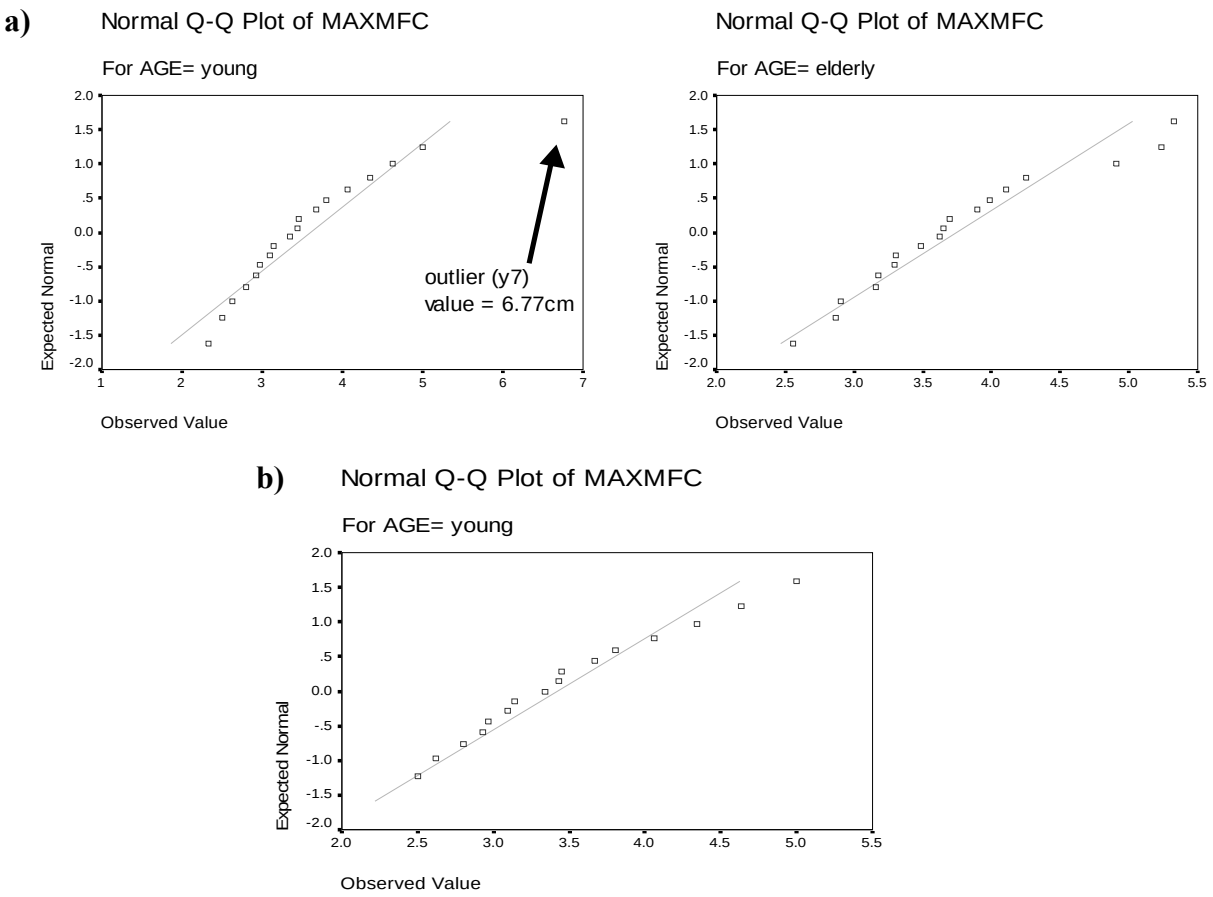


Figure 4.19: Example of normal and non-normal Q-Q plot.

a) shows non-normal distribution for the young group, caused by the outlier 6.77cm (y7) whilst Q-Q plot for the elderly group is normal and therefore follows the straight line reasonably well; b) shows that the Q-Q plot for the young group is normal after outlier y7 is removed from the data set.

Recall the normal distribution follows a linear pattern when plotted on the normal Q-Q plot. Notice in part a) that there is one outlier in the young group, resulting in a non-normal distribution with a Shapiro-Wilks statistic of .020, whilst the elderly distribution is normal. It can be seen in part a) that the remainder of the young distribution is roughly linear and, therefore, a specific transformation was not applicable to this type of data set. Notice in part b) that when the outlier is removed the remainder of the data form a linear pattern.

Normal Q-Q plots and detrended normal Q-Q plots were examined for all data sets, particularly where normality assumption was violated, to determine whether alternative manipulations could be made to the data prior to performing inferential statistics. Two methods of dealing with non-normal distributions are to remove outliers or to transform the data (Afifi and Clark, 1990), however, neither of these methods produced a satisfactory result.

The data, therefore, were not transformed for a number of reasons: 1) For some variables, distributions were non-normal for one group but the comparison group was normal. In these cases, transforming the normal distributions led to a non-normal distribution; 2) There was no specific transformation to perform, i.e. the data sets were normal except for one outlier. It was not considered appropriate to remove outliers from the data sets because they were real data and, being small data sets, it is not possible to deem the outliers to be truly unrepresentative of the population sample examined. Indeed, removing the outliers for observation purposes still did not produce a normal distribution for some data sets.

Box plots were examined as part of exploratory data analysis (EDA). These were generated as part of the EDA function of SPSS (Inc.) statistical software. The use of box plots to examine the nature of the distributions was a useful tool since important information about the distribution were able to be easily determined. Figure 4.20 shows an example of the SPSS generated box plot of $median_{MTC}$ (median of the MTC distribution) for young and elderly groups. The respective values of each distribution parameter are also given.

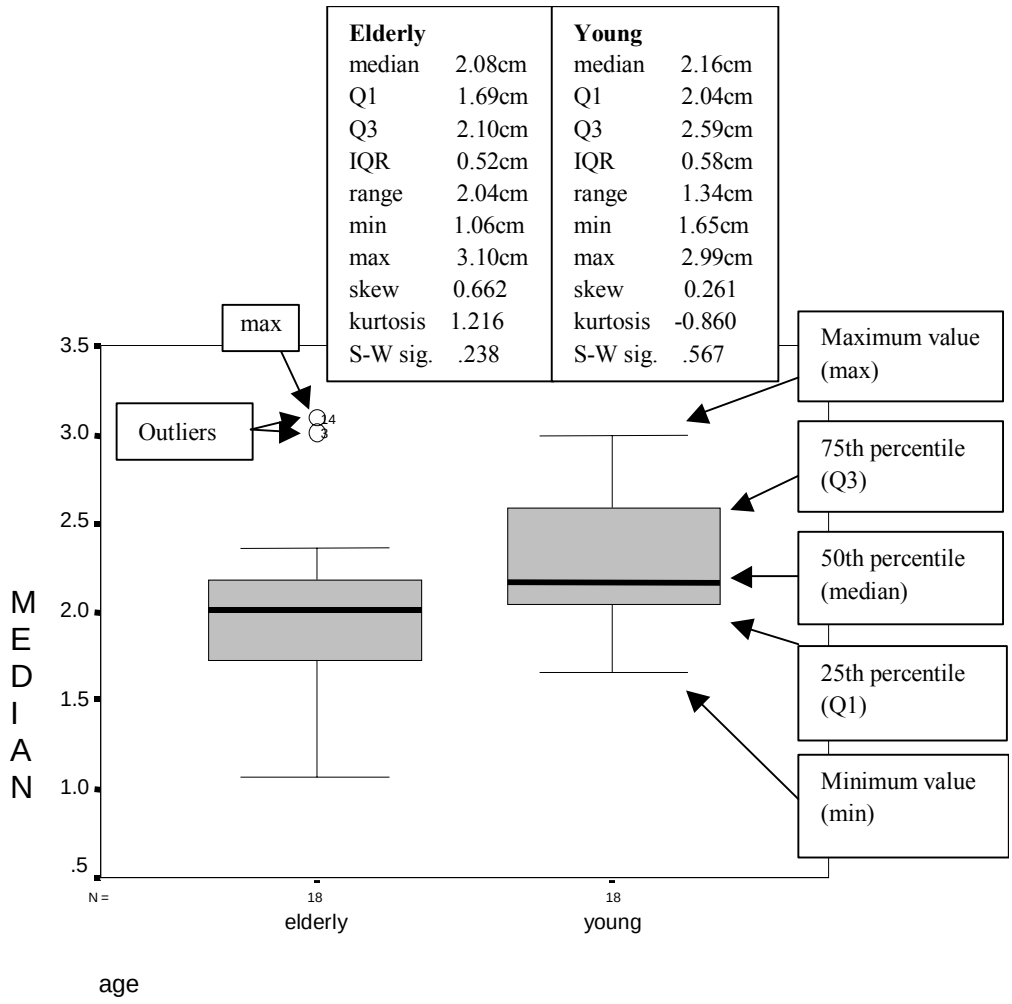


Figure 4.20: Box plot of $median_{MTC}$ for young and elderly groups.

○ denotes outlier (1.5 to 3 box lengths from upper edge of box, as determined in SPSS).

S-W sig. denotes Shapiro-Wilks significance (as determined in SPSS) – significance at .05 level indicates distribution is non-normal.

The darker horizontal line through the box represents the median, or 50th percentile. The lower boundary of the box is the 25th percentile (Q1) while the upper boundary is the 75th percentile (Q3). The minimum and maximum observed values within the distribution are represented by the horizontal lines at either end of the box, often referred to as whiskers. In the example shown, there are two outliers and these influence the layout of the box plot. Outliers are defined in SPSS as having values between 1.5 to 3 box lengths from the upper or lower edge of the box are denoted by ○. In the example shown in Figure 4.20, it can be seen that two outliers exist in the elderly group. It can also be seen that the maximum value is now denoted by the most extreme outlier (3.10cm). The upper whisker in this case denotes the maximum value neglecting the outliers and extremes. It is important to note that while outliers and extremes are highlighted, they are still included in the calculation of all descriptive statistics and other parameters describing the nature of the distribution. Extreme scores, defined in SPSS as being three or more box lengths from the upper or lower edge of the box, were only rarely found.

The use of box plots was an efficient method of identifying subjects differing substantially from the rest of the group (i.e. outliers and extremes). They also presented a very useful visual representation of the spread of values in each distribution. In each section of the results chapter, exploratory data analysis is presented first (including descriptive statistics, tests of normality and identification of outliers and extremes) followed by inferential statistics.

4.6.2 Inferential statistics

Where the group data were determined non-normal, a non-parametric test, although less powerful, was performed instead of the parametric equivalent. Specifically, the non-parametric Mann-Whitney U test instead of the parametric Independent t-test was employed for the non-normal distributions. The non-parametric Kruskal-Wallis H test instead of the parametric one-way ANOVA was used for non-normal distributions. The Wilcoxon signed-rank test was used as a non-parametric alternative to the repeated measures or paired t-test. Since some data violated the strict assumptions of normality required for ANOVA, multiple comparisons were made by utilising parametric tests for normally distributed and non-parametric tests for non-normally distributed data.

When performing multiple significance tests the chance of finding a 'significant' difference just by chance increases. A Bonferroni correction is typically used to protect against a Type 1 error (findings of false 'significance' – the error of rejecting the null hypothesis when it is true) when conducting multiple comparisons by reducing the *p-value* at which an outcome is considered significant. For example, if three t-tests are performed, in order for a t-test value to be considered significant, the *p-value* must fall below .0167 (= 0.05/3) to be significant at an α level of .05. However, Bonferroni correction also increases the chance of a Type II errors or increases the need to increase the sample size (Feise, 2002; Perneger, 1998; Bland and Altman, 1995). Since the sample size in this research is relatively small, the Bonferroni correction was not used and findings are discussed in light of this. It is recognised that the small group sample size is a limitation in this research, however, the sample size chosen (i.e. 48 subjects) was a realistic achievement given the time constraints. That is, data collection,

digitisation and parameter extraction alone took a minimum of 50 hours per subject, which is equal to a minimum of 2,400 hours in total for all 48 subjects. Data analysis also required many hours of work per subject in addition to the initial 2,400 hours of data collection and parameter extraction.

4.6.2.1.1 To address null hypothesis "No significant effect of age upon major descriptive statistics of the MTC distribution" (aim 1, hypothesis 1)

MTC Central tendency, namely $mean_{MTC}$, $median_{MTC}$ and $mode_{MTC}$, were examined via one-way ANOVA for age effects and interactions (age x central tendency measure). MTC intra-individual variability, namely SD_{MTC}, IQR_{MTC}, CV'_{MTC}, $range_{MTC}$, UQR_{MTC}, LQR_{MTC}, 98% rge_{MTC} and 90% rge_{MTC}, was examined for ageing effects via multiple Mann-Whitney U tests since the data were not normally distributed. MTC dispersion, namely min_{MTC}, max_{MTC}, $Q1_{MTC}$, $Q3_{MTC}$, $PC1_{MTC}$, $PC5_{MTC}$, $PC99_{MTC}$, $PC95_{MTC}$, were examined for age effects via multiple Independent t-test for normally distributed data and non-parametric Mann-Whitney U test for non-normally distributed data. MTC symmetry, namely S_{MTC} and distribution, namely K_{MTC}, were examined for ageing effects via separate non-parametric Mann-Whitney U tests since the data were not normally distributed.

Pearson's r was used to determine whether any MTC descriptive statistics were correlated. This allowed examination of different strategies utilised by the young and elderly group in order to avoid tripping on small unseen obstacles. Separate correlation

matrices were examined for young and elderly groups in an effort to identify different strategies for implementing MTC between the two groups.

Low MTC measures (5^{th} percentile of the MTC distribution – $PC5_{MTC(distr)}$) were examined for effect of age and walking condition and interactions via two-way ANOVA with post-hoc comparisons. Minimum values of MTC distributions for each walking condition ($min_{MTC(norm)}$ and $min_{MTC(distr)}$) were examined for ageing effects using independent t-test for normally distributed data and non-parametric Mann-Whitney U test for non-normally distributed data. Additionally, variability measures ($IQR_{MTC(distr)}$) were examined for age effects via multiple Mann-Whitney U tests given the non-normality of the data.

4.6.2.1.2 To address null hypothesis "No significant effect of walking condition upon major descriptive statistics of the MTC distribution" (aim 1, hypothesis 2)

Two-way ANOVA was used to examine effect of age and walking condition and interactions on $median_{MTC}$ and the extent of deviation from normal undistracted walking median MTC ($median_{MTC(norm)}$). Post-hoc comparisons using Tukey's HSD (Honestly Significant Differences) were performed in order to examine interactions. Tukey's HSD test is one of several methods for testing the significance of unplanned pairwise comparisons. It ensures that the chance of finding a significant difference in any comparison (under a null model) is maintained at the alpha level of the test. SPSS

software allows selection of Tukey's HSD, along with other options, for post-hoc comparisons.

Effect of walking condition on low MTC measures ($PC5_{MTC}$ and min_{MTC}) was examined via non-parametric Kruskal-Wallis test and then simple comparisons using multiple Mann-Whitney U tests for non-normally distributed data and independent t-tests for normally distributed data. Similarly, effect of walking condition for and IQR_{MTC} were examined for all conditions via Kruskal-Wallis test and then simple comparisons using multiple Mann-Whitney U tests.

Age effects were examined for task performance during distraction tasks. Performance was determined by task duration (*head turn*, *pouch* and *RTP* tasks) and accuracy (percentage of correctly identified shapes in *head turn* task and number and percentage of correct subtractions in *3s* task). Additionally, one-way repeated measures ANOVA was used to examine performance during ST and DT conditions for *3s* and *RTP* tasks (age and distraction task effects and interactions).

Non-parametric Spearman's rho was conducted to examine correlations between performance measures (accuracy and duration) for head turn task. Finally, Chi-square analyses were conducted in order to compare the frequency of level of effect of each distracted walking condition on $median_{MTC(norm)}$.

4.6.2.1.3 To address null hypothesis "No significant age effect upon predicted probability of tripping" (aim 2, hypothesis 1)

A series of Mann-Whitney U tests were employed to examine age-effects of calculated PT at each value of MTC ranging from 0.0cm to 6.0cm.

Chapter 5: Results

This chapter begins by presenting subject characteristics of the population studied, including pre-screening for the elderly subjects. Three major sub-sections follow:

- Presentation of results for the normal undistracted 20-minute walking condition;
- Presentation of results for predicting probability of tripping using the normal undistracted walking condition;
- Presentation of results for the distracted 10-minute walking condition.

Mean and median as measures of central tendency and SD and IQR as measures of variability are presented. Median and IQR are discussed as these are more accurate measures for non-normally distributed data but mean and SD are presented as a comparison.

Exploratory data analysis including descriptive statistics is presented first for each sub-section, followed by inferential statistics.

5.1 Subject characteristics

A total of 48 female adults (young and elderly) were screened for this investigation, with elderly subjects undergoing further examination to evaluate mobility level, falls history, vision and cognitive state. All 48 participants attending Victoria University for testing satisfied requirements of the screening tests and were included in the study.

Of the 48 subjects tested, data for twelve subjects (six young and six elderly) could not be used. As described in the methodology section this was due to an unusual walking pattern where there was no identifiable MTC, the key feature of this study. Therefore, the analysis of results is for the 36 subjects (18 young and 18 elderly) where calculation of MTC was successful. An alternative method of estimating ground clearance of the toe/foot during swing phase for these 12 subjects has been proposed in discussion section 6.3.4. Indeed, this would be an important area for further investigation in the future.

Comparison of subject characteristics, namely age, stature and mass, are presented in Table 5.1 (individual subject characteristics can be found in appendix G). As previously discussed, Bonferroni correction was not used in the multiple t-tests performed due to the increased chance of obtaining a Type II error given the small sample size (e.g. Feise, 2002; Perneger, 1998; Bland and Altman, 1995).

Table 5.1: Comparison of subject characteristics.

Variable	Young n = 18					Elderly n = 18					*p-value*
	mean	med	SD	IQR	range	mean	med	SD	IQR	range	
Age (years)	21.8	20.7	3.6	2.9	14.1	71.3	71.7	3.6	4.6	13.5	<.001**
Stature (m)	1.65	1.66	0.07	0.09	0.20	1.60	1.61	0.05	0.09	0.18	.021*
Mass (kg)	61.0	60.4	9.4	12.3	36.0	67.6	70.1	7.0	7.1	29.0	.022*

***denotes $p<.05$; ** denotes $p<.001$.**

Independent t-tests revealed significant difference on all measures of subject characteristics. Mean age for young and elderly were 21.8 years (SD = 3.6 years) and 71.3 years (SD = 3.6 years) respectively ($p<.001$). Young subjects were on average 5cm taller than their elderly counterparts with mean stature for young and elderly of 1.65m (SD = 0.07m) and 1.60m (SD = 0.05m) respectively ($p=.021$). Young subjects were an average of 6.6kg lighter than the elderly group. Mean mass was 61.0kg for the young group compared with 67.6kg for the elderly group.

In summary, the young and elderly groups in this study varied on subject characteristics such as mass and stature. The young subjects were taller and lighter than the elderly group. The elderly were, if anything, a more homogeneous group compared with the young group as seen by the smaller range of values.

5.2 Screening for elderly participants

As previously described in the methods chapter, screening tests including tests of visual function (visual acuity – logMAR score, and contrast sensitivity – Melbourne Edge Test (MET)), physical performance/mobility (Step Test and Timed Up-and-Go), level of fear of falling (Modified Falls Efficacy Scale – MFES) and cognitive state (Mini-Mental State Examination - MMSE) were conducted for the elderly participants in order to identify those with known risk factors for falls or characteristics known to alter normal gait and, therefore, eliminate them from the study. Table 5.2 shows subjects are within established normal ranges as referred to in section 4.1.2.3.

Table 5.2 : Screening tests for elderly group (n=18).

Screening Variable	Test score	mean	range	Normal ranges
Visual acuity	logMAR	-0.2	-0.3 - 0	< 0.3
	Snellen denomination 6/n	4.1	3 - 6	< 12
Contrast sensitivity	dB	23.8	20 - 24	> 16dB
Step test	Number of steps in 15s	18.5	17 - 21.5	> 17
Timed Up-and-Go	Time (s) to complete task	6.6	5.4 - 8.4	<13.4s
Mini Mental State Examination	Score out of 30	29.0	28 - 30	> 23
Modified Falls Efficacy Scale	Mean score out of 10	9.9	9.2 - 10	>9.44

5.3 Walking speed characteristics

A description of the variables examined in this section is detailed in Table 5.3.

Table 5.3: Waking speed variables.

Variable	Description
WS (m/s)	Walking speed (m/s).
RWS (stats/s)	Relative walking speed = walking speed/stature = (m/s)/(m) = statures/second (stats/s)
Strides	Number of strides taken during 20 minute normal undistracted walking trial (i.e. number of MTC points)

Comparison of walking speeds between young and elderly can be found in Figure 5.1.

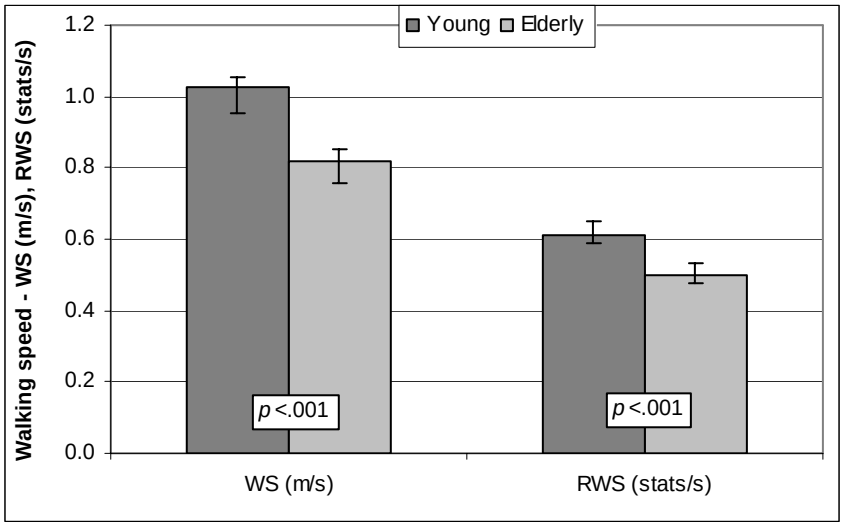


Figure 5.1: Comparison of group median walking speeds for young and elderly.

Note: median and IQR values are shown for walking speed (WS) and relative walking speed (RWS).

It can be seen in Figure 5.1 that walking speed is significantly faster in the young group (mean = 1.03m/s, n =18) vs. elderly group (mean = 0.83m/s, n = 18), $p<.001$. When normalised to stature, the young group were still significantly faster walkers compared

with the elderly (mean values: young = 0.63 stats/s, n = 18 vs. elderly = 0.52 stats/s, n = 18, $p<.001$). Number of strides completed in the 20-minute undistracted walking period as a function of walking speed (m/s) for young and elderly subjects can be found in Figure 5.2.

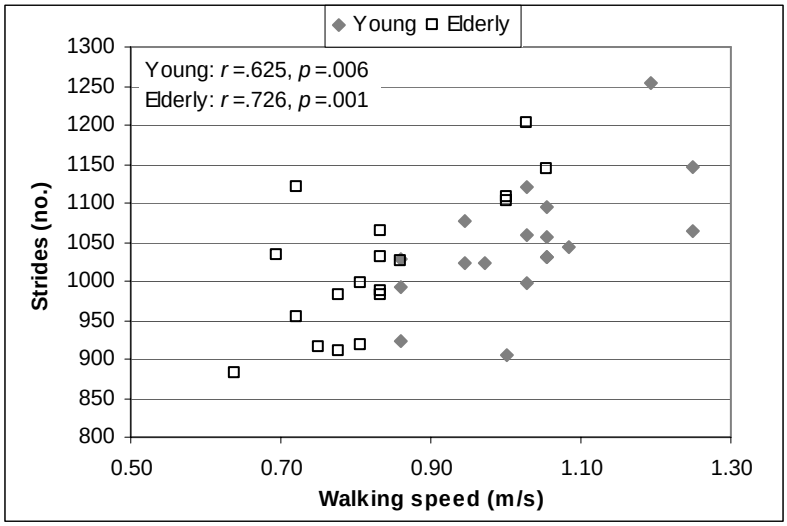


Figure 5.2: Number of strides completed in the 20-minute normal undistracted walking period as a function of walking speed (m/s).

Note: Pearson's correlation (*r*) is shown for young and elderly groups.

Although number of strides was not statistically significant between the two age groups (refer Table 5.4), it can be seen in Figure 5.2 that there is a significant positive correlation between walking speed and stride numbers for young (p=.006) and elderly (p=.001). That is, high stride numbers are associated with fast walking speeds and low stride numbers are associated with slower walking speeds.

Walking speed characteristics for young and elderly are listed in Table 5.4 (individual walking speed characteristics can be found in the appendices). Median and IQR values

are also shown in Table 5.4. Because the data were normally distributed it can be seen that the mean and median values are similar.

Table 5.4: Comparison of young and elderly walking speed characteristics.

	Variable	WS (m/s)	RWS (stats/s)	Strides (no.)
Young n = 18	mean	1.03	0.63	1048
	med	1.03	0.61	1038
	SD	0.12	0.08	78
	IQR	0.10	0.06	50
	range	0.39	0.28	347
Elderly n = 18	mean	0.83	0.52	1020
	med	0.82	0.50	1011
	SD	0.12	0.08	90
	IQR	0.10	0.06	132
	range	0.42	0.28	320
	t (df = 34)	-4.996	-3.927	.999
	p- value	<.001*	<.001*	.325

***denotes p<.001.**

As seen in Table 5.4, significant age effects existed across all measures except for stride numbers. Young adults walked significantly faster (approximately 24%) than elderly adults ($p<.001$). A significant difference was still evident when walking speed was normalised to height, with young adults walking approximately 21% faster than elderly ($p<.001$) on this measure.

Walking speed for the young group ranged from 0.86 m/s (young subject y17, y22 and y23) and 1.25m/s (young subject y7 and y14). Although the mean walking speed for the young group was within the normal range of 0.94 – 1.66m/s for females between 18 – 49 years, as stated by Whittle (1993), the lowest walking velocity (0.86m/s) shared by three subjects (y17, y22 and y23) were below the normal range. For the elderly group walking velocities ranged from 0.64m/s (elderly subject e10) to 1.06m/s (elderly

subject e6). Although the mean walking velocity for the elderly group was within the normal range of 0.80 – 1.52 m/s for females between 65 – 80 years, as stated by Whittle (1993), seven subjects were below this range (elderly subject e5, e7, e10, e12, e14, e15, e17). The normal ranges reported by Whittle are for overground walking and it was found in this study that, on average, self-selected comfortable walking speeds overground were 28% faster than self-selected comfortable walking speed on the treadmill (34% faster for elderly, 23% faster for young). The treadmill is a different terrain, which has a different comfortable walking speed. The equivalent overground walking speed, therefore, places subjects within Whittle's normal ranges.

5.4 Normal, undistracted walking

5.4.1 Describing the MTC distribution

Variables examined in this section have been described in the methods section 4.5. These include descriptive statistics of the MTC distribution for:

1. Central tendency (namely $mean_{MTC}$, $median_{MTC}$ and $mode_{MTC}$);
2. Variability – indication of: a) intra-individual variability in the MTC distribution on a stride-to-stride basis (SD_{MTC}, IQR_{MTC}, CV'_{MTC}), b) the spread of MTC throughout the entire MTC distribution ($range_{MTC}$), c) the spread of MTC within the upper (UQR_{MTC}) and lower (LQR_{MTC}) end of the MTC distribution, and d) the spread of MTC after the most extreme values are removed from the distribution leaving the middle 98% (98% rge_{MTC}) and middle 90% (90% rge_{MTC});
3. Dispersion – an indication of how the MTC points are dispersed throughout the MTC distribution by examining: a) the minimum and maximum values (min_{MTC}, max_{MTC}), b) the lower one and five percent of the MTC distribution ($PC1_{MTC}$, $PC5_{MTC}$), c) the lower and upper quarter of the MTC distribution ($Q1_{MTC}$ and $Q3_{MTC}$), and d) the upper one and five percent of the MTC distribution ($PC99_{MTC}$ and $PC95_{MTC}$);
4. Symmetry (namely S_{MTC}) ; and
5. Distribution (namely K_{MTC})

This section presents results in three sub-sections: 1) central tendency, 2) variability/dispersion and 3) symmetry/distribution. Within each sub-section, exploratory data analysis is presented followed by inferential statistics.

5.4.2 Exploratory data analysis

Selected descriptive statistics can be found in Table 5.5 for the young group whilst elderly group descriptive statistics are listed in Table 5.6. As explained in the method section, since the number of cases (*n*) was less than 50, Shapiro-Wilks statistic for normality was used and several non-normal data sets were identified.

Table 5.5: Descriptive statistics for the young group (n = 18) during normal, undistracted walking.

Tests of normality: Shapiro-Wilks (S-W). *(p<.05) denotes non-normal distribution.

Young	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Strides (no.)	1048	1038	78.4	49.5	906	1253	0.667	2.078	0.301
$mean_{MTC}$ (cm)	2.30	2.20	0.41	0.54	1.65	3.04	0.334	-0.707	0.525
$median_{MTC}$ (cm)	2.28	2.16	0.39	0.55	1.65	2.99	0.261	-0.860	0.538
$mode_{MTC}$ (cm)	2.24	2.15	0.38	0.55	1.70	2.90	0.370	-0.888	0.360
SD_{MTC} (cm)	0.27	0.22	0.13	0.12	0.17	0.71	2.593	8.149	0.010 *
IQR_{MTC} (cm)	0.34	0.29	0.16	0.10	0.22	0.94	3.110	11.083	0.010 *
CV'_{MTC} (%)	14.76	13.87	5.30	3.52	10.09	33.39	2.780	9.401	0.010 *
$range_{MTC}$ (cm)	2.19	1.82	1.08	1.18	1.25	5.15	1.522	2.103	0.010 *
UQR_{MTC} (cm)	1.14	0.82	0.74	0.75	0.52	3.37	1.924	3.876	0.010 *
LQR_{MTC} (cm)	0.70	0.56	0.39	0.31	0.41	2.01	2.503	7.255	0.010 *
98% rge_{MTC} (cm)	1.34	1.12	0.58	0.66	0.79	3.15	1.991	4.966	0.001 *
90% rge_{MTC} (cm)	0.87	0.73	0.40	0.31	0.56	2.26	2.758	9.066	0.000 *
min_{MTC} (cm)	1.42	1.42	0.39	0.39	0.38	2.10	-0.700	2.028	0.382
max_{MTC} (cm)	3.60	3.39	1.08	1.06	2.33	6.77	1.605	3.332	0.020 *
$Q1_{MTC}$ (cm)	2.12	2.00	0.36	0.54	1.54	2.80	0.253	-0.731	0.569
$Q3_{MTC}$ (cm)	2.46	2.35	0.46	0.57	1.77	3.40	0.539	-0.299	0.617
$PC1_{MTC}$ (cm)	1.73	1.68	0.31	0.28	1.24	2.35	0.230	-0.371	0.688
$PC5_{MTC}$ (cm)	1.90	1.81	0.34	0.37	1.36	2.51	0.258	-0.519	0.588
$PC99_{MTC}$ (cm)	3.07	2.99	0.71	0.69	2.13	5.04	1.282	2.337	0.090
$PC95_{MTC}$ (cm)	2.78	2.70	0.60	0.62	1.95	4.37	1.172	1.857	0.153
S_{MTC}	0.47	0.33	0.43	0.46	-0.21	1.55	1.083	1.082	0.071
K_{MTC}	1.49	1.05	1.57	1.48	0.01	6.70	2.327	6.823	0.010 *

Table 5.6: Descriptive statistics for the elderly group (n = 18) during normal, undistracted walking.

Tests of normality: Shapiro-Wilks (S-W). *(p<.05) denotes non-normal distribution.

Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Strides (no.)	1020	1011	89.5	132.0	883	1203	0.350	-0.605	0.713
$mean_{MTC}$ (cm)	2.04	2.04	0.50	0.40	1.08	3.12	0.642	1.234	0.240
$median_{MTC}$ (cm)	2.01	2.01	0.49	0.42	1.06	3.10	0.662	1.216	0.291
$mode_{MTC}$ (cm)	1.96	1.95	0.52	0.48	1.10	3.20	0.995	1.421	0.096
SD_{MTC} (cm)	0.34	0.32	0.09	0.10	0.20	0.55	0.686	-0.081	0.436
IQR_{MTC} (cm)	0.44	0.41	0.13	0.19	0.25	0.69	0.704	-0.433	0.233
CV'_{MTC} (%)	22.49	20.04	6.87	7.14	15.33	41.40	1.573	2.472	0.010 *
$range_{MTC}$ (cm)	2.65	2.43	0.79	1.07	1.52	4.56	0.730	0.282	0.316
UQR_{MTC} (cm)	1.50	1.31	0.65	0.57	0.65	3.67	2.198	6.954	0.010 *
LQR_{MTC} (cm)	0.71	0.61	0.29	0.33	0.35	1.53	1.428	2.792	0.033 *
98% rge_{MTC} (cm)	1.61	1.52	0.44	0.52	0.97	2.66	0.781	0.293	0.377
90% rge_{MTC} (cm)	1.10	1.02	0.31	0.36	0.63	1.75	0.645	-0.370	0.231
min_{MTC} (cm)	1.10	1.08	0.41	0.34	0.24	1.83	-0.198	0.231	0.763
max_{MTC} (cm)	3.75	3.64	0.79	0.87	2.55	5.32	0.728	-0.060	0.301
$Q1_{MTC}$ (cm)	1.80	1.80	0.47	0.42	0.83	2.82	0.446	1.279	0.378
$Q3_{MTC}$ (cm)	2.24	2.23	0.54	0.39	1.27	3.40	0.702	1.125	0.182
$PC1_{MTC}$ (cm)	1.37	1.35	0.41	0.36	0.44	2.18	0.046	1.156	0.500
$PC5_{MTC}$ (cm)	1.54	1.50	0.43	0.38	0.60	2.45	0.262	1.183	0.486
$PC99_{MTC}$ (cm)	2.99	2.94	0.72	0.60	2.02	4.79	1.007	1.379	0.109
$PC95_{MTC}$ (cm)	2.64	2.64	0.63	0.47	1.62	4.08	0.808	1.011	0.169
S_{MTC}	0.77	0.60	0.64	0.51	-0.06	2.97	2.580	8.818	0.010 *
K_{MTC}	3.15	0.71	8.48	2.08	-0.07	36.84	4.129	17.311	0.010 *

It can be seen that ten data sets in the young group were non-normal, as measured by a significant S-W statistic (p<.05) whilst there were only five in the elderly group.

Group skew values were all positive except min_{MTC} distribution for young group (-0.700) and elderly (-0.198). The highest group skew value was found in the IQR_{MTC} distribution for the young group (3.110) and K_{MTC} distribution for the elderly (4.129). The highest group kurtosis value was found in the IQR_{MTC} distribution for the young group (11.083) and K_{MTC} distribution for the elderly group (17.311).

5.4.2.1 Outliers and extreme values

Outlier and extreme values, identified during exploratory data analysis as part of SPSS software, have been defined in the methods section 4.6.1. Subjects deemed as outliers and extremes for group analysis were not removed prior to further analysis since there was no justifiable reason to do so. Outliers and extremes are identified in order to gain a greater understanding of the nature of the group distribution and to support the statistical tests employed.

For central tendency measures of the MTC distribution, it can be seen that there were no outliers or extreme values for young subjects, however, some outliers were reported for elderly subjects (refer Table 5.7).

Table 5.7: Individual MTC distribution central tendency measures.

(denotes outlier, as defined by SPSS*)**

subject	$mean_{MTC}$ (cm)	$median_{MTC}$ (cm)	$mode_{MTC}$ (cm)
y1	2.59	2.59	2.6
y2	2.05	2.03	2.0
y5	3.04	2.99	2.9
y6	2.15	2.12	2.1
y7	2.98	2.82	2.4
y9	1.89	1.89	1.9
y12	2.06	2.05	1.9
y14	1.99	1.98	2.0
y15	2.22	2.17	2.1
y16	2.36	2.36	2.4
y17	2.63	2.63	2.7
y18	2.39	2.39	2.3
y19	2.59	2.59	2.6
y20	2.19	2.16	2.2
y21	2.86	2.85	2.9
y22	2.07	2.08	2.0
y23	1.72	1.72	1.7
y24	1.65	1.65	1.7
e1	2.06	2.00	2.0
e2	2.38	2.36	2.3
e3	3.10*	3.02*	3.0*
e4	1.60	1.58	1.5
e5	1.07*	1.06	1.1
e6	1.85	1.81	1.7
e7	2.15	2.09	1.9
e8	2.05	2.01	2.0
e10	2.02	2.03	2.1
e11	1.60	1.58	1.5
e12	1.76	1.72	1.6
e13	2.14	2.11	2.1
e14	2.19	2.18	2.2
e15	3.12*	3.10*	3.2*
e17	2.31	2.27	2.1
e19	1.93	1.89	1.8
e23	1.91	1.86	1.7
e24	1.50	1.48	1.5

Individual variability measures, and subjects identified as outliers, are shown in Table 5.8. It can be seen that there were only two outliers in the elderly group (e24 for UQR_{MTC} distribution and e17 for LQR_{MTC} distribution). In the young group, there was one subject (y17) identified as an extreme in one measure while another subject (y7) was identified as an outlier for three and extreme for four of the variability measures.

Table 5.8: Individual MTC distribution variability measures.

(denotes outlier*; *** denotes extreme, as defined by SPSS*)**

Subject	SD_{MTC} (cm)	IQR_{MTC} (cm)	CV'_{MTC} (%)	$range_{MTC}$ (cm)	UQR_{MTC} (cm)	LQR_{MTC} (cm)	$98\%rge_{MTC}$ (cm)	$90\%rge_{MTC}$ (cm)
y1	0.21	0.28	10.88	1.52	0.71	0.53	1.01	0.67
y2	0.22	0.27	13.24	1.94	0.96	0.70	1.18	0.68
y5	0.38	0.44	14.69	3.19	1.76	0.99	1.96	1.18
y6	0.22	0.29	13.89	1.39	0.64	0.45	1.02	0.73
y7	0.71**	0.94**	33.39**	5.15*	3.37*	0.84	3.15**	2.26*
y9	0.21	0.27	14.26	1.52	0.78	0.47	1.01	0.67
y12	0.33	0.39	19.19	2.28	1.21	0.68	1.71	1.06
y14	0.17	0.22	11.24	1.28	0.52	0.54	0.79	0.56
y15	0.32	0.38	17.55	2.64	1.68	0.58	1.61	0.99
y16	0.22	0.28	11.91	1.93	0.83	0.81	1.09	0.73
y17	0.37	0.46	17.50	3.96	1.49	2.01**	1.76	1.16
y18	0.20	0.27	11.20	1.25	0.57	0.41	0.91	0.63
y19	0.27	0.31	12.10	2.43	0.92	1.20	1.38	0.86
y20	0.30	0.32	15.00	3.14	2.31	0.51	1.65	0.89
y21	0.23	0.29	10.09	1.70	0.81	0.61	1.14	0.76
y22	0.18	0.23	11.09	1.45	0.78	0.44	0.88	0.60
y23	0.20	0.25	14.70	1.32	0.66	0.41	0.97	0.64
y24	0.18	0.23	13.86	1.28	0.56	0.49	0.89	0.59
e1	0.31	0.33	16.56	2.26	1.50	0.42	1.52	1.01
e2	0.31	0.41	17.25	2.62	1.32	0.89	1.45	1.00
e3	0.55	0.69	22.74	3.41	1.84	0.88	2.66	1.75
e4	0.24	0.31	19.44	1.52	0.80	0.41	1.09	0.77
e5	0.34	0.44	41.40	3.05	2.03	0.58	1.58	1.02
e6	0.29	0.35	19.37	2.20	1.30	0.55	1.43	0.89
e7	0.36	0.43	20.63	3.21	1.90	0.87	1.81	1.12
e8	0.40	0.55	27.21	2.60	1.30	0.75	1.87	1.31
e10	0.28	0.38	18.66	1.72	0.65	0.70	1.31	0.96
e11	0.20	0.25	16.03	1.79	1.19	0.35	0.97	0.63
e12	0.32	0.41	23.93	2.23	1.23	0.58	1.42	1.02
e13	0.32	0.38	18.22	2.17	1.17	0.61	1.51	1.03
e14	0.25	0.33	15.33	2.11	1.30	0.47	1.21	0.79
e15	0.45	0.55	17.86	3.17	1.54	1.08	2.13	1.47
e17	0.47	0.61	26.93	3.54	1.40	1.53*	2.08	1.56
e19	0.49	0.67	35.14	3.43	1.86	0.90	2.23	1.55
e23	0.36	0.47	25.47	2.10	1.02	0.60	1.59	1.18
e24	0.27	0.34	22.64	4.56	3.67*	0.56	1.13	0.78

Individual dispersion measures, and subjects identified as outliers and extremes, are shown in Table 5.9. It can be seen that three young subjects had outliers, two of which (y17 and y21) were outliers for one measure each while the remaining subject (y7) was identified as an outlier for three of the dispersion measures. Two elderly subjects (e3 and e15) were identified as outliers for six measures each while one subject (e5) was identified as an outlier for five measures of dispersion.

Table 5.9: Individual MTC distribution dispersion measures.

(denotes outlier, as defined by SPSS*)**

Subject	min_{MTC} (cm)	max_{MTC} (cm)	$Q1_{MTC}$ (cm)	$Q3_{MTC}$ (cm)	$PC1_{MTC}$ (cm)	$PC5_{MTC}$ (cm)	$PC99_{MTC}$ (cm)	$PC95_{MTC}$ (cm)
y1	1.92	3.43	2.45	2.73	2.13	2.27	3.15	2.94
y2	1.20	3.14	1.91	2.18	1.60	1.74	2.78	2.43
y5	1.81	5.00	2.80	3.24	2.21	2.51	4.17	3.70
y6	1.54	2.93	1.99	2.29	1.69	1.82	2.71	2.54
y7	1.62	6.77*	2.46	3.40	1.90	2.11	5.04*	4.37*
y9	1.28	2.80	1.75	2.02	1.44	1.57	2.44	2.24
y12	1.17	3.45	1.85	2.24	1.32	1.56	3.03	2.63
y14	1.34	2.62	1.88	2.10	1.62	1.73	2.41	2.29
y15	1.43	4.06	2.00	2.38	1.62	1.79	3.24	2.78
y16	1.41	3.34	2.22	2.51	1.85	2.00	2.94	2.74
y17	0.38*	4.34	2.39	2.85	1.85	2.08	3.61	3.24
y18	1.84	3.09	2.26	2.52	1.94	2.08	2.85	2.71
y19	1.24	3.67	2.44	2.75	1.86	2.16	3.24	3.02
y20	1.49	4.63	2.00	2.32	1.63	1.80	3.28	2.69
y21	2.10	3.80	2.70	2.99	2.35*	2.51	3.49	3.26
y22	1.51	2.96	1.95	2.18	1.66	1.77	2.54	2.37
y23	1.17	2.50	1.59	1.84	1.27	1.40	2.24	2.05
y24	1.05	2.33	1.54	1.77	1.24	1.36	2.13	1.95
e1	1.44	3.70	1.86	2.19	1.55	1.66	3.07	2.67
e2	1.28	3.90	2.17	2.58	1.71	1.92	3.16	2.92
e3	1.83	5.24	2.71*	3.40*	2.13*	2.33*	4.79*	4.08*
e4	1.03	2.55	1.44	1.75	1.14	1.26	2.23	2.03
e5	0.24*	3.29	0.83*	1.27*	0.44*	0.60*	2.02	1.62
e6	1.10	3.30	1.65	2.00	1.33	1.46	2.76	2.35
e7	1.04	4.25	1.92	2.35	1.49	1.67	3.30	2.80
e8	1.02	3.62	1.77	2.32	1.25	1.47	3.11	2.77
e10	1.14	2.86	1.84	2.21	1.36	1.53	2.67	2.48
e11	1.11	2.90	1.46	1.71	1.20	1.32	2.17	1.95
e12	0.95	3.18	1.53	1.95	1.17	1.29	2.59	2.31
e13	1.32	3.49	1.93	2.31	1.47	1.67	2.98	2.69
e14	1.54	3.65	2.01	2.35	1.68	1.82	2.90	2.61
e15	1.74	4.91	2.82*	3.37*	2.18*	2.45*	4.31*	3.92*
e17	0.45	3.99	1.98	2.59	1.47	1.60	3.54	3.16
e19	0.67	4.10	1.57	2.24	1.00	1.20	3.23	2.75
e23	1.06	3.16	1.66	2.13	1.24	1.41	2.83	2.58
e24	0.76	5.32	1.32	1.66	0.96	1.11	2.09	1.89

Individual symmetry/distribution measures, and subjects identified as outliers and extremes, are shown in Table 5.10. It can be seen that one young subject (y20) was identified as an outlier for one measure and an extreme for the other. There was one elderly subject (e24) identified as an extreme in both measures of symmetry/distribution.

Table 5.10: Individual MTC symmetry/distribution measures.

Test of normality: Kolmogorov-Smirnov (K-S) statistic. # denotes K-S statistic not significant and distribution deemed normally distributed; **denotes outlier*; ** *denotes extreme, as defined by SPSS*)

Subject	S_{MTC}	K_{MTC}	K-S sig.
y1	0.21	0.39	.172 #
y2	0.70	2.04	<.001
y5	0.86	2.38	<.001
y6	0.41	0.12	<.001
y7	0.96	0.96	<.001
y9	0.37	0.67	.049
y12	0.57	1.32	<.001
y14	0.11	0.28	.039
y15	1.16	3.21	<.001
y16	0.20	1.30	.053
y17	0.22	2.30	.001
y18	0.11	0.01	.200 #
y19	-0.21	1.96	.004
y20	1.55*	6.70**	<.001
y21	0.39	0.82	.001
y22	0.29	1.14	.002
y23	0.27	0.51	.200 #
y24	0.22	0.63	.200 #
e1	1.25	2.53	<.001
e2	0.34	0.64	.003
e3	0.79	0.90	<.001
e4	0.51	0.32	.001
e5	0.95	3.31	.001
e6	1.04	2.09	<.001
e7	1.07	2.84	<.001
e8	0.43	0.19	.001
e10	-0.06	-0.07	.200 #
e11	0.92	2.68	<.001
e12	0.62	0.78	<.001
e13	0.45	0.58	<.001
e14	0.66	1.81	.020
e15	0.39	0.62	<.001
e17	0.42	0.20	<.001
e19	0.48	0.40	.004
e23	0.58	0.10	<.001
e24	2.97**	36.84**	.043

5.4.3 Inferential statistics

Results of inferential statistical tests for the normal undistracted walking data are presented in this section within five sub-sections, namely:

- Central tendency;
- Variability/dispersion;
- Symmetry/distribution;
- Correlations between MTC distribution descriptive statistics; and
- Probability of tripping

As previously outlined, many of the distributions for group analysis were not normally distributed. When outliers exist, the effect is to increase skew of the distribution, thereby falsely elevating the mean. In these circumstances the use of mean for group central tendency is not the most precise measure (refer methods section 4.5 for further detail). Standard deviation (SD), being based on the mean, is also not an accurate measure of group variability for this type of data. Throughout this thesis, therefore, data for group central tendency is represented by the group median (as opposed to mean) and group variability is represented by the group IQR (as opposed to SD). Actual group mean and median values are presented as measures of central tendency and group SD, IQR and CV' as measures for variability for illustrative purposes. Likewise, actual mean, SD and CV' values are included for comparison with the selected parameter of group median and IQR only.

The combined group data for the young and elderly are presented first in this section. This involved combining each subject's MTC distribution to form one MTC distribution each for the young and elderly groups.

5.4.3.1 Combined group MTC data

Histograms of combined young (n = 18,869) and combined elderly MTC data (n = 18,365) are shown in Figure 5.3. There are some prominent distinctions between the young and elderly group. Central tendency measures, $mean_{MTC}$ and $median_{MTC}$, show no significant age differences but do show a trend toward significance with values higher in the young group ($mean_{MTC}$ ~12% greater and $median_{MTC}$ ~13% greater, refer Table 5.11). Variability, as measured by SD_{MTC} and IQR_{MTC}, is significantly greater in the elderly group (SD_{MTC} ~22% greater and IQR_{MTC} 11% greater, refer Table 5.13). The elderly group tends to have greater frequency of MTC points closer to zero with smaller min_{MTC} (~ 37% smaller), $PC1_{MTC}$ (~45% smaller) and $PC5_{MTC}$ (~25% smaller). It can be seen that below approximately 1.2cm only a small amount of MTC data points exist among the young group compared with the elderly group. In fact, only two data points are below 1.2cm (one or 0.006% at 0.4cm and one or 0.006% at 1.1cm), while there are nine points at 1.2cm (.051%). In contrast, the elderly group have more data points at the lower end of the distribution with 4.002% of the distribution (735 strides) below 1.2cm and $PC5_{MTC}$ = 1.21cm. The young group distribution is more peaked (leptokurtic) than the elderly group (K_{MTC} ~93% greater) with MTC points around the central tendency reaching over 4.5% of the distribution compared with the elderly peak of the distribution being under 4.5%. S_{MTC} is also greater in the young group and can be noted by the steeper left hand side of the distribution and longer tail to the right (i.e.

greater max_{MTC} of 6.77cm). Each of these MTC descriptive statistics will be discussed in the following relevant sub-sections.

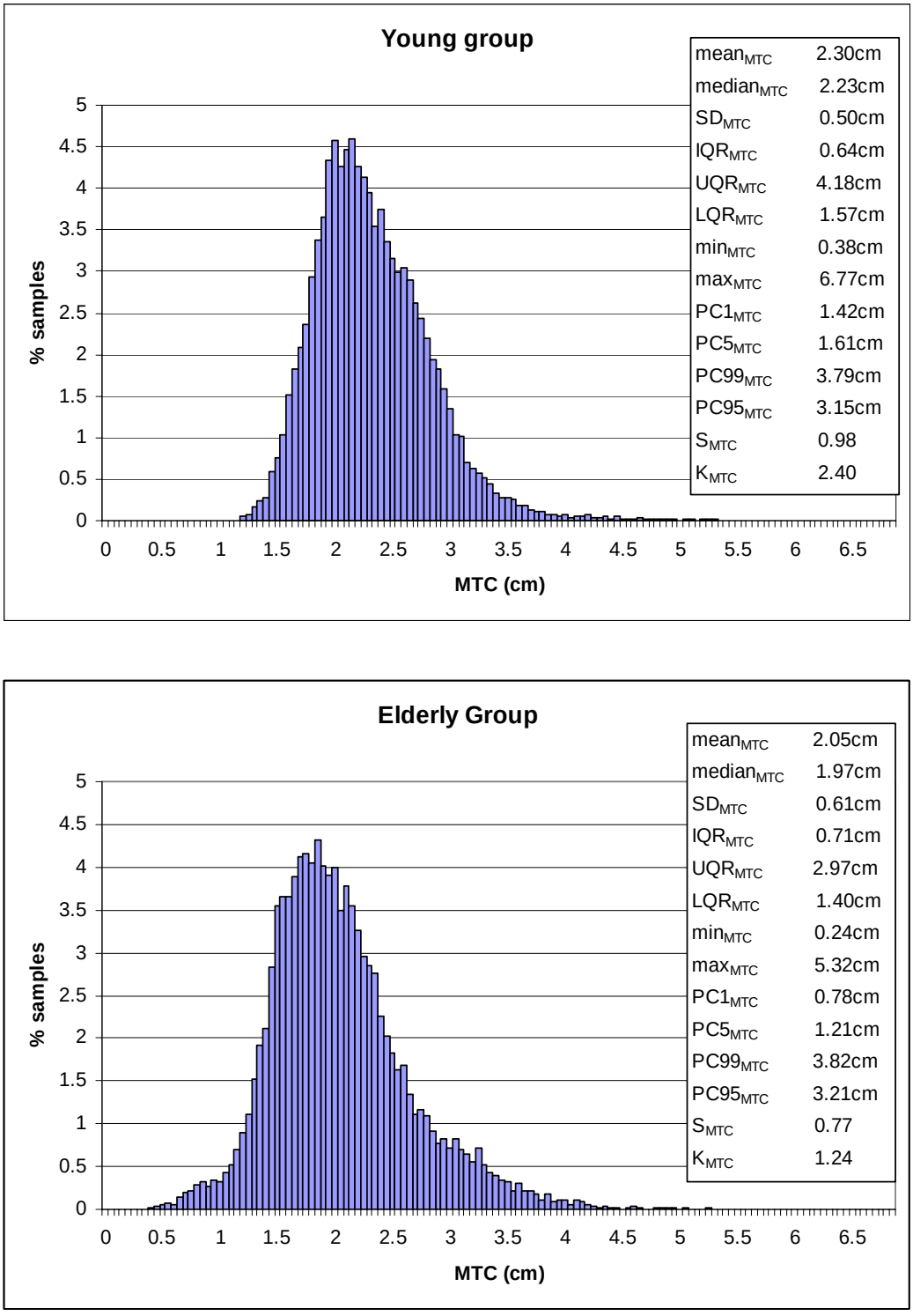


Figure 5.3: Histograms of combined young and combined elderly group MTC distributions.

5.4.3.2 Central Tendency

The use of the three central tendency measures of MTC, namely mean, median and mode, has been discussed in the methods section 4.5.1, where support for the use of median over mean and mode is discussed. As a comparison, mean, median and mode were calculated for each individual and were used in a one-way ANOVA to reveal age differences on the three separate central tendency measures.

Group median values for each MTC distribution central tendency measure is shown in Figure 5.4. Comparison of young and elderly MTC central tendency are presented in Table 5.11, whilst individual central tendency values can be seen in Table 5.7. A trend toward significant age effects exists for all three central tendency measures with young subjects having higher MTC on all three central tendency measures compared with elderly. $Mean_{MTC}$ was higher than $median_{MTC}$ for both groups, caused by the positive skew evident in the MTC distributions.

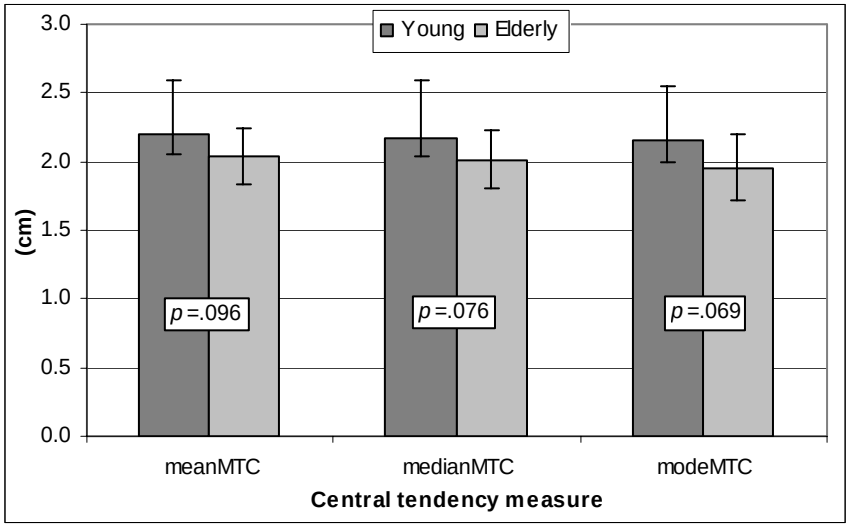


Figure 5.4: Comparison of group MTC central tendency.
Note: group median and IQR (error bars) for $mean_{MTC}$, $median_{MTC}$ and $mode_{MTC}$ are shown.

Table 5.11: Comparison of young and elderly MTC central tendencies via one-way ANOVA.

	Variable	$mean_{MTC}$ (cm)	$median_{MTC}$ (cm)	$mode_{MTC}$ (cm)
Young n = 18	mean	2.30	2.28	2.24
	med	2.20	2.16	2.15
	SD	0.41	0.39	0.38
	IQR	0.54	0.55	0.55
	range	1.38	1.34	1.20
Elderly n = 18	mean	2.04	2.01	1.96
	med	2.04	2.01	1.95
	SD	0.50	0.49	0.52
	IQR	0.40	0.42	0.48
	range	2.05	2.04	2.10
	F (1,34)	2.924	3.360	3.536
	p- value	0.096	0.076	0.069

Note: Data is for group $mean_{MTC}$, $median_{MTC}$ and $mode_{MTC}$ using median as the group central tendency and IQR as the group variability on these measures.

Shapiro-Wilks statistic was not significant suggesting normality assumption was not violated. The Levene statistic was not significant, suggesting homogeneity of variances assumption was not violated (refer Table 5.12).

Table 5.12: Levene's test of homogeneity of variances (between age groups) for central tendency measures of normal, undistracted walking MTC.

Variable	Sig.
$mean_{MTC}$ (cm)	0.904
$median_{MTC}$ (cm)	0.886
$mode_{MTC}$ (cm)	0.551

5.4.3.3 Variability/Dispersion

Variability measures of the MTC distribution, namely SD_{MTC}, IQR_{MTC}, CV'_{MTC}, $range_{MTC}$, UQR_{MTC}, LQR_{MTC}, 98% rge_{MTC} and 90% rge_{MTC} and dispersion measures of the MTC distribution, namely min_{MTC}, max_{MTC}, $Q1_{MTC}$, $Q3_{MTC}$, $PC1_{MTC}$, $PC5_{MTC}$,

$PC99_{MTC}$ and $PC95_{MTC}$ are included in this section. Non-normal distributions have been highlighted in Table 5.5 for the young group and Table 5.6 for the elderly group. As described in the methods section, Mann-Whitney U test was employed for the data sets with non-normal distribution.

5.4.3.3.1 Variability measures

Group comparisons using median and IQR (error bars) of each variability measure are shown in Figure 5.5, Figure 5.6, and Figure 5.7.

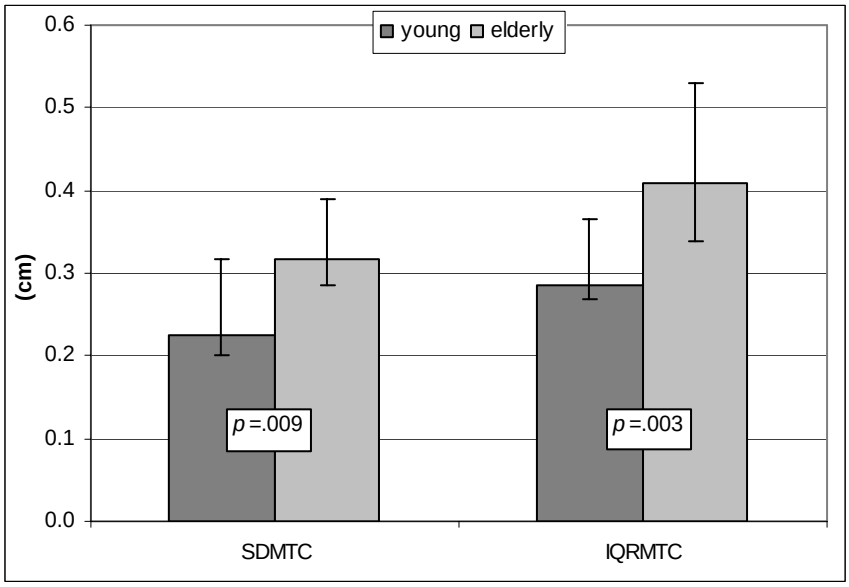


Figure 5.5: Comparison of group SD_{MTC} and IQR_{MTC}.
Note: group median and IQR (error bars) for SD_{MTC}, IQR_{MTC} are shown.

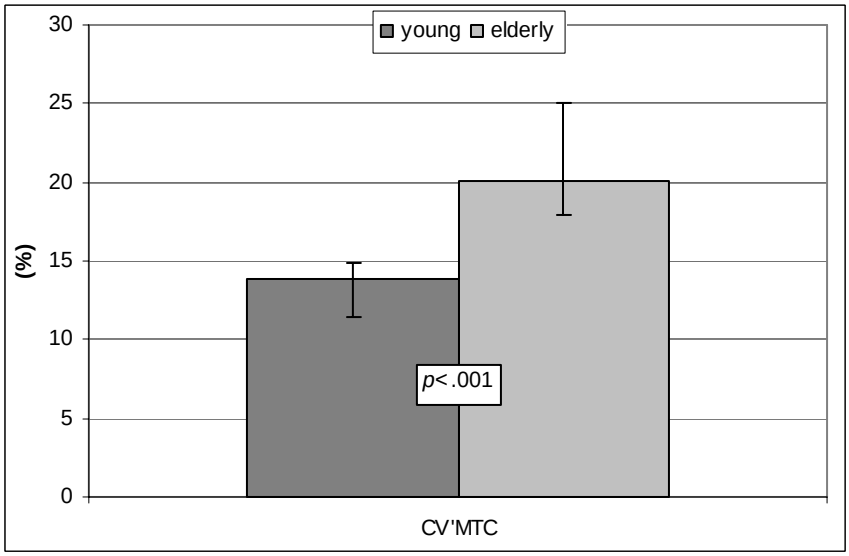


Figure 5.6: Comparison of group CV'.

Note: group median and IQR (error bars) for CV'_{MTC} are shown.

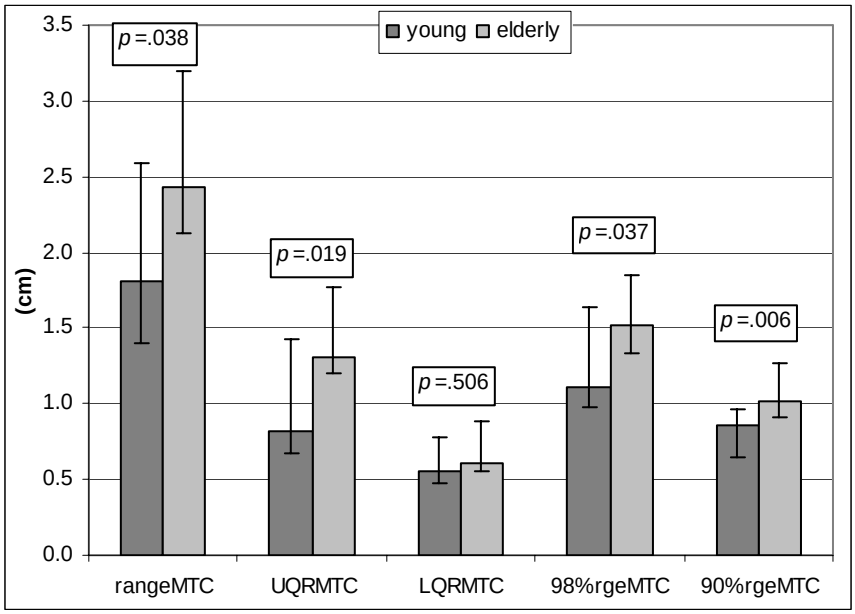


Figure 5.7: Comparison of group $range_{MTC}$, UQR_{MTC}, LQR_{MTC}, 98% rge_{MTC} and 90% rge_{MTC}.

Note: group median and IQR (error bars) for group $range_{MTC}$, UQR_{MTC}, LQR_{MTC}, 98% rge_{MTC} and 90% rge_{MTC} are shown.

$range_{MTC}$ = range of values in the MTC distribution, UQR_{MTC} = upper quartile range, LQR_{MTC} = lower quartile range, 98% rge_{MTC} = MTC distribution range with lower and upper 1% trimmed, 90% rge_{MTC} = MTC distribution range with lower and upper 5% trimmed.

A comparison of young and elderly variability measures are presented in Table 5.13, whilst individual variability measures can be seen in Table 5.8.

Table 5.13: Comparison of MTC intra-individual variability measures between young and elderly groups via Mann-Whitney U test.

	Variable	SD_{MTC} (cm)	IQR_{MTC} (cm)	CV'_{MTC} (%)	$range_{MTC}$ (cm)	UQR_{MTC} (cm)	LQR_{MTC} (cm)	$98\%rge_{MTC}$ (cm)	$90\%rge_{MTC}$ (cm)
Young n = 18	mean	0.27	0.34	14.77	2.19	1.14	0.70	1.34	0.87
	med	0.22	0.28	13.87	1.82	0.82	0.56	1.11	0.73
	SD	0.13	0.16	5.30	1.08	0.74	0.39	0.58	0.40
	IQR	0.12	0.10	3.52	1.18	0.75	0.31	0.66	0.31
	range	0.54	0.72	23.31	3.90	2.85	1.60	2.36	1.71
Elderly n = 18	mean	0.34	0.44	22.49	2.65	1.50	0.71	1.61	1.10
	med	0.32	0.41	20.04	2.43	1.31	0.61	1.51	1.02
	SD	0.09	0.13	6.87	0.79	0.65	0.29	0.44	0.31
	IQR	0.10	0.19	7.14	1.07	0.57	0.33	0.52	0.36
	range	0.35	0.43	26.07	3.04	3.02	1.18	1.69	1.13
	Z	-2.579	-2.990	-2.072	-2.072	-2.342	-.681	-2.089	-2.738
	p- value	.009**	.003**	<.001***	.038*	.019*	.506	.037*	.006**

*** denotes $p < .05$; ** denotes $p < .01$; *** denotes $p < .001$.**

For all measures of variability, the non-parametric Mann-Whitney U test was employed to examine age effects. It can be seen in Table 5.13, Figure 5.5, Figure 5.6 and Figure 5.7 that the elderly group had higher values for each measure of variability. Additionally, age effects on variability measures were statistically significant on all variables except LQR_{MTC}. This data shows the elderly are more variable in MTC on a stride-to-stride basis than the young group. Significant age effects are limited to the upper end of the MTC distribution (UQR_{MTC}), with only minimally higher MTC in the LQR_{MTC} in the elderly compared with young. The 98% rge_{MTC} and 90% rge_{MTC} show that there are distinct differences between the young and elderly with the upper and lower 1% and 5% (the most extreme MTC points) removed.

5.4.3.3.2 Dispersion measures

Group comparisons of each dispersion measure are shown in Figure 5.8. A comparison of young and elderly dispersion measures are presented in Table 5.14, whilst individual dispersion measures can be seen in Table 5.9.

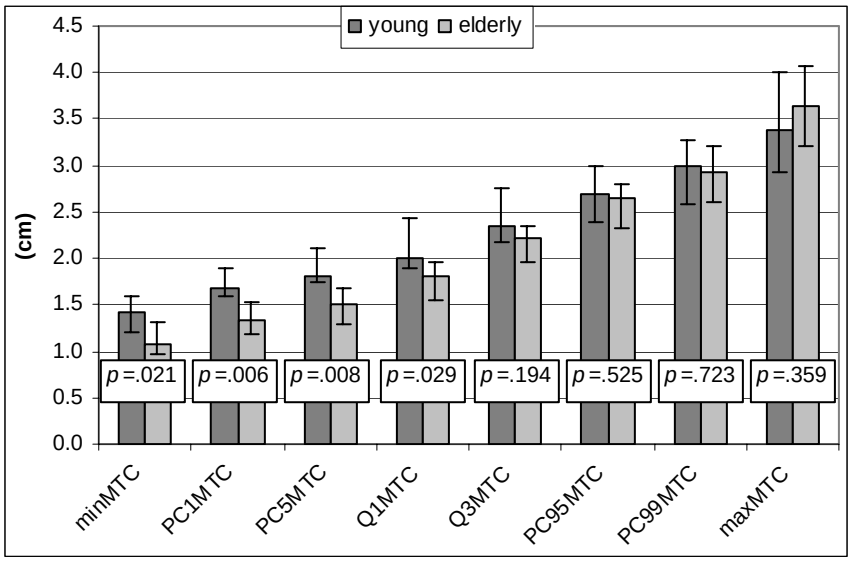


Figure 5.8: Comparison of group MTC dispersion measures.

Note: group median and IQR (error bars) of each variable are shown.

min_{MTC} = minimum MTC in the distribution, $PC1_{MTC}$ = 1st percentile, $PC5_{MTC}$ = 5th percentile, $Q1_{MTC}$ = 25th percentile or 1st quartile, $Q3_{MTC}$ = 3rd quartile or 75th percentile, $PC95_{MTC}$ = 95th percentile, $PC99_{MTC}$ = 99th percentile, max_{MTC} = maximum MTC in the distribution

Table 5.14: Comparison of young and elderly MTC dispersion measures.

	Variable	min_{MTC} (cm)	max_{MTC} (cm) #	$Q1_{MTC}$ (cm) #	$Q3_{MTC}$ (cm)	$PC1_{MTC}$ (cm)	$PC5_{MTC}$ (cm)	$PC99_{MTC}$ (cm)	$PC95_{MTC}$ (cm)
Young n = 18	mean	1.42	3.60	2.12	2.46	1.73	1.90	3.07	2.77
	med	1.42	3.39	2.00	2.35	1.68	1.81	2.98	2.70
	SD	0.39	1.08	0.36	0.46	0.31	0.34	0.71	0.60
	IQR	0.39	1.06	0.54	0.57	0.28	0.37	0.69	0.62
	range	1.72	4.44	1.26	1.63	1.11	1.16	2.92	2.42
Elderly n = 18	mean	1.10	3.74	1.80	2.24	1.37	1.54	2.99	2.64
	med	1.08	3.63	1.80	2.23	1.35	1.50	2.94	2.64
	SD	0.41	0.79	0.47	0.53	0.41	0.43	0.72	0.63
	IQR	0.34	0.87	0.42	0.39	0.36	0.38	0.60	0.47
	range	1.58	2.77	1.99	2.13	1.74	1.84	2.78	2.46
	t (34)	-2.423	(*Z*)-.918	(Z)-2.279	-1.324	-2.954	-2.821	-.358	-.643
	p- value	.021*	.359	.029*	.194	.006**	.008**	.723	.525

 # denotes Mann-Whitney U conducted; Independent t-test conducted for all others.

***t-value* shown for all independent t-test, except max_{MTC} and $Q1_{MTC}$, where *Z-value* is shown for Mann-Whitney U test; * denotes $p<.05$; ** denotes $p<.01$.**

Parametric independent t-test was conducted for all measures except max_{MTC} and $Q1_{MTC}$, for which the non-parametric Mann-Whitney U was employed due to non-normality of the data. Age effects were noted for all dispersion measures on the left (lower) side of the MTC distribution, namely min_{MTC}, $PC1_{MTC}$, $PC5_{MTC}$ and $Q1_{MTC}$. Specifically, the elderly compared with the young were 24% lower for min_{MTC} ($p<.05$), 10% lower for $Q1_{MTC}$ ($p<.05$), 24% lower for $PC1_{MTC}$ ($p<.01$) and 21% lower for $PC5_{MTC}$ ($p<.01$).

5.4.3.4 Symmetry/distribution

Comparison of young and elderly measures of symmetry, namely S_{MTC}, and distribution, namely K_{MTC}, are presented in Figure 5.9 and Table 5.15 whilst individual symmetry measures can be found in Table 5.10. Table 5.10 also shows that only one elderly subject was deemed normally distributed, as determined by Kolmogorov-

Smirnov statistic (e10). Four young subjects were normally distributed (y1, y18, y23 and y24) while one other was approaching significance and, therefore, close to non-normal (y16).

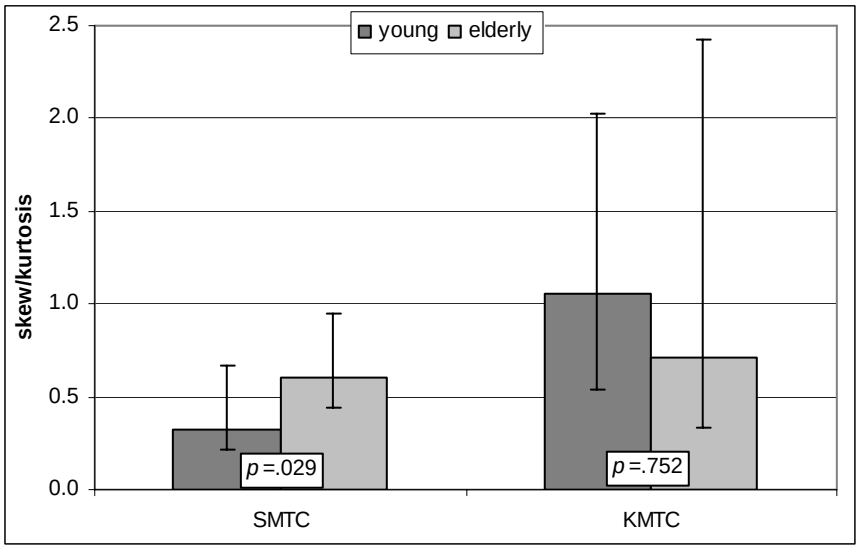


Figure 5.9: Comparison of group MTC symmetry/distribution measures.

Note: Group median and IQR (error bars) are shown.

S_{MTC} = skew of the MTC distribution, K_{MTC} = kurtosis of the MTC distribution.

Table 5.15: Comparison of young and elderly MTC symmetry/distribution measures.

	Variable	S_{MTC} (cm)	K_{MTC} (cm)
Young n = 18	mean	0.47	1.49
	med	0.33	1.05
	SD	0.43	1.57
	IQR	0.46	1.48
	range	1.76	6.69
Elderly n = 18	mean	0.77	3.15
	med	0.60	0.71
	SD	0.64	8.48
	IQR	0.51	2.08
	range	3.03	36.91
	Z	-2.183	-0.316
	p- value	0.029*	0.752

*** denotes $p<.05$.**

Due to non-normality of the data, the non-parametric Mann-Whitney U test was employed to determine whether age effects existed for symmetry/distribution measures. It can be seen that the elderly group had significantly higher S_{MTC} (82%) than the young group (p=.029). K_{MTC} was not significantly different between the groups (p=.752).

The substantially greater range in the elderly group can be attributed to the high extreme value of 36.84 (subject e24), much higher than the highest value in the young group of 6.70 (subject y20). Removing these two extremes for demonstrative purposes reduces group range for the young group from 6.69 to less than half at 3.2. Conversely, the elderly group range is reduced from 36.91 more than ten-fold to 3.38.

5.4.3.5 Correlations between MTC distribution descriptive statistics

Pearson's r was used to determine whether any correlations between descriptive statistics existed. Determining correlations between descriptive statistics highlights the various strategies of implementing MTC adopted by the young and elderly groups. Figure 5.10 shows a comparison of major group MTC descriptive statistics correlations for the young and elderly groups. Only correlations with a Pearson's r significance of at least p<.05 for either young or elderly group are shown.

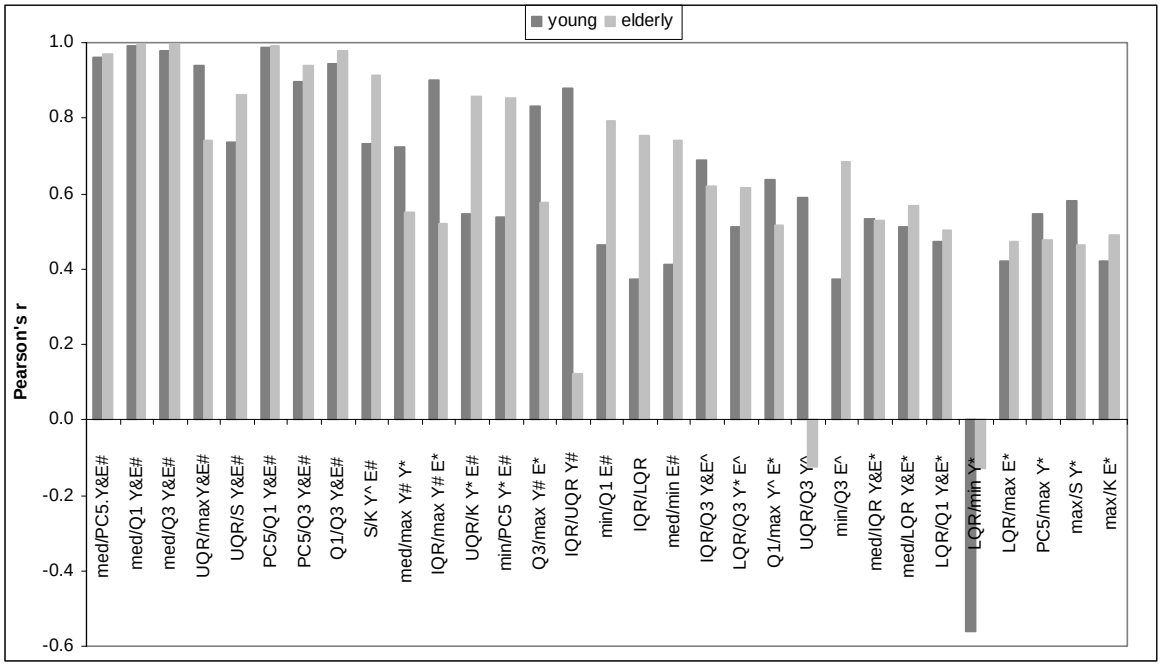


Figure 5.10: Comparison of major group MTC distribution descriptive statistics correlations using Pearson's r.

 # denotes *p*<.001; ^ denotes *p*<.01; * denotes *p*<.05.

Table 5.16 shows a correlation matrix of descriptive statistics for the young group while Table 5.17 shows correlation matrix for the elderly group.

Table 5.16: Young group correlation matrix of descriptive statistics - Pearson's r-value and *p*-value (in brackets) is shown.

	IQR	UQR	LQR	min	PC5	Q1	Q3	PC95	max	S	K
median	0.532 *(.023)**	0.450 *(.061)*	0.512 *(.030)**	0.414 *(.088)*	0.961 *(.000)#*	0.990 *(.000)#*	0.979 *(.000)#*	0.907 *(.000)#*	0.724 *(.001)#*	0.081 *(.751)*	0.098 *(.700)*
IQR		0.879 *(.000)#*	0.372 *(.129)*	0.014 *(.956)*	0.304 *(.220)*	0.413 *(.088)*	0.691 *(.002)^*	0.835 *(.000)#*	0.899 *(.000)#*	0.410 *(.091)*	0.108 *(.669)*
UQR			0.293 *(.237)*	0.028 *(.911)*	0.247 *(.324)*	0.343 *(.163)*	0.591 *(.010)*	0.743 *(.000)#*	0.940 *(.000)#*	0.736 *(.001)#*	0.547 *(.019)**
LQR				-0.562 *(.015)**	0.387 *(.112)*	0.474 *(.047)**	0.512 *(.003)**	0.489 *(.040)**	0.419 *(.084)*	-0.138 *(.584)*	0.213 *(.396)*
min					0.538 *(.021)**	0.462 *(.054)*	0.371 *(.129)*	0.300 *(.226)*	0.176 *(.485)*	0.164 *(.515)*	-0.138 *(.586)*
PC5						0.988 *(.000)#*	0.895 *(.000)#*	0.772 *(.000)#*	0.548 *(.019)**	-0.006 *(.981)*	0.049 *(.846)*
Q1							0.944 *(.000)#*	0.843 *(.000)#*	0.636 *(.005)^*	0.023 *(.927)*	0.079 *(.756)*
Q3								0.973 *(.000)#*	0.830 *(.000)#*	0.167 *(.507)*	0.102 *(.687)*
PC95									0.924 *(.000)#*	0.296 *(.234)*	0.149 *(.555)*
max										0.579 *(.012)**	0.421 *(.082)*
S											0.734 *(.001)#*

*** denotes p<.05; ^ denotes p<.01; # denotes p<.001.**

Table 5.17: Elderly group correlation matrix of descriptive statistics - Pearson's r-value and p-value (in brackets) is shown.

	IQR	UQR	LQR	min	PC5	Q1	Q3	PC95	max	S	K
median	0.530 *(.024)**	-0.150 *(.552)*	0.566 *(.014)**	0.740 *(.000)#*	0.968 *(.000)#*	0.994 *(.000)#*	0.994 *(.000)#*	0.972 *(.000)#*	0.550 *(.018)**	-0.359 *(.143)*	-0.311 *(.209)*
IQR		0.122 *(.630)*	0.753 *(.000)#*	-0.031 *(.904)*	0.313 *(.205)*	0.436 *(.071)*	0.618 *(.006)^*	0.693 *(.001)#*	0.518 *(.028)**	-0.293 *(.237)*	-0.246 *(.325)*
UQR			0.069 *(.786)*	-0.251 *(.316)*	-0.196 *(.435)*	-0.175 *(.486)*	-0.124 *(.625)*	-0.101 *(.690)*	0.740 *(.000)#*	0.863 *(.000)#*	0.857 *(.000)#*
LQR				-0.129 *(.610)*	0.400 *(.100)*	0.502 *(.034)**	0.616 *(.006)^*	0.653 *(.003)^*	0.473 *(.048)**	-0.299 *(.228)*	-0.177 *(.481)*
min					0.853 *(.000)#*	0.793 *(.000)#*	0.686 *(.002)^*	0.624 *(.006)^*	0.259 *(.299)*	-0.178 *(.479)*	-0.217 *(.387)*
PC5						0.990 *(.000)#*	0.939 *(.000)#*	0.897 *(.000)#*	0.475 *(.047)**	-0.301 *(.225)*	-0.284 *(.254)*
Q1							0.977 *(.000)#*	0.946 *(.000)#*	0.518 *(.028)**	-0.339 *(.169)*	-0.299 *(.228)*
Q3								0.991 *(.000)#*	0.576 *(.012)**	-0.365 *(.137)*	-0.320 *(.196)*
PC95									0.588 *(.010)^*	-0.359 *(.144)*	-0.342 *(.165)*
max										0.465 *(.052)*	0.490 *(.039)**
S											0.912 *(.000)#*

*** denotes p<.05; ^ denotes p<.01; # denotes p<.001.**

For both groups there was a high positive correlation ($p<.001$) between $median_{MTC}$ and dispersion measures in both the upper and lower portions of the MTC distribution, namely $PC5_{MTC}$, $Q1_{MTC}$, $Q3_{MTC}$, $PC95_{MTC}$. A high positive correlation existed between $median_{MTC}$ and max_{MTC} for both groups, however, the association was stronger for the young group ($p<.001$) compared with the elderly ($p<.05$). $Median_{MTC}$ was also positively correlated with IQR_{MTC} for both young and elderly ($p<.05$) and LQR_{MTC} ($p<.05$). For the elderly group, $median_{MTC}$ was highly positively correlated with min_{MTC} ($p<.001$) but strength of this association was seen only at $p<0.1$ level in the young group ($p=.088$) and indicates a trend only.

In the elderly group, min_{MTC} was also highly positively correlated ($p<.001$) with IQR_{MTC} and other measures within the lower portion of the distribution ($PC5_{MTC}$, $Q1_{MTC}$) and to a lesser extent ($p<.01$) with measures in the upper portion of the distribution ($Q3_{MTC}$ and $PC95_{MTC}$). These correlations were not observed in the young group where min_{MTC} was positively correlated with $PC5_{MTC}$ ($p<.05$) and negatively correlated with LQR_{MTC} ($p<.05$). Examination of correlations with $PC5_{MTC}$ revealed similarities between the young and elderly groups with high correlations ($p<.001$) between $median_{MTC}$, $Q1_{MTC}$, $Q3_{MTC}$ and $PC95_{MTC}$ and correlations ($p<.05$) with max_{MTC}.

In both the young and elderly groups, S_{MTC} was highly correlated with K_{MTC} and UQR_{MTC} ($p<.001$). S_{MTC} in the young group was also correlated with max_{MTC} ($p<.05$), whereas, the elderly group showed a trend towards significance ($p=.052$).

5.4.3.6 Probability of tripping

The probability of tripping (PT) has been described in the methods section. PT was calculated for each individual at various obstacle heights from zero to 6cm in 0.1cm increments using MTC data obtained during the 20-minute normal undistracted treadmill walking. The probability of the individual tripping on an xcm obstacle is also the probability of MTC of the same height occurring. For example, determining the probability of tripping on an unseen 0.2cm obstacle at the point of MTC also assumes the MTC at that point will also be 0.2cm. Mann-Whitney U tests were employed to determine whether age effects existed for PT at each obstacle height. Figure 5.11 and Figure 5.12 show profiles of PT for young and elderly groups. PT was calculated at each value of MTC(y) for each individual. The profiles in Figure 5.11 and Figure 5.12 show mean (mean PT at each value of MTC(y) for each group), median (median PT at each value of MTC(y) for each group), max (greatest PT at each value of MTC(y) for each group) and min (smallest PT at each value of MTC(y) for each group).

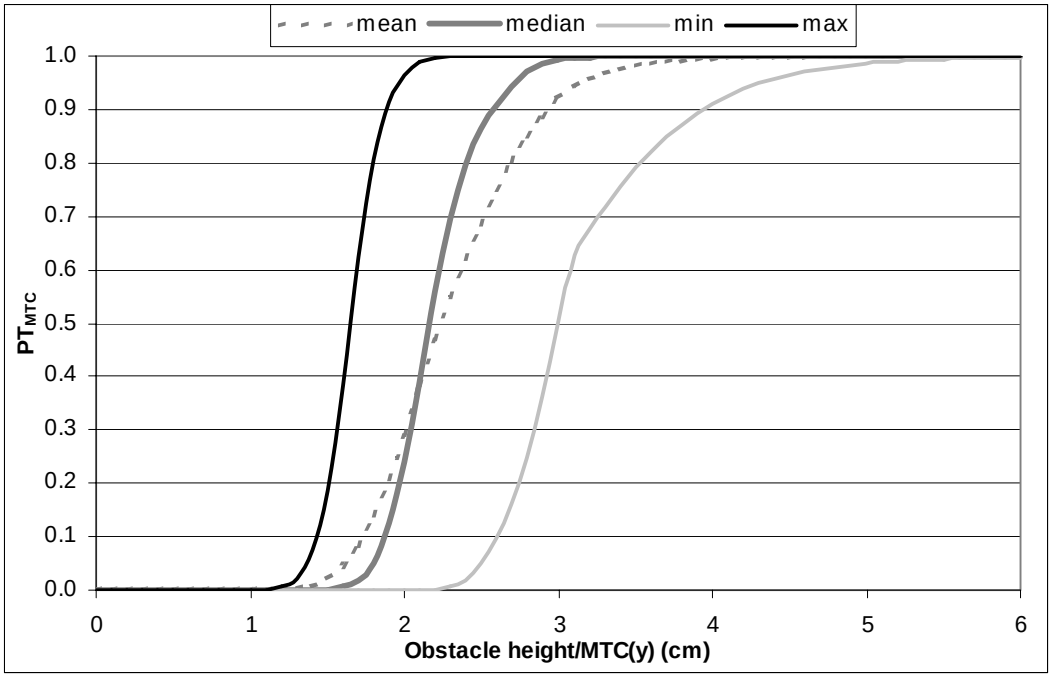


Figure 5.11: PT profile for young subjects.

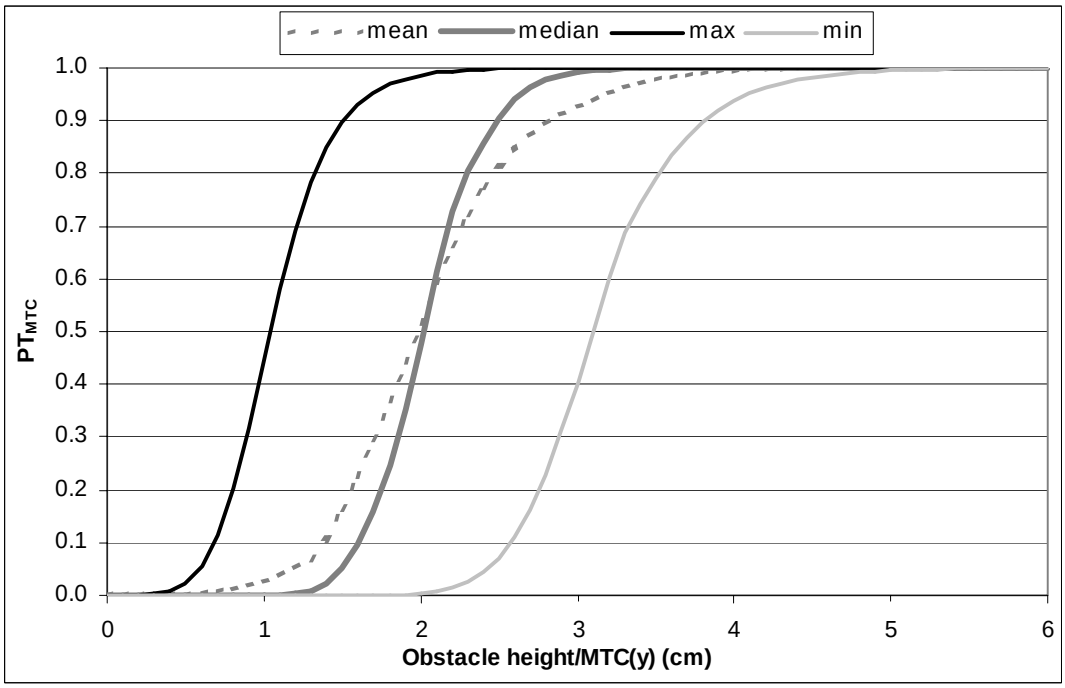


Figure 5.12: PT profile for elderly subjects.

It can be seen in Figure 5.11 and Figure 5.12 that there is a greater spread of PT in the elderly group compared with the young as seen by the broader space between the min and max values. Also notable is the higher PT at smaller obstacle heights for the elderly group.

Table 5.18 shows group median PT at each height. It can be seen that from obstacle heights of 0cm (i.e. the ground) up to 0.8cm there are no significant differences between the two groups. While min PT are the same between the two groups, the max values can be seen to be greater in the elderly. For example, at obstacle height (MTC) of 0.9cm, the maximum for the young group was 0.0004, a very small likelihood of tripping, compared with 0.32, a high likelihood of tripping, for the elderly group. Cross-referencing to Table 5.19, which shows frequency of tripping, i.e. number of strides per trip, it can be seen that the maximum PT value (minimum frequency) is equivalent to the foot striking the obstacle once every 2,688 strides for the young group compared with once every 3.2 strides for the elderly at MTC(y) = 0.9cm.

Significant differences can be seen from obstacle height of 0.9cm through until 2.0cm. The significance increases from 0.9cm (p=.026) and peaks at 1.4cm (p=.004), and then rises again until 2.0cm (p=.037), where the two groups steadily become more alike until the highest obstacle height of 6.0cm. The greatest difference between the young and elderly at the 1.4cm obstacle height is equivalent to the elderly striking the obstacle once every 46.5 strides compared with every 3,757 strides for the young group.

Table 5.18: Probability of tripping (PT) using group median at selected obstacle heights (MTC) that occur at the point of MTC.

MTC	Young			Elderly			Z	*p-value*
	median	min	max	median	min	max		
0.0	0.0000001	0.0000001	0.000004	0.0000001	0.0000001	0.000003	-.594	.553
0.1	0.0000001	0.0000001	0.000007	0.0000001	0.0000001	0.00004	-.528	.598
0.2	0.0000001	0.0000001	0.00001	0.0000001	0.0000001	0.0003	-.528	.598
0.3	0.0000001	0.0000001	0.00002	0.0000001	0.0000001	0.0019	-.421	.674
0.4	0.0000001	0.0000001	0.00003	0.0000001	0.0000001	0.0075	-.828	.407
0.5	0.0000001	0.0000001	0.00005	0.0000001	0.0000001	0.023	-.877	.380
0.6	0.0000001	0.0000001	0.00009	0.0000001	0.0000001	0.055	-1.282	.200
0.7	0.0000001	0.0000001	0.0001	0.0000001	0.0000001	0.11	-1.543	.123
0.8	0.0000001	0.0000001	0.0002	0.0000001	0.0000001	0.20	-1.530	.126
0.9	0.0000001	0.0000001	0.0004	0.000007	0.0000001	0.32	-2.226	.026*
1.0	0.0000001	0.0000001	0.0006	0.00006	0.0000001	0.45	-2.446	.014*
1.1	0.0000003	0.0000001	0.001	0.0006	0.0000001	0.58	-2.574	.010**
1.2	0.000004	0.0000001	0.006	0.003	0.0000001	0.69	-2.731	.006**
1.3	0.00004	0.0000001	0.023	0.008	0.0000001	0.78	-2.794	.005**
1.4	0.0003	0.0000001	0.074	0.022	0.0000001	0.85	-2.915	.004**
1.5	0.0014	0.0000001	0.19	0.051	0.0000005	0.90	-2.832	.005**
1.6	0.006	0.0000001	0.38	0.095	0.000006	0.93	-2.721	.007**
1.7	0.016	0.0000001	0.62	0.16	0.00005	0.95	-2.658	.008**
1.8	0.050	0.0000007	0.81	0.25	0.0002	0.97	-2.594	.009**
1.9	0.13	0.000007	0.91	0.35	0.001	0.98	-2.389	.017*
2.0	0.24	0.00005	0.97	0.48	0.003	0.99	-2.008	.037*
2.5	0.86	0.051	1.00	0.90	0.071	1.00	-.775	.438
3.0	0.99	0.50	1.00	0.99	0.40	1.00	-.032	.975
4.0	1.00	0.91	1.00	1.00	0.94	1.00	-.020	.984
5.0	1.00	0.99	1.00	1.00	1.00	1.00	-.029	.977
6.0	1.00	1.00	1.00	1.00	1.00	1.00	-1.00	.317

*** denotes p<.05, ** denotes p<.01.**

Table 5.19: PT frequencies using group median at selected obstacle heights (MTC) that occur at the point of MTC.

MTC	Young			Elderly		
	median	min	max	median	min	max
0.0	10,000,000	270,086	10,000,000	10,000,000	369,566	10,000,000
0.1	10,000,000	153,227	10,000,000	10,000,000	24,934	10,000,000
0.2	10,000,000	88,583	10,000,000	10,000,000	2,938	10,000,000
0.3	10,000,000	52,006	10,000,000	10,000,000	531	10,000,000
0.4	10,000,000	30,936	10,000,000	10,000,000	134	10,000,000
0.5	10,000,000	18,618	10,000,000	10,000,000	44.2	10,000,000
0.6	10,000,000	11,322	10,000,000	10,000,000	18.1	10,000,000
0.7	10,000,000	6,951	10,000,000	10,000,000	8.8	10,000,000
0.8	10,000,000	4,305	10,000,000	8,387,510	5.0	10,000,000
0.9	10,000,000	2,688	10,000,000	268,502	3.2	10,000,000
1.0	10,000,000	1,691	10,000,000	17,187	2.2	10,000,000
1.1	3,657,330	891	10,000,000	1,552	1.7	10,000,000
1.2	244,887	173	10,000,000	368	1.4	10,000,000
1.3	26,230	43.1	10,000,000	139	1.3	10,000,000
1.4	3,757	13.6	10,000,000	46.5	1.2	10,000,000
1.5	717	5.3	10,000,000	22.2	1.12	1,873,474
1.6	178	2.6	10,000,000	11.4	1.08	165,855
1.7	64.5	1.6	10,000,000	6.5	1.05	22,063
1.8	20.0	1.2	1,477,960	4.1	1.03	4,081
1.9	7.9	1.1	144,655	2.8	1.02	993
2.0	4.2	1.04	18,859	2.1	1.01	304
2.5	1.2	1.0001	19.5	1.11	1.001	14.1
3.0	1.01	1.00000095	2.0	1.008	1.00001415	2.5
4.0	1.00002	1.00000095	1.10	1.00007	1.00000095	1.07
5.0	1.00000095	1.00000095	1.014	1.00000095	1.00000095	1.005
6.0	1.00000095	1.00000095	1.0022	1.00000095	1.00000095	1.0004

5.5 Distracted walking.

Distraction conditions were presented during a ten-minute period of treadmill walking either preceding or following the 20-minute undistracted walking condition. Distraction conditions examined in this section are described in Table 5.20. A more thorough description of these tasks can be found in the methods chapter (section 4.3.4.2).

Table 5.20: Distraction tasks performed concurrently with treadmill walking.

Condition	Description
Norm	Normal, undistracted treadmill walking.
Pouch	Retrieving a requested item (handkerchief) from a waist pouch with rear opening.
Cough	Coughing twice with hand brought to mouth.
Video	Watching a wildlife video on a screen mounted directly in front.
Head turn	Counting the number of objects on a board placed at the left and the right.
3s	Counting backwards by 3s.
RTP	RTP (Reaction Time Probe). Reacting to a visual probe (red "R") which appears on a screen mounted directly in front by pressing hand-held button.
RTP&delay	RTP task, as described above, plus the randomised delay period (0 - 500ms). RTP&delay was used to examine MTC descriptive statistics in order to increase the number of strides over which the distraction occurred.

The data for this section were examined in several ways:

1) the $median_{MTC}$ for each distraction task ($median_{MTC(distr)}$) was compared with the $median_{MTC}$ for normal undistracted walking ($median_{MTC(norm)}$);

2) the deviation from the $median_{MTC(norm)}$ for each distraction task was examined as a) the percentage change from normal, undistracted walking and b) a modified Z score (termed $Z'_{(distr)}$) and calculated for each individual as:

$$(median_{MTC(norm)} - median_{MTC(distr)}) / IQR_{MTC(norm)}$$ **Equation 5.5.1**

3) Differences in task performance including duration (*head turn* task), accuracy (*head turn* accuracy in correctly identifying shapes, single- (ST) and dual-task (DT) accuracy for *3s* task (number of correct subtractions performed) and reaction time (RT) for *RTP* and *RTP&delay*), variability (IQR) and low MTC measures ($PC5_{MTC}$) for prolonged distraction tasks (*3s* and *video*) compared with normal undistracted walking.

Normal undistracted walking MTC was collected during a 20-minute period of continuous walking whilst distraction task duration ranged from around one second (*RTP&delay* task) to 60 seconds (*3s* and *video* task). Whilst it is preferable to compare data sets of similar sizes, the realistic nature of the distraction tasks employed in this study made this difficult. One of the major aims was to collect a large data set for normal undistracted walking. The smaller data sets used in the distraction tasks are, however, similar size to most published research (i.e. up to 10 strides for example). Distraction tasks consisted of varying stride numbers, considerably less than during normal undistracted walking (refer Table 5.21 for group and Table 5.22 for individual stride numbers).

Table 5.21: Comparison of stride numbers during each walking condition.

	Variable	norm (n)	pouch (n)	cough (n)	video (n)	head turn (n)	3s (n)	RTP&delay (n)
Young n = 18	mean	1048	9.2	2.9	53.2	10.0	53.3	3.9
	med	1038	9.0	3.0	53.5	9.5	53.5	4.0
	SD	78.4	3.3	1.3	3.2	3.2	2.8	1.0
	IQR	49.5	2.0	1.0	5.0	1.8	4.0	2.0
	range	347	13.0	5.0	10.0	12.0	9.0	3.0
Elderly n = 18	mean	1020	10.7	3.2	51.7	15.3	52.1	3.6
	med	1011	9.5	3.0	51.0	13.5	52.0	3.5
	SD	89.5	5.1	1.1	4.7	7.2	3.6	0.8
	IQR	132	3.5	2.0	5.0	5.8	4.3	1.0
	range	320	23.0	3.0	18.0	30.0	14.0	3.0

Table 5.22: Individual stride numbers for each walking condition.

Subject	normal (n)	pouch (n)	cough (n)	video (n)	head turn (n)	3s (n)	RTP&delay (n)
e1	997	8	2	49	7	51	3
e2	1032	14	4	54	17	54	4
e3	981	9	2	52	9	49	3
e4	1025	7	2	50	11	52	4
e5	916	10	2	49	13	47	3
e6	1144	7	4	60	14	57	3
e7	983	11	3	49	14	49	2
e8	1107	12	5	56	19	57	3
e10	883	6	3	46	12	53	4
e11	1065	9	4	53	13	52	3
e12	954	7	4	50	28	51	4
e13	919	10	2	44	9	46	3
e14	911	9	5	47	17	48	4
e15	1121	12	3	53	37	52	3
e17	1034	11	3	54	12	52	4
e19	1203	13	2	62	15	60	5
e23	988	9	3	48	11	52	4
e24	1102	29	5	55	17	55	5
y1	1121	9	1	57	9	55	5
y2	1253	14	6	57	17	58	5
y5	997	10	3	51	10	55	5
y6	1043	17	3	56	9	53	3
y7	1063	9	3	56	5	57	5
y9	1058	9	2	54	8	54	4
y12	906	7	2	51	10	52	3
y14	1147	14	6	57	17	58	5
y15	1031	4	3	48	9	51	4
y16	1032	5	2	53	8	54	4
y17	923	8	3	47	11	49	5
y18	1023	10	2	52	9	51	3
y19	1024	8	2	52	10	51	5
y20	1076	9	3	56	10	55	3
y21	1057	9	4	50	14	50	2
y22	992	8	2	50	8	49	3
y23	1027	5	3	54	6	53	3
y24	1096	11	3	56	10	55	3

The MTC data for each distraction task were inserted into the normal undistracted walking data sets. Each set of $MTC_{(distr)}$ data was inserted into the middle of the $MTC_{(norm)}$ data set separately. Descriptive statistics were examined for $MTC_{(distr)}$ alone and $MTC_{(norm)}$ with $MTC_{(distr)}$ inserted. Figure 5.13 shows an example of the stability $median_{MTC}$, with each $MTC_{(distr)}$ data set inserted into the middle of the entire $MTC_{(norm)}$ data set. Note that large fluctuations can be seen at the beginning as each new MTC data point is added. The time series fluctuates at the beginning with the addition of each new MTC data point until relative stability is achieved. In this example, there was an unusual increase in descriptive statistics due to a block of strides which included three of the highest five MTC points. These types of influences on descriptive statistics are explored in the discussion chapter. It can be seen that it took until approximately stride 225 for median to stabilise.

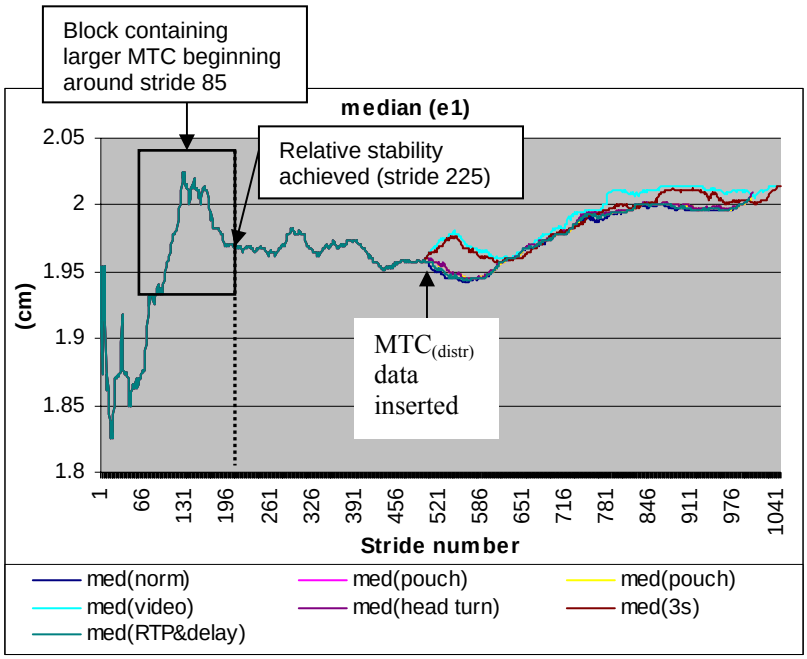


Figure 5.13: Stability of $median_{MTC}$ for one elderly subject (e1) for entire $MTC_{(norm)}$ data set with $MTC_{(distr)}$ for each distraction inserted in the middle.

Figure 5.14 through to Table 5.16 show time series for $median_{MTC}$, IQR_{MTC}, S_{MTC} and K_{MTC} for one elderly subject (e1) for each $MTC_{(distr)}$ data set inserted in the middle of $MTC_{(norm)}$ data set. For this example, the graphs are shown from stride 225 in order to focus on the effect of each distraction on MTC descriptive statistics with each set of $MTC_{(distr)}$ data inserted into the middle of the $MTC_{(norm)}$ data. The MTC data for subject e1 is shown here to demonstrate the effect of distractions on stability of descriptive statistics. Subject responses to distractions varied and choosing a typical subject was not a straightforward process. Elderly subject e1 was chosen since her MTC descriptive statistics for normal undistracted walking were close to the group median.

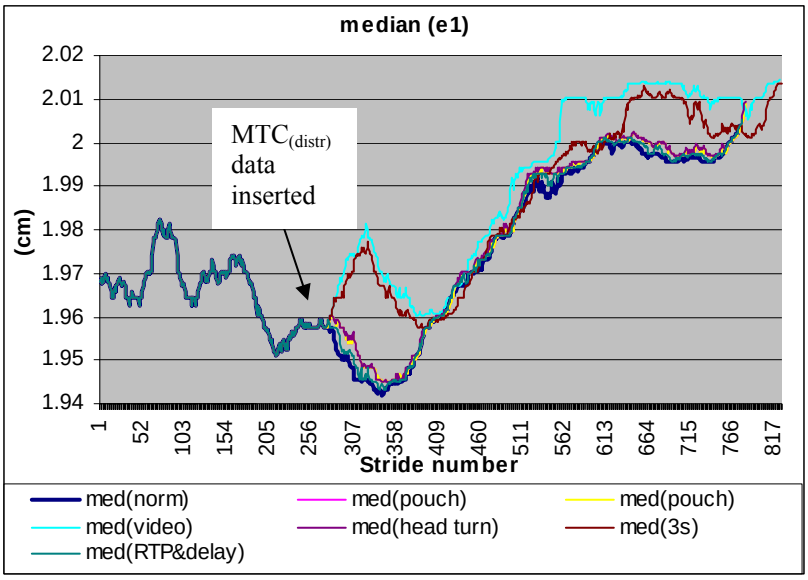


Figure 5.14: Time series of $median_{MTC}$ values during normal and each distraction condition for one typical elderly subject (e1). Data shown from stride 225. Stride numbers shown on x axis should add 225 in order to obtain correct stride number.

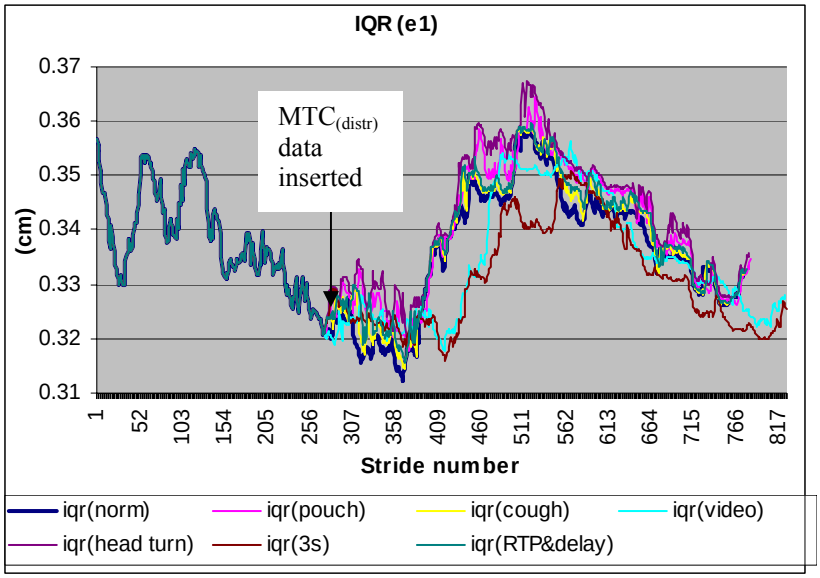


Figure 5.15: Time series of IQR_{MTC} values during normal and each distraction condition for one typical elderly subject (e1). Data shown from stride 225. Stride numbers shown on x axis should add 225 in order to obtain correct stride number.

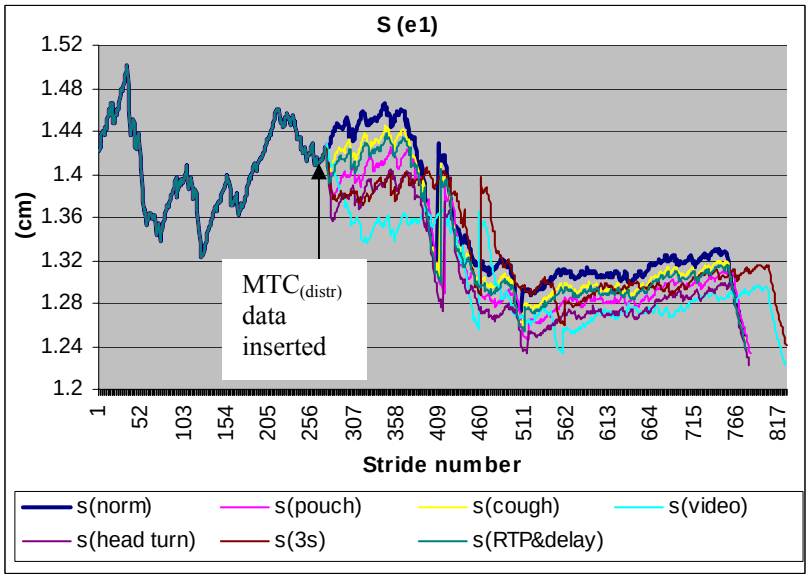


Figure 5.16: Time series for S_{MTC} during normal and each distraction condition for one typical elderly subject (e1). Data shown from stride 225. Stride numbers shown on x axis should add 225 in order to obtain correct stride number.

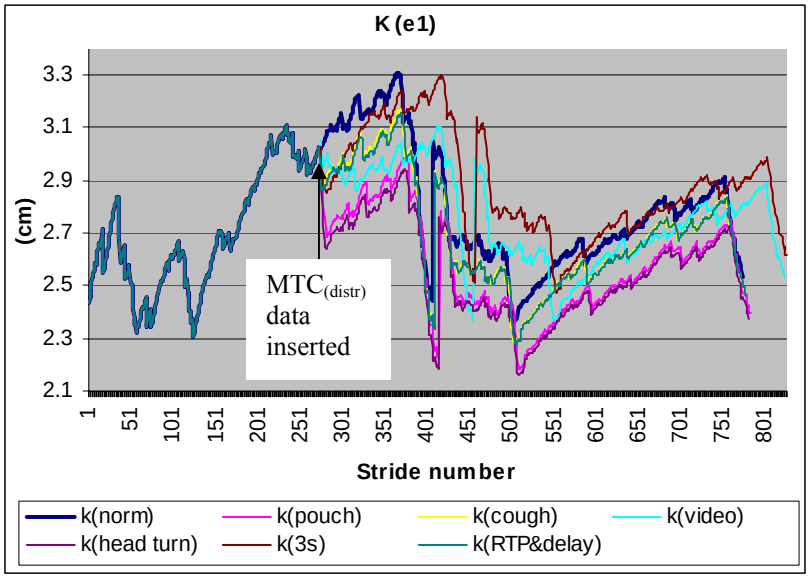


Figure 5.17: Time series for K_{MTC} during normal and each distraction condition for one typical elderly subject (e1). Data shown from stride 225. Stride numbers shown on x axis should add 225 in order to obtain correct stride number.

It can be seen in Figure 5.14 to Figure 5.17 that each distraction caused disruptions of varying degrees to the MTC descriptive statistics. For example, in the time series for $median_{MTC}$ (Figure 5.14) it can be seen that each distraction caused a deviation from the $median_{(norm)}$ time series. This deviation, however, was most marked in the two prolonged distractions, namely video and 3s tasks. In these two tasks, the $median_{MTC}$ increased whereas a decrease was seen in all other distractions. Although the increase is visible in the time series, it differs only minimally from $median_{(norm)}$. For example, at the peak of $median_{MTC}$ for the video task (stride 323), $median_{MTC}$ was 1.98cm compared with $median_{MTC}$ for normal walking of 1.94cm at the same stride. A difference of only 0.04cm when $MTC_{(norm)}$ and $MTC_{(distr)}$ are examined together.

Table 5.23 shows descriptive statistics for one subject (e1) during normal undistracted walking and with distraction task data inserted into normal undistracted walking data.

It can be seen in Table 5.23 and Figure 5.14 to Figure 5.17 that descriptive statistics either remained unchanged or changed only minimally with the insertion of distraction task MTC data into normal undistracted walking data. Data for each distraction task was therefore examined separately from $MTC_{(norm)}$.

Table 5.23: Comparison of descriptive statistics for $MTC_{(norm)}$ and each $MTC_{(distr)}$ data set combined with $MTC_{(norm)}$ for typical elderly subject (e1).

Variable	norm	pouch	cough	video	head turn	3s	RTP&delay
$mean_{MTC}$ (cm)	2.06	2.07	2.06	2.07	2.07	2.06	2.06
$median_{MTC}$ (cm)	2.00	2.01	2.00	2.01	2.01	2.01	2.01
SD_{MTC} (cm)	0.31	0.31	0.31	0.31	0.31	0.31	0.31
S_{MTC} (cm)	1.25	1.23	1.24	1.22	1.22	1.24	1.24
K_{MTC}	2.53	2.39	2.47	2.53	2.37	2.61	2.47
min_{MTC} (cm)	1.44	1.44	1.44	1.44	1.44	1.44	1.44
max_{MTC} (cm)	3.70	3.70	3.70	3.70	3.70	3.70	3.70
$range_{MTC}$ (cm)	2.26	2.26	2.26	2.26	2.26	2.26	2.26
$Q1_{MTC}$ (cm)	1.86	1.86	1.86	1.87	1.86	1.87	1.86
$Q3_{MTC}$ (cm)	2.19	2.20	2.19	2.20	2.20	2.19	2.19
IQR_{MTC} (cm)	0.33	0.33	0.33	0.33	0.34	0.33	0.33
$PC1_{MTC}$ (cm)	1.55	1.55	1.55	1.55	1.55	1.55	1.55
$PC5_{MTC}$ (cm)	1.66	1.66	1.66	1.67	1.66	1.66	1.66
CV'_{MTC} (%)	16.56	16.66	16.57	16.28	16.70	16.15	16.59

5.5.1 Effect of distractions on MTC central tendency.

The effect of each distraction is examined in two ways:

- Difference in $median_{MTC(norm)}$ and $median_{MTC(distr)}$ for each distracted condition, and
- MTC deviation of each distraction $median_{MTC(distr)}$ relative to the $median_{MTC(norm)}$ ($Z'_{(distr)}$). Refer section 5.5 for further detail.

The $median_{MTC}$ and $Z'_{(distr)}$ was calculated for each subject and inferential statistics performed on the group data to determine age effects. Exploratory data analysis is presented first in order to explore the nature of the distribution and identify any outliers or non-normal distributions. Exploratory data analysis sections are followed by inferential statistics.

5.5.1.1 Exploratory Data Analysis

Exploratory data analysis was performed using SPSS statistical software. Selected descriptive statistics for $median_{MTC}$ for each walking condition can be found in Table 5.24 and Table 5.25.

Table 5.24: Descriptive statistics of median$_{MTC}$ for the young group (n = 18) for each normal and distracted walking condition.

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Young	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Norm	2.28	2.16	0.39	0.55	1.65	2.99	0.261	-0.860	.567
Pouch	2.47	2.32	0.45	0.68	1.81	3.51	0.766	-0.175	.131
Cough	2.60	2.47	0.50	0.43	2.12	3.75	1.328	0.781	.003*
Video	2.29	2.26	0.36	0.54	1.79	2.91	0.334	-0.974	.325
Head turn	2.67	2.61	0.61	0.73	1.93	4.39	1.312	2.464	.068
3s	2.30	2.21	0.39	0.59	1.55	2.87	0.029	-0.827	.223
RTP&delay	2.48	2.41	0.46	0.64	1.92	3.72	1.119	1.621	.117

Table 5.25: Descriptive statistics of median$_{MTC}$ for the elderly group (n = 18) for each normal and distracted walking condition.

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Norm	2.01	2.01	0.49	0.42	1.06	3.10	0.662	1.216	.238
Pouch	2.19	2.25	0.39	0.66	1.48	2.81	-0.271	-1.126	.410
Cough	2.09	2.06	0.40	0.42	1.28	2.87	0.078	0.202	.914
Video	1.93	1.89	0.33	0.57	1.43	2.47	0.223	-1.279	.227
Head turn	2.36	2.36	0.42	0.51	1.55	3.17	0.234	-0.130	.928
3s	2.02	2.01	0.34	0.54	1.55	2.56	0.220	-1.091	.247
RTP&delay	2.11	2.13	0.38	0.33	0.89	2.59	-1.889	5.402	.004*

It can be seen that only one data set for the young group (*cough* task) and one data set for the elderly group (*RTP&delay* task) were non-normally distributed as measured by significant (p<.05) S-W statistic. Group skew and kurtosis of median$_{MTC}$ for each task (walking condition) for young and elderly groups can be found in Table 5.24 and Table 5.25. Skew values are all positively skewed for the young group ranging from 0.029 (*3s* task) to 1.328 (*cough* task). Two distributions, however, were found to have negative skew in the elderly group, namely *pouch* task (-0.271) and *RTP&delay* task (-

1.889). Skew values range from -1.889 (RTP&delay) to 0.662 (norm). Kurtosis values range from –0.974 (*video* task) to 2.464 (*head turn* task).

Individual $median_{MTC}$ for each condition can be found in Table 5.26. Outliers and extremes, as identified in SPSS, have been described in the methods chapter. For the young group, three outliers were identified for *cough* task (y1 – 3.75cm, y19 – 3.56cm and y7 – 3.38cm) and one outlier for *head turn* task (y7 – 4.39cm). For the elderly subjects there were two high outliers in the *norm* task (e3 – 3.02cm and elderly subject e15 – 3.10cm) and one extreme low value in the *RTP&delay* task (e5 – 0.89cm).

Table 5.26: Individual median$_{MTC}$ for all walking conditions.

(* denotes outlier; ** denotes extreme, as defined by SPSS.)

subject	norm (cm)	pouch (cm)	cough (cm)	video (cm)	head turn (cm)	3s (cm)	RTP&delay (cm)
y1	2.59	3.02	3.75*	2.52	3.06	2.76	2.85
y2	2.03	2.36	2.54	2.19	2.58	2.21	2.46
y5	2.99	2.98	2.67	2.82	2.51	2.74	3.01
y6	2.12	2.13	2.13	2.17	2.22	1.89	2.40
y7	2.82	3.51	3.38*	2.60	4.39*	2.87	3.72
y9	1.89	2.07	2.23	1.82	2.35	1.86	2.03
y12	2.05	2.21	2.39	1.95	2.79	2.12	2.12
y14	1.98	2.13	2.23	1.94	2.08	1.89	2.19
y15	2.17	2.36	2.64	2.35	2.68	2.19	2.67
y16	2.36	2.60	2.57	2.43	2.83	2.55	2.51
y17	2.63	2.85	2.52	2.33	3.38	2.38	2.35
y18	2.39	2.28	2.41	2.48	2.63	2.20	2.42
y19	2.59	3.06	3.56*	2.91	3.28	2.84	2.95
y20	2.16	1.81	2.21	2.02	2.10	2.17	2.06
y21	2.85	2.70	2.95	2.88	3.01	2.85	2.81
y22	2.08	2.25	2.12	2.15	2.27	2.09	2.26
y23	1.72	2.09	2.25	1.79	1.93	1.54	1.92
y24	1.65	2.07	2.27	1.88	2.02	2.25	1.94
e1	2.00	2.62	2.67	2.12	2.57	2.11	2.55
e2	2.36	2.44	2.32	2.25	2.36	1.90	2.01
e3	3.02*	2.60	2.87	2.47	3.03	1.99	2.59
e4	1.58	1.88	1.70	1.53	1.55	1.55	2.06
e5	1.06	1.48	1.28	1.43	2.00	1.72	0.89**
e6	1.81	2.24	2.19	1.64	1.86	1.61	2.11
e7	2.09	1.82	1.73	1.69	2.41	2.56	2.44
e8	2.01	1.64	2.06	1.86	2.04	1.85	2.15
e10	2.03	1.76	1.81	1.98	2.24	2.03	2.22
e11	1.58	2.19	1.99	1.65	2.38	1.58	1.97
e12	1.72	2.81	2.01	2.04	2.01	2.56	2.09
e13	2.11	2.60	2.13	1.88	2.17	2.05	2.16
e14	2.18	2.46	2.65	2.36	2.93	2.17	2.29
e15	3.10*	2.37	2.23	2.36	2.54	2.35	2.44
e17	2.27	2.50	2.29	2.36	2.37	2.49	2.37
e19	1.89	2.01	2.05	1.60	3.17	1.89	1.96
e23	1.86	2.25	2.07	1.90	2.72	2.34	2.07
e24	1.48	1.76	1.58	1.63	2.14	1.62	1.63

$Z'_{(distr)}$ descriptive statistics, calculated as part of exploratory data analysis in SPSS, can be found in Table 5.27 and Table 5.28.

Table 5.27: Descriptive statistics for MTC Z'$_{(distr)}$ score of each distraction for young group (n = 18) for each distraction task.

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Young	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Pouch	0.59	0.66	0.78	0.99	-1.09	1.83	-0.424	-0.135	.699
Cough	1.09	0.81	1.27	1.56	-0.73	4.12	0.944	0.512	.212
Video	0.10	0.12	0.47	0.58	-0.64	1.01	0.476	-0.428	.381
Head turn	1.11	1.47	0.87	1.05	-1.11	2.20	-1.096	1.045	.063
3s	0.10	0.03	0.80	1.00	-0.80	2.61	1.806	4.862	.005*
RTP&delay	0.61	0.80	0.61	0.82	-0.60	1.58	-0.457	-0.641	.551

Table 5.28: Descriptive statistics for MTC Z' $_{(distr)}$ score of each distraction) for elderly group (n = 18) for each distraction task.

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Pouch	0.59	0.83	1.10	1.56	-1.31	2.65	0.139	-0.504	.580
Cough	0.30	0.27	0.87	0.72	-1.58	2.01	-0.008	0.489	.910
Video	-0.11	-0.14	0.60	0.82	-1.34	0.83	-0.249	-0.469	.953
Head turn	0.91	0.64	1.11	1.83	-1.00	3.18	0.373	-0.740	.156
3s	0.09	0.00	0.93	0.66	-1.49	2.04	0.234	0.114	.633
RTP&delay	0.36	0.38	0.80	0.72	-1.19	1.66	-0.153	-0.252	.588

It can be seen in Table 5.27 and Table 5.28 that only *3s* distraction in the young group is non-normally distributed. Individual Z'$_{(distr)}$ score of each distraction can be found in Table 5.29. There were no extreme values but some outliers were evident. Whilst there was only one outlier for the young group (y24 with a Z'$_{(distr)}$ score of 2.61 for the *3s* task), there were several in the elderly group. There were two outliers in the elderly group for *cough* task (e1 = 2.01 and e15 = -1.58), two in the *3s* task (e5 = 1.50 and e12 = 2.04) and one for the *RTP&delay* task (e15 = -1.19). It is possible that the small number of strides included in *RTP&delay* and *cough* tasks might account for the larger spread of values within the group.

Table 5.29: Individual $Z'_{(distr)}$ score for each distraction.

*** denotes outlier, as defined by SPSS.**

subject	pouch	cough	video	head turn	3s	RTP&delay
y1	1.52	4.12	-0.27	1.66	0.59	0.92
y2	1.19	1.86	0.58	2.03	0.66	1.58
y5	-0.03	-0.73	-0.39	-1.11	-0.58	0.03
y6	0.02	0.04	0.15	0.34	-0.80	0.94
y7	0.73	0.60	-0.23	1.68	0.05	0.96
y9	0.66	1.27	-0.24	1.72	-0.12	0.51
y12	0.43	0.89	-0.24	1.90	0.19	0.19
y14	0.67	1.12	-0.19	0.42	-0.42	0.91
y15	0.52	1.24	0.49	1.34	0.06	1.32
y16	0.86	0.73	0.23	1.66	0.68	0.54
y17	0.48	-0.24	-0.64	1.64	-0.53	-0.60
y18	-0.41	0.10	0.36	0.92	-0.69	0.12
y19	1.50	3.09	1.01	2.20	0.79	1.13
y20	-1.09	0.15	-0.43	-0.20	0.01	-0.33
y21	-0.52	0.34	0.09	0.55	-0.01	-0.14
y22	0.72	0.18	0.31	0.84	0.07	0.81
y23	1.48	2.12	0.29	0.85	-0.68	0.80
y24	1.83	2.68	0.99	1.59	2.61*	1.25
e1	1.84	2.01*	0.34	1.72	0.31	1.66
e2	0.17	-0.12	-0.27	-0.01	-1.13	-0.87
e3	-0.61	-0.22	-0.80	0.01	-1.49	-0.63
e4	0.98	0.38	-0.15	-0.12	-0.09	1.55
e5	0.94	0.49	0.83	2.13	1.50*	-0.38
e6	1.21	1.08	-0.50	0.13	-0.59	0.83
e7	-0.63	-0.84	-0.92	0.73	1.09	0.80
e8	-0.68	0.08	-0.27	0.05	-0.29	0.26
e10	-0.71	-0.58	-0.13	0.57	0.02	0.50
e11	2.43	1.63	0.31	3.18	0.01	1.58
e12	2.65	0.69	0.78	0.71	2.04*	0.89
e13	1.28	0.05	-0.60	0.16	-0.16	0.13
e14	0.82	1.39	0.52	2.23	-0.04	0.32
e15	-1.31	-1.58*	-1.34	-1.00	-1.35	-1.19*
e17	0.39	0.04	0.16	0.16	0.36	0.16
e19	0.17	0.23	-0.44	1.91	0.00	0.10
e23	0.83	0.44	0.08	1.83	1.01	0.44
e24	0.84	0.31	0.43	1.97	0.42	0.44

5.5.1.2 Inferential statistics

5.5.1.2.1 Median$_{MTC}$

Group median median$_{MTC}$ and group variability in median$_{MTC}$ as measured by IQR are shown for each walking condition in Figure 5.18. A two-way ANOVA was conducted to examine main effect of age and task (walking condition) and interactions between these variables. Normality assumption was violated for two variables only and therefore was of little concern (1993). Homogeneity of variance assumption is the primary concern for two-way ANOVA (Coakes and Steed, 1999) and this assumption, using Levene's test of equality of error variances (Design: Intercept+AGE+TASK*TASK) was not violated with a significance value of .756.

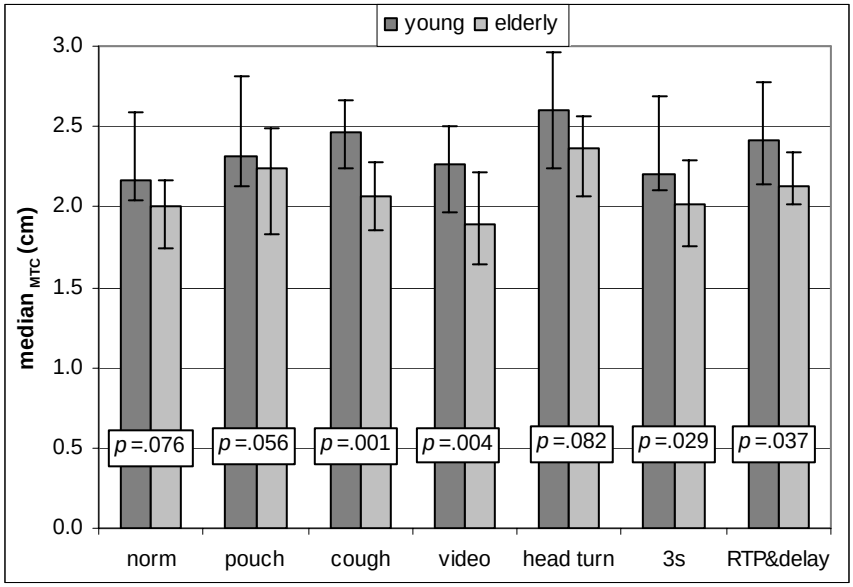


Figure 5.18: Comparison of group median$_{MTC}$ for each walking condition using median and IQR (error bars).

Because the data were not normally distributed for *cough* and *RTP&delay* task, the non-parametric Mann-Whitney U test was used to identify age effects for these two tasks. Independent t-test was used for all other tasks to identify age effects. Comparison of young and elderly $median_{MTC}$ during undistracted and distracted walking is presented in Table 5.30, whilst individual $median_{MTC}$ have been presented in Table 5.26.

Table 5.30: Comparison of $median_{MTC}$ of walking conditions.

	Variable	norm (cm)	pouch (cm)	cough (cm)#	video (cm)	head turn (cm)	3s (cm)	RTP&delay (cm)#
Young n = 18	mean	2.28	2.47	2.60	2.29	2.67	2.30	2.48
	med	2.16	2.32	2.47	2.26	2.61	2.21	2.41
	SD	0.39	0.45	0.50	0.36	0.61	0.39	0.46
	IQR	0.55	0.68	0.43	0.54	0.73	0.59	0.64
	range	1.34	1.70	1.63	1.12	2.46	1.32	1.80
Elderly n = 18	mean	2.01	2.19	2.09	1.93	2.36	2.02	2.11
	med	2.01	2.25	2.06	1.89	2.36	2.01	2.13
	SD	0.49	0.39	0.40	0.33	0.42	0.34	0.38
	IQR	0.42	0.66	0.42	0.57	0.51	0.54	0.33
	range	2.04	1.33	1.59	1.04	1.62	1.01	1.69
	t (34)	-1.833	-1.978	Z =-3.227	3.135	-1.793	2.283	Z =-2.088
	p- value	.076	.056	.001**	.004**	.082	.029*	.037*

*** denotes p<.05; ** denotes p<.01.**

 # denotes Mann-Whitney U test and therefore *Z* value given in place of *t*-value. Independent t-test used for all others.

It can be seen in Figure 5.18 and Table 5.30 that the elderly group have lower $median_{MTC}$ (at least $p<0.05$) for each walking condition except *norm*, *pouch* and *head turn* tasks (which indicate a trend only) compared with the young group. Compared with the young group, the elderly were 0.41cm or 16% lower for *cough* task ($p<.001$), 0.37cm or 16% lower for *video* task ($p<.01$), 0.2cm or 9% lower for *3s* task ($p<.05$), 0.28cm or 11% lower for *RTP&delay* task ($p<.05$).

The lowest $median_{MTC}$ was found during the *video* task in the elderly group (1.89cm) which was the only distraction task to produce a $median_{MTC}$ lower than $median_{MTC(norm)}$. It was the only walking condition with $median_{MTC}$ below 2cm. The highest $median_{MTC}$ for both groups was during the *head turn* task with the elderly being 0.25cm (~10%) lower than the young group (young = 2.61cm, elderly = 2.36cm). Group $median_{MTC}$ for each distraction increased from group $median_{MTC(norm)}$ for all distractions except in the elderly group where group $median_{MTC}$ remained the same for *3s* task (2.01cm) and decreased 0.12cm (~6%) in *video* task ($median_{MTC(norm)}$ = 2.01cm vs. $median_{MTC(video)}$ = 1.89cm).

Table 5.31 shows significant main effects for age (p<.001) and walking condition (p=.001) but no significant interactions (p=.906). As shown in Table 5.32, post-hoc multiple comparisons on task (walking condition) factor using Tukey's HSD revealed the only distraction tasks significantly different to $median_{MTC(norm)}$ was *head turn* distraction task (p=.005).

Table 5.31: Test of between-subject effects using $median_{MTC}$ (via two-way ANOVA).

Variable	sig.	Observed power
Age (x2)	<.001	1.000
Walking condition (x7)	.001	.972
Interaction (age*task)	.906	.151

Table 5.32: Post-hoc comparisons using Tukey's HSD for $median_{MTC(norm)}$ (via two-way ANOVA).

Task	sig.
Pouch	.528
Cough	.432
Video	1.000
Head turn	.005
3s	1.000
RTP&delay	.755

One-way ANOVA was conducted for the young and elderly groups separately. Test of homogeneity of variances using Levene's statistic was not significant for both young and elderly (Table 5.33) suggesting this primary assumption was not violated.

Table 5.33: Test of homogeneity of variances using Levene's statistic for young and elderly one-way ANOVAs.

Group	sig.
Young	.735
Elderly	.903

As shown in Table 5.34, between groups ANOVA revealed significant differences for the elderly group (F (1,6) = 2.274, p=.041) and a trend toward significance for the young group (p=.055).

Table 5.34: Between groups results of one-way ANOVAs comparing median$_{MTC}$.

Group	df	F-value	sig.
Young	6	2.132	.055
Elderly	6	2.274	.041

Examination of post-hoc multiple comparisons using Tukey's HSD for the elderly group revealed there were no significant differences between the median$_{MTC(norm)}$ and each distraction task median$_{MTC(distr)}$ (Table 5.35).

Table 5.35: Post-hoc comparisons with median$_{MTC(norm)}$ using Tukey's HSD via one-way ANOVA for elderly group.

Task	sig.
Pouch	.816
Cough	.997
Video	.997
Head turn	.119
3s	1.000
RTP&delay	.988

5.5.1.2.2 $Z'_{(distr)}$ score ($median_{MTC(distr)}$ relative to $median_{MTC(norm)}$)

Group $Z'_{(distr)}$ score for each distraction task are shown in Figure 5.19 and Table 5.36.

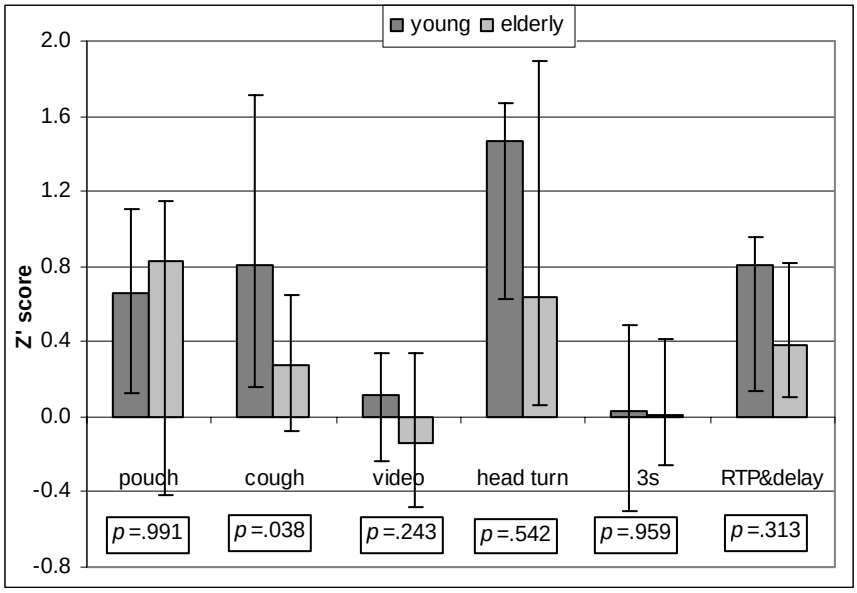


Figure 5.19: Comparison of group $Z'_{(distr)}$ score (Z' score of $median_{MTC(distr)}$ relative to $median_{MTC(norm)}$) using group median and IQR (error bars).

One-way ANOVA was conducted to identify age effects for $Z'_{(distr)}$ score (deviation of $median_{MTC(distr)}$ relative to $median_{MTC(norm)}$). Test of homogeneity of variances using Levene's statistic revealed this assumption was not violated for any variable (refer Table 5.36).

Table 5.36: Comparison of deviation ($Z'_{(distr)}$ score) of each $median_{MTC(distr)}$ relative to $median_{MTC(norm)}$ using one-way ANOVA.

	Variable	pouch	cough	video	head turn	3s	RTP&delay
Young n = 18	mean	0.59	1.09	0.10	1.11	0.10	0.61
	med	0.66	0.81	0.12	1.47	0.03	0.80
	SD	0.78	1.27	0.47	0.87	0.80	0.61
	IQR	0.99	1.56	0.58	1.05	1.00	0.82
	range	2.92	4.85	1.65	3.31	3.42	2.18
Elderly n = 18	mean	0.59	0.30	-0.11	0.91	0.09	0.36
	med	0.83	0.27	-0.14	0.64	0.00	0.38
	SD	1.10	0.87	0.60	1.11	0.93	0.80
	IQR	1.56	0.72	0.82	1.83	0.66	0.72
	range	3.96	3.58	2.17	4.18	3.53	2.85
	F (1,34)	.000	4.652	1.412	.379	.003	1.047
	***p*- value**	.991	.038*	.243	.542	.959	.313

*** denotes p< .05.**

Table 5.36 and Figure 5.19 show that the only significant differences between young and elderly was for the *cough* task with median young and elderly values of 0.81 and 0.27 respectively (p=.038). The *head turn* task elicited the greatest deviation from $median_{MTC(norm)}$ for the young group (1.47) while the greatest deviation in the elderly group was seen in the *pouch* task (0.83). The *3s* task elicited the smallest deviation for both groups with group median values for young and elderly of 0.03 and 0.00 respectively. The two prolonged tasks, namely the *video* and *3s* task, resulted in the two lowest scores of deviation from $median_{MTC(norm)}$ for both groups. For the young group, group median $Z'_{(distr)}$ score was 0.12 and 0.03 respectively, whilst in the elderly, *3s* task resulted in 0.00 deviation and *video* task resulted in –0.14 deviation.

A two-way ANOVA was conducted to examine main effect of age and task (walking condition) and interaction between these variables. Normality assumption was violated for one variable only (young subjects *3s* task) (refer Table 5.27 and Table 5.28) and

therefore was of little concern (Coakes and Steed, 1999). Homogeneity of variance using Levene's test of equality of error variances was calculated and was significant with a *p*-value of .010. The ANOVA was therefore conducted at a more conservative alpha level of .01 (Coakes and Steed, 1999). Table 5.37 shows that, at an alpha level of .05, significant differences exist for the main effects of age (p=.044) and distraction (p<.001) but no significant interactions (p=.454). However, at a more conservative level of .01 due to violation of homogeneity of variances assumption, it can be seen that significant differences exist only on the distraction factor.

Table 5.37: Test of between-subject effects via two-way ANOVA.

Variable	sig.	Observed power
Age (x2)	.044	.285
Distraction (x6)	<.001	.987
Interaction (age*distaction)	.454	.145

Note: calculated using p = .01.

Post-hoc multiple comparisons on distraction factor using Tukey's HSD revealed no significant differences between $Z'_{(distr)}$ score for normal undistracted walking and the distracted walking conditions.

5.5.1.3 Chi-square test to compare effect of distractions

Chi-square test was performed to compare frequencies of level of effect of distraction tasks for both young and elderly groups. Level of effect was determined by examining $Z'_{(distr)}$ score for each individual for each distraction task. No effect was defined as less than $1*Z'_{(distr)}$ score, small effect was defined as being greater than $1*Z'_{(distr)}$ score but less than $2*Z'_{(distr)}$ score, and large effect was defined as greater than $2*Z'_{(distr)}$ score.

Figure 5.20 shows a plot of the chi-square test results, specifically, charting the percentage of young and elderly subjects showing no effect, small effect or large effect due to performing each distraction task. The associated data for the chi-square test can be found in Table 5.38.

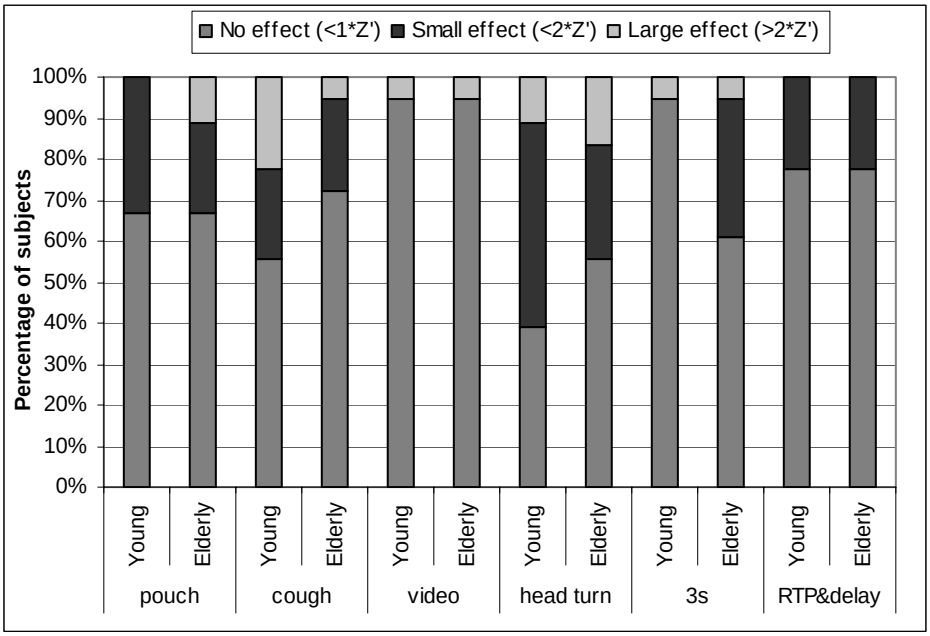


Figure 5.20: Frequencies of level of effect of distractions via Chi-square test.

Table 5.38: Chi-square test of frequencies of level of effect of distractions.

***denotes significance at .05 level; ** denotes significant at .01 level.**

Level of effect	pouch		cough		video		head turn		3s		RTP&delay	
	Young	Elderly	Young	Elderly	Young	Elderly	Young	Elderly	Young	Elderly	Young	Elderly
No effect (<1*Z')	12	12	10	13	17	17	7	10	17	11	14	14
Small effect (<2*Z')	6	4	4	4	0	0	9	5	0	6	4	4
Large effect (>2*Z')	0	2	4	1	1	1	2	3	1	1	0	0
Asymp. Sig.	*.157*	*.009***	*.135*	*.002***	*<.001***	*<.001***	*.115*	*.115*	*<.001***	*.016**	*.018**	*.018**

Figure 5.20 clearly shows that the *video* task had the greatest number of subjects showing no effect in response to the *video* task with young and elderly being the same in their level of effect. That is, approximately 94% (n = 17) of young and 94% (n = 17) of elderly showed no effect whilst 6% (n = 1) of each group showed a large effect. The distraction having an effect on the greatest proportion of subjects was the *head turn* task 50% (n = 9) showing a small effect and 11% (n = 2) showing a large effect in the young group and 28% (n = 5) showing a small effect and 17% (n = 3) showing a large effect in the elderly group.

The *cough* task had the greatest proportion of subjects showing a large effect where young were more affected than elderly. Here, the young subjects had 22% (n = 4) showing a large effect and 22% (n = 4) showing a small effect whilst the elderly had 22% (n = 4) showing a small effect and only 6% (n = 1) showing a large effect. It can be seen that the *RTP&delay* and video tasks resulted in similar effect on the young and elderly subjects. There were no large effects for the young or elderly group for the *RTP&delay* task but both had a small effect (~22%, n = 4, each of young and elderly group). Similarly, the *pouch* task for the young group resulted in no large effects in the young group but some elderly subjects (11%, n = 2) showed a large effect. In the *3s* task, while both young and elderly group had similar proportions of the group showing large effect (6%, n = 1, each), the remainder of the young group showed no effect (94%, n = 17) while only 61% (n = 11) of the elderly group showed no effect and the remaining 33% (n = 6) showed a small effect.

It can be seen in Table 5.38 that significant differences existed in the elderly group for *pouch* distraction (p=.009), *cough* distraction (p=.002), *video* distraction (p<.001), *3s*

distraction (p=.016) and *RTP&delay* distraction (p=.018). In the young group, differences existed for the *video* distraction (p<*.001*), *3s* distraction (p<.001) and *RTP&delay* distraction (p=.018).

5.5.2 Effect of distractions on low MTC measures (min_{MTC} and $PC5_{MTC}$)

Low measures of the MTC distribution during distracted walking conditions were examined for young and elderly groups since strides with low MTC are most at risk of hitting unseen obstacles. Low MTC measures examined during distracted walking conditions include min_{MTC} (examined for each distracted walking condition) and $PC5_{MTC}$ (examined for the two prolonged distraction tasks, namely *video* and *3s*). Although stride numbers within each walking condition vary, min_{MTC} can be compared across all walking conditions (undistracted and distracted walking conditions). $PC5_{MTC}$ was only examined for the two prolonged distraction tasks since these tasks contained larger numbers of strides enabling a meaningful fifth percentile measure to be calculated. As described in the methods chapter, the small data sets associated with some distraction tasks made calculation of $PC5_{MTC}$ either meaningless or not possible. Additionally, $PC1_{MTC}$ was not examined for any of the distraction tasks since, like $PC5_{MTC}$, larger data sets are required in order to produce a meaningful first percentile measure that can be compared with normal undistracted walking data.

5.5.2.1 Exploratory data analysis

Selected descriptive statistics for the young and elderly groups on $PC5_{MTC}$ measures during normal undistracted walking, and the two prolonged distractions tasks, *video* and *3s*, are presented in Table 5.39 and Table 5.40.

Table 5.39: Descriptive statistics for the young group (n = 18) for $PC5_{MTC}$ for three walking conditions. Tests of normality: Shapiro-Wilks (S-W).

Young	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Norm	1.90	1.81	0.34	0.37	1.36	2.51	0.258	-0.519	.588
Video	1.97	1.94	0.36	0.60	1.48	2.62	0.322	-1.072	.358
3s	2.01	1.95	0.37	0.56	1.33	2.65	0.193	-0.757	.538

Table 5.40: Descriptive statistics for the elderly group (n = 18) for $PC5_{MTC}$ for three walking conditions. Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Norm	1.54	1.50	0.43	0.38	0.60	2.45	0.254	1.191	.523
Video	1.57	1.56	0.35	0.54	0.91	2.14	0.008	-0.915	.606
3s	1.65	1.60	0.34	0.64	1.25	2.18	0.227	-1.510	.037

It can be seen in Table 5.39 and Table 5.40 that all data sets were normally distributed for the young group and only one data set was non-normal for the elderly group (*3s* distraction condition). It can be seen, therefore, that group skew and kurtosis are low with the lowest kurtosis value of -1.510 being in the elderly group *3s* distribution, which was the only non-normal distribution. The highest group kurtosis value was also within the elderly group for the *norm* condition (1.191).

Table 5.41 shows individual $PC5_{MTC}$ for the *norm*, *video* and *3s* conditions, showing individuals identified as outliers. There were no extremes or outliers for the young group but there were three outliers for the elderly group for the *norm* condition only. For the elderly, there were two high outliers for the *norm* distribution (e15 = 2.45cm and e3 = 2.33cm) and one low outlier (e5 = 0.60cm).

Table 5.41: Individual $PC5_{MTC}$ for *norm*, *video* and *3s* conditions.
(* denotes outlier, as defined by SPSS.)

Subject	norm	video	3s
y1	2.27	2.30	2.47
y2	1.74	1.87	1.98
y5	2.51	2.43	2.34
y6	1.82	1.96	1.62
y7	2.11	2.18	2.38
y9	1.57	1.61	1.65
y12	1.56	1.57	1.75
y14	1.73	1.62	1.71
y15	1.79	1.97	1.81
y16	2.00	2.16	2.24
y17	2.08	1.78	2.02
y18	2.08	2.25	1.98
y19	2.16	2.50	2.65
y20	1.80	1.68	1.84
y21	2.51	2.62	2.61
y22	1.77	1.92	1.92
y23	1.40	1.48	1.33
y24	1.36	1.53	1.83
e1	1.66	1.94	1.87
e2	1.92	1.93	1.61
e3	2.33*	2.14	1.49
e4	1.26	1.18	1.29
e5	0.60*	0.91	1.28
e6	1.46	1.32	1.28
e7	1.67	1.28	2.18
e8	1.47	1.28	2.18
e10	1.53	1.48	1.59
e11	1.32	1.44	1.31
e12	1.29	1.73	2.07
e13	1.67	1.64	1.49
e14	1.82	2.09	1.76
e15	2.45*	1.84	2.00
e17	1.60	1.80	1.93
e19	1.20	1.24	1.25
e23	1.41	1.70	1.93
e24	1.11	1.31	1.29

Selected descriptive statistics for min_{MTC} during normal undistracted and each distracted walking condition are presented in Table 5.42 and Table 5.43.

Table 5.42: Descriptive statistics for the young group (n = 18) for min_{MTC} for all walking conditions (undistracted and distracted). * ($p<.05$) denotes non-normal distribution. Tests of normality: Shapiro-Wilks (S-W).

Young	Mean	Median	SD	IQR	Min.	Max.	Skew.	Kurt.	S-W sig.
Norm	1.42	1.42	0.39	0.39	0.38	2.10	-0.720	2.073	.331
Pouch	2.12	2.06	0.39	0.47	1.50	3.01	0.671	0.092	.556
Cough	2.38	2.28	0.55	0.53	1.70	3.75	1.298	1.650	.026*
Video	1.79	1.83	0.39	0.66	1.31	2.60	0.409	-0.714	.311
Head turn	2.26	2.10	0.59	0.69	1.67	3.86	1.348	1.817	.019*
3s	1.85	1.83	0.37	0.51	1.25	2.48	0.252	-0.789	.662
RTP&delay	2.24	2.14	0.52	0.70	1.60	3.65	1.281	1.837	.049*

Table 5.43: Descriptive statistics for the elderly group (n = 18) for min_{MTC} for all walking conditions (undistracted and distracted). Tests of normality: Shapiro-Wilks (S-W). * ($p<.05$) denotes non-normal distribution.

Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew	Kurt	S-W sig.
Norm	0.44	0.41	0.13	0.21	0.25	0.69	0.724	-0.379	.161
Pouch	0.41	0.35	0.23	0.25	0.15	0.92	1.195	0.575	.010*
Cough	0.26	0.29	0.11	0.15	0.04	0.44	-0.596	-0.173	.529
Video	0.31	0.28	0.11	0.19	0.14	0.49	0.625	-0.869	.036*
Head turn	0.59	0.44	0.32	0.49	0.23	1.38	0.984	0.420	.012*
3s	0.38	0.36	0.13	0.19	0.20	0.63	0.650	-0.495	.214
RTP&delay	0.21	0.16	0.14	0.21	0.04	0.61	1.301	2.136	.046*

It can be seen in Table 5.42 that, for the young group, *norm*, *pouch*, *video* and *3s* conditions were normally distributed while *cough*, *head turn* and *RTP&delay* conditions were deemed non-normal due to the significant Shapiro-Wilks statistic (S-W). Table 5.43 shows that, for the elderly group, *norm*, *cough* and *3s* conditions were normally distributed while *pouch*, *video*, *head turn* and *RTP&delay* conditions were non-normal.

Table 5.44 shows individual min_{MTC} for each walking condition (undistracted and all distracted walking conditions). It can be seen that there are several outliers and one extreme, as determined using SPSS exploratory data analysis. There are four outliers in the young group, one low outlier for *norm* (y17), two high outliers for *cough* (y1 and y19) and one outlier for *head turn* (y7). In the elderly group there is one low outlier for *norm* (e5) and one extreme low for *RTP&delay* (e5).

Table 5.44: Individual min_{MTC} for undistracted and all distracted walking conditions. (*denotes outlier; ** denotes extreme)

Subject	norm (cm)	pouch (cm)	cough (cm)	video (cm)	head turn (cm)	3s (cm)	RTP&delay (cm)
y1	1.92	2.68	3.75*	2.21	2.84	2.35	2.65
y2	1.20	2.14	2.04	1.79	1.95	1.85	1.85
y5	1.81	2.61	2.60	2.33	2.19	2.02	2.95
y6	1.54	1.94	2.12	1.91	1.83	1.47	2.20
y7	1.62	2.22	2.05	2.02	3.86*	2.18	3.65
y9	1.28	1.84	2.23	1.40	2.01	1.53	1.79
y12	1.17	1.82	2.37	1.32	1.91	1.68	1.60
y14	1.34	1.79	2.08	1.51	1.82	1.32	1.72
y15	1.43	2.13	2.62	1.62	2.23	1.65	2.11
y16	1.41	2.06	2.55	2.11	2.51	2.09	2.34
y17	0.38*	2.36	2.38	1.31	2.52	1.96	2.17
y18	1.84	2.06	2.34	2.12	2.32	1.94	2.23
y19	1.24	3.01	3.52*	1.86	3.14	2.48	2.63
y20	1.49	1.50	1.71	1.57	1.72	1.53	1.93
y21	2.10	2.53	2.83	2.60	2.73	2.48	2.73
y22	1.51	1.89	2.09	1.86	1.78	1.81	2.07
y23	1.17	1.62	1.90	1.35	1.67	1.25	1.79
y24	1.05	1.91	1.70	1.39	1.67	1.66	1.85
e1	1.44	1.95	2.60	1.88	2.31	1.63	2.38
e2	1.28	1.73	1.94	1.76	1.74	1.53	1.68
e3	1.83	1.76	2.61	2.02	2.25	1.23	2.47
e4	1.03	1.46	1.48	1.08	1.21	0.91	1.89
e5	0.24*	1.16	0.96	0.73	1.22	0.74	0.68**
e6	1.10	1.92	1.56	1.27	1.42	1.19	1.90
e7	1.04	1.46	1.63	1.03	1.90	1.90	2.12
e8	1.02	1.46	1.63	1.03	1.90	1.90	2.12
e10	1.14	1.28	1.11	1.39	1.40	1.28	2.01
e11	1.11	1.77	1.72	1.29	2.14	1.26	1.97
e12	0.95	2.06	1.45	1.59	1.22	1.88	2.04
e13	1.32	2.15	2.09	1.47	1.87	0.86	1.79
e14	1.54	2.12	2.19	1.98	1.98	1.66	2.24
e15	1.74	1.49	2.17	1.69	2.23	1.94	2.42
e17	0.45	2.00	2.09	1.68	1.84	1.76	2.13
e19	0.67	1.28	1.75	1.06	1.58	0.84	1.30
e23	1.06	1.95	1.72	1.64	2.08	1.89	1.99
e24	0.76	1.24	1.34	1.25	1.72	1.20	1.47

5.5.2.2 Inferential statistics

Group $PC5_{MTC}$ using median and IQR are charted in Figure 5.21 whilst the respective data is presented in Table 5.45. A two-way ANOVA was conducted to examine main effect of age and task (walking condition) and interactions between these variables. Normality assumption was violated for one variable only and therefore was of little concern (Coakes and Steed, 1999). Homogeneity of variance assumption is the primary concern for two-way ANOVA (Coakes and Steed, 1999) and this assumption, using Levene's test of equality variances was not violated with a significance value of .999.

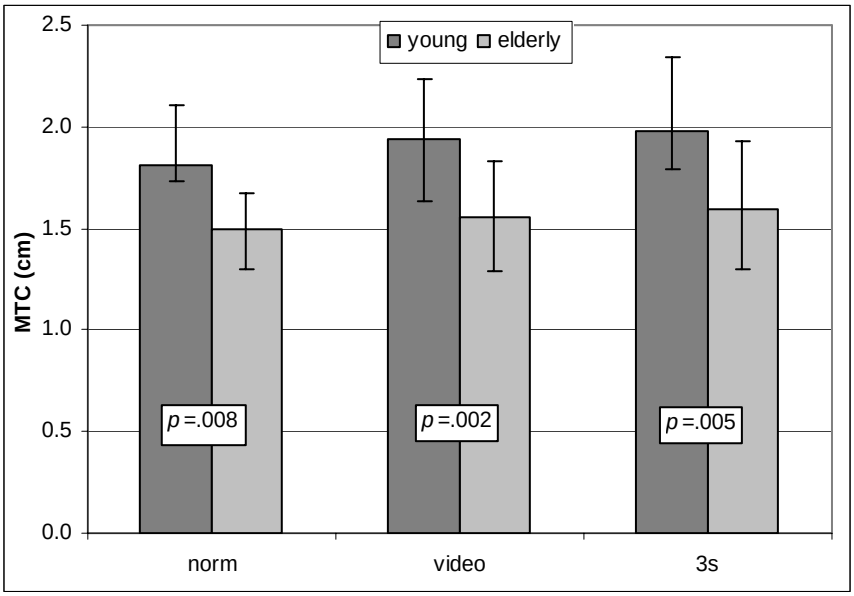


Figure 5.21: Comparison of group $PC5_{MTC}$ using median values and IQR (error bars).

Table 5.45: Comparison of $PC5_{MTC}$ measures between young and elderly via one-way ANOVA.

	Variable	norm (cm)	video (cm)	3s (cm)
Young n = 18	mean	1.90	1.97	2.01
	med	1.81	1.94	1.98
	SD	0.34	0.36	0.37
	IQR	0.37	0.60	0.56
	range	1.16	1.14	1.32
Elderly n = 18	mean	1.54	1.57	1.65
	med	1.50	1.56	1.60
	SD	0.43	0.35	0.34
	IQR	0.38	0.54	0.64
	range	1.84	1.23	0.93
	F (1,34)	7.859	11.579	8.940
	p- value	.008*	.002*	.005*

*** denotes p<.01.**

Table 5.46 shows significant main effect for age only (p<.001). Since there were no significant differences on the main effect for walking condition, post-hoc multiple comparisons were not necessary. Although not significant, for both groups, the *norm* condition had the lowest measure of $PC5_{MTC}$, followed by the *video* task and then the *3s* task as the highest value.

Table 5.46: Test of between-subject effects via two-way ANOVA for $PC5_{MTC}$.

Variable	sig.	Observed power
Age (x2)	.000	.999
Walking condition (x3)	.454	.183
Interaction (age*walking condition)	.959	.056

One-way ANOVA on age was conducted to find where the significant differences existed. As shown in Figure 5.21 and Table 5.45, significant age effects were evident for $PC5_{MTC}$ measures in all walking conditions with the young group having higher measures of $PC5_{MTC}$ for each condition compared with the elderly group.

Figure 5.22 shows comparison of group min_{MTC} for undistracted (*norm*) and distracted walking conditions. The respective data are presented in Table 5.47.

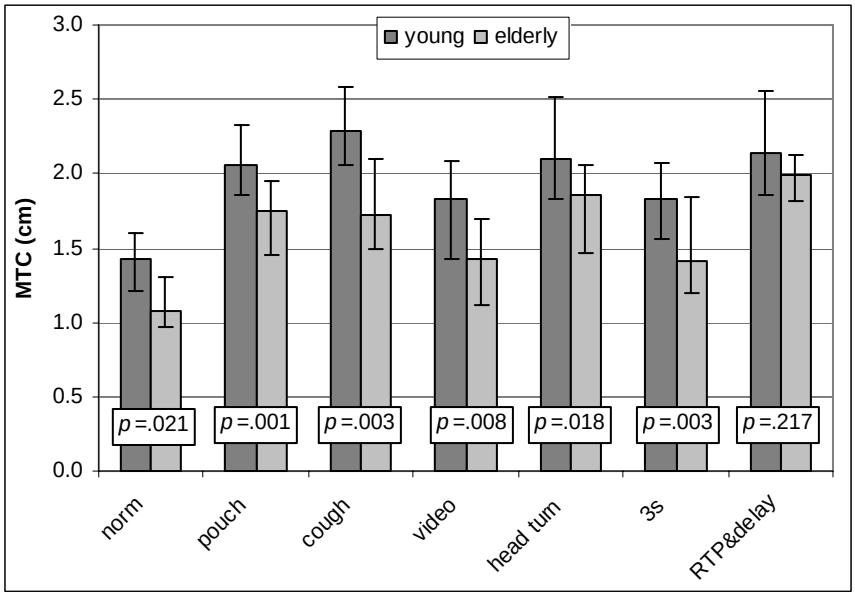


Figure 5.22: Comparison of group min_{MTC} during undistracted and distracted walking conditions using median values and IQR (error bars).

Table 5.47: Comparison of min_{MTC} between young and elderly via independent t-test and Mann-Whitney U test.

	Variable	norm (cm)	pouch (cm)	cough # (cm)	video (cm)	head turn # (cm)	3s (cm)	RTP&delay # (cm)
Young n = 18	mean	1.42	2.12	2.38	1.79	2.26	1.85	2.24
	med	1.42	2.06	2.28	1.83	2.10	1.83	2.14
	SD	0.39	0.39	0.55	0.39	0.59	0.37	0.52
	IQR	0.39	0.47	0.53	0.66	0.69	0.51	0.70
	range	1.72	1.50	2.05	1.29	2.19	1.23	2.05
Elderly n = 18	mean	1.10	1.68	1.78	1.44	1.78	1.42	1.92
	med	1.08	1.75	1.72	1.43	1.86	1.41	2.00
	SD	0.41	0.33	0.45	0.37	0.37	0.42	0.43
	IQR	0.34	0.49	0.59	0.57	0.59	0.66	0.31
	range	1.58	1.00	1.64	1.28	1.10	1.20	1.79
	t (34)	-2.419	-3.622	(Z)-3.006	-2.840	(Z)-2.373	-3.228	(Z)-1.234
	p- value	.021*	.001***	.003**	.008**	.018*	.003**	.217

*** denotes $p<.05$; ** denotes $p<.01$; *** denotes $p<.001$**

 # denotes Mann-Whitney U test and therefore *Z* value given in place of t-value. Independent t-test used for all others.

It can be seen in Figure 5.22 and Table 5.47 that min_{MTC} is significantly lower (at least at .05 level) for the elderly group across all conditions except *RTP&delay*.

Table 5.48 shows comparison of min_{MTC} on walking condition factor for young and elderly groups. It can be seen in Table 5.48 $min_{MTC(norm)}$ was significantly lower than each of the distraction tasks for both young and elderly.

Table 5.48: Comparison of min_{MTC} across walking conditions for young and elderly groups.

Distraction	Young		Elderly	
	t (34)	p-value	t (34)	p-value
Pouch	-5.396	<.001	-4.728	<.001
Cough #	(Z)-4.683	<.001	(Z)-3.829	<.001
Video	-2.921	.006**	-2.629	.013*
Head turn #	(Z)-4.303	<.001	(Z)-4.113	<.001
3s	-3.397	.002**	-2.377	.023*
RTP&delay #	(Z)-4.398	<.001	(Z)-4.303	<.001

Note: table shows comparison of normal undistracted walking condition compared with each distraction. Independent t-test was performed for all others. * denotes p<.05; ** denotes p<.01; all others significant at p<.001.

5.5.3 Effect of distractions on variability (IQR_{MTC})

5.5.3.1 Exploratory data analysis

Selected descriptive statistics for variability as measured by IQR_{MTC} for normal undistracted walking and distracted walking conditions are presented in Table 5.49 and Table 5.50. Non-normal distributions were evident as determined by signficant S-W statistic for five of the young group distributions. High skew and kurtosis is also observed for most of the distributions deemed non-normal due to significant S-W

statistic. Only *video* and *RTP&delay* tasks were deemed normal, however the S-W statistic was approaching significance (p<.07). Four elderly distributions were non-normal and three deemed normal, namely *norm*, *cough* and *3s* tasks.

Table 5.49: Descriptive statistics for young group (n = 18) variability as measured by IQR_{MTC} for each walking condition.

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Young	Mean	Median	SD	IQR	Min.	Max.	Skew	Kurt	S-W sig.
Norm	0.34	0.29	0.16	0.10	0.22	0.94	3.118	11.120	<.001*
Pouch	0.25	0.20	0.16	0.18	0.08	0.66	1.492	1.801	.005*
Cough	0.26	0.18	0.38	0.30	0.00	1.64	3.065	10.951	<.001*
Video	0.30	0.28	0.12	0.10	0.16	0.58	1.073	0.725	.066
Head turn	0.37	0.39	0.21	0.25	0.11	0.96	1.335	2.903	.024*
3s	0.27	0.23	0.15	0.12	0.13	0.75	2.238	5.935	.001*
RTP&delay	0.21	0.17	0.11	0.18	0.08	0.41	0.556	-1.083	.069

Table 5.50: Descriptive statistics for elderly group (n = 18) variability as measured by IQR_{MTC} for each walking condition.

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew	Kurt	S-W sig.
Norm	0.44	0.41	0.13	0.19	0.25	0.69	0.724	-0.379	.161
Pouch	0.41	0.35	0.23	0.22	0.15	0.92	1.195	0.575	.010*
Cough	0.26	0.29	0.11	0.14	0.04	0.44	-0.596	-0.173	.529
Video	0.31	0.28	0.11	0.15	0.14	0.49	0.625	-0.869	.036*
Head turn	0.59	0.44	0.32	0.47	0.23	1.38	0.984	0.420	.012*
3s	0.38	0.36	0.13	0.15	0.20	0.63	0.650	-0.495	.214
RTP&delay	0.21	0.16	0.14	0.19	0.04	0.61	1.301	2.136	.046*

Table 5.51 shows individual variability measures (IQR_{MTC}) for each walking condition (undistracted and distracted walking conditions).

Table 5.51: Individual variability measure (IQR_{MTC}) for each walking condition.

*** denotes outlier; ** denotes extreme, as defined by SPSS.**

Subject	norm (cm)	video (cm)	head turn (cm)	3s (cm)	pouch (cm)	cough (cm)	RTP&delay (cm)
y1	0.28	0.33	0.39	0.31	0.17	0.00	0.08
y2	0.27	0.29	0.23	0.21	0.22	0.37	0.26
y5	0.44	0.31	0.23	0.22	0.17	0.25	0.17
y6	0.29	0.17	0.47	0.15	0.21	0.07	0.13
y7	0.94	0.58	0.96	0.75	0.57	1.64	0.32
y9	0.27	0.24	0.45	0.18	0.20	0.00	0.33
y12	0.39	0.30	0.39	0.26	0.10	0.02	0.37
y14	0.22	0.16	0.11	0.20	0.37	0.16	0.35
y15	0.38	0.39	0.45	0.24	0.08	0.20	0.41
y16	0.28	0.23	0.15	0.27	0.15	0.02	0.09
y17	0.46	0.45	0.63	0.50	0.66	0.43	0.20
y18	0.27	0.25	0.45	0.13	0.20	0.07	0.14
y19	0.31	0.52	0.18	0.19	0.11	0.04	0.25
y20	0.32	0.32	0.19	0.33	0.27	0.26	0.13
y21	0.29	0.23	0.40	0.29	0.16	0.35	0.09
y22	0.23	0.19	0.46	0.14	0.36	0.03	0.10
y23	0.25	0.16	0.17	0.19	0.37	0.20	0.17
y24	0.23	0.26	0.33	0.35	0.14	0.54	0.18
e1	0.33	0.21	0.23	0.20	0.44	0.07	0.14
e2	0.41	0.30	0.39	0.29	0.42	0.11	0.15
e3	0.69	0.35	0.80	0.57	0.92	0.26	0.20
e4	0.31	0.25	0.37	0.30	0.28	0.22	0.18
e5	0.44	0.48	0.86	0.35	0.78	0.32	0.28
e6	0.35	0.24	0.31	0.26	0.33	0.44	0.12
e7	0.43	0.30	0.88	0.39	0.29	0.32	0.32
e8	0.55	0.30	0.88	0.39	0.29	0.32	0.32
e10	0.38	0.49	0.44	0.29	0.37	0.40	0.24
e11	0.25	0.14	0.45	0.22	0.15	0.37	0.09
e12	0.41	0.22	0.82	0.52	0.44	0.34	0.08
e13	0.38	0.19	0.39	0.35	0.17	0.04	0.38
e14	0.33	0.26	0.44	0.45	0.21	0.18	0.06
e15	0.55	0.49	0.24	0.24	0.51	0.19	0.15
e17	0.61	0.38	0.96	0.63	0.49	0.27	0.33
e19	0.67	0.48	1.38	0.57	0.89	0.30	0.61
e23	0.47	0.24	0.38	0.37	0.24	0.25	0.04
e24	0.34	0.22	0.39	0.37	0.25	0.34	0.13

There were two extreme values for the elderly group and six for the young group. For the young group there was one high extreme value above the mean for the *norm* condition (y7 = .94cm), one high extreme above the mean for *cough* condition (y7 = 1.64cm), two extremes above the mean for *video* condition (y7 = 0.58cm and y19 = 0.52cm), one extreme above the mean for the *head turn* task (y7 = 0.96cm) and one

high extreme above the mean for *3s* condition (y7 = 0.75cm). For the elderly group there were two extreme values above the mean for *pouch* condition only (e3 = 0.92cm and e19 = 0.89cm).

5.5.3.2 Inferential statistics

As previously discussed, since the data in this research are typically not normally distributed, the measures of median for group central tendency and IQR for group variability have been chosen. Data for all except two variables in the young group (*video* and *RTP&delay*) and three in the elderly group (*normal*, *cough* and *3s*) were not normally distributed. Group IQR_{MTC} for each condition is charted in Figure 5.23 and group IQR_{MTC} data presented in Table 5.52.

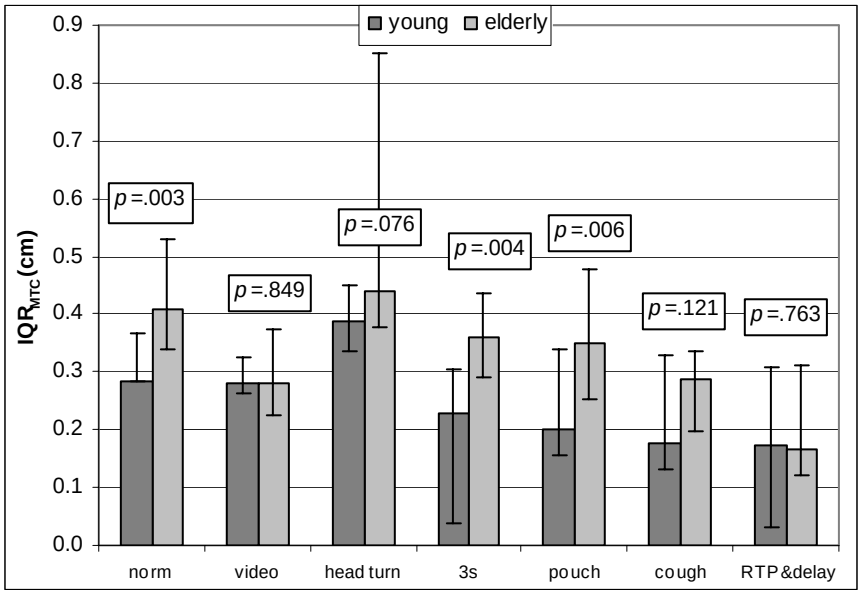


Figure 5.23: Group IQR_{MTC} for each walking condition using median and IQR (error bars).

Table 5.52: Comparison of variability as measured by IQR_{MTC} for each walking condition (via Mann-Whitney U tests).

	Variable	norm (cm)	video (cm)	head turn (cm)	3s (cm)	Pouch (cm)	Cough (cm)	RTP&delay (cm)
Young n = 18	mean	0.34	0.30	0.37	0.27	0.25	0.26	0.21
	med	0.28	0.28	0.39	0.23	0.20	0.18	0.17
	SD	0.16	0.12	0.21	0.15	0.18	0.30	0.18
	IQR	0.10	0.10	0.25	0.12	0.18	0.30	0.18
	range	0.72	0.43	0.85	0.63	0.58	1.64	0.33
Elderly n = 18	mean	0.44	0.31	0.59	0.38	0.41	0.26	0.21
	med	0.41	0.28	0.44	0.36	0.35	0.29	0.16
	SD	0.13	0.11	0.32	0.13	0.23	0.11	0.14
	IQR	0.19	0.15	0.47	0.15	0.22	0.14	0.19
	range	0.43	0.35	1.16	0.43	0.77	0.41	0.57
	Z	-2.993	-0.190	-1.776	-2.850	-2.692	-1.520	-.301
	p- value	.003*	.849	.076	.004*	.006*	.121	.763

*** denotes $p<.01$**

It can be seen in Figure 5.23 and Table 5.52 IQR_{MTC} was significantly higher in the elderly group for *norm*, *3s* and *pouch* condition ($p<.01$). IQR_{MTC} was greater in the elderly for *head turn* task and was approaching significance at $p<.05$ level ($p = .076$).

The non-parametric Kruskal-Wallis test was used to identify differences in IQR_{MTC} between walking conditions ($IQR_{MTC(norm)}$ and $IQR_{MTC(distr)}$ for each distraction task) and any age effects. Table 5.53 shows significant age effects existed for IQR_{MTC} ($p<.001$) while the location of these differences have been shown in Table 5.52 .

Table 5.53: Kruskal-Wallis test on age for IQR_{MTC}.

Variability measure	sig.
IQR_{MTC}	<.001

Table 5.54 shows significant differences between the variability in the walking conditions on IQR_{MTC} for the elderly group ($p<.001$) and young group ($p=.004$).

Table 5.54: Kruskal-Wallis test on walking condition for IQR_{MTC}.

Group	sig.
Young	.004
Elderly	<.001

Simple comparisons using multiple non-parametric Mann-Whitney U tests were conducted to examine where the differences lie between walking conditions. Table 5.55 shows Z and *p-values* for all comparisons.

Table 5.55: Multiple comparisons of IQR_{MTC}(norm) with IQR_{MTC} for all distractions using non-parametric Mann-Whitney U test for IQR_{MTC}.

Distraction	Young		Elderly	
	Z	*p-value*	Z	*p-value*
Video	-.728	.467	-2.946	.003**
3s	-2.138	.032*	-1.520	.129
Head turn	-.491	.623	-1.188	.235
Pouch	-2.629	.009**	-1.156	.248
Cough	-2.486	.013*	-3.737	<.001***
RTP&delay	-2.786	.005**	-4.164	<.001***

*** denotes *p*<.05; ** denotes *p*<.01; *** denotes *p*<.001.**

It can be seen in Table 5.55 that, in the elderly group $IQR_{MTC(norm)}$ was significantly higher than IQR_{MTC} for *video* (p=.003), *cough* (p<.001) and *RTP&delay* (p<.001). In the young group, $IQR_{MTC(norm)}$ was significantly higher than IQR_{MTC} for *3s* (p=.032), *pouch* (p=.009), *cough* (p=.013) and *RTP&delay* (p=.005). As seen in Table 5.52, head turn task had the highest group IQR_{MTC} in the elderly (0.44cm) and young (0.39cm) group.

5.5.4 Age effects of task duration and performance

In this section task duration is compared between the groups for *pouch*, *cough*, *head turn* and *RTP*. The two prolonged tasks, namely *video* and *3s* task, were not examined for age effects since the duration was predetermined at 60s and therefore did not vary between subjects. Note that the analysis of the reaction time probe task (*RTP*) includes reaction time (RT) only (from the presentation of the visual "R" probe on the screen in front until the subject presses the hand-held button). Analysis of MTC data and the associated descriptive statistics for this task included the delay period also since it is argued that during this time subjects are distracted and it allows a more reasonable number of strides to be examined (referred to as *RTP&delay*). Since the delay period is randomised (ranging from 0 – 500ms) and, therefore, is not consistent across subjects, it is not included in the analysis of age effects of RT.

This section also examines age effects of task accuracy during the *head turn* task between the two groups. As described in the methods section subjects were required to count the number of shapes to the left and then the right. *Head turn* accuracy therefore refers to the percentage of shapes correctly identified.

A comparison of single- (ST) and dual-task (DT) performance on the *RTP* and *3s* task for the young and elderly group is also included. As described in the methods chapter performance for the *RTP* task was the time taken to respond by pressing a hand-held button to the visual "R" probe that appeared on the screen (RT). Performance for the *3s* task was the number and percentage of correct subtractions by threes performed in a 60s period. As previously described, the *RTP* and *3s* tasks were performed on their

own (single-task, ST) and during the treadmill walking (dual-task, DT). By examining the difference in performance during the ST and DT conditions it is possible to make inferences about the demands of the divided attention task (dual-task).

5.5.4.1 Exploratory data analysis

5.5.4.1.1 Task duration

Selected descriptive statistics of distraction task durations are presented in Table 5.56 and Table 5.57.

Table 5.56: Descriptive statistics for elderly group (n = 18) for distraction task duration (s). Tests of normality: Shapiro-Wilks (S-W). *(p<.05) denotes non-normal distribution.

Young	Mean	Median	SD	IQR	Min.	Max.	Skew	Kurt	S-W sig.
Pouch	9.6	9.2	3.4	3.0	3.2	18.2	0.70	1.77	.344
Cough	2.5	2.4	1.0	0.5	1.0	5.0	1.58	3.00	.001*
Head turn	11.1	10.4	3.6	3.6	6.3	20.8	1.34	1.87	.033*
RTP	0.6	0.5	0.1	0.1	0.5	0.8	1.53	2.65	.019*

Table 5.57: Descriptive statistics for elderly group (n = 18) for distraction task duration (s). Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew	Kurt	S-W sig.
Pouch	10.7	10.5	2.5	4.1	6.7	14.9	0.08	-0.93	.551
Cough	2.7	2.4	0.9	1.3	1.0	4.5	0.37	-0.35	.613
Head turn	19.7	17.1	8.4	7.4	11.0	42.6	1.82	2.99	.001*
RTP	0.6	0.6	0.1	0.1	0.5	0.9	0.80	0.23	.313

Using Shapiro-Wilks statistic, three non-normal data sets were identified for the young group (*cough*, *head turn* and RTP tasks) and one for the elderly group (*head turn* task). These distributions all had the largest skew and kurtosis values.

Individual distraction task durations are shown in Table 5.58. There were four outliers and two extremes identified for the young group whilst there were only two outliers for the elderly group.

Table 5.58: Individual task durations.

Note: RTP includes reaction time only (no delay period included).

*** denotes outlier; ** denotes extreme (as defined in SPSS).**

Subject	pouch (s)	cough (s)	video (s)	head turn (s)	3s (s)	RTP (s)
y1	9.8	1.4	60	9.6	60	0.80*
y2	13.7	5.0**	60	16.3	60	0.57
y5	10.0	2.2	60	9.8	60	0.53
y6	18.2*	2.0	60	9.0	60	0.61
y7	8.7	2.5	60	7.8	60	0.62
y9	9.8	2.2	60	8.2	60	0.52
y12	7.3	2.1	60	12.2	60	0.53
y14	13.7	5.0**	60	16.3	60	0.66
y15	7.5	2.4	60	12.8	60	0.50
y16	3.2	1.0*	60	8.1	60	0.54
y17	7.3	2.5	60	11.7	60	0.54
y18	11.0	2.3	60	10.7	60	0.57
y19	8.6	2.8	60	11.0	60	0.55
y20	8.5	2.7	60	10.6	60	0.70
y21	10.8	2.6	60	20.8*	60	0.51
y22	8.4	1.5	60	7.8	60	0.59
y23	5.0	2.4	60	6.3	60	0.51
y24	10.5	2.3	60	10.3	60	0.48
e1	13.0	1.5	60	26.0	60	0.56
e2	14.8	3.4	60	23.8	60	0.62
e3	10.5	2.0	60	14.5	60	0.77
e4	7.8	2.1	60	13.8	60	0.60
e5	13.0	2.5	60	16.8	60	0.69
e6	6.7	2.4	60	13.4	60	0.54
e7	12.5	2.4	60	16.6	60	0.66
e8	11.3	4.5	60	18.3	60	0.65
e10	7.4	2.5	60	14.4	60	0.58
e11	8.5	3.6	60	19.0	60	0.52
e12	7.5	4.2	60	37.3*	60	0.66
e13	12.9	2.0	60	17.9	60	0.69
e14	9.9	3.1	60	22.8	60	0.54
e15	14.9	2.9	60	42.6*	60	0.61
e17	10.5	2.4	60	14.3	60	0.51
e19	11.5	1.0	60	15.0	60	0.78
e23	9.6	2.0	60	11.0	60	0.87
e24	10.1	3.9	60	17.3	60	0.49

5.5.4.1.2 Task performance

Task performance variables examined in this section include *head turn* performance (i.e. accuracy – percentage of shapes correctly identified to the left and the right; and duration – time taken to complete the task); *3s* performance during ST condition (performed whilst standing stationary) and DT condition (performed concurrently with treadmill walking) for number of subtractions (the number of subtractions performed in the 60s period) and accuracy (percentage of subtractions correct); Reaction time in the *RTP* task during ST (performed whilst stationary) and DT conditions (performed concurrently with treadmill walking). Selected descriptive statistics for age effects of task performance are presented in and Table 5.59 and Table 5.60.

Table 5.59: Descriptive statistics for selected measures of task performance in *head turn*, *3s* and *RTP* tasks for the young group (n = 18).

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Task	Young	Mean	Median	SD	IQR	Min.	Max.	Skew	Kurt.	S-W sig.
Head turn	Accuracy (%)	97.5	100.0	4.7	0.0	88.9	100.0	-1.46	0.14	<.001*
	Duration (s)	11.1	10.5	3.6	3.6	6.3	20.8	1.34	1.87	.033*
3s	ST no. subtractions (n)	28.0	28.5	6.2	7.5	17.0	39.0	0.09	-0.38	.703
	ST accuracy (%)	95.6	100.0	11.8	3.6	50.0	100.0	-3.83	15.33	<.001*
	DT no. subtractions (n)	26.4	26.0	6.7	8.5	17.0	40.0	0.35	-0.55	.892
	DT accuracy (%)	94.7	100.0	7.5	9.4	76.2	100.0	-1.37	1.08	<.001*
RTP	ST reaction time (ms)	465	463	38	57	412	565	1.02	1.38	.222
	DT reaction time (ms)	574	549	80	97	478	801	1.53	2.65	.019*

Note: RTP are reaction times with no delay period included.

Table 5.60: Descriptive statistics of selected measures of task performance in *head turn*, *3s* and *RTP* tasks for the elderly group (n = 18).

Tests of normality: Shapiro-Wilks (S-W). * (p<.05) denotes non-normal distribution.

Task	Elderly	Mean	Median	SD	IQR	Min.	Max.	Skew	Kurt.	S-W sig.
Head turn	Accuracy (%)	90.8	100.0	13.3	11.1	55.6	100.0	-1.50	1.68	<.001*
	Duration (s)	19.7	17.1	8.4	7.4	11.0	42.6	1.82	2.99	.001*
3s	ST no. subtractions (n)	27.6	24.0	13.8	24.8	11.0	52.0	0.54	-1.15	.289
	ST accuracy (%)	95.2	100.0	7.5	7.9	80.0	100.0	-1.29	0.05	.005*
	DT no. subtractions (n)	27.2	25.0	12.3	19.0	11.0	49.0	0.22	-1.05	.051
	DT accuracy (%)	96.4	96.9	4.1	5.8	86.4	100.0	-1.00	0.32	<.001*
RTP	ST reaction time (ms)	484	480	40	49	424	568	0.72	0.38	.282
	DT reaction time (ms)	630	613	103	148	492	871	0.80	0.23	.313

Note: RTP are reaction times with no delay period included.

Using the Shapiro-Wilks statistic, nine non-normal data sets were identified, namely young and elderly group *head turn* accuracy, *head turn* duration, ST *3s* accuracy, DT *3s* accuracy and young group DT reaction time for *RTP*.

5.5.4.2 Inferential statistics

5.5.4.2.1 Task duration

It should be noted that the *video* and *3s* tasks were predetermined 60-second duration for each subject and, therefore, were not included in the analysis. All other tasks were completed as quickly, accurately and safely as possible. Figure 5.24 shows comparison of time taken to complete distraction tasks.

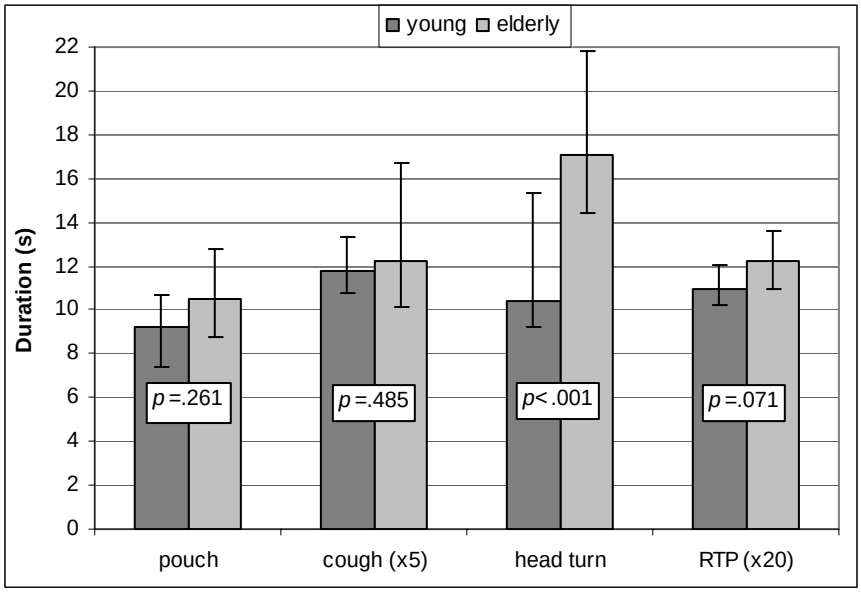


Figure 5.24: Group comparison of distraction task durations using median and IQR (error bars). Note: *cough* and *RTP* task have been magnified, i.e. *cough* (x5) and *RTP* (x20).

It can be seen in Figure 5.24 that the elderly group were significantly slower in time to complete the *head turn* task ($p<.001$). While not statistically significant, the elderly were slower in reaction times in *RTP*, which was approaching significance at the $p<.05$ level ($p = .071$). Table 5.61 shows respective group comparison data for distraction task durations whilst Table 5.58 shows individual times to complete the tasks.

Table 5.61: Comparison of time taken to complete each distraction task.

	Variable	pouch (s)	cough (s)#	head turn (s)#	RTP (s)
Young n = 18	mean	9.6	2.5	11.1	0.57
	med	9.2	2.4	10.4	0.55
	SD	3.4	1.0	3.6	0.08
	IQR	3.0	0.5	3.6	0.08
	range	15.0	4.0	14.5	0.32
Elderly n = 18	mean	10.7	2.7	19.7	0.63
	med	10.5	2.4	17.1	0.61
	SD	2.5	0.9	8.4	0.10
	IQR	4.1	1.3	7.4	0.14
	range	8.2	3.5	31.6	0.38
	t (34)	1.114	Z=-.698	Z=-4.161	-1.803
	p- value	.261	.485	<.001*	.071

Note: RTP duration is for reaction time only (no delay period included).

 # denotes Mann-Whitney U test performed and therefore Z value given instead of t-value (Independent t-test performed for remaining variables).

*** denotes p<.001.**

5.5.4.2.2 RTP task performance during single task (ST) and dual task (DT) conditions

Exploratory data analysis revealed the data were normally distributed for all except the young group on the DT *RTP* condition. One-way repeated measures ANOVA was conducted to reveal main effects on task condition (ST or DT) as measured by reaction times and any age effects. Figure 5.25 shows comparison of group data for *RTP* task during the ST and DT condition.

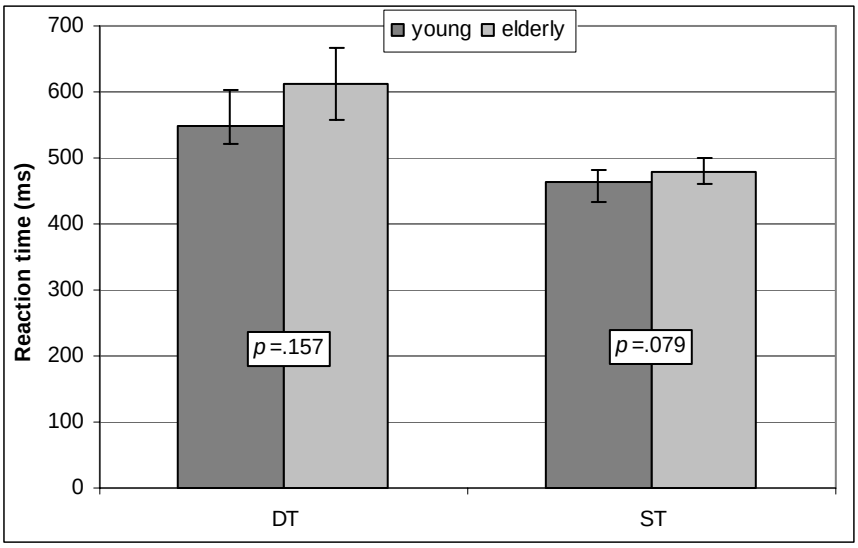


Figure 5.25: Group comparison of reaction times during ST and DT conditions for *RTP* task using median and IQR.

It can be seen in Figure 5.25 that no significant age effects existed for reaction times for *RTP* task under ST and DT conditions, however, the slower reaction time in the elderly during the ST condition was approaching significance at the $p<.05$ level ($p = .079$). The respective data can be found in Table 5.62.

Table 5.62: Group comparison (parameter estimates) for reaction time during the ST and DT condition for *RTP* task.

	Variable	DT (ms)	ST (ms)
Young n = 18	mean	573.9	465.0
	med	548.5	462.9
	SD	80.3	38.3
	IQR	83.5	48.8
	range	323.0	153.8
Elderly n = 18	mean	629.8	483.8
	med	612.5	479.5
	SD	103.2	39.7
	IQR	135.8	39.4
	range	379.0	144.4
	t (34)	1.447	1.813
	p- value	.157	.079

Dual task (DT) condition – performed concurrently with treadmill walking.

Single task (ST) condition – performed during static standing on the treadmill immediately following treadmill walking.

*** note reaction times only are reported here (randomised delay period is not included).**

Table 5.63 shows homogeneity of variances assumption, as determined by non-significant Levene's statistic, was not violated.

Table 5.63: Levene's test of equality of error variances (between age groups) in ST and DT reaction time.

Variable	Sig.
ST reaction time	.931
DT reaction time	.234

Table 5.64 shows main effect for reaction time was significant, F (1,34) =73.366, $p<.001$ but no significant interaction ($p=.221$).

Table 5.64: Test of Within-Subjects effects.

Variable	Sig.	Observed Power
Reaction time (RT) x 2 conditions	<.001**	1.000
Interaction (age*RT)	.221	.228

As presented in Figure 5.25 and Table 5.62, parameter estimates in Table 5.65 show the main effect for age is significant, F (1,34) = 4.132, $p = .050$ and, therefore, approaching a higher level of significance of $p<.05$.

Table 5.65: Test of between-subjects effects for reaction time.

Variable	Sig.	Observed Power
Age	.050	.506

Finally, pairwise comparisons and multivariate tests revealed significant differences on reaction time ($p<.001$) for both the young and elderly groups. This significance level remained after further comparisons using paired t-test for the elderly group and the non-parametric Wilcoxon signed rank test for the young group (refer Table 5.66).

Table 5.66: Pairwise comparisons of single- and dual-task conditions for young and elderly groups.

Group	Statistical test employed	*p-value*
Young	Wilcoxon Signed Ranks Test	<.001**
Elderly	Paired samples test	<.001**

**** denotes p<.001.**

Table 5.67: Individual reaction times(RT) for ST and DT conditions.

*** denotes outlier**

Subject	RT condition	
	DT (ms)	ST (ms)
y1	801.0*	465.0
y2	573.0	460.8
y5	534.0	452.8
y6	608.0	422.8
y7	622.0	487.0
y9	516.0	437.4
y12	533.0	411.6
y14	655.0	469.0
y15	499.0	455.0
y16	544.0	514.2
y17	537.0	465.6
y18	572.0	425.8
y19	553.0	498.4
y20	697.0	565.4
y21	512.0	432.6
y22	591.0	503.2
y23	506.0	469.8
y24	478.0	432.8
e1	559.0	452.4
e2	615.0	560.8
e3	771.0	500.2
e4	597.0	476.2
e5	687.0	469.6
e6	541.0	488.0
e7	664.0	483.6
e8	647.0	568.2*
e10	576.0	528.0
e11	524.0	423.8
e12	661.0	478.8
e13	691.0	514.8
e14	539.0	426.6
e15	610.0	486.0
e17	510.0	465.8
e19	782.0	449.6
e23	871.0	480.2
e24	492.0	455.0

5.5.4.2.3 Head turn task performance

Several subjects achieved the highest possible score for accuracy in the *head turn* task (i.e. 100% or nine correct out of nine). This ceiling effect resulted in a meaningless median value for central tendency and a meaningless variability measure. In this section, therefore, mean will be used as a descriptor of group central tendency.

The non-parametric Mann-Whitney U test was used to examine age effects on *head turn* duration and accuracy (i.e. percentage of correctly identified shapes to the left and right). Group comparisons of head turn accuracy and duration can be found in Figure 5.26 while the respective data is detailed in Table 5.68.

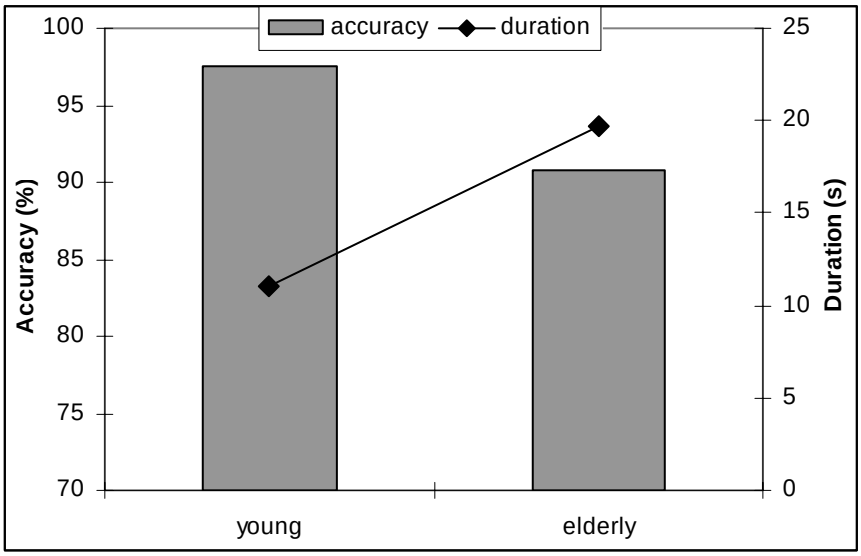


Figure 5.26: Group comparison of *head turn* accuracy and duration.

Table 5.68: Comparison of accuracy and duration of *head turn* task.

	Variable	accuracy (%)	duration (s)
Young n = 18	mean	97.5	11.1
	med	100.0	10.4
	SD	4.8	3.6
	IQR	0.0	3.6
	range	11.1	14.5
Elderly n = 18	mean	90.7	19.7
	med	100.0	17.1
	SD	13.3	8.4
	IQR	11.1	7.4
	range	44.4	31.6
	Z	-1.672	-4.161
	p- value	.094	<.001*

*** denotes p< .001.**

Figure 5.26 and Table 5.68 show that significant differences existed only on *head turn* duration with mean values for young and elderly of 11.1s and 19.7s respectively, Z= -4.161, $p<.001$, two-tailed. The elderly group, therefore, took on average 8.6s longer to complete the head turn task compared with the elderly. There were no significant age differences in accuracy for the *head turn* task.

The non-parametric Spearman's rho test was conducted to identify any correlations between the accuracy and duration of the *head turn* task for both the young and elderly groups. Table 5.69 shows no significant correlations existed. Table 5.70 shows individual accuracy and duration for the *head turn* task.

Table 5.69: Correlations for accuracy and duration of *head turn* task using non-parametric Spearman's rho.

Group	Correlation coefficient	Sig.
Young	.206	.412
Elderly	.128	.613

Table 5.70: Individual accuracy and duration results for *head turn* task.

*** denotes outlier**

Subject	Duration (s)	Accuracy %
y1	9.6	100.0
y2	16.3	88.9
y5	9.8	100.0
y6	9.0	88.9
y7	7.8	88.9
y9	8.2	88.9
y12	12.2	100.0
y14	16.3	100.0
y15	12.8	100.0
y16	8.1	100.0
y17	11.7	100.0
y18	10.7	100.0
y19	11.0	100.0
y20	10.6	100.0
y21	20.8	100.0
y22	7.8	100.0
y23	6.3	100.0
y24	10.3	100.0
e1	26.0	100.0
e2	23.8	55.6
e3	14.5	88.9
e4	13.8	88.9
e5	16.8	66.7
e6	13.4	88.9
e7	16.6	77.8
e8	18.3	100.0
e10	14.4	100.0
e11	19.0	100.0
e12	37.3	100.0
e13	17.9	77.8
e14	22.8	100.0
e15	42.6	100.0
e17	14.3	100.0
e19	15.0	100.0
e23	11.0	100.0
e24	17.3	88.9

5.5.4.2.4 3s performance during ST and DT conditions

Group comparison of *3s* task performance, that is the number of subtractions performed and the accuracy as measured by percentage of correct subtractions, are charted for ST and DT conditions in Figure 5.27.

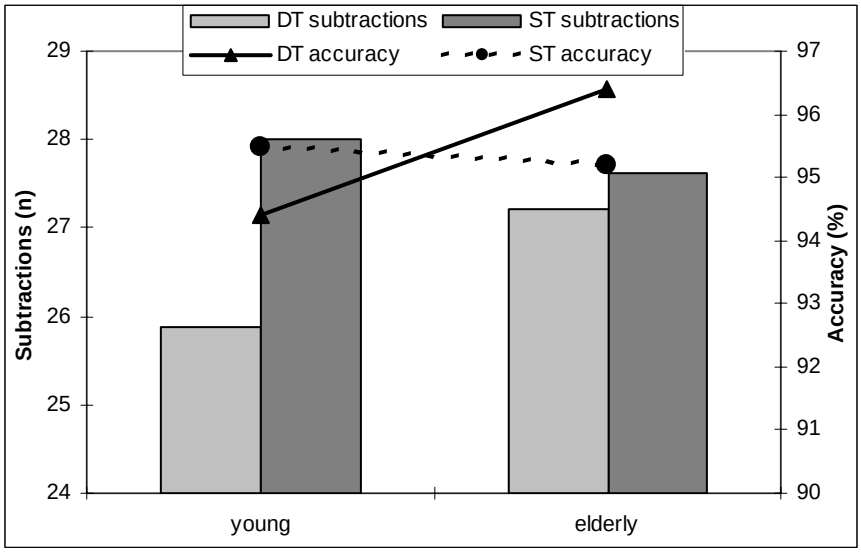


Figure 5.27: Group comparison of *3s* task performance during ST and DT conditions (number of subtractions performed and subtraction accuracy).

The data were analysed for age effects using independent t-test and Mann-Whitney U (Table 5.71).

Table 5.71: Comparison of ST and DT performance on the *3s* task.

	Variable	DT		ST	
		subtractions (n)	accuracy (%) #	subtractions (n)	accuracy (%) #
Young n = 18	mean	25.9	94.4	28.0	95.5
	med	26.0	100.0	28.5	100.0
	SD	6.7	7.5	6.2	11.8
	IQR	8.5	9.4	7.5	3.6
	range	23.0	23.8	22.0	50.0
Elderly n = 18	mean	27.2	96.4	27.6	95.2
	med	25.0	96.9	24.0	100.0
	SD	12.3	4.1	13.8	7.5
	IQR	19.0	5.8	24.8	7.9
	range	38.0	13.6	41.0	20.0
	t (34)	.253	Z=-.169	-.281	Z=-.396
	p- value	.802	.866	.781	.692

Note: Subtractions (n) – refers to the number of subtractions completed in the 60s period; Accuracy (%) – refers to the percentage of correct subtractions made in the 60s period; Dual task (DT) condition – subtractions performed concurrently with treadmill walking; Single task (ST) condition – subtractions performed during static standing on the treadmill.

While some differences can be seen between young and elderly in Figure 5.27, it can be seen in Table 5.71, however, that no significant age effects were found for performance in *3s* task during ST or DT conditions.

Differences in performance during the ST and DT condition were examined by Paired t-test and non-parametric Wilcoxon Signed Rank test (Table 5.72).

Table 5.72: Comparison of performance during ST and DT condition during *3s* task.

Variable	Statistical test employed	*p-value*	
		Young	Elderly
Subtractions	Paired samples test	.004*	.741
Accuracy	Wilcoxon Signed Ranks Test	.333	.498

It can be seen in Table 5.72 that significant difference existed for the young group only between number of subtractions completed during DT compared with ST ($p<.01$). Data

from Table 5.71 shows mean number of subtractions for young group during DT and ST conditions were 25.9 and 28.0 respectively. Individual ST and DT performance (number of subtractions completed and subtraction accuracy) during the *3s* task are presented in Table 5.73. It can be seen that the majority of subjects (eight during DT and 11 during ST for the young and 10 during DT and 11 during ST for young groups) achieved a maximum of 100% accuracy. This justifies the use of mean as a measure of group central tendency in this situation as opposed to median (refer Table 5.71).

Table 5.73: Individual ST and DT performance during the *3s* task.

subject	DT condition		ST condition	
	subtr.	accuracy	subtr.	accuracy
	n	%	n	%
y1	20	80.0	20	50.0
y2	29	89.7	28	100.0
y5	23	100.0	25	100.0
y6	17	88.2	22	100.0
y7	30	93.3	33	97.0
y9	36	100.0	33	100.0
y12	27	100.0	30	100.0
y14	17	88.2	17	88.2
y15	25	100.0	30	100.0
y16	18	100.0	25	96.0
y17	32	100.0	37	100.0
y18	27	100.0	26	96.2
y19	25	100.0	27	100.0
y20	40	100.0	39	100.0
y21	30	93.3	31	100.0
y22	23	95.7	29	100.0
y23	21	76.2	24	95.8
y24	35	100.0	39	97.4
e1	38	100.0	42	100.0
e2	16	100.0	14	100.0
e3	11	90.9	15	80.0
e4	11	90.9	15	80.0
e5	25	96.0	22	86.4
e6	23	95.7	24	95.8
e7	37	100.0	43	100.0
e8	25	100.0	33	100.0
e10	32	93.8	24	100.0
e11	49	100.0	52	100.0
e12	44	100.0	46	100.0
e13	22	86.4	18	83.3
e14	11	100.0	15	100.0
e15	30	96.7	28	100.0
e17	23	95.7	13	100.0
e19	45	100.0	50	100.0
e23	13	92.3	11	90.9
e24	35	97.1	32	96.9

Chapter 6: Discussion

This chapter includes sub-sections for normal undistracted walking condition and distracted walking condition. Each sub-section begins with major group observations and discussion on an individual basis. Age effects and different strategies to ensure safe walking for the young and elderly are discussed. Discussion of methodological issues encountered concludes this chapter.

6.1 Normal undistracted walking.

6.1.1 MTC Central Tendency (intention of the locomotor system)

This section discusses the justification for choosing an alternative measure of central tendency to the mean, which is commonly the only measure of central tendency reported. A comparison of $mean_{MTC}$ obtained in this research with mean values published in the literature is also provided. There are no published data for $median_{MTC}$ or $mode_{MTC}$.

Measures of central tendency, namely mean, median and mode, of a distribution refer to the typical or representative value of the group of scores. In a normal distribution the mean, median and mode are all equal. The normal distribution curve is shown in Figure 6.1.

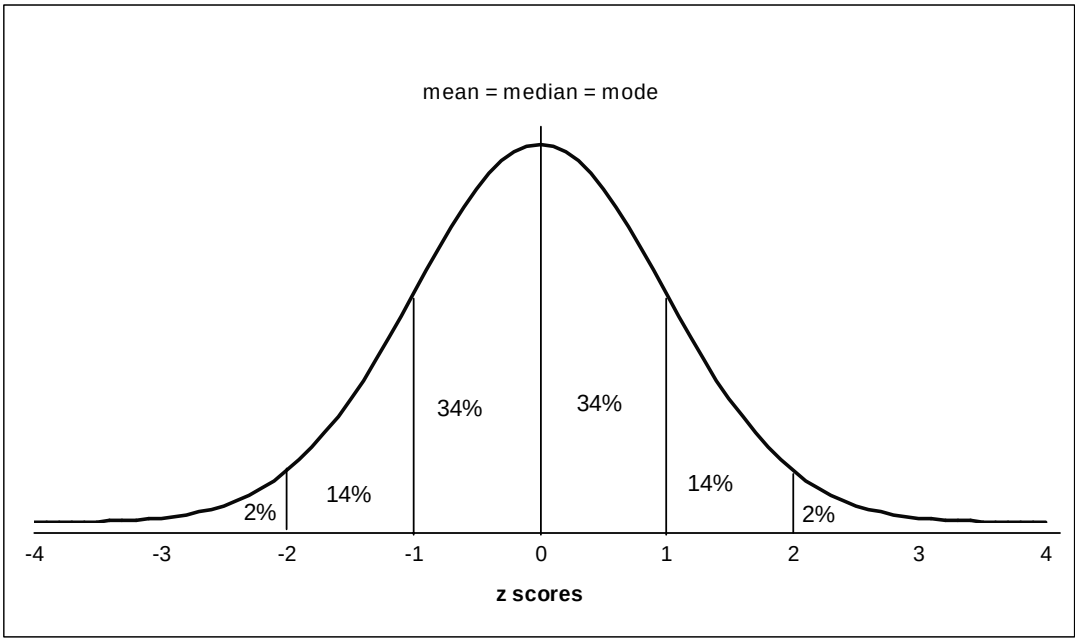


Figure 6.1: The normal distribution (Gaussian curve).

It can be seen in Figure 6.1 that the distribution is unimodal (one peak) and the measures of central tendency (mean, median and mode) are all located in the centre of the peak. Exactly 50% of the scores fall above the mean and 50% fall below the mean. It is symmetrical with tails of approximately the same shape and length. Approximately 34% of the scores lie between one standard deviation (z-score) below the mean and 34% lie between one standard deviation above the mean. In other words, approximately 68% of the scores are within one standard deviation of the mean.

In non-normal distributions, such as in a positively skewed distribution typical of this research (refer Figure 6.2), the mean, median and mode can be quite different requiring some thought in selecting the best estimate of central tendency.

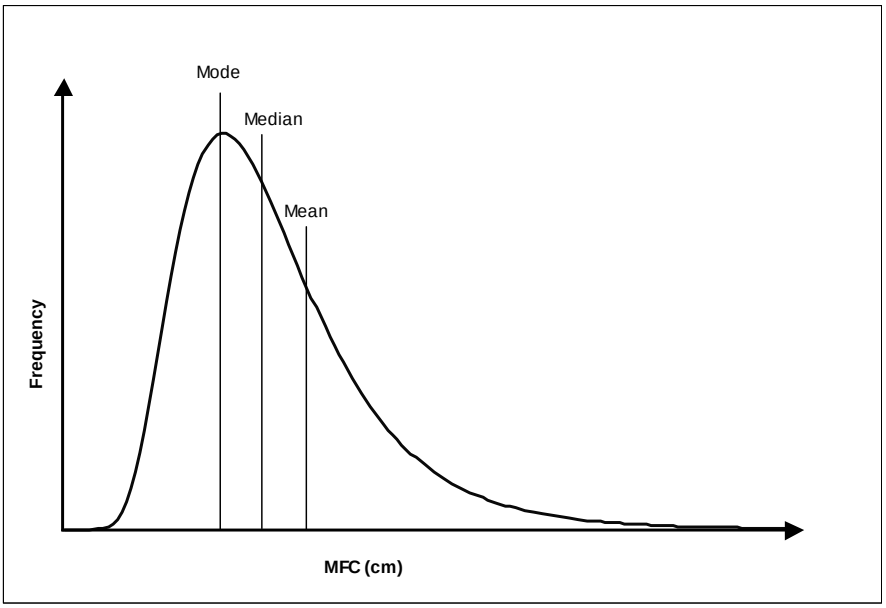


Figure 6.2: Positively skewed distribution.

The mean of a data set is defined as the numerical average of a set of values and is the most commonly used descriptive statistic. The mean considers all information about the data and is the most sensitive measure of central tendency to outliers and skewed distributions. This can be a disadvantage with skewed data and outliers since the mean value will be pulled towards the extreme (i.e. increased relative to central tendency) and therefore may not give an accurate representation of central tendency (Vincent, 1999; Elston and Johnson, 1994).

The median, or 50^{th} percentile, is the middle value in a set of ranked data. Unlike the mean, it is not sensitive to outliers and is more representative of the majority of scores than the mean when extreme scores exist (Vincent, 1999). The mode can be defined as the most frequently occurring value in a set of data (Vincent, 1999; Elston and Johnson, 1994). It too could be argued to be the most accurate measure of central tendency in skewed distributions. Mode, however, is typically used when only a rough estimate of central tendency is required and from a statistical perspective is not a robust measure.

Mode can vary considerably depending on sample size and the bin size used to calculate it (Begg *et al.*, 2007).

Since the individual MTC distributions in this research are systematically positively skewed (i.e. not normally distributed), mean, median and mode were examined in order to determine which best represented central tendency. It was also necessary to determine which measure of central tendency in these MTC distributions best represents what the human control system was attempting to implement.

The role of the locomotor system during walking is to achieve sufficient foot clearance to prevent tripping whilst minimising energy expenditure. The goal is to implement a consistent MTC, with success of this task measured via the central tendency of the MTC distribution. The mean is not the most accurate measure since it is highly affected in skewed distributions. The mode perhaps gives the best indication of the intent of the locomotor system since it reports the most frequently occurring MTC. Whilst arguably the best representation of the locomotor system's attempt to implement a consistent MTC, it is not a robust measure. In this research, it is proposed that median is a more accurate descriptor of central tendency and, therefore, gives a better representation of the intention of the locomotor system. The median being better, a discussion of mean values is included since these are typically reported in the literature. While there are a few studies that have examined MTC, of those published, all have reported mean and SD values, and have not reported median and IQR.

As reported in the results section 5.4.3.2, elderly subjects showed a trend toward lower MTC as a group on all three central tendency measures (refer Table 5.11). $Mode_{MTC}$

and $median_{MTC}$ were, however, approaching significance at $p<.05$ with values of $p=.069$ and $p=.076$ respectively. If Bonferroni correction had been employed, the level of significance required to reject the null hypothesis would have been $p<.016$. Being conservative, there were no age differences for the three central tendency measures.

Consistent with Figure 6.2, group MTC values are arranged in descending order of $mean_{MTC}$, $median_{MTC}$ and $mode_{MTC}$. As previously discussed, group mean and group median of the three measures are given. Group mean values are all higher than group median values due to the skewed group data. Group median has been selected as the best representation of group central tendency since much of the group data were not-normally distributed. The group mean is included for comparison with other reported MTC data since these are typically the group values reported.

Group mean $mean_{MTC}$ for young and elderly were 2.30cm (SD = 0.41cm) and 2.04cm (SD = 0.50cm) respectively. Winter (1991a) also reported greater mean MTC for young adults compared with elderly subjects with MTC of 1.29cm and 1.12cm respectively. Karst *et al.* (1999) also reported mean MTC for elderly females of 1.29 cm (SD = 0.68cm). The MTC values reported by Winter (1991a) and Karst *et al.* (1999) are lower than those found in this study and may be due to different research methodologies employed. For example, Winter's and Karst's studies evaluated MTC during overground walking, whilst this study measured MTC during treadmill walking. There are no other measures of central tendency, namely median or mode, for MTC published in the literature. Marker placement and determination of MTC also differed between the studies. The results of this study show only a trend toward lower MTC in

the elderly group compared with the young group (approximately 0.15cm or 7% lower using group median of median$_{MTC}$).

Intuitively, the lower MTC increases the risk of tripping on small, unseen obstacles while walking. As Winter (1991a) highlighted, a relatively small change in the hip, knee and ankle motion can strongly influence the end-point trajectory of the toe, thus resulting in large changes in toe clearance. Given the declined levels of strength and balance seen in the elderly, it is expected that these factors would contribute to a lower MTC in the elderly adults. The lack of statistically significant age effects in median$_{MTC}$ may be due to the sample studied being relative fit and healthy. The ability of the locomotor system to produce a consistent MTC was similar with both the young and elderly adults suggesting that with respect to medianMTC there was no significant difference in the likelihood of tripping between the young and elderly adults.

6.1.2 Variability/Dispersion (extent of control exhibited by the locomotor system)

The variability of a distribution is a measure of the extent to which the scores are spread around a given location, typically the mean. Studies typically report standard deviation as a measure of variability. As discussed in this research, however, individual MTC distributions are non-normal and, therefore, it is proposed that an alternative measure of variability be used for MTC data. This section discusses the important distinction between intra-individual (within-individual) and inter-individual (group) variability and justification for the selection of an alternative measure of intra-individual variability. This section also examines the precision of the locomotor

system in controlling the foot trajectory on an intra-individual and group basis and the extent of variability in this task.

In order to further examine the variability or dispersion of MTC about the intended MTC height ($median_{MTC}$), additional parameters were measured. These included $range_{MTC}$ ($max_{MTC} - min_{MTC}$), LQR_{MTC} (lower quartile range: $Q1_{MTC} - min_{MTC}$), UQR_{MTC} (upper quartile range: $max_{MTC} - Q3_{MTC}$), 98% rge_{MTC} (middle 98% of the distribution with upper 1% and lower 1% removed) and 90% rge_{MTC} (middle 90% of the distribution with upper 5% and lower 5% removed), min_{MTC}, max_{MTC} and various percentile measurements including $PC1_{MTC}$ (1^{st} percentile), $PC5_{MTC}$ (fifth percentile), $PC99_{MTC}$ (99^{th} percentile), $PC95_{MTC}$ (95^{th} percentile), $Q1_{MTC}$ (1^{st} quartile) and $Q3_{MTC}$ (3^{rd} quartile). These are discussed in relation to precision of the locomotor system in implementing MTC.

6.1.2.1 Intra-individual variability in MTC as measured by SD, IQR and CV'

Standard deviation measures the spread of values about the mean and is typically utilised as a measure of variability in research. However, since its calculation relies on the mean value, it may not be the most appropriate measure for non-normal distribution such as in this research. For non-normal distributions interquartile range ($75^{th} - 25^{th}$ percentile) is arguably a better estimate of the MTC variance about an individual's planned MTC height since, unlike standard deviation, it is not affected by outliers or skewed distributions. Coefficient of variance (CV) is commonly employed in research to indicate the degree to which a set of data varies. Its calculation involves both the mean and standard deviation and, like SD, may not be an appropriate measure of

variability for skewed distributions. By modifying CV by replacing standard deviation with IQR and mean with median a more reliable measure of variability can be obtained (Begg *et al.*, 2007):

$$CV' = (IQR/median) \times 100 \qquad \textbf{Equation 6.1.1}$$

Intra-individual variability gives an indication of the locomotor system's precision in implementing a consistent MTC. Group variability is typically presented in the literature, however, studies examining intra-individual descriptive statistics (e.g. intra-individual variability) are scarce. Most studies utilise SD as a measure of variability (intra- and inter-individual).

As shown in Table 5.13, Figure 5.5 and Figure 5.6, SD_{MTC}, IQR_{MTC} and CV'_{MTC} is significantly higher in the elderly compared with the young, where SD_{MTC} young = 0.22cm vs. elderly = 0.28cm (p<.01), IQR_{MTC} young = 0.28cm vs. elderly = 0.41cm (p<.01) and CV'_{MTC} young = 13.87 vs. elderly 20.04 (p<.001). These results show the elderly group exhibited a significantly higher degree of intra-individual variability compared with the young group. SD_{MTC}, IQR_{MTC} and CV'_{MTC} all illustrate a significantly greater MTC dispersion about the intended MTC height in the elderly group.

The young group contained data for one subject that was identified during exploratory data analysis as an extreme outlier for IQR_{MTC} and SD_{MTC} (young subject y7, refer Table 5.8) and the elderly group contained data for one subject that was identified as an outlier for CV'_{MTC} (elderly subject e5, refer Table 5.8). The use of median and IQR

instead of mean and SD is, therefore, supported since mean value will be erroneously high due to the high outliers.

Figure 6.3 shows the large max_{MTC} (6.77cm) that occurred during walking for young subject y7. The high max_{MTC} of 6.77cm occurred early in the walking at stride 112 of a total of 1063 strides.

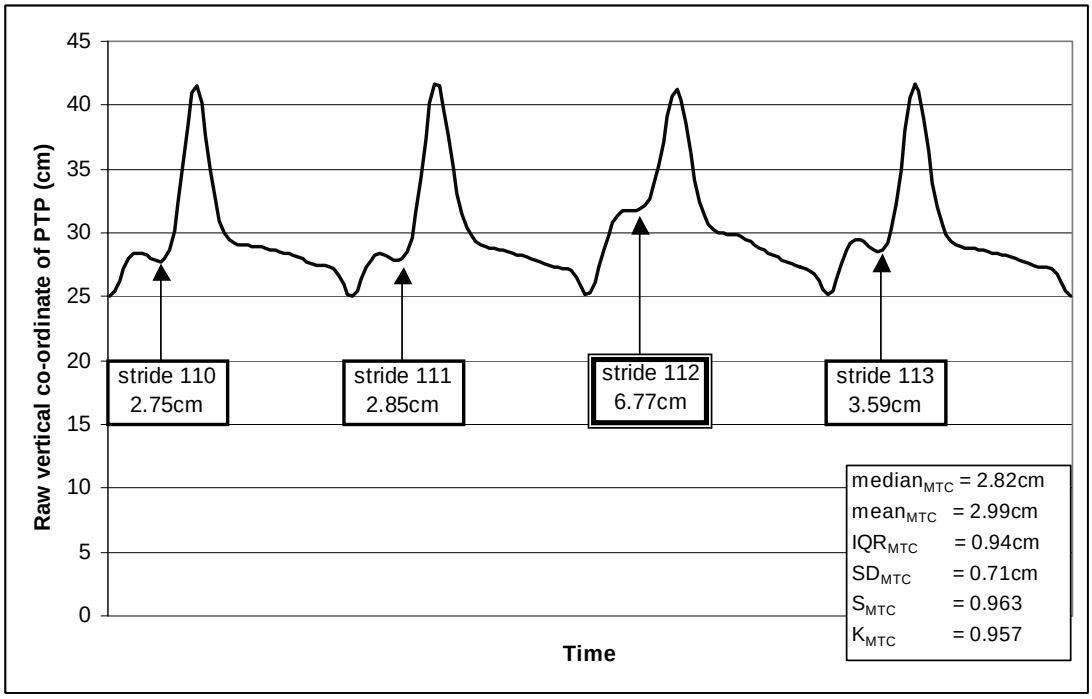


Figure 6.3: Extract of four strides for subject y7, showing large max_{MTC}.

The large max_{MTC} was the largest of all subjects and identified as an outlier. It can be seen to occur at stride 112.

It can be seen in Figure 6.3 that the two strides preceding max_{MTC} (6.77cm at stride 112) were close to the $median_{MTC}$ (2.82cm). Max_{MTC} was more than double the $median_{MTC}$ and the next stride was well above the $median_{MTC}$ also (3.59cm). It is not known what caused this large increase in $median_{MTC}$. These unusually high (or low) MTC should be investigated in future research. Although not within the scope of this

research, examination of bilateral MTC could be a useful area for future research and could help explain some of the reasons for outliers found in this research.

For illustrative purposes, the identified young extreme was deleted from the data set and the resulting group mean and standard deviation, and group median and IQR, for SD_{MTC}, IQR_{MTC} and CV'_{MTC} were re-calculated. The change in young group IQR_{MTC} descriptive statistics is shown in Figure 6.4.

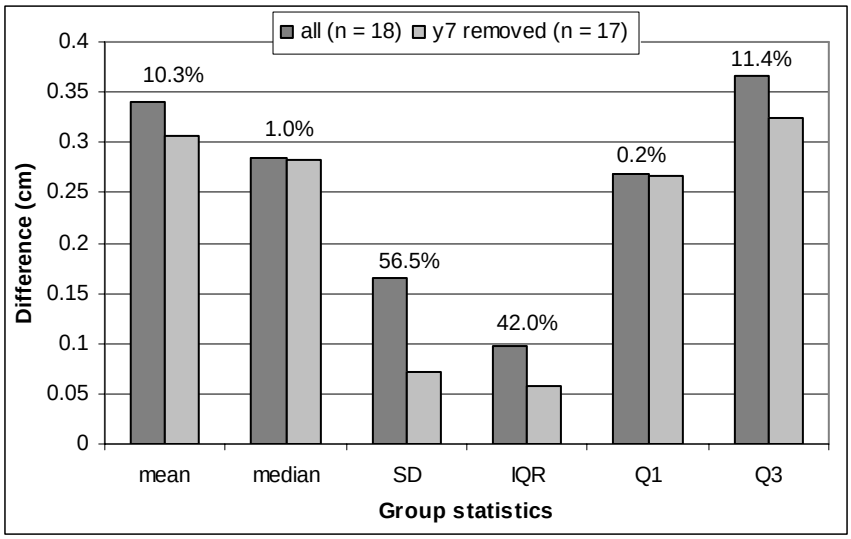


Figure 6.4: Comparison of young group IQR_{MTC} descriptive statistics for all (n = 18) and with extreme y7 removed (n=17).

Note: values above each pair of bars shows percentage difference in group descriptive statistics between n = 18 (all) and n = 17 (y7 removed).

It can be seen in Figure 6.4 that deleting young subject y7 from the data set resulted in larger changes to group central tendency as measured by mean compared with median and greater changes in group variability as measured by SD compared with IQR. For example, deleting data for young subject y7 from the young group resulted in a decrease in group mean IQR_{MTC} of 10.3% (from 0.34cm to 0.31cm with y7 deleted) whilst group median experienced effectively no change (1.0%). This shows the mean

and SD are affected more by only one extreme value and supports the use of median and, to a lesser extent, IQR as alternative, more accurate measures of central tendency and variability in a sample size of 18. Since IQR is a measure of variability within a distribution, it would be expected that the value reflect the occurrence of outliers within a data set. Although the difference in group IQR with the outlier (subject y7) removed is still quite high at 42% difference, there appears to be less variation than in SD (56% difference). It would be desirable to investigate appropriate measures of variability in future research.

While deleting y7 from the young group data set resulted in changes to the group descriptive statistics, it still did not produce a normal distribution as determined by Shapiro-Wilks statistic (p=.027). Since the young group was still non-normally distributed Mann-Whitney U test was performed and statistically significant age effects remained whilst comparing all subjects (n=18) with y7 removed ($p<.01$).

Group SD of $mean_{MTC}$ is presented in the literature as a measure of inter-individual or inter-group variability. In this research, group SD of $mean_{MTC}$ was 0.41cm and 0.50cm for young and elderly adults respectively. Group SD of $mean_{MTC}$ in the literature varies, e.g. 0.66cm and 0.62cm for young individuals as reported by Pijnappels *et al.* (2001) and Winter (1991a) respectively, and 0.62cm and 0.50cm for elderly individuals as reported by Karst *et al.* (1999) and Winter (1991a) respectively. The values reported in the literature are typically higher than in this study. In contrast to this research Winter (1991a) did not find significant age differences but found lower variability in the elderly group, concluding that the elderly had lost some of their neural plasticity and had become a more homogenous group. Winter's (1991a) study analysed a

minimum of eight separate strides of overground walking over a period of an hour while this research analysed each stride during 30 minutes of continuous treadmill walking. This major difference in data sample size and method (separate overground walking trials versus continuous treadmill walking at a constant velocity) may account for the differences in variability in MTC.

Consistent with published findings, this research found an individual's walking pattern can be highly variable. Indeed, Winter (1991a) highlighted that intra-individual variability can be greater for trials collected minutes apart compared with those collected days apart. The higher intra-individual variability in the elderly group for IQR_{MTC} and CV'_{MTC} indicate the young group exhibit greater control of the foot trajectory. That is, the locomotor system appears to be more precise in the young group since there is less dispersion of MTC values about the intended $median_{MTC}$.

Traditional views equate increased intra-individual variability with instability of the locomotor system and therefore increased intra-individual variability of gait parameters have been characterised as predictors for falling (e.g. Hausdorff *et al.*, 2001; Hausdorff *et al.*, 1997; Maki, 1997; Winter, 1991a; Gabell and Nayak, 1984; Guimaraes and Isaacs, 1980). Adopting this traditional view, the elderly subjects in this research are at an increased risk of falling since intra-individual variability is higher, suggesting less precision of the locomotor system in implementing MTC. The increased intra-individual variability is thought to be an indication of impaired adaptive control and an inability to compensate for instability and therefore an indication of increased falls risk.

It has been found that the increased intra-individual variability in elderly populations may be due to the reduced walking velocity and not to some pathological cause (e.g. Dingwell and Marin, 2006; Dingwell and Cavanagh, 2001; Dingwell and Cusumano, 2000). Figure 6.5 shows relative walking speed (RWS) plotted against IQR_{MTC} for each individual.

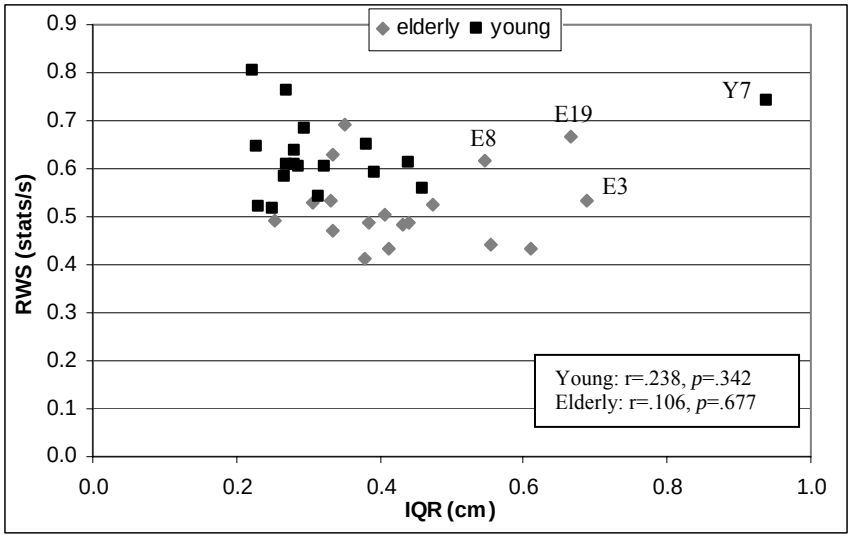


Figure 6.5: Relative walking speed (RWS) as a function of IQR_{MTC}. Three elderly and one young outlier subjects (labelled).

It can be seen in Figure 6.5 that no correlation exists between these two variables. The spread of elderly data, however, is greater than the young group. While the young group are clustered closer together, there is one outlier (y7). The correlation remains non-significant with this outlier removed from the data set. For this sample, therefore, the increased intra-individual variability in the elderly group is not related to slower walking speed.

6.1.2.2 Variability and dispersion of MTC as measured by the spread of MTC in the distribution.

Figure 6.6 shows various variability/dispersion measures including $range_{MTC}$, LQR_{MTC}, UQR_{MTC}, 98% rge_{MTC} and 90% rge_{MTC}.

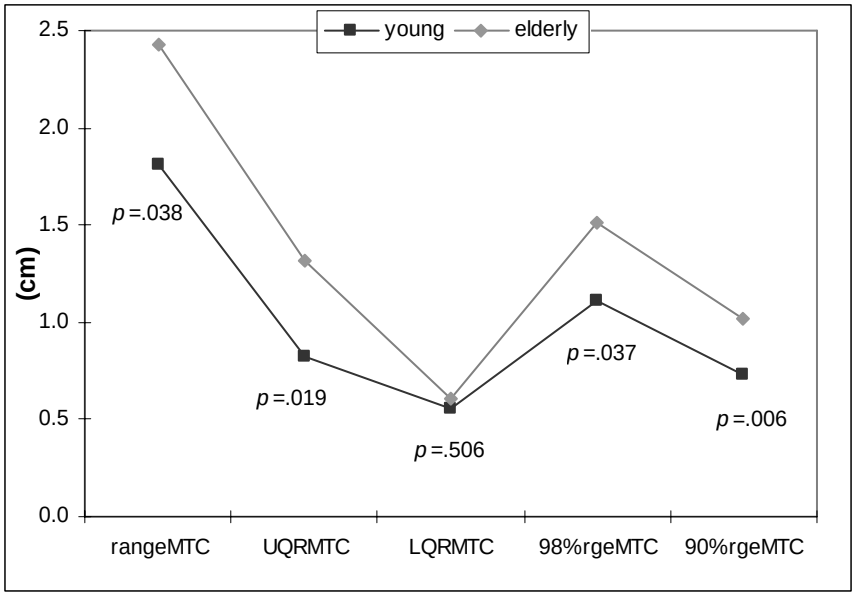


Figure 6.6: Comparison of various MTC variability/dispersion measures using group median values of each measure.

It can be seen in Figure 6.6 that all values are higher in the elderly group and all are statistically significant (at least $p<.05$) except within the lower end of the distribution (LQR_{MTC}). Greater $range_{MTC}$ for the elderly group is expected given their lower min_{MTC} and higher max_{MTC} (refer Figure 6.7). This difference is statistically significant ($p=.038$) suggesting that as a group the elderly exhibit less control of the foot trajectory with MTC values further from the median. These significant differences remained when the upper 1% and lower 1% (98% rge_{MTC}; $p=.037$) and upper 5% and lower 5%

(90% rge_{MTC}; p=.006) of the distribution (i.e. the most extreme MTC points) were removed.

The $range_{MTC}$ is useful in determining total dispersion for the MTC distribution but does not provide information as to where in the distribution MTC points are located relative to central tendency. UQR_{MTC} encompasses all MTC points between the 75th percentile and max_{MTC} whilst LQR_{MTC} encompasses all MTC points from min_{MTC} to the 25th percentile in each individual's MTC distribution. As Figure 6.6 shows, UQR_{MTC} is higher (approximately 59%) for the elderly group (group median: young 0.82cm vs. elderly 1.31cm) and has the greatest significant age effect (p=.019). The elderly group, therefore, exhibits a greater spread of MTC within this relatively unimportant right side of the distribution.

The spread of MTC values within the LQR_{MTC} is similar between the young and elderly groups (group medians: young = 0.56cm vs. elderly = 0.61cm) and, although not statistically significant, is a very important finding. It appears on initial examination that the elderly group exhibit a similar degree of control in the critical lower portion of the distribution. However, closer examination of parameters within the lower portion of the distribution reveals some important differences. Figure 6.7 shows percentile values and min_{MTC} and max_{MTC} for the entire MTC distribution.

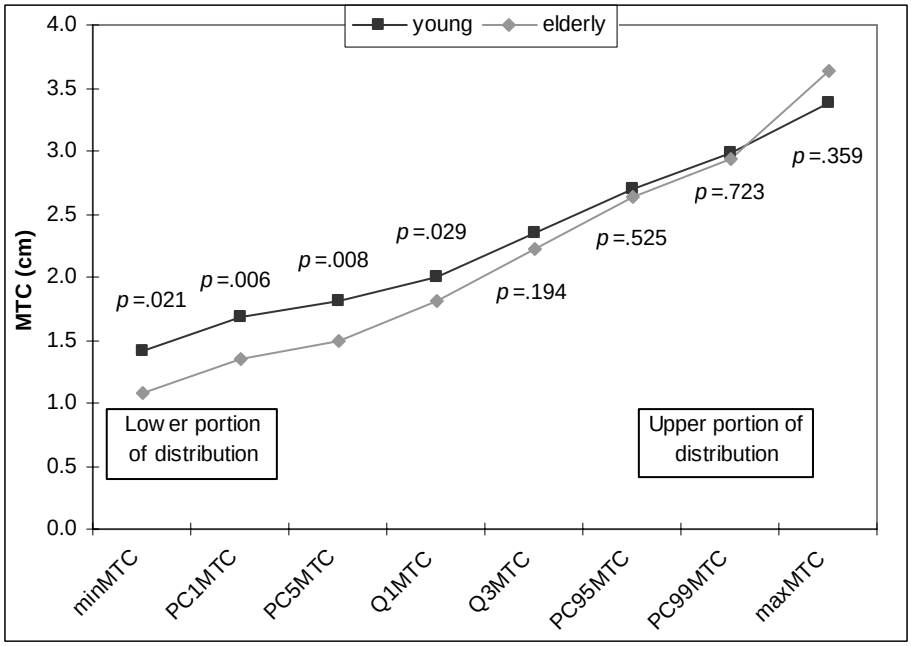


Figure 6.7: Comparison of dispersion variables of the lower and upper portions of the MTC distribution.

It can be seen in Figure 6.7 that in the lower portion of the distribution, namely for $Q1_{MTC}$, $PC5_{MTC}$, $PC1_{MTC}$ and min_{MTC}, MTC is significantly lower in the elderly for all measures. In the upper portion of the distribution there are no significant age effects. Elderly are lower on all measures except max_{MTC}, where they have higher values. Although range of values in the lower quartile of the MTC distribution (LQR_{MTC}) is similar between groups, the elderly group tend to have smaller MTC values within this range. Thus, the elderly tend to have smaller MTC, which, keeping all other factors constant, would increase the likelihood of tripping on unseen obstacles. This supports the notion that the elderly group in this research display less control of the locomotor system compared with the young group. These results show that examining central tendency and intra-individual variability (e.g. mean and SD or median and IQR) are not sufficient to gain a true understanding of the nature of the MTC distribution. For example, age effects for $median_{MTC}$ showed a trend only (p=.076) while all measures in

the lower portion of the distribution were significant at $p<.05$. The greatest differences were found at the lowest one percent ($PC1_{MTC}$, elderly = 1.35cm young = 1.68cm, $p=.006$) and lowest five percent ($PC5_{MTC}$, elderly = 1.50cm, young = 1.81cm, $p=.008$) of the MTC distribution. Future studies should endeavour to examine MTC at the low, more dangerous end of the MTC distribution.

6.1.2.2.1 Dispersion of MTC - Low MTC measures

As shown in Figure 6.7 the elderly group are significantly lower on all measures within the lower portion of the distribution. Although it initially appears the young and elderly display similar control in the lower portion of the distribution (LQR_{MTC}), the significantly lower min_{MTC} ($p=.021$), $PC1_{MTC}$ ($p=.006$), $PC5_{MTC}$ ($p=.008$) and $Q1_{MTC}$ ($p=.029$) shown by the elderly group suggest they are more likely to trip on small, unseen obstacles while walking.

In a large data set as used in this research, the min_{MTC} is a rare event, less than one in every 1,000 strides. The impact of such a low MTC is also dependent on the travel terrain at that instant. For example, if min_{MTC} occurred when MTC coincided with a raised portion of the footpath and the subject did not see this, a trip is likely to occur. Although min_{MTC} is a one-off event, it may be the irregular occurrence of unusually small MTC that causes a trip and a potentially injurious fall. $PC1_{MTC}$ and $PC5_{MTC}$ were measured, as it is likely that these parameters are more robust than min_{MTC}. Examination of the lowest MTC points is an important part of this research since these events are most likely to cause tripping on unseen obstacles. $PC1_{MTC}$ and $PC5_{MTC}$ were

measured as it is likely that these parameters are more robust than min_{MTC}. That is, min_{MTC} is a one-off event and sample size would need to be much larger to obtain a robust and reliable value for this parameter. $PC1_{MTC}$ and $PC5_{MTC}$, like min_{MTC} show similar trends of lower values for the elderly group. Given that the frequency of tripping is indicative of trip-related falls risk (Pavol *et al.*, 1999), examination of unusually small MTC that occur whilst walking and their characteristics is advantageous to trip-related falls research.

Five elderly subjects and only one young subject had min_{MTC} below 1cm. However, none of the young subjects were below 1cm on other measures in the lower portion of the distribution. The lowest min_{MTC} was 0.24cm (elderly subject e5), and this subject also had values below 1cm on all measures in the lower portion of the distribution ($Q1_{MTC}$ = 0.83cm, $PC1_{MTC}$ = 0.44cm, $PC5_{MTC}$ = 0.60cm). In fact, this subject appeared to have poor control of the foot trajectory with the smallest values on all variables in the lower portion of the distribution and highest value on UQR.

It is useful to examine this critical lower end of the MTC distribution since it is here where smaller MTC values may lead to a trip on an unseen obstacle. Whilst it is useful to examine central tendency of MTC (e.g. median) in order to examine the intent of the locomotor system, the spread of MTC values, particularly at the lower portion of the distribution is also critical. Since the elderly group has smaller MTC in the lower portion of the distribution and greater variability/dispersion of MTC, it is reasonable to suggest that, keeping all other factors constant, the elderly are at a higher risk of tripping on small unseen obstacles.

6.1.3 Symmetry/Distribution

Measures of symmetry/distribution, namely skew and kurtosis, are an important part of this research. A normal distribution has a skew value of zero indicating the distribution is symmetrical. Skewed distributions, therefore, are asymmetrical and have longer tails on one side of the distribution. The constraint of the ground results in scores piling at the lower end of the distribution, because scores lower than zero (the ground) are not possible and hence the positively skewed distribution (see Figure 6.8). Infrequently occurring high MTC values result in the long tail to the right side of the distribution, however, MTC are constrained at the high end also given the greater energy expenditure required.

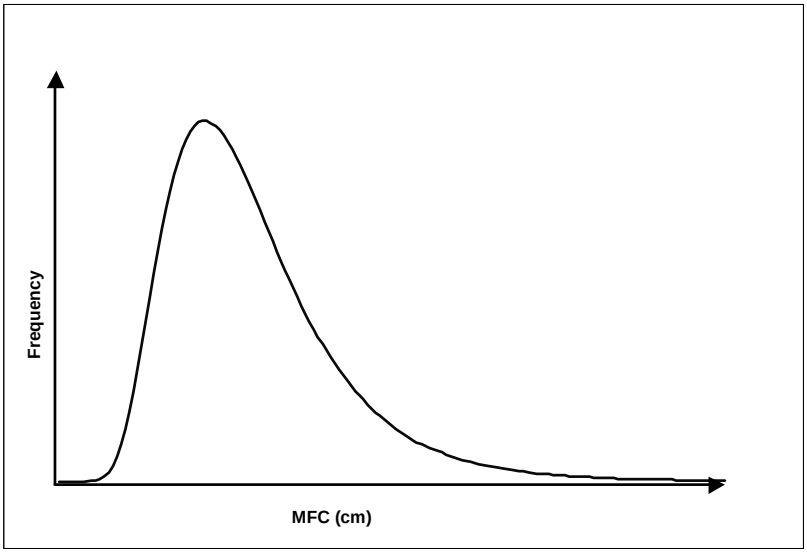


Figure 6.8: Positively skewed distribution.

As previously described in the methods section 4.5, kurtosis refers to the peakedness (or flatness) of a distribution compared with the normal curve. A normal distribution has a kurtosis value of zero. Negative kurtosis (platykurtosis) indicates a distribution is flatter than normal whilst positive kurtosis (leptokurtosis) indicates that higher

frequencies exist around the central tendency measure (therefore more peaked than normal) and/or the presence of some extreme values resulting in the thicker tails.

Skew and kurtosis are rarely reported in the literature despite their importance in determining the nature of the distribution. Skew and kurtosis influence the most appropriate measures of central tendency and variability used as descriptive statistics. The need to model skew and kurtosis to accurately estimate probability of tripping is also highlighted in this research (discussed later in section 6.1.4).

All skew (S_{MTC}) values were positive except for one young subject (y19, -0.21) and one elderly subject (e10, -0.06). Similarly, all kurtosis (K_{MTC}) values were positive except for one elderly subject (e10, -0.07). These negative S and K values were, however, only marginally below zero. The positive S_{MTC} suggests the constraint of the ground limited the spread of MTC to the left of the distribution. This is a critical element that means MTC distributions will always be non-normal and therefore consideration is required in selecting the most appropriate descriptive measures (e.g. central tendency and variability).

S_{MTC} was significantly higher in the elderly group compared with the young (p=.029) with group medians of 0.60 vs. 0.33 for the young group. No significant age differences existed for K_{MTC}. Within the elderly group there was one subject (e24) who had the highest S_{MTC} (2.97) and K_{MTC} (36.84). The large S_{MTC} and K_{MTC} for elderly subject e24 were due to two large MTC points of a data set of 1102 strides. Table 6.1 shows that deleting the largest and largest two MTC points in the distribution can considerably reduce S_{MTC} and K_{MTC} for the individual.

Table 6.1: Comparison of e24 variables with all data and some extremes removed.

Variable	all data	max deleted	max 1&2 deleted
$mean_{MTC}$	1.50	1.49	1.49
$median_{MTC}$	1.48	1.48	1.48
SD_{MTC}	0.27	0.25	0.24
S_{MTC}	2.97	0.67	0.25
K_{MTC}	36.84	3.93	0.58
min_{MTC}	0.76	0.76	0.76
max_{MTC}	5.32	3.48	2.82
$range_{MTC}$	4.56	2.72	2.06
$Q1_{MTC}$	1.32	1.32	1.32
$Q3_{MTC}$	1.66	1.66	1.66
$PC1_{MTC}$	0.96	0.96	0.96
$PC5_{MTC}$	1.11	1.11	1.11
IQR_{MTC}	0.34	0.33	0.33
CV'_{MTC}	22.64	22.62	22.61
Group mean S_{MTC}	***0.77***	***0.64***	***0.62***
Group median S_{MTC}	***0.60***	***0.60***	***0.54***
Group mean K_{MTC}	***3.15***	***1.32***	***1.14***
Group median K_{MTC}	***0.71***	***0.71***	***0.63***

It can be seen in Table 6.1 that individual (e24) $median_{MTC}$ is not affected when max_{MTC} and the next highest MTC are deleted and there is only a slight change in $mean_{MTC}$ (0.01cm or approximately 0.7% decrease). Large changes in S_{MTC} (from 2.97 to 0.67 and 0.25) and K_{TMC} (from 36.84 to 3.93 and 0.58) can be seen. Deleting the largest MTC in the distribution (5.32cm which occurred at stride 1030) resulted in group mean S_{MTC} of 0.64 (0.17 or 22% less than group mean considering all points) vs. group median S_{MTC} of 0.60 (unchanged from group median considering all points). Deleting the largest MTC also resulted in a group mean K_{MTC} of 1.32 (1.83 or 58% less than group mean considering all points) vs. group median of 0.71 (unchanged from group median considering all points). The change in descriptive statistics highlights that just one outlier can have a considerable affect on an individual's MTC profile and has the potential to alter group statistics (S_{MTC} and K_{MTC}). The greater changes in

$mean_{MTC}$ and SD_{MTC}, as opposed to little change in $median_{MTC}$ and IQR_{MTC} support the use of $median_{MTC}$ and IQR_{MTC} in skewed distributions such as in this research.

Figure 6.9 shows a comparison of group median S_{MTC} and K_{MTC} for the elderly for a) original elderly MTC data unmodified (n = 18); b) elderly data re-calculated after max_{MTC} of subject e24 was deleted (n = 18); and c) elderly data with subject e24 deleted (n = 17) group with the extreme e24 modified and deleted. Group median for the young group S_{MTC} and K_{MTC} are also shown.

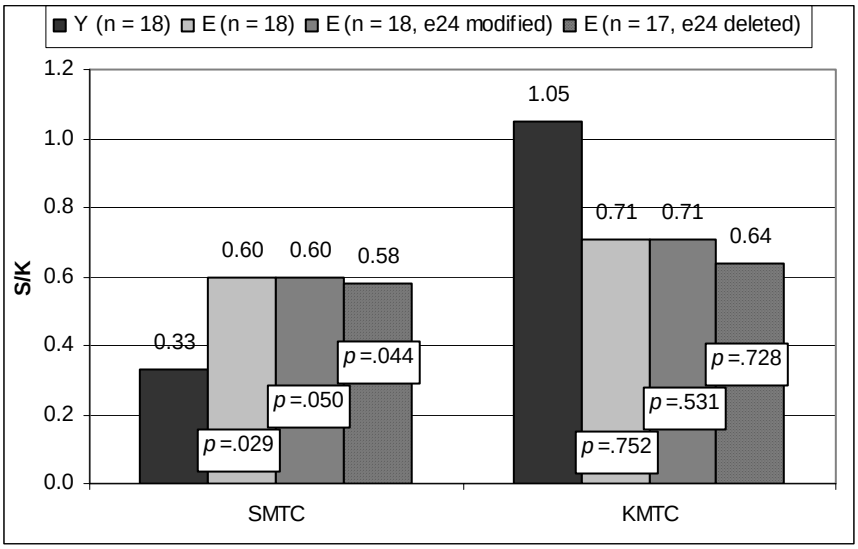


Figure 6.9: Comparison of group median S_{MTC} and K_{MTC} with elderly e24 extreme modified and deleted from elderly group.

It can be seen in Figure 6.9 that, despite the change to group S_{MTC} by deleting the extreme points, the elderly remain higher than young on S_{MTC}. Using all original elderly data resulted in the highest level of significant age effects for S_{MTC} (p=.029) while modifying or deleting the entire e24 data set resulted in a decrease in the level of

statistical significance. Changes to the data sets did not produce significant differences for K_{MTC}.

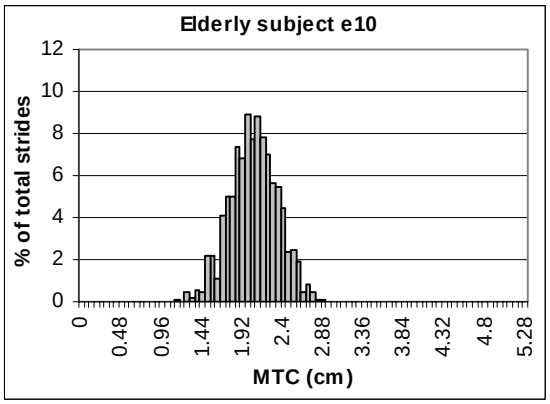
Whilst deleting these points was interesting for comparison they were included in the overall data since there was no reasonable justification for excluding them. That is, the large MTC points, like small ones, do occur occasionally and may be due to a minor trip or some other disturbance to gait. This situation highlights the high variability in an individual's gait and how descriptive statistics can be influenced by only one large extreme MTC. It should be noted also that the effect on central tendency and variability of one outlier in a large data set as used in this research (i.e. 1102 strides for subject e24) is small but would have a greater impact on the smaller data sets that are typically used in the literature.

Figure 5.3 shows combined group histograms for the young and elderly groups. Each MTC distribution was combined to form a histogram and group descriptive statistics were calculated based on the single combined MTC distribution. It can be seen that the young distribution is more peaked (leptokurtic) than the elderly distribution. In fact, K_{MTC} for the young group is almost double (93%) that of the elderly group (young = 2.40 vs. elderly = 1.24). It can be seen that frequencies of MTC around the central tendency ($median_{MTC}$) reach over 4.5% of the total distribution in the young group but fewer than 4.5% for the elderly distribution. This shows that more young subjects had MTC close to the central tendency. S_{MTC} is higher for the young group (young = 0.98 vs. elderly = 0.77), largely due to the high max_{MTC} (6.77cm vs. 5.32 for elderly) thereby lengthening the tail on the right of the distribution.

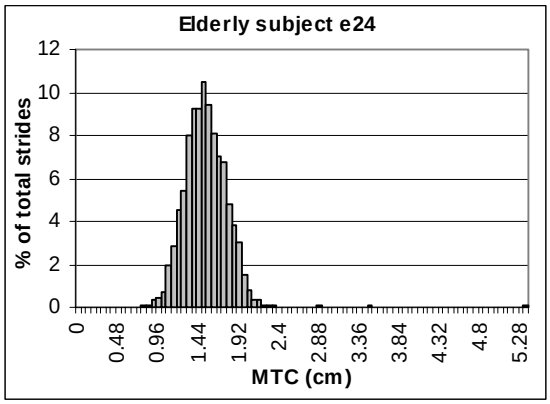
It can also be seen that the elderly group has a longer and thicker tail on the critical left side of the distribution. This indicates more small MTC points for the elderly group. In fact, it can be seen that the curve begins to rise steadily from the left side after approximately 1cm for the elderly distribution whereas it is approaching 1.5cm for the young distribution. Confirming this is the lower MTC at both $PC1_{MTC}$ and $PC5_{MTC}$ for the elderly group. For $PC1_{MTC}$ the elderly group were 0.64cm or 45% lower than the young group (elderly = 0.78cm vs. young = 1.42cm). Likewise, the elderly group was 0.40cm or 25% lower than the young group for $PC5_{MTC}$ (elderly = 1.21cm vs. young = 1.61cm). On an individual basis all but two subjects (young subject y19 and elderly subject e10) had positively skewed MTC distributions. Positive skew would be expected since the ground constraint (y = 0cm) reduces the number of MTC points close to zero and eliminates the possibility of points less than zero. Interestingly, elderly subject e10 was also the only subject to have negative kurtosis in the MTC distribution, although this was very close to zero and the closest to zero of all subjects. In fact, the skew (-0.06) and kurtosis (-0.07) values were the closest to zero of all subjects, and therefore e10 had a MTC distribution closest to a normal distribution of all subjects. This subject (e10) was the only elderly subject to have normally distributed MTC data as measured by Kolmogorov-Smirnov statistic.

Figure 6.10 shows three different histograms depicting three different MTC distributions, that is, chart a) with near-normal distribution, chart b) with high skew and kurtosis and chart c) distribution with skew and kurtosis 'typical' of the elderly group, defined as such since it is the closest to the group median S_{MTC} of 0.60 and K_{MTC} of 0.71.

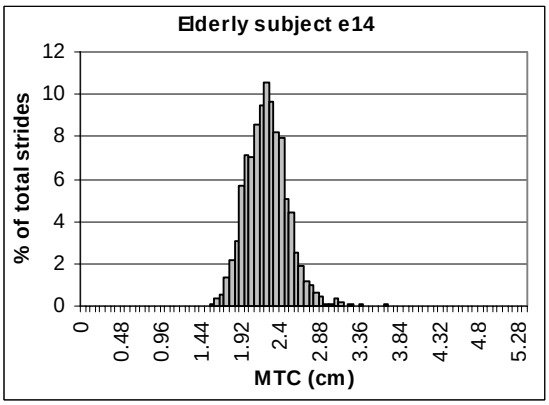
a)



b)



c)



	subject	strides	mean (cm)	median (cm)	skew	kurtosis	min (cm)	max (cm)
a)	e10	883	2.02	2.03	-0.06	-0.07	1.14	2.86
b)	e24	1102	1.5	1.48	2.97	36.84	0.76	5.32
c)	e14	911	2.19	2.18	0.67	1.81	1.54	3.65

Figure 6.10: Selected MTC histograms for elderly subjects; a) shows a histogram with near normal skew and kurtosis; b) shows a histogram with a high skew and kurtosis; c) shows a histogram of a 'typical' elderly subject with respect to skew and kurtosis. Corresponding descriptive statistics for each chart can be found in the accompanying table.

Since each MTC distribution varied in sample size (i.e. each varied in total stride numbers), the histograms have been normalized to show a relative frequency of percentage of total strides. It can be seen that chart a) is almost symmetrical with the MTC values clustered roughly around the mean of 2.02cm. In a normal distribution mean and median are equal and in this distribution median is almost equal to mean at 2.03cm. Chart b) shows a more peaked distribution with a longer tail to the right due to three high outliers (2.82cm, 3.48cm and 5.32cm). As already discussed, the

distribution approaches normal with the largest alone or the largest two outliers deleted. Chart c) shows an MTC distribution typical of the elderly group skew and kurtosis. Several larger MTC points can be seen resulting in skew to the right (positive skew).

Only one elderly subject (e10) and five young subjects (y1, y16, y18, y23 and y24) had normally distributed MTC data as measured by Kolmogorov-Smirnov statistic (refer Table 5.10). The nature of the MTC distribution and the constraint on the left hand side will almost always result in a non-normal distribution, i.e. skewed to the right. The length of the tail to the right (higher MTC) will be constrained by the need to conserve energy. The shape, or normality, of a distribution is typically not considered in the research but it has important implications on conducting statistical tests since most classical statistical tests assume normality of the data.

Figure 6.11 shows kurtosis of the MTC distribution as a function of skew of the MTC distribution for young and elderly subjects. A normal distribution, shown at the bottom left, has a skew value of 0 and kurtosis value of 0, and can be seen marked on the graph.

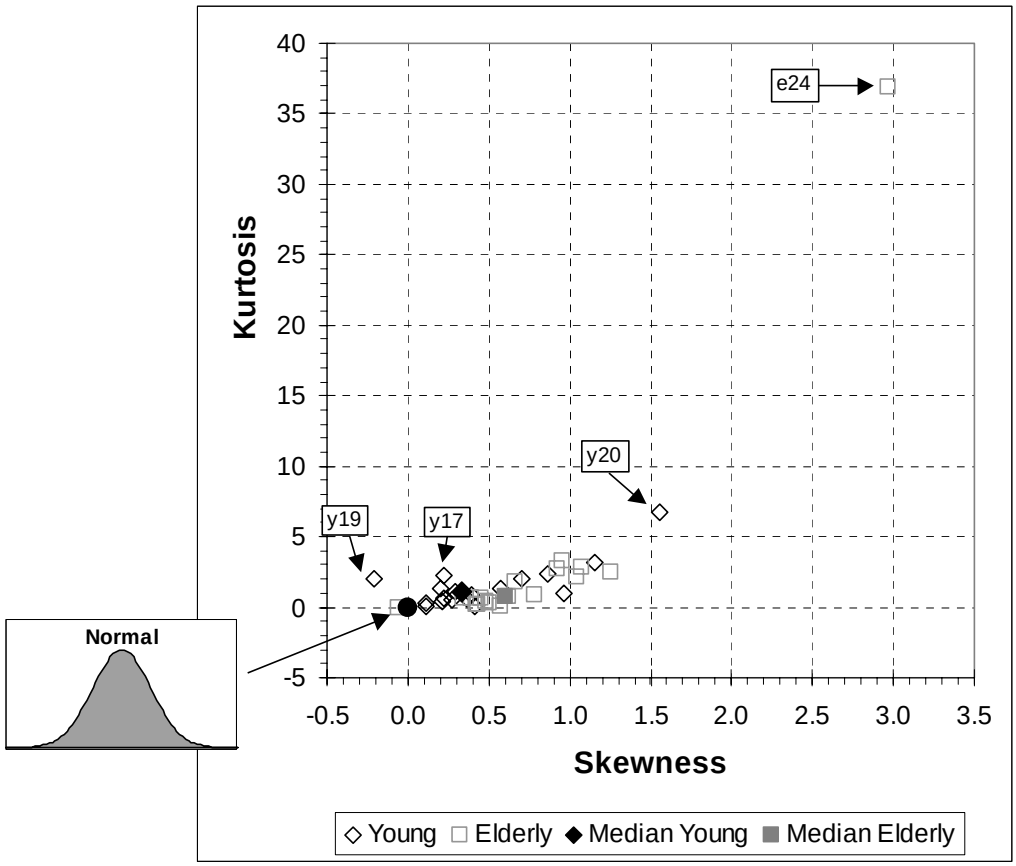


Figure 6.11: Relationship of K_{MTC} as a function of S_{MTC} and comparison of three different distributions.

The S_{MTC} and K_{MTC} in this study are systematically non-zero. All but two subjects (elderly subject e10 and young subject y19) have positive S_{MTC} and all but one (elderly subject e10) has positive K_{MTC} (refer results section, Table 5.10). Four subjects stand out as being different from the rest. These include three young subjects, young subject y17 (S_{MTC} = 0.22, K_{MTC} = 2.30), young subject y19 (S_{MTC} = -0.21, K_{MTC} = 1.96) and young subject y20 (S_{MTC} = 1.55, K_{MTC} = 6.70) and one elderly subject, elderly subject e24, who had the highest S_{MTC} and K_{MTC} of the entire sample (S_{MTC} = 2.97, K_{MTC} = 36.84).

The only other subject with negative S_{MTC}, elderly subject e10, who was also the only subject to have a negative K_{MTC} value, does not differ from the group clustered around the log normal curve by visual examination. In fact, this subject, with a $S_{MTC} = –0.06$ and $K_{MTC} = –0.07$, is the closest to the normal distribution of skew = 0 and kurtosis = 0.

The median S_{MTC} and K_{MTC} for young and elderly subjects are also shown. It can be seen that the elderly median is more skewed but the young distribution has higher kurtosis. For the young group, $S_{MTC} = 0.328$ and $K_{MTC} = 1.051$, whilst the elderly group have median $S_{MTC} = 0.600$ and $K_{MTC} = 0.710$. The higher median S_{MTC} for the elderly is due to their $median_{MTC}$ being lower and the occurrence of some larger MTC points. The aim of the locomotor system is to reduce the number of points in the lower end of the distribution in order to avoid tripping. With an already low $median_{MTC}$, the occurrence of any lower MTC increases the risk of tripping in the elderly group. S_{MTC} and K_{MTC} can be considerably altered by even a few extreme MTC points and has been discussed in relation to elderly subject e24 (refer Table 6.1) who had high S_{MTC} (2.97) and K_{MTC} (36.84). It was shown that when the two extreme high MTC points were deleted from the data set, the individual's MTC profile changed considerably.

S_{MTC} had a significant positive correlation with UQR_{MTC} for both young and elderly groups (young r = 0.736, p=.001; elderly r = 0.863, p<.001). Significant correlation existed after outlier and extreme subjects (as identified in SPSS) were removed from the data set (young group – UQR_{MTC} y7 = 3.37, S_{MTC} y20 = 1.55; elderly group UQR_{MTC} e24 = 3.67, S_{MTC} e24 = 2.97). A high UQR_{MTC}, therefore, is associated with an increased S_{MTC}. This strategy, employed by both the young and elderly groups, ensured MTC were not close to the constraint of the ground. The young group also

showed a significant positive correlation with max_{MTC} (r=0.579, *p*=.012), however, the elderly group showed a trend toward significance (r=.465, *p*=.052). This shows that, in the young group, increase in S_{MTC} was more affected by max_{MTC}, a one-off event. In contrast, the elderly S_{MTC} was more affected by the greater UQR_{MTC}, or a greater proportion of the MTC distribution in the upper end of the distribution. These results suggest that the elderly have made an attempt to reduce the likelihood of the foot striking the ground by having a greater proportion of strides in the upper end (higher MTC) of the distribution.

K_{MTC} showed significant positive correlation with UQR_{MTC} also (young r=.547, *p*=.019; elderly r=.857, *p*<.001). K_{MTC} was also highly correlated with S_{MTC} for both groups (young r=.734, *p*=.001; elderly r=.912, *p*<.001). K_{MTC} showed a significant positive correlation with max_{MTC} for the elderly group but not the young group (young r=.421, *p*=.082; elderly r=.490, *p*=.039). The reverse was shown when extremes were removed from the data set. That is, after young extreme subjects (y20 with max_{MTC} = 6.77cm and K_{MTC} = 6.70) and elderly extreme subjects (e24 K_{MTC} = 36.84) were removed, significant correlation was seen in the young group between max_{MTC} and K_{MTC} (r=.721, *p*=.002) but not the elderly (r=-.027, *p*=.918).

These correlations support the suggestion that positive S_{MTC} and K_{MTC} are strategies used to increase MTC in the upper portion of the distribution, thereby minimizing those close to the constraint of the ground for both young and elderly. In fact, the study by Begg *et al.* (2007) also concluded that increasing S_{MTC} was a strategy employed by older adults to reduce the risk of tripping and that S_{MTC} and K_{MTC} were highly correlated in both groups (young: *r*=0.60, *p*=0.01; elderly: *r*=0.95, *p*<0.01).

6.1.4 Probability of tripping

This section discusses PT_{MTC}, calculated for young and elderly individuals from MTC(y) 0.0cm to 6.0cm. This section begins with general observations, including justification for the use of median over mean for group central tendency. Age effects of probability of tripping (PT) at the different obstacle height/MTC(y) are examined and case studies of individual profiles are used to illustrate pertinent points. Finally, individuals identified at high and low risk of tripping are identified and discussed.

Figure 6.12 shows the group median PT as a function of MTC(y) and also shows max (the maximum PT_{MTC} at each value of MTC(y)) and min (minimum PT_{MTC} at each value of MTC(y)) for both groups.

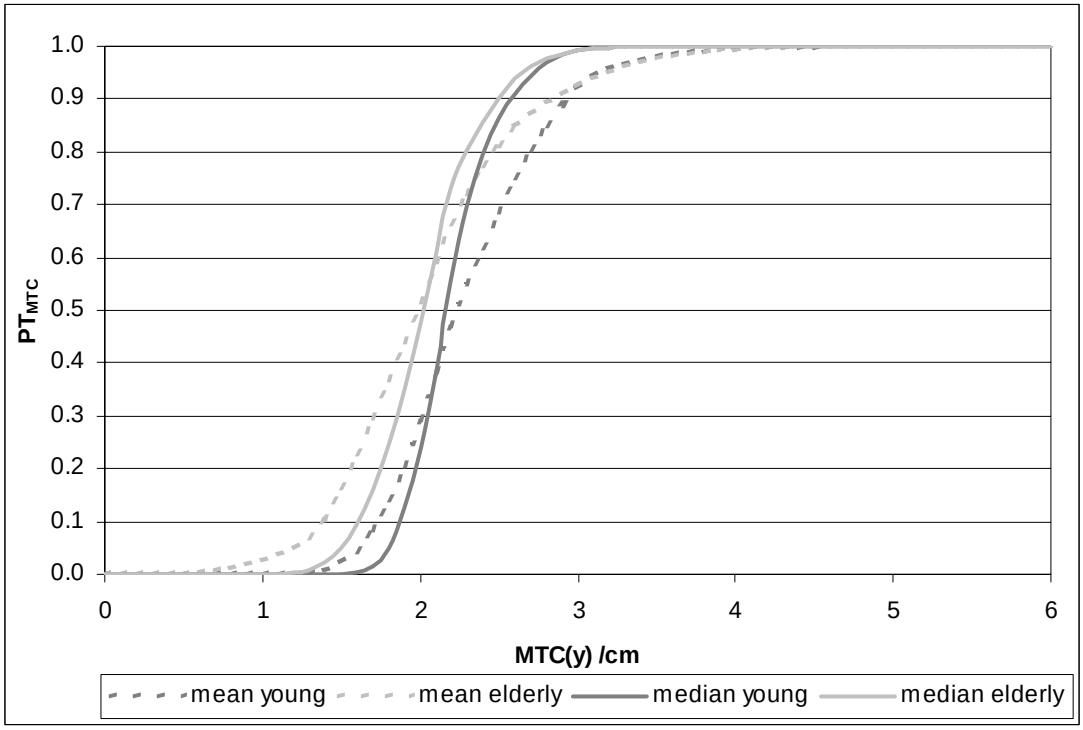


Figure 6.12: Mean and median PT_{MTC}.

The difference between the group mean and median as a measure of group central tendency for PT is noticeable in Figure 6.12. It can be seen that the majority of the MTC points lie between the PT_{MTC} = 0.05 and PT_{MTC} = 0.95. At PT_{MTC} = 0.05, the median values for young and elderly are MTC(y) = 1.8cm and 1.5cm respectively, whilst mean values are lower with values of MTC(y) = 1.6cm and 1.2cm respectively. Similarly, at the opposite end of the distribution, the median values of MTC(y) at PT_{MTC} = 0.95 for young and elderly are approaching unity at MTC(y) = 2.7cm and 2.6cm respectively, whilst mean values for the two groups are equal at a value of MTC(y)=3.2cm. Given the non-normality of the group data this profile illustrates the importance of choosing the median over mean for non-normally distributed data.

Figure 6.13, chart a) shows group median, minimum (min) and maximum (max) PT_{MTC} at each value of MTC(y).

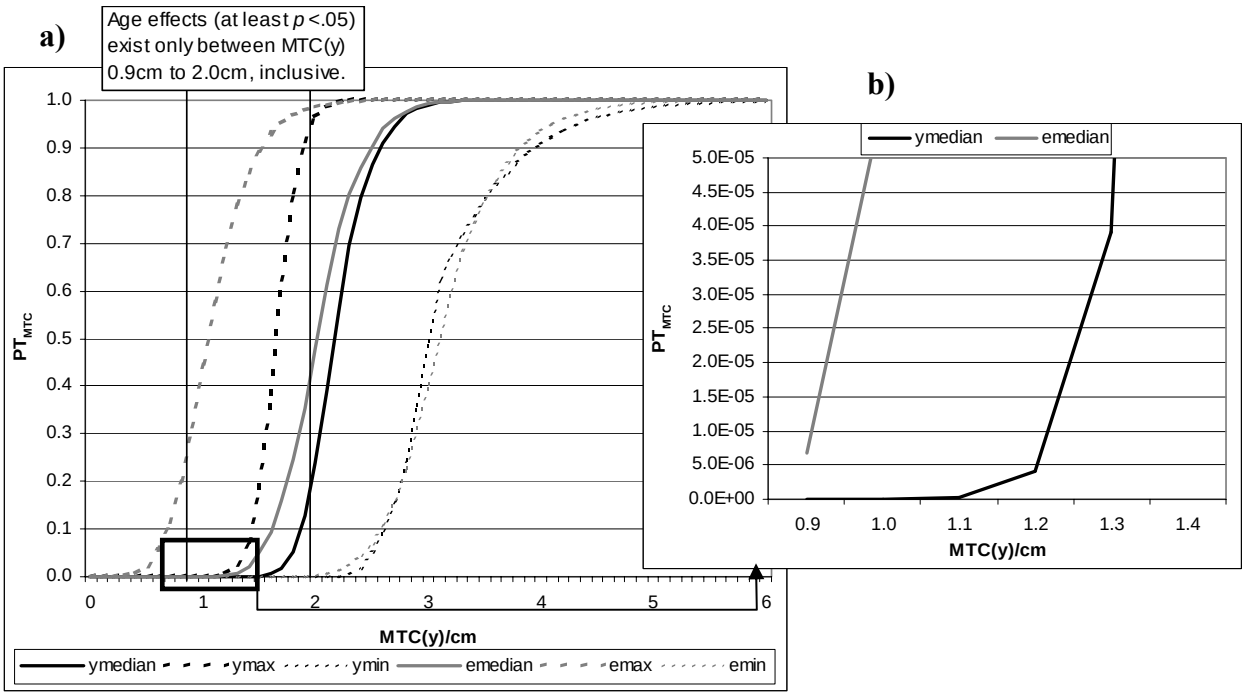


Figure 6.13: Median, minimum (min) and maximum (max) PT_{MTC}(y) for young and elderly. y=young group; e = elderly group.

While initial examination of Figure 6.13 chart a) suggests no difference in group median PT_{MTC} from MTC(y) = 0.0cm to approximately 1.3cm, and in the upper end from approximately 3.0cm, it can be seen in Table 5.18 and Figure 6.13 chart b) that infinitesimally small, but statistically significant, differences in PT_{MTC} exist from MTC(y) = 0.9 to 2.0cm. That is, PT_{MTC} is significantly higher in the elderly compared with the young group between MTC(y) = 0.9cm to 2.0cm. The significantly higher PT_{MTC} in the elderly is not unexpected given the elderly group's significantly lower $median_{MTC}$ (young = 2.16cm vs. elderly = 2.01cm, p=.076, refer Table 5.11 and Figure 5.4), min_{MTC} (young = 1.42cm vs. elderly = 1.08cm, p=.021, refer Table 5.14 and Table 5.11) and $PC5_{MTC}$ (young = 1.79cm, elderly = 1.54cm, p=.029, refer Table 5.14 and Figure 5.8) and significantly higher IQR_{MTC} (young = 0.28cm vs. elderly = 0.41cm, p=.003, refer Table 5.13 and Figure 5.5). For example, PT_{MTC}(0.9cm) was $<1x10^{-7}$ (less than 1 in 10,000,000 strides) for the young and $7x10^{-6}$ (1 in 268,502 strides, p=.026, refer Table 5.18 and Table 5.19) for the elderly. PT_{MTC}(1.5cm) = 0.001 (1 in 717 strides) for the young group and 0.05 (1 in 22 strides) for the elderly group, p=.005). These results all suggest the elderly are at a greater risk of tripping on unseen obstacles 0.9cm to 2.0cm compared with the young subjects.

It can be seen in Figure 6.13 chart a) that the young and elderly groups differ minimally for minimum PT (low PT). In contrast, however, maximum PT (high PT) for the two groups is quite different with the elderly having higher PT. Notice also that the difference between the young and elderly groups is largest at the critical lower end of the distribution. For example, the maximum PT_{MTC}(0.5cm) = 0.02 (1 in every 44.2 strides) for elderly and $5.4x10^{-5}$ (1 in every 18,618 strides) for young subjects. Thus, the maximum PT_{MTC}(y) values calculated for the elderly group show that they are at a

higher risk of tripping at smaller values of MTC. Keeping all other factors constant, the elderly are more likely to trip on smaller obstacles.

The inter-individual variability can be seen by the difference between the maximum and minimum PT_{MTC}. Much useful information, therefore, can be gleaned by examination of individual PT profiles. The profile of PT_{MTC} as a function of obstacle height/MTC(y) is presented for each individual in Figure 6.14 and Figure 6.15. The group mean and median PT_{MTC} are also shown.

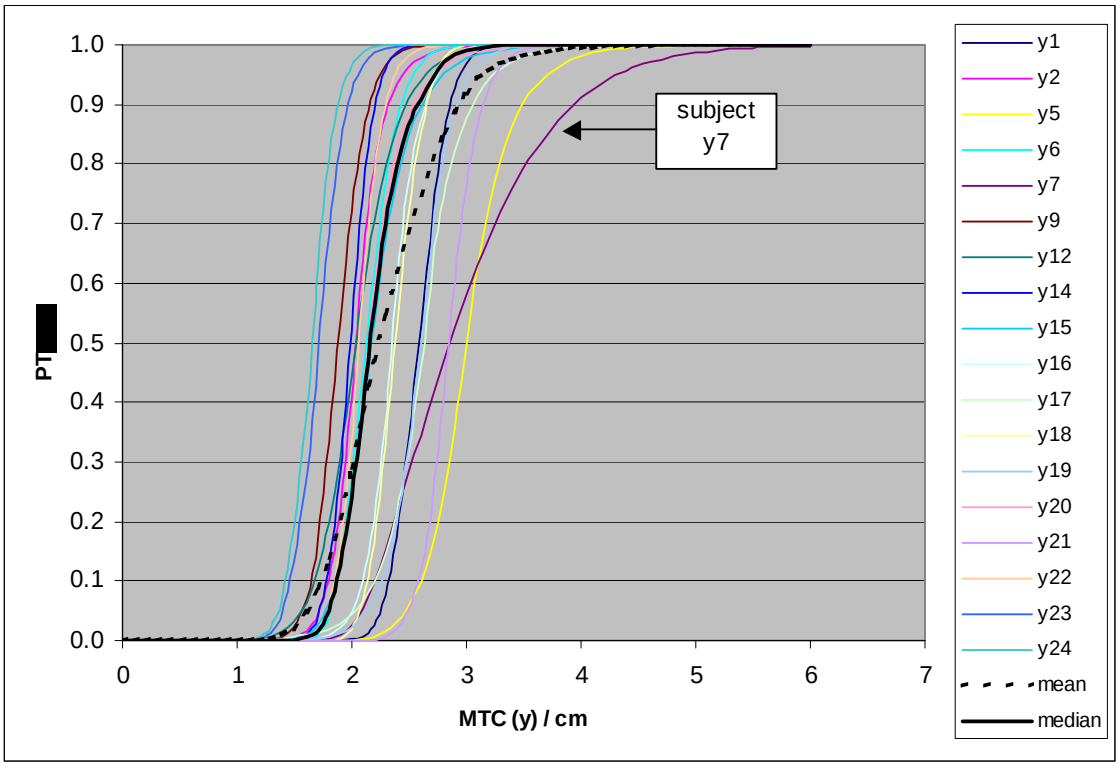


Figure 6.14: PT_{MTC} vs obstacle height / MTC(y) for young group.

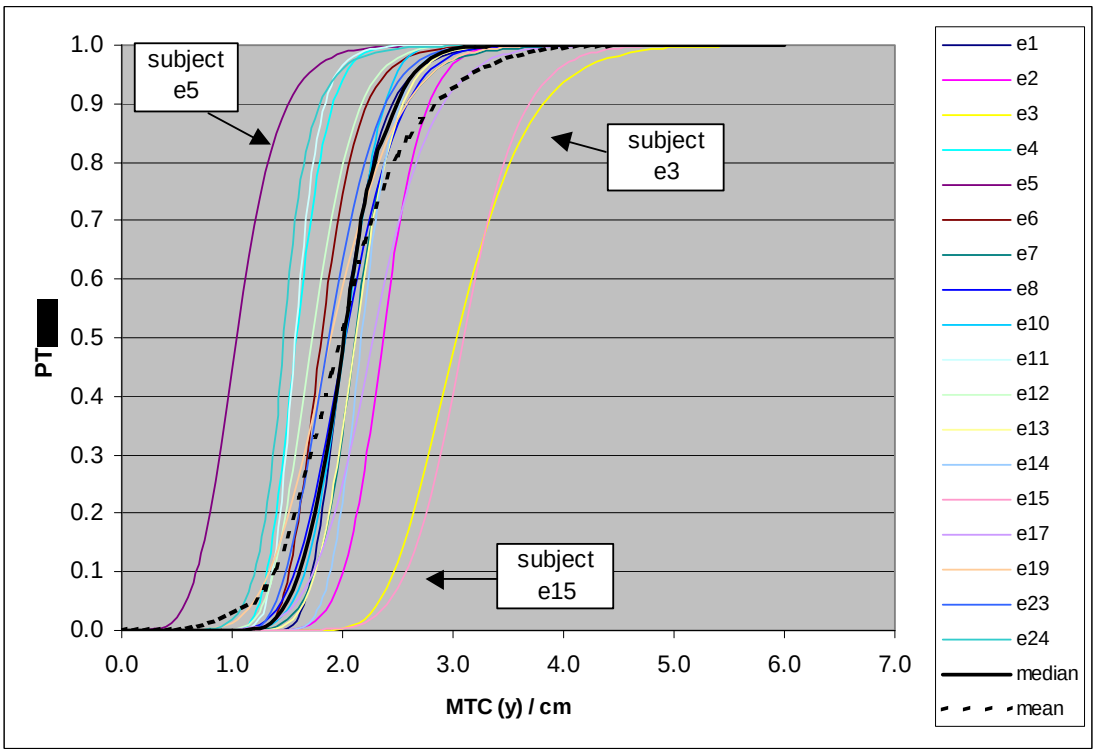


Figure 6.15: PT_{MTC} vs obstacle height / MTC(y) for elderly group.

The first general observation of Figure 6.14 and Figure 6.15 is that at a given value of PT_{MTC}, the corresponding MTC(y) is lower in the elderly compared with the young. For example, the value of MTC at which a trip is expected at approximately every second stride is MTC(y) = 2.0cm for the elderly group and MTC(y) = 2.2cm for the young group (PT_{MTC}(2.0cm) = 0.5 for the elderly and PT_{MTC}(2.2cm) = 0.5 for the young). This is not a surprising result given that the elderly have significantly lower $median_{MTC}$ (2.01cm) compared with the young (2.16cm) (p=.076, refer Figure 5.4 and Table 5.11). Compounding this situation is the significantly lower MTC in the lower portion of the MTC distribution (refer Table 5.13, Table 5.14, Figure 5.7 and Figure 5.8) and the significantly higher IQR_{MTC} (p=.003, refer Figure 5.5 and Table 5.13) of the elderly individuals resulting in an increased frequency of low MTC, which increase the risk of tripping.

Group $median_{MTC}$ is approximately equal to a PT_{MTC} = 0.5 (1 in every two strides). Significant age effects were found at MTC(y) = 2.0cm with the young group having a risk of tripping half that of the elderly (young PT_{MTC}(2.0cm) = 0.24 or 1 in every 4.2 strides vs. elderly PT_{MTC}(2.0cm) = 0.48 or 1 in every 2.1 strides, p=.037, refer Table 5.18 and Table 5.19. Table 6.2 shows each individual's $median_{MTC}$ and the frequency of tripping when MTC(y) = individual $median_{MTC}$. The results suggest that, keeping all other factors constant, an individual has a risk of tripping every second stride at MTC(y) = $median_{MTC}$, which is an important finding. It seems that, keeping all other factors constant, each individual has equal PT at MTC(y)=$median_{MTC}$. While PT is approximately equal at individual $median_{MTC}$, it can be seen that subjects vary and that the value of MTC(y) at which $PT_{MTC} \approx 0.5$ ranges from 1.6cm to 2.5cm for the young

group and 1.7cm to 2.1cm for the elderly group. Clearly the lower values of PT_{MTC} are more at risk of tripping given the smaller MTC.

Table 6.2: Individual frequencies of tripping at MTC(y) = individual median$_{MTC}$.

subject	Frequency of tripping (strides/trip)	median$_{MTC}$ (cm)	subject	Frequency of tripping (strides/trip)	median$_{MTC}$ (cm)
y1	1.9	2.59	e1	2.1	2.00
y2	2.5	2.03	e2	1.8	2.36
y5	2.0	2.99	e3	2.1	3.02
y6	2.3	2.12	e4	1.9	1.58
y7	2.1	2.82	e5	1.7	1.06
y9	1.9	1.89	e6	2.1	1.81
y12	1.7	2.05	e7	2.1	2.09
y14	1.9	1.98	e8	2.1	2.01
y15	1.9	2.17	e10	2.1	2.03
y16	1.7	2.36	e11	1.8	1.58
y17	2.2	2.63	e12	2.1	1.72
y18	1.9	2.39	e13	2.1	2.11
y19	2.0	2.59	e14	1.8	2.18
y20	1.7	2.16	e15	2.0	3.10
y21	1.7	2.85	e17	1.9	2.27
y22	1.7	2.08	e19	2.0	1.89
y23	2.1	1.72	e23	1.9	1.86
y24	1.6	1.65	e24	1.8	1.48
median	**1.8**	**2.16**	**median**	**2.1**	**2.01**
min	1.6	1.7	min	1.7	1.1
max	2.5	3.0	max	2.1	3.1

Three elderly subjects in Figure 6.14 (e3, e5 and e15) are highlighted and one young subject in Figure 6.15 (y7) since they are most obviously different from the remainder of the two respective groups. Elderly subject e3 and e15 are highlighted due to the lower PT_{MTC} compared with the group while elderly subject e5 has increased PT_{MTC} compared with the rest of the group. Young subject y7 has a lower PT_{MTC} at the higher values of MTC(y). Apart from young subject y7, there are no apparent outliers for the young group, although there clearly are some differences in the group. To illustrate the differences between these four subject, Figure 6.16 shows values of PT_{MTC} = 0.01 (frequency of tripping approximately 1 in 100 strides), 0.1 (frequency of tripping

approximately 1 in every 10 strides), 0.5 (frequency of tripping approximately 1 in every 2 strides) and 0.9 (frequency of tripping approximately 1 in every 1.1 strides) and the corresponding MTC(y). These PT_{MTC} were chosen in order to give a range of PT_{MTC} with both high and low values. The group medians for the young and elderly are also shown.

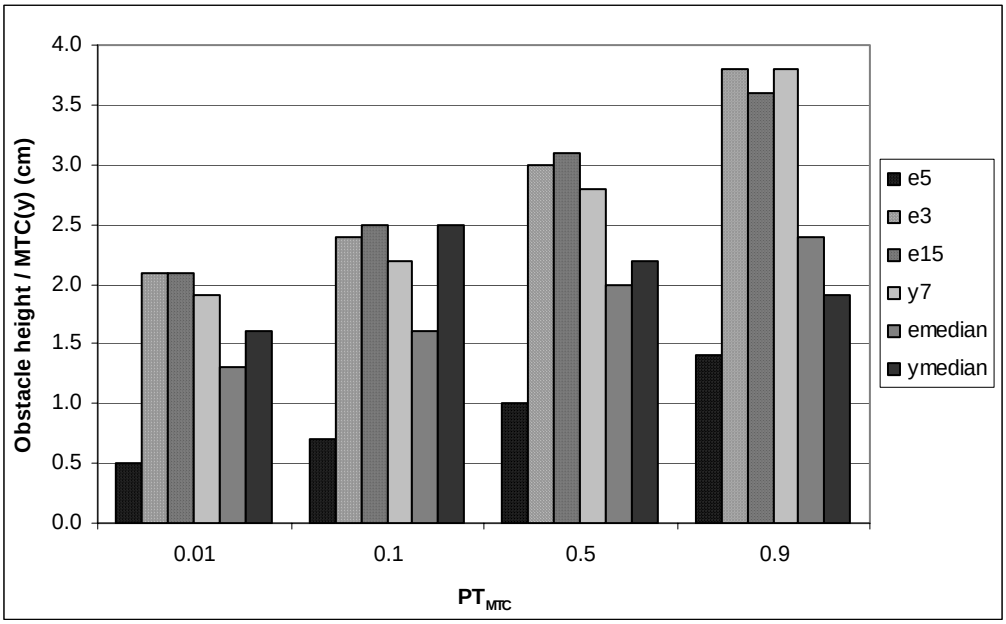


Figure 6.16: MTC(y) at values of PT_{MTC} = 0.1, 0.5 and 0.9.

It can be seen in Figure 6.16 that at each value of PT_{MTC}, elderly subject e5 has lower values of MTC(y), resulting in an increased PT_{MTC} at smaller values of MTC(y). This represents a considerable risk of tripping for elderly subject e5 and is a concern given that tripping frequency is a strong predictor for falls (Pavol *et al.*, 1999). This is perhaps not surprising given e5 had the lowest $median_{MTC}$ (1.06cm) and lowest values of all measures within the lowest end of the MTC distribution, namely min_{MTC} (0.24cm), $Q1_{MTC}$ (0.83cm), lowest $PC1_{MTC}$ (0.44cm) and $PC5_{MTC}$ (0.60cm), refer Figure 5.4, Figure 5.8 and Table 5.11 and Table 5.14. Given that elderly subjects are less likely to recover from a trip leading to a possible fall, elderly subject e5 is

identified at a high risk of tripping on unseen obstacles during undistracted walking. While apparently healthy and physically active the PT method and use of MTC descriptive statistics appear to be sensitive in detecting higher risk of tripping. Individuals with PT profiles and MTC descriptive statistics like e5 should be targeted for preventative programs.

One young subject (y7) is identified as differing from the remainder of the young group. It can be seen that up to approximately PT_{MTC} = 0.25, the profile for y7 is similar to the rest of the group. The PT for the remainder of the distribution is somewhat less than the group and from approximately PT_{MTC} = 0.65, subject y7 has the lowest PT (i.e. from approximately MTC(y) = 3cm upwards. The fact that y7 had such low PT_{MTC} at low values of MTC(y) is not surprising given the high values in the MTC distribution. For example, y7 had high $median_{MTC}$ (2.82cm), min_{MTC} (1.62cm), $Q1_{MTC}$ (2.46cm), $Q3_{MTC}$ (3.40cm), which all assist in reducing the risk of tripping by minimising the frequency of MTC close to the ground. Table 6.3 shows PT_{MTC} at various values of MTC(y) for young subject y7 and group median for young and elderly groups. The data presented in Table 6.3 assist in illustrating the very low PT in y7 and the very high PT in e5 compared with the rest of the two groups.

Table 6.3: PT_{MTC} and Frequency of tripping at various obstacle heights/MTC(y) for young subject y7, elderly subject e5, young group and elderly group median.

MTC(y)	PT_{MTC}				Frequency of tripping			
	y7	e5	young median	elderly median	y7	e5	young median	elderly median
1.1	0.0000001	0.58	0.0000003	0.001	10,000,000	1.7	3,657,330	1552
1.4	0.0000001	0.85	0.0003	0.02	10,000,000	1.2	3,757	46.5
2.0	0.026	0.986	0.24	0.48	38.6	1.014	4.18	2.09
2.2	0.098	0.994	0.56	0.73	10.2	1.006	1.80	1.37
3.4	0.757	0.99994	0.9996	0.9990	1.32	1.00006	1.0004	1.001
3.5	0.792	0.99996	0.9998	0.9993	1.26	1.00004	1.0002	1.0007

It can be seen in Table 6.3 that at higher values of MTC(y) (i.e. 3.4cm and 3.5cm), PT_{MTC} is minimally lower in y7 and minimally higher in e5 compared with the group median for young and elderly. For example, at PT_{MTC}(3.4cm) = 0.9996 (1 in 1.32 strides) for young subject y7, 0.9996 (1 in 1.00006 strides for elderly subject e5, 0.79 (1 in 1.0004 strides) for young group median and 0.9990 (1 in 1.001 strides) for the elderly group median. More important findings, however, exist at the lower end of the profile. For example, PT_{MTC}(1.4cm) < $1x10^{-7}$ (less than 1 in 10,000,000 strides) for young subject y7, 0.85 (1 in 1.2 strides) for elderly subject e5, $3x10^{-4}$ (1 in 3,757 strides) for young group median and 0.02 (1 in 46.5 strides) for elderly group median. These results show that at MTC(y)=1.1cm and 1.4cm, elderly subject e5 has much greater PT compared with all subjects. In contrast, subject y7 has a much lower PT compared with the young group median and, to a greater extent, with the elderly group median.

This research has shown a promising method of identifying individuals at risk of tripping on small unseen obstacles during undistracted walking. This is a useful addition to falls prevention research since tripping is one of the most common reasons for falling (e.g. Kreisfeld *et al.*, 2004; Cripps and Carman, 2001; Hill *et al.*, 1999) and, moreover, tripping frequency has been cited as a risk factor for falls (Pavol *et al.*, 1999). The methods described in this research appear to be sensitive enough to identify higher tripping risk in a group of apparently healthy and physically active elderly females.

6.1.5 Walking velocity

Although walking velocity was not a key variable for this research, its relevance is discussed here due to the possible link with falls. The young group walked significantly faster on the treadmill (~19%) than the elderly group (1.03m/s vs. 0.83m/s, p=.001). Statistical significance remained when walking velocities were normalised with height. Mean walking velocities were within normal limits stated by Whittle (1993), however, some individuals were below these. These discrepancies, however, are attributed to the methodological issue of treadmill vs. overground walking. The normal ranges stated by Whittle are for overground walking and, as stated previously, the normal, comfortable treadmill walking speed in this research is slower than overground. That is, walking speed on the treadmill was on average 23% lower than self-paced overground walking for the young group and approximately 38% lower for the elderly group. Three subjects in the young group, each sharing the same walking velocity, were below the normal range (~9%) and 7 subjects in the elderly group were below the normal range (~7%). While treadmill walking speed was below normal limits, overground walking speed for all subjects was well within normal limits.

Walking speed is related to stature due to its influence on stride length. Correlations using Pearson's r showed walking speed was indeed significantly correlated with stature and was higher for the elderly group (young group r = .625, p=.006; elderly group r = .726, p=.001). On a group basis, walking speed was correlated with stature, as expected. However, there were some subjects whose walking speed was not correlated with their stature. For example, young subject y2, was one of the shortest

young subjects but was one of the fastest walkers. In comparison, young subject y17 was equal shortest among young subject and also walked the slowest.

Friedman *et al.* (1988) normalised walking speed by expressing this as relative walking speed (RWS) for healthy elderly persons of approximately 0.75 stats/s, which corresponds with approximately 1.2 m/s. According to this assessment, all subjects were below the healthy elderly RWS of 0.75 stats/s and ranged from 0.41 stats/s (elderly subject e10) to 0.69 stats/s (elderly subject e6). However, Freidman *et al.* (1988) measured overground walking, in contrast to treadmill walking in this study. As previously discussed, subjects walking on a treadmill choose comfortable walking speeds slower than that chosen for overground walking. Since self-selected comfortable walking speed on the treadmill was approximately 38% slower than self-paced comfortable walking overground, RWS for the elderly group was the equivalent of 2.2 stats/s overground, well above Friedman *et al.*'s (1988) normal range. The fact that all elderly participants scored within the normal range for physical performance tests suggests there were no physical impairments causing slower walking performance. In fact, the elderly as a group scored at the low end of the scale for the Timed-Up-And-Go task (i.e. performed the task quickly).

The significantly slower walking speeds in the elderly adults is consistent with typical age-related changes to gait. The fact that significant age differences remained once stature was considered suggests that walking speed was not merely influenced by height. Slower walking speed has been suggested as more risky in terms of falling and has been linked with reduced physical fitness (McGibbon and Krebs, 2001; Judge *et al.*, 1996a; Ostrosky *et al.*, 1994; Winter, 1991a; 1991b; Murray *et al.*, 1969), however,

slower walking speed in the elderly has also been suggested as an adaptation toward a safer more stable gait (e.g. Cunningham *et al.*, 1982). The results of this research suggest the sample studied walked with gait velocities similar to that expected of elderly adults compared with young adults. Slower walking speed increases the chance of recovering from a trip and preventing a subsequent fall. While young adults might have adequate reactive responses to prevent a fall following a trip, the elderly may not coordinate these reactions in sufficient time to prevent a fall. It is, therefore, an advantage to not 'hurry' while walking in order to allow sufficient time to respond to environmental hazards that might lead to tripping and potential falls.

6.2 Distraction tasks

In this section, the dual-task conditions of walking while performing each distraction task are discussed. The effect of distraction tasks with respect to the change in various descriptive statistics of the MTC distribution is explored. The change in $median_{MTC}$ ($median_{MTC(distr)}$) relative to normal undistracted $median_{MTC}$ ($median_{MTC(norm)}$) will be discussed first. Variability, as measured by IQR_{MTC}, is discussed for normal undistracted walking and each distraction task. Examination of low MTC is crucial to this research and, therefore, min_{MTC} is discussed for each walking condition. $PC5_{MTC}$, as a measure of low MTC, is also discussed for normal undistracted walking and the two prolonged distraction tasks, namely *video* and *3s* tasks.

Age effects are discussed for each distraction task and different strategies used by the two groups are proposed. The effect of the different tasks on locomotor control and precision are discussed and inferences made on the types of distractions most likely to lead to tripping on unseen obstacles. An important part of this section is a discussion of distractions on an individual basis since each individual varies considerably and this important information is ignored when discussed purely as a group. Case studies of subjects with typical and unusual data assist in illustrating the effect of the distractions and the different strategies employed to implement MTC.

Given the small number of strides in each distraction task (i.e., less than 60), calculation of probability of tripping was not possible. Assumptions can be made about the risk of tripping in that lower MTC increases the risk of contacting smaller obstacles

while walking. It was shown in section 6.1.4 that at an individual's $median_{MTC}$, PT ≈ 0.5 (i.e. trip every second stride). Discussing $median_{MTC}$, as well as low MTC (min_{MTC} and $PC5_{MTC}$) and variability in MTC (IQR_{MTC}), a reasonable estimate of tripping risk can be made. As outlined in section 2.3.1, the true probability of tripping ($TPT_{MTC(y)}$) is dependent on the probability of the obstacle occurring at the point of MTC ($P_{MTC(y)}$) and whether the obstacle is seen or not (refer Equation 2.3.2 to Equation 2.3.5). Obviously, if an obstacle is seen an individual can make adjustments in an attempt to avoid contacting the obstacle. If an obstacle is not seen, and the obstacle appears at the point of MTC, the risk of tripping is increased, particularly in individuals with low MTC. Many factors, including the level of distractedness, influence the likelihood of an individual seeing an obstacle. For this research it is assumed that during the distraction tasks the individual fails to see obstacles obstructing the walking path.

The section consists of:

- Major observations of central tendency ($median_{MTC}$), intra-individual and variability (IQR_{MTC}) and low MTC (min_{MTC} and $PC5_{MTC}$)
- Discussion of each distraction task
    - Prolonged distractions (*video* and *3s* tasks)
    - Instantaneous/short distractions (*head turn*, *pouch*, *cough*, *RTP&delay*)
- Comparison of prolonged and instantaneous/short distractions
- Discussion of methodological issues relative to this research

6.2.1 General observations

Group $median_{MTC}$ for normal undistracted walking and each distraction task can be seen in Figure 6.17.

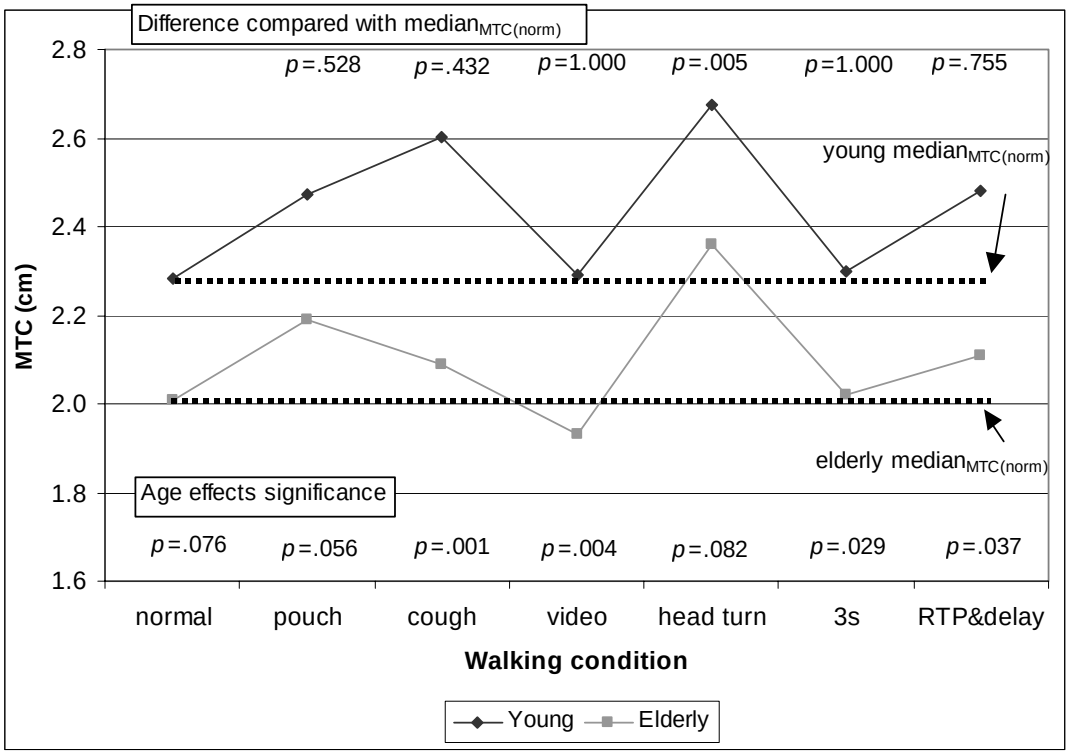


Figure 6.17: $Median_{MTC}$ for undistracted and distracted walking conditions for young and elderly.

$Median_{MTC(norm)}$ (shown as dotted line) for young and elderly groups illustrates the deviation from this value for each distraction task. Age effects significance is shown at the bottom whilst significance of $median_{MTC(norm)}$ compared with $median_{MTC(distr)}$ is shown at the top.

It can be seen in Figure 6.17 that the distraction tasks resulted in a deviation from $median_{MTC(norm)}$ in largely the same direction for the young and elderly. The magnitude of deviation from $median_{MTC(norm)}$ is also relatively similar between the groups. It can be seen at the top of the chart that only *head turn* task was significantly different to $median_{MTC(norm)}$. Separate one-way ANOVAs for the young and elderly groups, however, did not show significant difference for either group between the two tasks. It

can also be seen that significant age effects existed for all walking conditions (undistracted and distracted) at least at $p<0.5$, except *norm* and *pouch* tasks. At the $p<.01$ level, significant age effects were found for *cough* ($p=.001$) and *video* ($p=.004$) while at the $p<.05$ level, significant age effects were found for *3s* ($p=.029$) and *RTP&delay* ($p=.037$). The significantly lower median_{MTC} seen in the elderly group for all walking conditions compared with the young results in an increased risk of tripping.

Figure 6.18 presents $\text{median}_{MTC(norm)}$ compared with $\text{median}_{MTC(distr)}$ (as in Figure 6.17) as the percentage change from $\text{median}_{MTC(norm)}$ for each distraction.

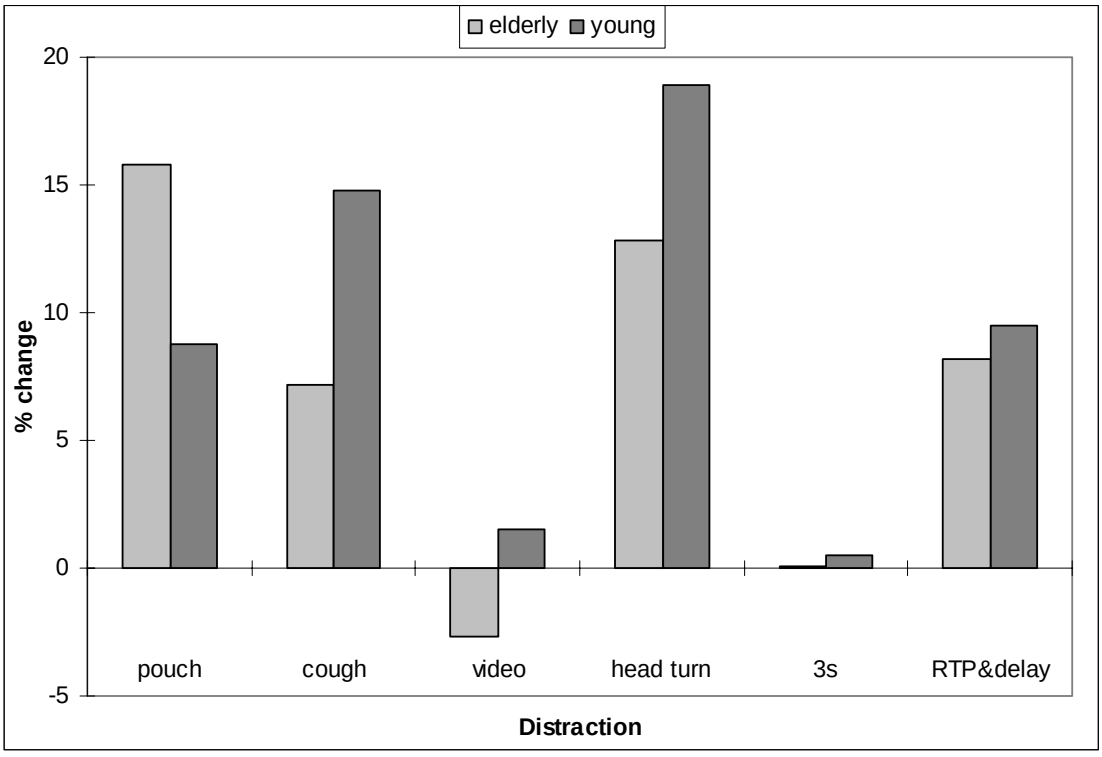


Figure 6.18: Group median percentage change from $\text{median}_{MTC(norm)}$ in response to each distraction.

Figure 6.18 illustrates the effect of each distraction on both groups by showing group median percentage deviation from $\text{median}_{MTC(norm)}$. It can be seen that only one

distraction caused group $median_{MTC}$ to change in the negative direction (*video* task for the elderly) and this was significantly different to the young group (p=.004). This is an important finding and suggests that, as a group, tasks requiring vision to be directed towards an additional concurrent task while walking result in lower MTC, thereby increasing the risk of tripping. There was virtually no change for each group during the *3s* task and, despite similar percentage change for the two groups, a significant age effect was found (p=.029). It can be seen that the task causing the greatest group deviation for the young group was the *head turn* task while for the elderly, the *pouch* task caused the greatest deviation.

It can also be seen in Figure 6.18 that the percent increase in $median_{MTC(distr)}$ compared with $median_{MTC(norm)}$ was greater in the young group for all conditions except the *pouch* task. The increased MTC seen in the young group reduces their likelihood of tripping on small unseen obstacles.

The results in Figure 6.18 show group median deviation for each distraction. The direction of deviation from $median_{MTC(norm)}$ included increases for some subjects and a decrease in $median_{MTC(distr)}$ compared with $median_{MTC(norm)}$ for others. Individual MTC for each condition will be discussed shortly but, firstly, it is useful to observe the median absolute deviation from $median_{MTC(norm)}$, that is, the non-directional deviation. Figure 6.19 shows the absolute percentage change from $median_{MTC(norm)}$ for each distraction task for young and elderly groups.

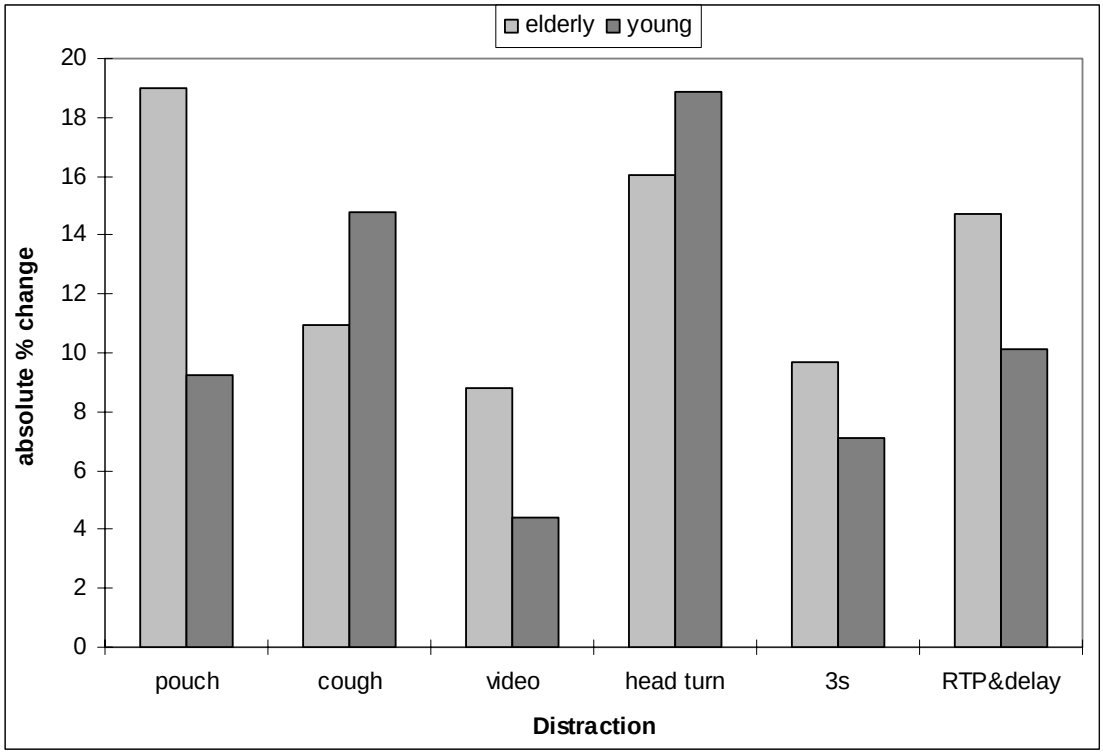


Figure 6.19: Absolute percentage change from median$_{MTC(norm)}$ for each distraction.

It can be seen in Figure 6.19 that the *pouch* task elicited the greatest absolute percentage deviation from median$_{MTC(norm)}$ for the elderly group, followed by the *head turn* task. In contrast, the *head turn* task elicited the greatest deviation from normal for the young group, followed by the *cough* task.

Finally, Figure 6.20 shows a profile of each distraction task with respective percentage deviation from median$_{MTC(norm)}$ for each subject.

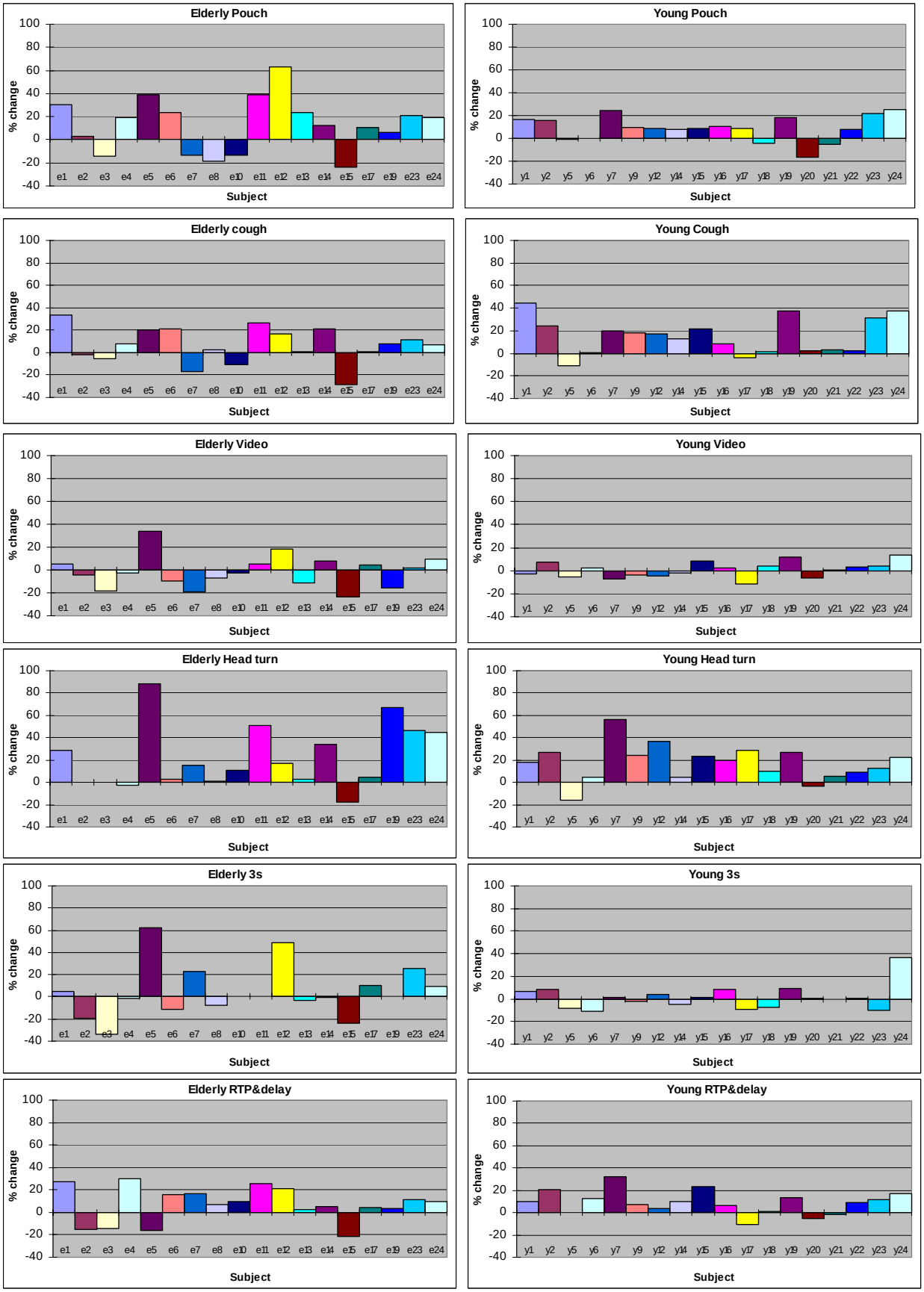


Figure 6.20: Percentage deviation from normal undistracted walking for each subject for each distraction.

Figure 6.20 gives an overall summary of the effect of each distraction for each individual and is useful in describing the effect of the distraction tasks in conjunction with the charts depicted in Figure 6.17, Figure 6.18 and Figure 6.19. The chart presents a clear profile of the effect of each distraction on each subject with respect to the percentage deviation from $median_{MTC(norm)}$.

There are several trends to be gleaned from Figure 6.20. These will be briefly described here and discussed more thoroughly later within the respective distraction task sections. On initial examination of Figure 6.17 and Figure 6.18 the magnitude of effect appears to be greater in the young group for four of the six distraction tasks (*cough*, *head turn*, *3s*, *RTP&delay*). Examination of group data in Figure 6.19, however, shows that expressed as absolute deviation from $median_{MTC(norm)}$, the elderly in fact were more affected than the young on four of the six distraction tasks (*pouch*, *video*, *3s* and *RTP&delay*). Although the group median is greater for young group on some distraction measures it can be seen in Figure 6.20 that there is greater inter-individual variability amongst the elderly subjects and some have quite a high deviation from $median_{MTC(norm)}$.

Figure 6.20 also shows that the young group appear to be relatively unaffected by each of the distraction tasks (except the *cough* and *head turn* tasks) compared with the elderly group. Both young and elderly are affected by the *head turn* task but some elderly individuals stand out as having greater percentage changes (e5 = 88% and e19 = 67%). Most of the subjects experienced an increase in $median_{MTC}$ due to the *head turn* task but there were three elderly and two young subjects who experienced a decrease in $median_{MTC}$. Of these only two were noticeably different to $median_{MTC(norm)}$ (elderly

subject e15 = -18% and young subject y5 = -15%). The trend towards positive deviation may be a mechanism to ensure adequate foot clearance in order to reduce the likelihood of tripping. Indeed, the study by Begg *et al.* (2007) concluded that increasing MTC was a possible mechanism for reducing the risk of tripping. Negative deviation, that is, having $median_{MTC}$ lower than $median_{MTC(norm)}$, suggests an increased likelihood of tripping compared with undistracted walking. Additionally, given that obstacles may be seen and avoided during normal undistracted walking, the nature of distracted walking results in obstacles more likely to be undetected. This is a particular concern in the elderly, for whom the negative deviation is more pronounced, since they are least likely to recover from a trip. Since tripping frequency has been suggested as a strong predictor for falls in elderly (Pavol *et al.*, 1999), individuals experiencing a decrease in MTC are particularly at risk of tripping and, potentially, falling.

Six young and six elderly individuals have systematic positive deviation for all distractions although in some subjects the deviation was almost negligible for some distractions (e.g. deviation of 1% for *3s* task in young subject y15). The systematic positive deviation is most noticeable in elderly subject e12 who has the largest magnitude in deviation (17% - 63%). Only two other subjects had noticeable deviation greater than 10% (young subject y19 and y24), which was still not close to the extent of subject e12. Compared with normal undistracted walking, it appears these subjects have implemented a protective strategy by increasing MTC to reduce the likelihood of tripping (Begg *et al.*, 2007). Only one subject had a systematic negative deviation, elderly subject e15, who had deviations ranging from -18% to -28%. Negative deviation is an interesting finding since it is an indication that compensatory elevation of foot clearance has not been implemented to reduce the chance of the foot hitting the

ground during the distracted period. The smaller foot clearance may be an indication of increased risk of tripping on small obstacles.

Examination of the deviation from normal $median_{MTC}$ identified elderly subject e5 as having the greatest deviation from normal of all subjects. Whilst the data for elderly subject e15 for normal undistracted walking indicates a low likelihood of tripping, the data during distracted walking show a different trend. Elderly subject e15 was the only subject with systematic negative deviation from normal undistracted $median_{MTC}$ during the distraction tasks (i.e. $median_{MTC(distr)}$ decreased compared with $median_{MTC(norm)}$). Intuitively, a $median_{MTC}$ lower than during normal undistracted walking $median_{MTC}$ indicates an increased risk of tripping. It is reasonable to suggest there are poor compensatory mechanisms during the distractions since it would be expected that MTC would elevate to avoid tripping. However, whilst the deviation from normal was negative, the $median_{MTC}$ for normal walking was the highest of all subjects and the $median_{MTC}$ for each distraction task was actually higher than that for elderly subject e5. That is, while elderly subject e15 is at an increased risk of tripping during distractions compared with undistracted walking, the higher overall MTC results in a reduced likelihood of tripping compared with the rest of the group.

Intra-individual variability in MTC (IQR_{MTC}) can be described as a measure of the precision of the locomotor system in implementing a consistent MTC. Individual IQR_{MTC} between walking conditions for young and elderly are charted in Figure 6.24. It can be seen that IQR_{MTC} is greater for the elderly group in all walking conditions and significant age effects existed at $p<.01$ for *norm*, *3s* and *pouch* (refer Table 5.52 and Figure 5.23). This finding supports previous research that found the elderly have

greater variability in various temporal and spatial gait measures (e.g. Danion *et al.*, 2003; Hausdorff *et al.*, 1997; Patla, 1997). Greater intra-individual variability in stride kinematics has been suggested as a predictor for falling in elderly populations (e.g. Maki, 1997; Gabell and Nayak, 1984). High IQR_{MTC} observed in some subjects, therefore, indicates less precision of the locomotor system. Compared with the young, it would seem the elderly are at a greater risk of tripping not only during normal undistracted walking but also during distractions such as *3s*, *pouch* and *head turn*.

Several distraction tasks had significantly lower IQR_{MTC} compared with $IQR_{MTC(norm)}$ for both the elderly and the young subjects. The lower IQR_{MTC} compared with $IQR_{MTC(norm)}$ appears to be a protective effect in that an effort is made to reduce stride-stride variability in MTC during the distracted periods to reduce the risk of tripping. In the elderly group differences between normal undistracted walking (0.41cm) included *video* task (0.28cm, p=.003), *cough* (0.29cm, p<.001) and *RTP&delay* (0.16cm, p<.001). For the elderly group, the lower IQR_{MTC} in the *video*, *cough* and *RTP&delay* task suggests an attempt was made to reduce the risk of tripping. Given the significantly lower $median_{MTC}$ during the *video* task ($median_{MTC(norm)}$ = 2.26cm vs. $median_{MTC(video)}$ = 1.89cm, p=.004), the significantly lower IQR_{MTC} during the *video* task seems to be a strategy to decrease the risk of tripping in an already high risk situation. In the young group, the differences in IQR_{MTC} were between normal undistracted walking and *3s* (0.23cm, p=.032), *pouch* (0.20cm, p=.009), *cough* (0.18cm, p=.013) and *RTP&delay* (0.17cm, p=.005).

Gabell and Nayak (1984) hypothesised that the increased intra-individual variability in their elderly group might indicate an inability to compensate for instability and,

therefore, the elderly might be at increased risk for falls under circumstances where balance is challenged. In this research, IQR_{MTC} was significantly higher in the elderly compared with young for some walking conditions (i.e. normal undistracted walking, head turn, 3s and pouch; refer Table 5.52) and, therefore, consistent with Gabell and Nayak's findings. Both groups, however, did show significantly smaller IQR_{MTC} during some distraction tasks (refer Table 5.55). This suggests both young and elderly groups did make an attempt to reduce the risk of tripping during the distracted periods by improving the precision in implementing a consistent MTC.

A more comprehensive understanding of the locomotor control system in implementing MTC, and the precision in this task, can be gained by examining the lowest MTC points in the distribution in conjunction with measures of central tendency ($median_{MTC}$) and intra-individual variability (IQR_{MTC}). Although the control system attempts to produce consistent strides with MTC somewhat clustered around the median measure, irregular low and high MTC points occur occasionally. Intuitively, it is the low MTC points that are most likely to lead to tripping on unseen obstacles and, therefore, should be examined in research related to tripping and potential falls. Since increased tripping frequency has been implicated as the prime risk-factor for trip-related falls (Pavol *et al.*, 1999), it is vital to examine small MTC during walking in order to identify individuals potentially at risk of tripping. Low MTC measures examined are min_{MTC} for all distraction tasks and $PC5_{MTC}$ for the prolonged distractions. Figure 6.21 shows group comparison of $median_{MTC}$, min_{MTC} and $PC5_{MTC}$ for young and elderly.

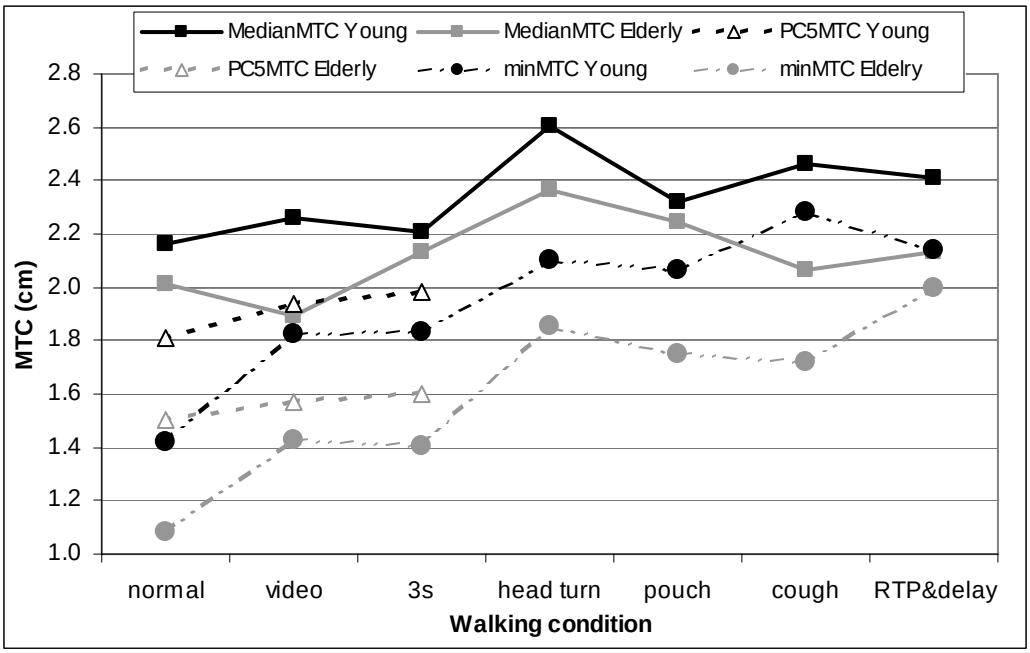


Figure 6.21: Comparison of median $_{MTC}$, min_{MTC} and $PC5_{MTC}$ for normal undistracted, *video* and *3s* walking conditions.

Note: $PC5_{MTC}$ could not be reliably calculated for *head turn*, *pouch*, *cough* and *RTP&delay* tasks given the lower number of strides associated with these tasks.

It can be seen in Figure 6.21 that the elderly have smaller MTC compared with the young group for all measures of $median_{MTC}$, $PC5_{MTC}$ and min_{MTC}. $PC5_{MTC}$ was only minimally higher for the two distraction tasks compared with normal undistracted walking for both the young and elderly, and no significant differences existed (refer Table 5.46). Significant age effects, however, existed for all three walking conditions on $PC5_{MTC}$. The elderly were significantly lower on $PC5_{MTC}$ for each of the three walking conditions (*normal* p=.008, *video* p=.002, *3s* p=.005; refer Table 5.45 and Figure 5.21). Compared with the young, the elderly group's smaller $PC5_{MTC}$ increases the risk of tripping on small obstacles. For both groups, the risk of tripping is no different for each of the three walking conditions.

As shown in Figure 6.21, min_{MTC} is significantly lower in the elderly group compared with the young for all walking conditions except *RTP&delay*, where no significant age effects existed (refer Table 5.47 and Figure 5.22). The lower min_{MTC} in the elderly increases the risk of tripping on small obstacles compared with the young. An important finding is that, unlike $PC5_{MTC}$, min_{MTC} is significantly higher for all distraction tasks compared with $min_{MTC(norm)}$ (refer Table 5.48). The higher min_{MTC} during the distraction tasks suggests a real strategy implemented by both young and elderly to reduce the number of MTC points close to the ground.

It can also be seen in Figure 6.21 that the elderly $median_{MTC}$ for *video* condition (1.89cm), which experienced a decrease from $median_{MTC(norm)}$, is lower than the young $PC5_{MTC}$ for *video* (1.94cm). This is an important finding suggesting the elderly are more at risk of tripping compared with the young given the central tendency, or intended MTC height, is lower than the young group's $5PC_{MTC}$ distribution for *video* task. During the *video* task, the elderly group had only minimal increase in $PC5_{MTC}$ measure from normal undistracted walking (0.06cm) but also experienced a decrease in $median_{MTC}$ (0.12cm). Although the difference is functionally small, it warrants discussion since it is the only distraction task where a decrease in $median_{MTC}$ was experienced and it was only observed in the elderly group. The combination of smaller $median_{MTC}$ and only minimally increased $PC5_{MTC}$ results in more of MTC values closer to the ground. The small decrease in $median_{MTC}$ during tasks that require prolonged visual attention may lead to situations in which elderly are at a greater risk of tripping.

Figure 6.22 and Figure 6.23 show individual $PC5_{MTC}$ for young and elderly during normal undistracted walking, *video* and *3s* tasks.

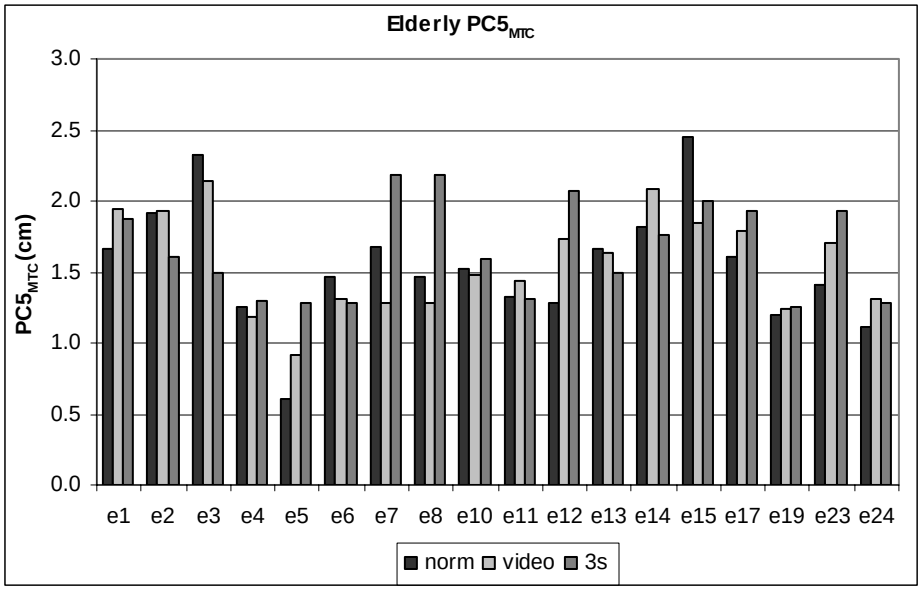


Figure 6.22: Individual $PC5_{MTC}$ for normal undistracted walking, *video* and *3s* tasks for elderly subjects.

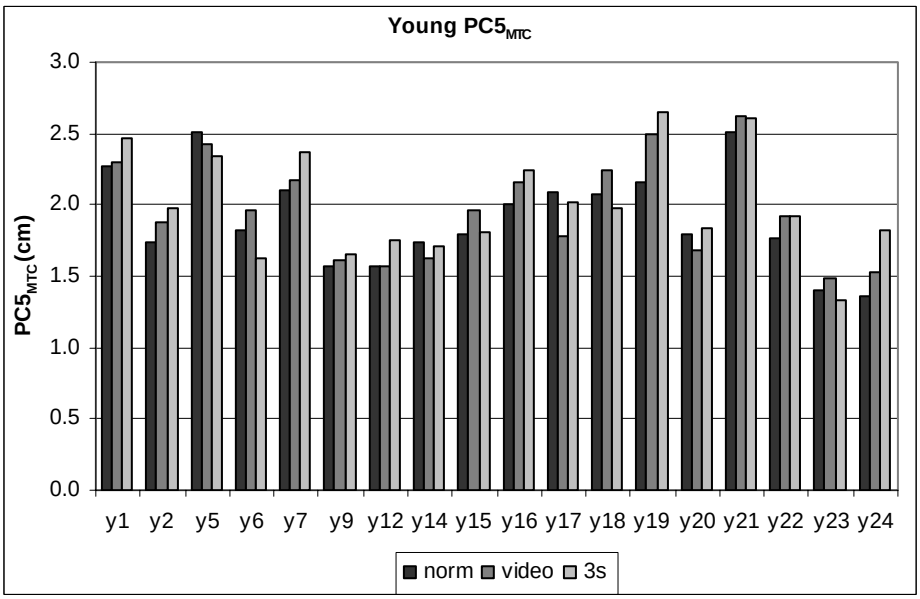


Figure 6.23: Individual $PC5_{MTC}$ for normal undistracted walking, *video* and *3s* tasks for young subjects.

It can be seen in Figure 6.22 and Figure 6.23 that $PC5_{MTC}$ varies between the normal undistracted, *video* and *3s* tasks differently for each individual, particularly for the elderly group. An increase in $PC5_{MTC}$ while distracted effectively reduces the risk of tripping, however, it can be seen that some individuals actually experienced a decrease in $PC5_{MTC}$ in response to the distraction tasks. Most noticeable are elderly subjects e3 and e15 and, to a lesser extent, elderly subject e6 and young subject y5. This situation reinforces the importance of individual-specific analysis.

Figure 6.24 shows individual IQR_{MTC} for all walking conditions while Figure 6.25 shows individual min_{MTC} for all walking conditions. These charts have been arranged in ascending order for each variable (IQR_{MTC} and min_{MTC}) within each group (young and elderly). These will be referred to during discussion of individual subjects.

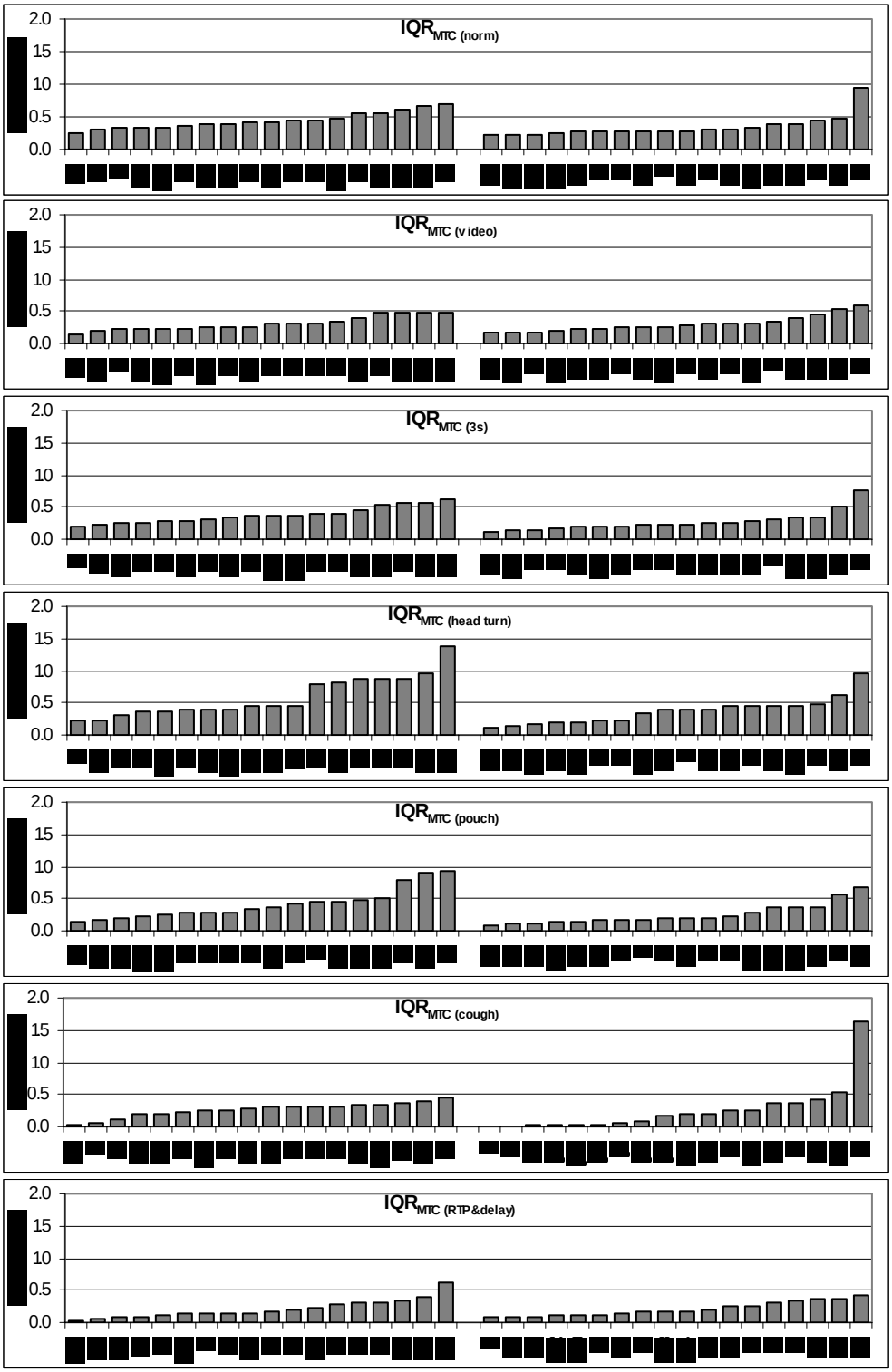


Figure 6.24: Intra-individual variability (IQR_{MTC}) between walking conditions for elderly subjects.

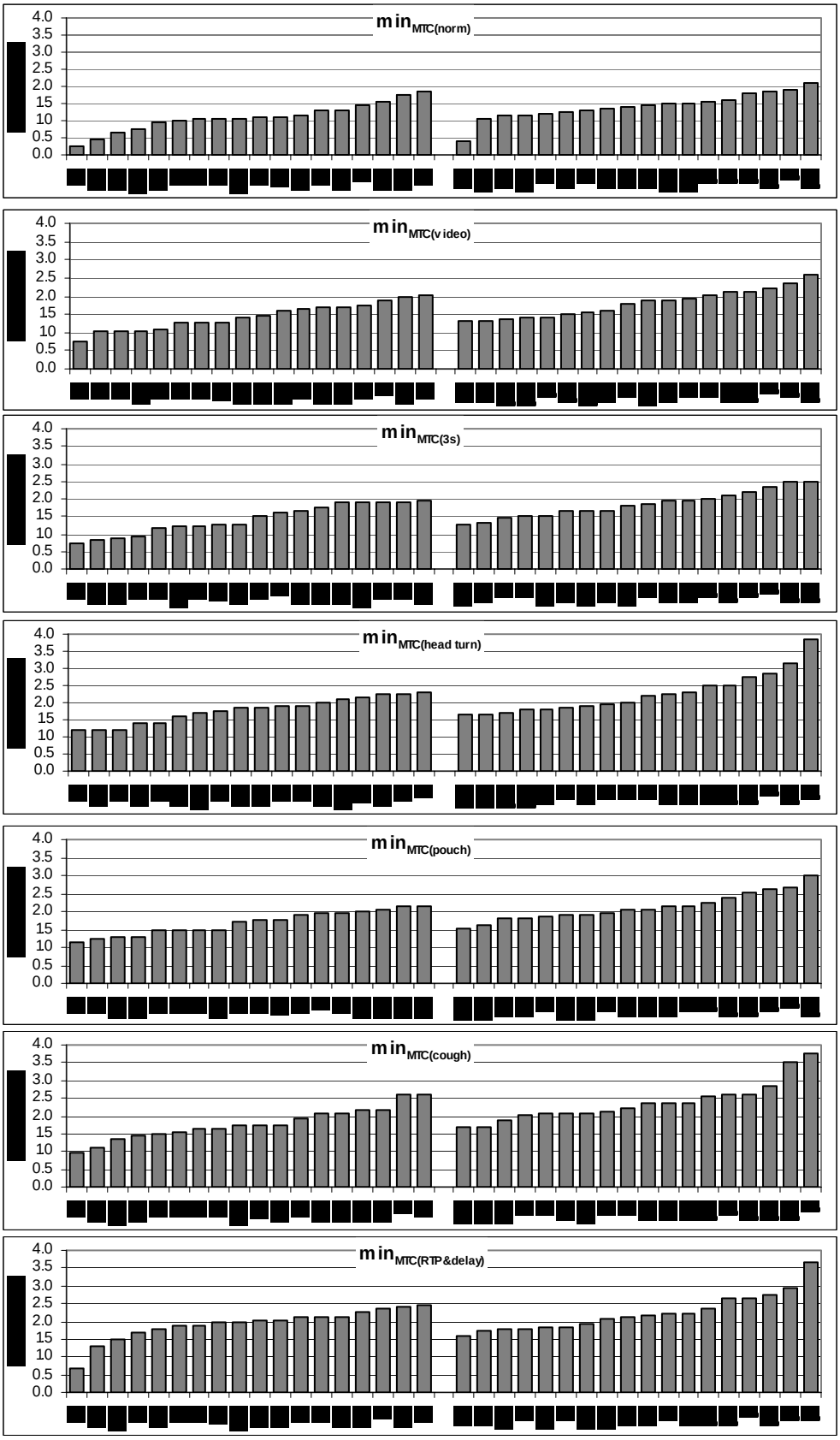


Figure 6.25: Individual min_{MTC} for all subjects by walking condition.

6.2.2 Prolonged Distractions

6.2.2.1 Video task

For the young group, the *video* task produced a group $median_{MTC}$ of 2.29cm (0.01cm greater than $median_{MTC(norm)}$ refer Table 5.30), the second lowest $median_{MTC}$ of the distraction tasks. For the elderly group the *video* task had the lowest $median_{MTC}$, and in fact, was the only task to produce group $median_{MTC}$ less than $median_{MTC(norm)}$ (*video* = 1.89cm vs. *normal* = 2.01cm). This is a very important finding and suggests that, for the elderly in particular, tasks requiring vision to be directed towards a secondary task increase the risk for tripping.

The *video* task had the greatest number of individuals in the elderly group with a decrease in $median_{MTC}$ compared with $median_{MTC(norm)}$. Ten individuals decreased in $median_{MTC}$ in response to the *video* task, ranging from –2.4% (e10 $median_{MTC(norm)}$ = 2.03cm to $median_{MTC(video)}$ = 1.98cm) to –23.9% (e15 $median_{MTC(norm)}$ = 3.10cm to $median_{MTC(video)}$ = 2.36cm). In the young group, the number of individuals with a decrease in $median_{MTC}$ during the *video* task was also the highest but was equal with the other prolonged distraction task, i.e. the *3s* task. Eight young individuals experienced a decrease in $median_{MTC}$ ranging from -2.1% (y14 $median_{MTC(norm)}$ = 1.98cm to $median_{MTC(video)}$ = 1.94cm) to -11.2% (y17 $median_{MTC(norm)}$ = 2.63cm to $median_{MTC(video)}$ = 2.33cm). Given the greater number of elderly individuals experiencing a decrease in $median_{MTC}$ in response to the *video* distraction, and the greater percentage in that deviation, it appears the *video* task affects the elderly more

than the young and places them at an increased risk of tripping compared with the young.

The chi-square test to compare the frequencies of level of effect of distraction tasks showed a significant result for both young and elderly groups ($p<.001$ for both groups). The chi-square test showed that both groups were largely unaffected by the *video* task, i.e. 17 young and 17 elderly individuals showed no effect, whilst one elderly (e15) and one young (y19) showed a large effect. For the elderly group, the *video* task, therefore, had the lowest effect on MTC for the majority of individuals. This is a concern since the lack of increased MTC to compensate for the inability to watch for tripping hazards increases the risk of tripping. While the young and elderly both had the same level of non-affected individuals, the greatest concern is in the elderly group since they are less likely to recover from a trip should one occur.

No ageing effect existed for IQR_{MTC} in the *video* task with young and elderly being equal with $IQR_{MTC(video)}$ = 0.28cm. Additionally, the $IQR_{MTC(video)}$ on this task was smaller than $IQR_{MTC(norm)}$ for both groups but the difference significantly smaller in the elderly only (p=.003). The difference in IQR_{MTC} between *normal* and *video* distraction for the elderly was 0.13cm less (*norm* = 0.41cm vs. *video* = 0.28cm) and 0.01cm less (*norm* = 0.29cm vs. *video* = 0.28cm) in the young group. Given that the elderly group had significantly lower $median_{MTC(video)}$ (young = 2.26cm vs. elderly 1.89cm) and significantly lower $PC5_{MTC(video)}$ (young = 1.94cm vs. elderly 1.56cm), it is reasonable to suggest the elderly group could not afford to be more variable. As previously discussed, the *video* task in the elderly group resulted in the only decrease in group $median_{MTC(distr)}$ compared with $median_{MTC(norm)}$.

On an individual basis, Figure 6.20 shows that the level of effect was greater in the elderly subjects and that ten elderly and eight young subjects had lower $median_{MTC(video)}$ compared with $median_{MTC(norm)}$. The greatest decrease in $median_{MTC}$ was seen in elderly subject e15 ($median_{MTC(norm)}$ = 3.10cm vs. $median_{MTC(video)}$ = 2.54cm). Compared with undistracted walking, elderly subject e15 is at a higher risk of tripping on obstacles given the smaller $median_{MTC}$ during the *video* task. Low MTC measures, however, were higher than the group suggesting an attempt to reduce the risk of hitting obstacles while walking ($min_{MTC(video)}$ = 1.69cm vs. elderly group = 1.43cm; $PC5_{MTC(video)}$ 1.84cm vs. elderly group = 1.56cm). Stride-stride variability, as measured by IQR_{MTC}, was equal highest for e15 (0.49cm compared with elderly group $IQR_{MTC(video)}$ = 0.28cm, refer Table 5.50, Table 5.52 and Figure 6.24).

While elderly subject e15 is identified at a higher risk of tripping, Table 5.26 shows that, elderly subject e5 had the lowest $median_{MTC}$ during the *video* task of all subjects and, despite experiencing an increase in $median_{MTC}$ during the *video* task ($median_{MTC(norm)}$ = 1.06cm vs. $median_{MTC(video)}$ = 1.43cm) the small MTC places this individual at a higher risk of tripping. Elderly subject e5 also had the smallest $median_{MTC(norm)}$ of all subjects (1.06cm vs. elderly group median = 2.01cm). $Min_{MTC(video)}$ for e5 was the lowest (0.73cm compared with elderly group $min_{MTC(video)}$ = 1.43cm, refer Table 5.44, Table 5.47 and Figure 6.25), as was $PC5_{MTC(video)}$ (0.91cm compared with group $PC5_{MTC(video)}$ = 1.56cm, refer Table 5.41, Table 5.45 and Figure 6.21). In addition to the small MTC, stride-stride variability in MTC is also quite high in this subject, in fact, equal second highest at 0.48cm (compared with elderly group $IQR_{MTC(video)}$ = 0.28cm, refer Table 5.50 and Table 5.52). Given the small MTC and

reduced precision in the locomotor system in implementing MTC, elderly subject e5 is identified as at a higher risk of tripping.

The *video* task was one of two prolonged tasks of a set duration of 60 seconds, considerably longer than any distraction task examined in the literature. The task required vision to be directed towards the monitor set up in front of the subject. Some structural interference may therefore be present for this task since vision is required to maintain balance concurrently with attending to the video played on the monitor. It has been postulated in dual-task research that structural interference, or where both the primary and secondary tasks share a common sensory or response modality, should be avoided (e.g. Abernethy, 1988). However, as other researchers have noted (e.g. Marsh and Geel, 2000), structural interference occurs in everyday life and is of interest in the area of dual-task research and falls prevention. The effect of such a distraction was of interest in this research in order to examine the influence on MTC and the risk of tripping during situations that would be encountered in real life.

The request for subjects to concentrate on the *video* and answer some questions on the content was to ensure attention was directed towards the video. The goal was for the subjects to concentrate on the video content to ensure attention was divided between the video and walking. The answers to questions on the video content were not of interest. There are no published studies of this kind to compare with the findings of this research. It is reasonable to imagine a scenario where an individual has their attention focused on an object whilst walking (e.g. observing scenery whilst walking in a park).

The findings for the *video* task are interesting in that there is a marked difference in response for the elderly subjects. It is the only distraction task resulting in a group median negative deviation from $median_{MTC(norm)}$. It is reasonable to suggest that the reduced $median_{MTC}$ achieved during this task, on top of an already lowered $median_{MTC(norm)}$ for the elderly group predisposes them to a potential trip relative to the young. It appears, however, that some attempts to reduce the frequency of MTC close to the ground have been made with min_{MTC} significantly higher in both the young ($p<.01$) and elderly ($p<.05$) groups. In the elderly group, IQR_{MTC} was significantly lower than $IQR_{MTC(norm)}$ ($p=.003$) suggesting an attempt of improved precision in implementing MTC. Moreover, the fact that attention is directed forward and not at the ground may further increase the risk of tripping since any irregularities in the walking terrain will not be seen.

6.2.2.2 3s task

As seen in Table 5.30 and Figure 5.18, the *3s* task elicited the second smallest group $median_{MTC(distr)}$ of all distraction tasks for both the young and elderly groups (young $median_{MTC(3s)}$ = 2.21cm vs. $median_{MTC(norm)}$ = 2.16cm, elderly $median_{MTC(3s)}$ = 2.01cm, effectively no change from $median_{MTC(norm)}$ = 2.01cm). There were no significant differences between $median_{MTC(norm)}$ and $median_{MTC(3s)}$ for young or elderly groups. These results suggest very little effect of the *3s* distraction in terms of change to $median_{MTC}$ but significant age effects did exist for $median_{MTC(3s)}$ ($p=.029$). The negligible increase in $median_{MTC(3s)}$ compared with $median_{MTC(norm)}$ is a concern particularly in the elderly group since it places them at an increased risk of tripping on small obstacles. The chi-square test revealed significant differences in both groups

(young $p<.001$, elderly $p=.016$). One young subject had a large effect (y24), whilst all other young subjects were unaffected. There were eleven elderly subjects unaffected, six experienced a small effect and one with a large effect (e12). The large effect in e12 was to increase $median_{MTC}$ ($median_{MTC(norm)}$ = 1.72cm vs. $median_{MTC(3s)}$ = 2.56cm, refer Table 5.26. While the *3s* task had a large effect on e12, the result was a protective effect since the increased MTC reduced the risk of hitting small obstacles. Again, the fact that eleven elderly subjects were largely unaffected by the *3s* tasks is a greater concern since it places them at an increased risk of tripping.

Significantly higher $IQR_{MTC(3s)}$ was found for the elderly group compared with the young (elderly = 0.36cm, young = 0.23cm, $p=.004$). The $IQR_{MTC(3s)}$ was smaller than $IQR_{MTC(norm)}$ and was significantly different in the young group ($p=.032$) but not the elderly group ($p=.129$). It can therefore be seen that, compared with the young, the elderly group had lower $median_{MTC(3s)}$ (young = 2.21cm vs. elderly = 2.01cm) and $PC5_{MTC(3s)}$ (young = 1.98cm vs. elderly = 1.60cm) and higher $IQR_{MTC(3s)}$ (young = 0.23cm vs. elderly = 0.36cm). The elderly would seem to be at an increased risk of tripping in situations where concentration on a secondary task is required during walking. On a group basis, it seems the only attempt to reduce the risk of tripping was to significantly increase min_{MTC} for both young ($p<.01$) and elderly ($p<.05$) groups (refer Table 5.48).

On an individual basis, Figure 6.20 shows that the young group showed very little change to $median_{MTC}$ during the *3s* task while some elderly individuals showed larger changes, both increase and decrease of $median_{MTC}$ relative to $median_{MTC(norm)}$. None of

the young subjects had their highest change to $median_{MTC}$ during the *3s* task while three elderly subjects did (e2 = -19.6% change, e3 = -34% change and e7 = 22.4% change).

Elderly subjects e5 and e12 had high changes (e5 = 62% change and e12 = 49% change; refer Figure 6.20). Elderly subject e5 also recorded the lowest $min_{MTC(3s)}$ of all subjects predisposing her to tripping relative to the rest of the group. The small $min_{MTC(3s)}$ was, however, greater than $min_{MTC(norm)}$, which was also the smallest in the group (refer Figure 6.25 and Table 5.44). This suggests some attempt was made to reduce the frequency of small MTC.

The decrease from $median_{MTC}$ is of interest since it may predispose an individual to tripping. The *3s* task resulted in the second highest number of elderly individuals experiencing a decrease in $median_{MTC}$, second to the other prolonged distraction task, i.e. *video* task. Eight elderly subjects experienced a decrease ranging from -0.7% (e14 $median_{MTC(norm)}$ = 2.18cm to $median_{MTC(3s)}$ = 2.17cm) to -34.0% e3 $median_{MTC(norm)}$ = 3.02cm to $median_{MTC(3s)}$ = 1.99cm. Elderly subject e3, with the highest negative deviation from $median_{MTC(norm)}$, began with an already high $median_{MTC}$, which was identified as an outlier in SPSS. Nevertheless, these two subjects (e3 and e14) are at an increased risk of tripping during this task compared with undistracted walking since MTC is lower. The lowest $median_{MTC}$ for *3s* task of all subjects was in elderly subject e4 ($median_{MTC(norm)}$ = 1.58cm vs. $median_{MTC(3s)}$ = 1.55cm). Elderly subject e4 had the fourth lowest $min_{MTC(3s)}$ making the combination of smallest $median_{MTC(3s)}$ and small $min_{MTC(3s)}$ an increased risk of tripping relative to the rest of the group.

In the young group, the number of individuals experiencing a decrease in $median_{MTC}$ was equal highest with *video* task, the other prolonged distraction task. That is, eight individuals experienced a decrease in $median_{MTC}$ due to the *3s* task ranging from an almost negligible –0.1% (y21) to –11.2% (y6 $median_{MTC(norm)}$ = 2.12cm vs. $median_{MTC(3s)}$ = 1.89cm).

The *3s* task is an interesting distraction to include in MTC research since its merit in evaluating the divided attention ability during a cognitive task such as this has been shown in the literature (e.g. Pellecchia, 2003; Rankin *et al.*, 2000). It does not require the use of resources responsible for dynamic balance and posture, namely vision, vestibular and proprioceptive sense. However, it does require considerable attention, particularly when conducted with a concurrent task, such as treadmill walking in this case.

Significant difference existed between single- (ST) and dual-task (DT) number of subtractions completed for the young group (p=.004) but not for the elderly. The young group experienced an increase in number of subtractions completed in the DT condition of approximately 8% compared with approximately 1.5% in the elderly group. This was accompanied by a modest increase in accuracy for the young group of approximately 1.1% and a decrease of 1.2% for the elderly, but the differences between ST and DT number of subtractions was not significant and no age effects were found. The greater number of subtractions completed indicate the task was easier to complete under ST conditions for the young. It was essential for this project to have the distraction presented first whilst walking on the treadmill and observing the change in MTC. Examining the DT versus ST condition was interesting but secondary to this

project. Order of ST and DT conditions was, therefore, not randomised and it is possible that improvements in performance in the ST condition are due to learning effect. No significant difference existed for either group between ST and DT conditions (young p=.333, elderly p=.498), and there were no significant age effects. The results show that 12 elderly and 14 young subjects either remained the same or improved their accuracy. This data suggests the task of subtracting by threes may not have been difficult enough.

6.2.3 Intermittent/short distractions

6.2.3.1 Head turn task

As reported in Figure 5.18 and Table 5.30, *head turn* task elicited the highest group $median_{MTC}$ for all walking conditions for both young and elderly groups (young $median_{MTC(norm)}$ = 2.16cm vs. $median_{MTC(head\ turn)}$ = 2.61cm; elderly $median_{MTC(norm)}$ = 2.01cm vs. $median_{MTC(head\ turn)}$ = 2.36cm). For the young and elderly combined, the head turn task was the only distraction with $median_{MTC}$ significantly different to $median_{MTC(norm)}$ (p=.005). No significant age effects existed, suggesting the young and elderly were no different in their response to the *head turn* task.

Chi-square analysis, where level of effect of each task was graded by the $Z'_{(distr)}$ from $median_{MTC(norm)}$, showed that during the *head turn* task the greatest number of individuals were affected by the task by some degree (refer Figure 5.20 and Table 5.38). That is, a total of 19 subjects (11 young and eight elderly) were affected to some degree by the *head turn* task. Moreover, equal with *cough* task, the *head turn*

task had the greatest number of individuals showing a large effect (>2*$Z'_{(distr)}$= 5 individuals – young = 2 individuals - y2, y19, elderly = 3 individuals – e5, e11, e14). This is an important finding and suggests that an everyday task of turning the head while walking is challenging enough to the locomotor system that MTC is altered by a large amount.

The observed increase $median_{MTC}$ is a mechanism to reduce the likelihood of tripping (Begg *et al.*, 2007). Similarly, the $min_{MTC(head\ turn)}$ is significantly higher than $min_{MTC(norm)}$ (p<.001 for young and elderly), suggesting an attempt to minimise MTC close to the ground and reduce the risk of tripping (refer Table 5.47 and Figure 5.22). Significant age effects existed for min_{MTC} with the young group exhibiting a higher min_{MTC} compared with the elderly (young $min_{MTC(norm)}$ = 1.42cm vs. $min_{MTC(head\ turn)}$ = 2.10cm, elderly $min_{MTC(norm)}$ = 1.08cm vs. $min_{MTC(head\ turn)}$ = 1.86cm). The lower minMTC in the elderly increases the risk of tripping relative to the young group.

Although $IQR_{MTC(head\ turn)}$ was higher than $IQR_{MTC(norm)}$ for both young and elderly (young: $IQR_{MTC(norm)}$ = 0.29cm vs. $IQR_{MTC(head\ turn)}$ = 0.39cm, and elderly: $IQR_{MTC(norm)}$ = 0.41cm vs. $IQR_{MTC(head\ turn)}$ = 0.44cm) significant differences were not found between normal undistracted and *head turn* conditions for either group. IQR_{MTC} was found to be significantly higher in the elderly group (young = 0.39cm, elderly = 0.44cm, p=.006, refer Table 5.52 and Figure 5.23). Interestingly, the *head turn* task was the only distraction task eliciting an increase in IQR_{MTC} compared with $IQR_{MTC(norm)}$ with all other distraction tasks resulting in a decrease in IQR_{MTC}. The increased IQR_{MTC} suggests less precision in the locomotor system in implementing a consistent MTC. While the locomotor system has made an attempt to reduce the risk of tripping by

increasing $median_{MTC}$ and min_{MTC}, the failure to lower IQR_{MTC} raises the risk of tripping. The fact that the elderly group took significantly longer (young = 10.4s vs. elderly = 17.1s, $p<.001$) also suggests the elderly had more difficulty with the *head turn* task (refer Table 5.61).

This data on its own suggests the *head turn* task had the greatest effect of all distraction tasks on both groups by eliciting the highest $median_{MTC}$. Examination of individual profiles, however, reveals some other important findings. Whilst group data shows an increase in $median_{MTC(head\ turn)}$ compared with $median_{MTC(norm)}$, it can be seen in Figure 6.20 that the *head turn* task caused a decrease in $median_{MTC}$ compared with $median_{MTC(norm)}$ in some subjects. Subjects with a decreased MTC may be at an increased risk of tripping in these situations. Three elderly and two young subjects showed a decrease in $median_{MTC(head\ turn)}$ compared with $median_{MTC(norm)}$. Elderly subject e15 had the greatest decrease in $median_{MTC}$ of 0.56cm or 18% (e15 $median_{MTC(norm)}$ = 3.10cm vs. $median_{MTC(head\ turn)}$ = 2.54cm). $Median_{MTC(norm)}$ for e15 was the highest of all subjects and was identified as an outlier. While $median_{MTC}$ decreased, min_{MTC} experienced an increase compared with $min_{MTC(norm)}$ ($min_{MTC(head\ turn)}$ = 2.23cm vs. $min_{MTC(norm)}$ = 1.74cm (refer Table 5.44). In fact, this was the highest min_{MTC} of all walking conditions for e15. Additionally, IQR_{MTC} during the *head turn* task was lower than during $IQR_{MTC(norm)}$ ($IQR_{MTC(head\ turn)}$ = 0.245cm vs. $IQR_{MTC(norm)}$ = 0.55cm, refer Table 5.51. Although elderly subjects appear to be at a greater risk of tripping during the *head turn* task given the lower $median_{MTC}$, the higher min_{MTC}, together with the decreased IQR_{MTC}, appear to be compensations made in an attempt to reduce the risk of tripping.

Whilst elderly subject e15 had the highest decrease in $median_{MTC}$ of all subjects during the *head turn* task, there were also subjects who experienced their highest increase in $median_{MTC}$ during the *head turn* task. In fact, six elderly and eleven young subjects experienced their greatest deviation from $median_{MTC(norm)}$ during the *head turn* task compared with all distraction tasks (refer Table 5.26). Of these subjects, five elderly subjects had increases of more than 45% (e5 = 88%, e11 = 51%, e19 = 67%, e23 = 47% and e24 = 45%) and only one young subject (y7 = 56%), suggesting a large effect on these subjects.

Figure 6.24 shows that some elderly individuals had very large IQR_{MTC} for the *head turn* task, in particular, e3, e5, e7, e8, e12, e17 and e19. Combined with higher IQR_{MTC}, some of these subjects also had some of the lowest min_{MTC} for the head task (refer Figure 6.25 and Table 5.44). For example, e5 and e12 both had equal second smallest min_{MTC} for the head turn task (1.22cm), suggesting that, they are at a higher risk of tripping. Their $min_{MTC(head\ turn)}$, however, is higher than during $min_{MTC(norm)}$ (e5 norm = 0.24cm and e12 norm = 0.95cm). The locomotor control system attempts to reduce the number of small MTC close to the ground, particularly during the *head turn* distraction task. In fact, it can be seen in Table 5.47 and Figure 5.22 that $min_{MTC(head\ turn)}$ is significantly higher than $min_{MTC(norm)}$ (refer Table 5.48) for both the young ($p<.001$) and elderly ($p<.001$).

Although subjects were informed to take the time they needed in order to complete the task with the greatest accuracy, some subjects may have placed more emphasis on either accuracy or completion of the task as quickly as possible. As suggested by Shumway-Cook *et al.* (1997b), allocation of attention is complex and depends on the

nature of the cognitive and postural task, the goal of the subject and the instructions given. It is possible some subjects took longer to ensure accuracy, for example, elderly subject e15 took the longest to complete the task (42.6s compared with the group median of 17.1s) but was 100% accurate. The longer period required to complete the task does seem to suggest some difficulty with the relatively simple task.

Other subjects, such as elderly subject e2, may have found the task so challenging that despite taking longer than average to complete the task (23.8s compared with the elderly group median of 17.1s), were still unable to be accurate (55.6% compared with group mean of 90.7%). This subject had the smallest change from $median_{MTC(norm)}$ of all subjects.

Some subjects may have perceived the *head turn* task to be a situation where the threat of injury was possible and therefore, adopted a posture-first strategy where maintenance of balance takes precedence over any concurrent task (e.g. Bloem *et al.*, 2001; Shumway-Cook *et al.*, 1997b). There may be a trade-off between task performance (accuracy and duration) and control of MTC. For example, elderly subject e2 was the least accurate of all subjects, taking longer than average, but experienced almost negligible change to $median_{MTC}$. In contrast, elderly subject e12 was faultless in accuracy but took longer to complete the task, perhaps to ensure the small change to $median_{MTC}$ experienced (change of 17% or $Z'_{(distr)}$ score of 0.71).

The *head turn* is a difficult task during static balance but during dynamic balance, such as during walking, all three systems that control balance, i.e. visual, vestibular and proprioceptive, are challenged. Stabilisation of the head assists in providing a stable

reference frame to co-ordinate body motion during complex movements (Mulavara *et al.*, 2002). Koceja *et al.* (1999) found healthy elderly subjects produced significantly greater sway compared with the young group in response to a volitional head movement. It may be that the elderly group in this research also had difficulty with head turning given the significantly longer time to complete the task, significantly lower $median_{MTC(3s)}$ $min_{MTC(3s)}$ and $PC5_{MTC(3s)}$, and significantly greater $IQR_{MTC(3s)}$.

6.2.3.2 Pouch task

No significant differences between $median_{MTC(norm)}$ and $median_{MTC(pouch)}$ and no age effects were found for $median_{MTC(pouch)}$, however, the difference was approaching significance at $p<.05$ (elderly $median_{MTC(pouch)}$ = 2.25cm vs. young $median_{MTC(pouch)}$ = 2.32cm, $p=.056$, refer Figure 5.18 and Table 5.30). It can be seen in Figure 6.18 that percentage change from $median_{MTC(norm)}$ was greater for the elderly group compared with the young. These results show that both groups increased $median_{MTC}$ to some degree, which is a strategy to reduce the risk of tripping (Begg *et al.*, 2007).

The chi-square test showed the elderly group had significant differences in frequencies in level of effect ($p=.009$) with 12 subjects showing no effect, four showing a small effect and two showing a large effect (refer Table 5.38 and Figure 5.20). There were no significant differences in frequencies of level of effect in the young group ($p=.157$) with 12 subjects showing no effect and six showing a small effect. Both young and elderly groups had 12 subjects each showing no effect. When carrying out an additional task while walking, there are fewer resources available for identifying hazards on the ground. Under these circumstances it is desirable to increase MTC in

order to compensate for obstacles that are not detected but have the potential to trip. A lack of effect of the distraction, or a lack of increased MTC, therefore, increases the risk of tripping.

Significant differences were found between $min_{MTC(pouch)}$ and $min_{MTC(norm)}$ for both the young and elderly groups (young $min_{MTC(norm)}$ = 1.42cm vs. $min_{MTC(pouch)}$ = 2.06cm, young $min_{MTC(norm)}$ = 1.08cm vs. $min_{MTC(pouch)}$ = 1.75cm, $p<.001$ for both groups, refer Table 5.47 and Table 5.48). Additionally, the elderly were significantly lower on $min_{MTC(pouch)}$ compared with the young ($p=.001$). It seems that both the young and elderly made attempts to reduce the number of MTC near the ground by increasing $median_{MTC}$ and min_{MTC}. Stride-stride variability decreased during the *pouch* task compared with $IQR_{MTC(norm)}$ and was significant in the young group but not the elderly (young $IQR_{MTC(norm)}$ = 0.28cm vs. $IQR_{MTC(pouch)}$ = 0.20cm, $p=.009$, elderly $IQR_{MTC(norm)}$ = 0.41cm vs. $IQR_{MTC(pouch)}$ = 0.35cm, not significant, $p=.129$, refer Table 5.52 and Table 5.55). The combined effect of increased $median_{MTC}$ and min_{MTC} and decreased IQR_{MTC} is to reduce the risk of tripping.

As shown in Figure 6.20, several elderly subjects have large deviations from $median_{MTC(norm)}$. Elderly subject e12 had the greatest deviation and this increase in $median_{MTC}$ was the greatest deviation from $median_{MTC(norm)}$ of all the tasks for this subject ($median_{MTC(norm)}$ = 1.72cm vs. $median_{MTC(pouch)}$ = 2.81cm). This large elevation in $median_{MTC}$ would reduce the likelihood of tripping on obstacles. Elderly subject e12 experienced only a small increase in IQR_{MTC} ($IQR_{MTC(norm)}$ = 0.41cm vs. $IQR_{MTC(pouch)}$ = 0.44cm, refer Table 5.51). Elderly subject e12 also experienced a large increase in min_{MTC} during the pouch task ($min_{MTC(norm)}$ = 0.95cm vs. $min_{MTC(pouch)}$ = 2.06cm, refer

Table 5.44. With only a small increase in IQR_{MTC} and an increased $median_{MTC}$ and min_{MTC}, it appears e12 is at a low risk of tripping in these conditions.

Five elderly subjects experienced a decrease in $median_{MTC}$ ranging from -13% (e7) to -23% (e15). While e15 experienced a large decrease in $median_{MTC}$, which would increase the risk of tripping relative to $median_{MTC(norm)}$, this subject had quite high $median_{MTC}$ to begin with ($median_{MTC(norm)}$ = 3.10cm) vs. $median_{MTC(pouch)}$ = 2.37cm, refer Table 5.26). $Min_{MTC(pouch)}$, however, is lower than $min_{MTC(norm)}$ (1.49cm and 1.74cm respectively, refer Table 5.44). IQR_{MTC} experienced only a slight decrease during the pouch task ($IQR_{MTC(norm)}$ = 0.55cm vs. $IQR_{MTC(pouch)}$ = 0.51cm, refer Table 5.52. For subject e5, compared with undistracted walking, the lower $median_{MTC}$ and min_{MTC} during the *pouch* task increase the risk of tripping. It appears some compensation was made, however, due to the slight decrease in intra-individual variability of MTC during the *pouch* task compared with undistracted walking, as measured by IQR_{MTC}.

6.2.3.3 Cough task

As seen in Figure 5.18 and Table 5.30, $median_{MTC}$ during the *cough* task was significantly lower in the elderly (young = 2.47cm, elderly = 2.06cm, p=.001). It should be noted that small strides numbers are analysed during the *cough* task. A median of three strides for each of the young and elderly groups is included in the *cough* task (refer Table 5.21). In the elderly group, stride numbers range from two to five while in the young group, strides range from one to six. This is in comparison to the median 1011 and 1048 strides in normal undistracted walking for the elderly and

young groups respectively. Figure 6.18 and Figure 6.19 shows that the young experienced a greater percentage increase $median_{MTC}$ in response to the *cough* task (young increase 15% to $median_{MTC(cough)}$ = 2.47cm, elderly increase 7% to $median_{MTC(cough)}$ = 2.06cm, refer Table 5.30). Min_{MTC} also increased significantly from $min_{MTC(norm)}$ for both groups (young $min_{MTC(norm)}$ = 1.42cm vs. $min_{MTC(cough)}$ = 2.28cm, elderly $min_{MTC(norm)}$ = 1.08cm vs. $min_{MTC(cough)}$ = 1.72cm, p<.001 for both groups, refer Table 5.47 and Table 5.48) but only the elderly $min_{MTC(cough)}$ was significantly lower than young $min_{MTC(cough)}$ (p=.003). Initial examination of this data reveals a greater attempt by the young group to reduce the risk of tripping by the greater increase in $median_{MTC(cough)}$. The increase, however, was not significantly different to $median_{MTC(norm)}$. It can be seen that an attempt has been made by both young and elderly groups to reduce the number of MTC points close to the ground by the significantly higher $min_{MTC(cough)}$. Additionally, $IQR_{MTC(cough)}$ was significantly lower than $IQR_{MTC(norm)}$ for both the young (p=.013) and the elderly (p<.001). For the young group, $IQR_{MTC(norm)}$ = 0.28cm vs. $IQR_{MTC(cough)}$ = 0.18cm), while for the elderly group, $IQR_{MTC(norm)}$ = 0.41cm vs. $IQR_{MTC(cough)}$ = 0.29cm (refer Table 5.52 and Table 5.55). No age effects existed for IQR_{MTC}, suggesting no difference in the young and elderly with respect to precision of the locomotor system in implementing a consistent MTC during this task. The significantly lower $median_{MTC(cough)}$ and $min_{MTC(cough)}$ in the elderly does suggest an increased risk of tripping compared with the young group.

Examination of Figure 6.20 shows the varying level of effect on the subjects. Five elderly subjects experienced a decrease in $median_{MTC}$ during the *cough* task (e2, e3, e7, e10 and e15) while two subjects experienced the greatest deviation from $median_{MTC}$ of all the walking conditions during the *cough* task (e1 = 33.2% increase and e15 = -

28.2% decrease). The decrease in $median_{MTC}$ experienced by e15 ($median_{MTC(norm)}$ = 3.10cm vs. $median_{MTC(cough)}$ = 2.23cm) is a concern placing this individual at an increased risk of tripping relative to normal undistracted walking. Three strides were examined for e15 during the *cough* task, suggesting caution in interpreting the results. Although $median_{MTC}$ decreased relative to normal undistracted walking in e15, min_{MTC} increased to help counteract the lower central tendency ($min_{MTC(norm)}$ = 1.74cm vs. $min_{MTC(cough)}$ = 2.17cm (refer Table 5.44). It can be seen in Figure 6.25 that elderly subject e15 had the fourth largest $min_{MTC(cough)}$ of all elderly subjects. IQR_{MTC} also decreased relative to normal undistracted walking which also suggests an attempt to reduce the frequency of low MTC ($IQR_{MTC(norm)}$ = 0.55cm vs. $IQR_{MTC(cough)}$ = 0.19cm, refer Table 5.51.

The lowest $median_{MTC(cough)}$ was found in elderly subject e5 (1.28cm) which places this individual at an increased risk of tripping on small obstacles compared with the rest of the elderly group (refer Table 5.30). Cough task for this individual involved the analysis of only two strides, which again suggests caution in interpreting the results. While being the lowest $median_{MTC(cough)}$, this is an increase from the individual's $median_{MTC(norm)}$ (1.06cm, refer Table 5.26). The low $median_{MTC}$ for this e5 is accompanied by the lowest min_{MTC} of all subjects during the *cough* task (0.96cm), however, this is increased from the individual's $min_{MTC(norm)}$ (0.24cm, refer Table 5.44). Additionally, e5 exhibits improved precision of the locomotor system in implementing a consistent MTC by reducing IQR_{MTC} during the *cough* task (0.32cm) relative to normal undistracted walking (0.44cm, refer Table 5.51). While e5 is at a greater risk of tripping compared with the group, attempts have been made to reduce this risk as evidenced by the increased $median_{MTC}$ and min_{MTC} from normal undistracted walking.

The *cough* task was chosen for this study since it is realistic situation that individuals would experience. There are no known studies examining the influence of a cough on gait and balance measures while walking. It may be that a simple event like coughing causes an individual to increase foot clearance most of the time in order to avoid the constraint of the ground.

6.2.3.4 RTP task

As seen in Table 5.30 and Figure 5.18 a significant age effect existed for $median_{MTC(RTP\&delay)}$ (p=.037) with the young group having higher $median_{MTC}$ compared with the elderly (young = 2.41cm vs. elderly = 2.13cm). The number of strides analysed in the *RTP&delay* task again requires consideration. In the young group, there was a median of four strides analysed, ranging from two to five strides. In the elderly, there was a median of 3.5 strides, ranging again from two to five strides. The elderly had significantly lower $median_{MTC(RTP\&delay)}$ compared with the young group (elderly = 2.13cm vs. young = 2.41cm, p=.037, refer Table 5.30 and Figure 5.18).

Examination of Figure 6.19 shows that expressed as an absolute percentage change from $median_{MTC(norm)}$ the elderly were more affected by the *RTP&delay* task with a change from $median_{MTC(norm)}$ of 15% compared to 10% change in the young. Furthermore, it can be seen in Figure 6.20 that some of the elderly individuals were quite affected by the *RTP&delay* task. In particular, four elderly subjects experienced a decrease in $median_{MTC}$ during the *RTP&delay* task ranging from -14% (e4, four strides) to -21% (e15, three strides). Three young individuals experienced a decrease in

$median_{MTC}$ but the decrease in the elderly subjects is more of a concern since the increased likelihood of tripping given the lower MTC is combined with a decreased likelihood of recovering from a trip should one occur.

Chi-square results showed significant differences in the frequencies of level of effect for both the young and elderly groups (p=.018). Fourteen young and 14 elderly showed no effect while four young and four elderly showed a small effect due to the *RTP&delay* task. This was the only task where there were no elderly subjects showing a large effect, however, with the small number of strides analysed, the chances of obtaining extreme values is reduced. It is also possible that the task was not difficult enough to induce a greater response.

Both the young and elderly group exhibited increased min_{MTC} during the *RTP&delay* task relative to normal undistracted walking min_{MTC} (young $min_{MTC(norm)}$ = 1.42cm vs. $min_{MTC(RTP\&delay)}$ = 2.14, p<.001; elderly $min_{MTC(norm)}$ = 1.08cm vs. $min_{MTC(RTP\&delay)}$ = 2.00cm, p<.001, refer Table 5.47, Table 5.48 and Figure 5.22). No age effects existed for $min_{MTC(RTP\&delay)}$ (p=.217). IQR_{MTC} was significantly lower during *RTP&delay* task compared with normal undistracted walking for both the young and elderly groups (young $IQR_{MTC(norm)}$ = 0.28cm vs. $IQR_{MTC(RTP\&delay)}$ = 0.17cm, p=.005; elderly $IQR_{MTC(norm)}$ = 0.41cm vs. $IQR_{MTC(RTP\&delay)}$ = 0.16cm, p<.001, refer Table 5.52 and Table 5.55). $IQR_{MTC(RTP\&delay)}$ was the smallest IQR_{MTC} measure of all walking conditions for both groups. The higher min_{MTC} and lower IQR_{MTC} during the *RTP&delay* task suggest a decreased risk of tripping. However, the small number of strides analysed reduce the chance of obtaining extreme low MTC.

RTP task was chosen since its merit as a tool in examining divided attention ability, like the *3s* task, has been demonstrated in the literature (e.g. Marsh and Geel, 2000; Shumway-Cook and Woollacott, 2000; McDowd, 1986). The *RTP* task involves structural interference since attentional resources are required for visual input for maintenance of balance concurrently with gaze being directed towards the monitor set up directly in front of the subject. The use of the hand-held button is thought to minimise any disturbance to gait due to reduced or altered arm swing.

As previously described, the *RTP* task was conducted in ST and DT conditions to examine any improvement during the ST condition. Performance on the ST condition, which was conducted immediately following the treadmill walking, was of secondary importance for this research. It was considered more important for this research to examine the influence the distraction tasks had on MTC and, therefore, was presented first during the treadmill walking for all subjects.

There was a significant improvement in reaction time from the DT to ST condition for young and elderly ($p<.001$ for both groups), but no age effect. Improvement in the ST condition, however, may be due to a learning effect since all subjects completed the ST condition last. Elderly subjects improved from 612.5ms during DT to 479.5ms during ST while the young improved from 548.5ms during DT to 462.9ms during ST.

The results of this study support findings in other studies examining reaction time in young and elderly in ST and DT conditions by showing reaction times of young adults are faster than elderly. This was found in the ST condition only, however, and no significant age effects were found for the DT condition. Typically young adults have

faster reaction times in both conditions and perform significantly better in the DT condition compared with elderly (e.g. Sparrow *et al.*, 2002a; Shumway-Cook and Woollacott, 2000). Testing reaction to visual stimuli in a divided attention format whilst walking is important in understanding the varying influences on gait it might have. While walking one might be confronted with various short duration situations in which a quick response is required. These types of distractions allow only small numbers of strides to be analysed. Future research should endeavour to examine the effect of longer duration distractions in which a visual stimulus exists (thereby including structural interference) and requires the subject to respond.

6.2.3.5 Type of distractions most likely to result in tripping and comparison of prolonged and short distractions

Determining the types of distractions most likely to lead to tripping was of particular interest in this research. Understanding the types of situations that increase the risk of tripping on small unseen obstacles is a useful accomplishment for falls prevention. This research examined the level of effect of each distraction as it compared with undistracted walking on measures of $median_{MTC}$, min_{MTC}, $PC5_{MTC}$ and IQR_{MTC}. The change in these measures during each distraction compared with during undistracted walking was calculated. The magnitude of change gives a good indication of the extent to which the distraction affected an individual.

To gain a more comprehensive understanding, the direction of the deviation also needs to be observed. Walking while distracted decreases the chance of seeing tripping hazards and, therefore, it is argued the risk of tripping is increased. One way of compensating for this is to increase MTC to reduce the chance of tripping on any unseen obstacles. On a group basis, it seems the prolonged distractions increase risk of tripping given the locomotor system's failure to adequately compensate for the disturbance. Group median data showed $median_{MTC}$ increased minimally for *3s* task (young = 0.47% from 2.16cm to 2.21cm vs. elderly = 0.07%, virtually unchanged from 2.01cm, p=.029) while there was a small increase $median_{MTC}$ for *video* task in the young and a decrease in the elderly (young = 1.50% from 2.16cm to 2.26cm vs. elderly = -2.71% from 2.01cm to 1.89cm, p=.004). This is in comparison to increases in $median_{MTC}$ during the short distractions of 8.77% - 18.89% for the young group and 7.18% - 15.79% for the elderly group. Given that $median_{MTC}$ is approximately equal to

tripping every second stride (refer section 6.1.4), the smaller $median_{MTC}$, particularly during the *video* task for the elderly group, increases the risk of tripping.

Min_{MTC} was higher than during undistracted walking compared with undistracted walking for all distractions, thereby demonstrating some effort to reduce the risk of tripping by attempting to limit small MTC. Of all distraction tasks, min_{MTC} was lowest during the prolonged distraction tasks compared with the short distractions, which seems to indicate that the locomotor system was more successful in attempting to reduce the tripping risk during the short distractions.

Intra-individual variability, as measured by IQR_{MTC}, has been discussed in this research as a measure of the locomotor system's accuracy in implementing MTC. During normal undistracted walking, the elderly had higher IQR_{MTC} compared with the young (p=.003), effectively increasing the risk of tripping on small unseen obstacles. During distracted walking, IQR_{MTC} decreased for all distractions except *head turn* task, where an increase relative to $IQR_{MTC(norm)}$ was experienced for both the young and elderly and was approaching significance at p<.05 (p=.076). It is suggested that by reducing, or at least preventing an increase in, IQR_{MTC} is one possible mechanism to reduce the risk of tripping (Begg *et al.*, 2007).

On an individual basis, elderly subject e5 is an interesting subject to examine. This subject had the lowest $median_{MTC}$ for each walking condition of all subjects (refer Table 5.26) and experienced large deviations from $median_{MTC(norm)}$ for most distraction tasks. IQR_{MTC} for elderly subject e5 was amongst the highest for most distraction tasks. Low min_{MTC} were also recorded for e5 with the lowest min_{MTC} of all elderly

subjects for all walking conditions except *head turn*, where e5 had the third smallest min_{MTC}. $PC5_{MTC}$ for normal undistracted walking and the prolonged distractions was also the smallest in e5 for normal undistracted and *video* task. The low $median_{MTC}$ and low MTC measures (min_{MTC} and $PC5_{MTC}$) combined with higher IQR_{MTC} increase the risk of tripping compared with other subjects.

In summary, the lower $median_{MTC}$ and min_{MTC} during the prolonged distractions seem to indicate a greater risk of foot contact with obstacles compared with short distractions in both the young and elderly groups. The lower $median_{MTC}$ and min_{MTC} observed in the elderly appears to place the elderly at a greater risk of tripping compared with the young during all conditions.

6.3 Methodological issues and practical applications

6.3.1 Tripping prevention strategies

This research has presented a new method of measuring MTC and predicting the likelihood of tripping during undistracted and distracted walking conditions in healthy elderly adults. The most prominent drawback of this useful method is the time consuming nature of the testing procedure and subsequent analysis rendering it unlikely to become a routine screening tool in its present form. Despite this, the results have revealed important findings relating to risk of tripping in elderly adults and some recommendations can be made with respect to tripping and falls prevention.

Tripping in healthy elderly adults, whilst already established as one of the most common causes of falls (Kreisfeld *et al.*, 2004; Cripps and Carman, 2001; Hill *et al.*, 1999; Sattin *et al.*, 1998; Lord *et al.*, 1993; Campbell *et al.*, 1990; Tinetti and Speechley, 1989; Overstall *et al.*, 1977), is more likely to occur in situations of divided attention. Implementing tripping prevention interventions could include a) modification of environment (reduce tripping hazards); b) gait practice under dual-task situations similar to those encountered in normal everyday life; and c) strength programs aimed at improving gait pattern and to produce safer, more stable gait. Visual assessment is also important, however, since all subjects in this study were assessed as having normal vision, it appears that risk of tripping is increased in elderly adults regardless of normal vision. It is reasonable to suggest that in healthy elderly adults, it appears that other factors are more likely to affect tripping risk.

While modification of tripping hazards in the home seems viable, it is impossible to eliminate tripping hazards in the community. Preventative strategies should focus on gait practice under dual-task conditions and specific strengthening of the lower body muscles to improve walking pattern (Lamoureux *et al.*, 2003; Lamoureux *et al.*, 2002). While it has already been suggested that falls and balance training incorporate dual task activities (e.g. Toulotte *et al.*, 2006; Brauer *et al.*, 2002; Bloem *et al.*, 2001), the findings of this research suggest such dual-tasking should incorporate some aspects of vision and include actions that would be encountered in everyday life given that the *video* task resulted in median MTC lower than during normal undistracted walking for most of the subjects, both young and elderly. In situations where vision is to be directed elsewhere whilst walking, young and elderly individuals might be at an increased risk of tripping on unseen obstacles. The consequences of tripping are far greater in the elderly given the greater likelihood of sustaining a fall following a trip and also sustaining an injury as a result of a fall. Sparrow *et al.* (2002a) also showed that visual reaction time performance was slower than an auditory reaction time task whilst walking when foot placement was required to fall within a specified target on the ground. As the authors suggested, elderly adults are at risk of falls in situations where vision is directed elsewhere while walking, such as watching for cars whilst crossing the road.

6.3.2 Calculating normal, comfortable overground walking velocity

As discussed in the literature review, the treadmill is useful in obtaining kinematic data during locomotion, particularly where multiple, continuous strides are required. There is no universal method of determining comfortable walking speed. Typically, this has been determined by calculating overground walking and then this speed is set on the treadmill. It was found during pilot testing for this research, however, that subjects found the treadmill walking speed to be too fast despite it being the same as their comfortable overground walking speed. The study by Alton *et al.* (1998) also reported subjects found the same overground walking speed set on the treadmill to be too fast and concluded that subjective experience of participants should be examined in future studies. It is reasonable to suggest that the treadmill, like any other walking surface, is a different terrain, which requires a different walking speed.

The protocol implemented in this research was to use subjects' subjective assessment of comfortable walking speed on the treadmill terrain. Subjects in this study stated the walking speed felt comfortable for the duration of walking and, therefore, it seems this method was satisfactory in obtaining preferred walking speed (PWS) on the treadmill in this research. Indeed, in a recent study, Dingwell and Marin (2006) successfully employed a similar method of determining PWS.

A standard protocol for estimating PWS on the treadmill would be a useful development. It appears that subjective experiences of the subject, as suggested by Alton *et al.* (1998) and, more recently, Dingwell and Marin (2006), may be an

important consideration and should be incorporated into the standard protocol for determining PWS on the treadmill.

6.3.3 Generalising results from treadmill walking

Using the treadmill for kinematic analysis such as in this research is an attractive option since it allows consecutive strides to be analysed over a long period (30 minutes). Treadmill walking was chosen for this research since there was no alternative way of collecting the large number of continuous strides during overground walking required for the type of analysis conducted (e.g. probability of tripping).

In this study, the treadmill is considered to be a walking terrain amongst many varied terrains one might experience (e.g. grass, gravel, undulating, etc.). It is therefore reasonable to suggest that different walking terrains are likely to produce different walking patterns. There are some conflicting findings in the literature regarding the generalization of treadmill and overground walking. Some studies have found that treadmill walking could not be generalized with overground walking (e.g. Wass *et al.*, 2005) but others have found the two walking terrains are comparable and reliable kinematic variables can be obtained after a relatively short period of six minutes of familiarisation (Matsas *et al.*, 2000). The first six minutes of data for each subject was not included in the analysis in order to obtain stable and reliable kinematics.

Although there is no standard protocol for treadmill familiarisation, the elderly subjects were given time to become familiarised on the same day, prior to testing, and all stated

they felt comfortable. Treadmill familiarization continued until the subject stated they felt comfortable, which was no longer than 15 minutes.

6.3.4 Data Normalisation

As described in the methods chapter, the Qbasic program used to determine MTC for each stride did not work for all subjects. This was due to an unusual gait where there was no actual MTC. As previously explained, since no MTC existed for these unusual cases, the Qbasic program identified the ground during the toe-off event as MTC. The subjects who did not have identifiable MTC for large portions of the data set were deemed unusual because the trajectory of the foot typically follows a predictable path (e.g. Whittle, 1993). There are no known studies reporting such a phenomenon. Since the key feature of this thesis was the study of MTC, subjects with this unusual data were not examined further. Future research should endeavour to examine data with no identifiable MTC since it is possible that these individuals may be at an increased risk of tripping.

An alternative method of dealing with the data for which the MTC Qbasic program did not work is proposed in this section. This is achieved by normalizing the collected, digitized PTP trajectory data with respect to timing of MTC within each stride. Two examples are shown to illustrate this method: a) an example of a young subject with regular PTP trajectory and all identified MTC within Qbasic program verified as correct; and b) one elderly subject where approximately 25% of the identified MTC were deemed incorrect. It was not within the scope of this research to complete a full

set of new results for every subject (i.e. n = 48) as a comparison. It is important, however, that this method be explored in future research.

The first step in normalising with respect to MTC timing is to define each stride. In this research, one stride was defined as between two consecutive toe-off (TO) events. Each TO event within the PTP vertical displacement data were identified. Figure 6.26 shows an extract of four strides from TO to TO event for young subject y14. Data for this subject was chosen since all identified MTC points, as calculated using the 2D foot model in the Qbasic program, were deemed to be correct.

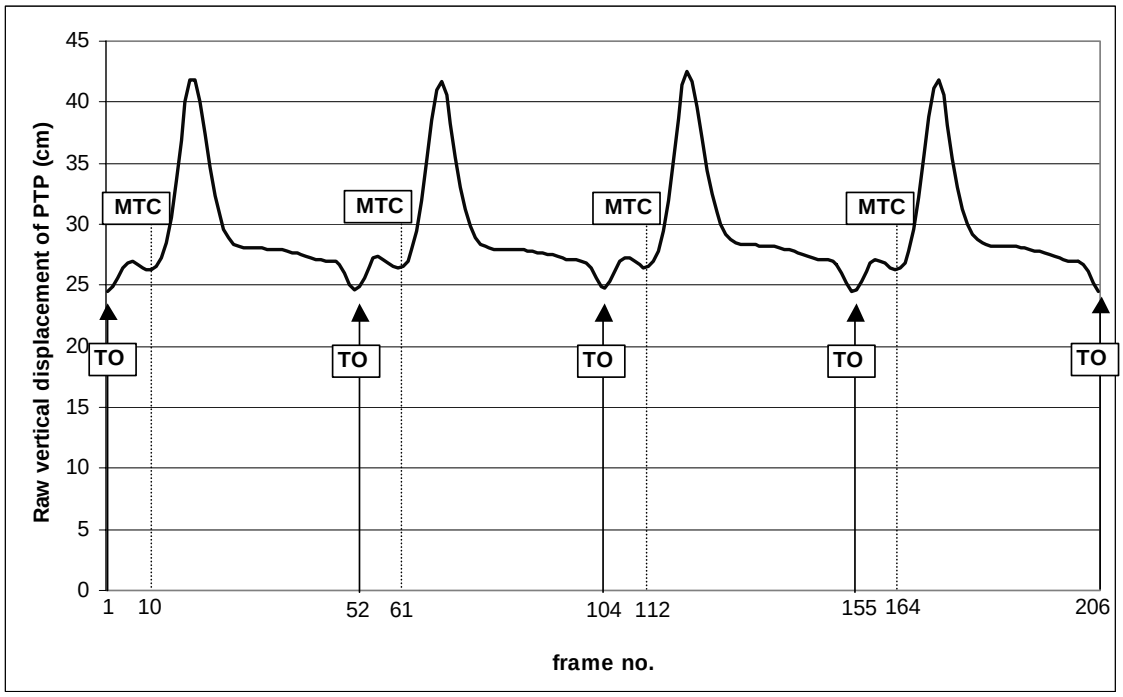


Figure 6.26: Example of four strides showing toe-off (TO) and accurate MTC events for one young subject (y14).

It can be seen in Figure 6.26 that TO is easily identified since it has the smallest vertical displacement of PTP. The TO events occurred at frames 1, 52, 104, 155 and

206. Next, MTC, calculated via the 2D foot model in the Qbasic program, are shown at frames 10, 61, 112 and 164. It can be seen that a 'dip' occurs at the point of MTC.

Once TO and MTC events have been identified, and the respective frame numbers at which they occurred noted, the timing of MTC (percentage of the stride at which it occurred) can now be determined. Table 6.4 shows the timing of MTC for the four strides illustrated in Figure 6.26.

Table 6.4: Calculation of MTC timing for each stride (MTC_{time}) and mean MTC_{time} for the four strides ($MTC_{time(mean)}$).

Stride no.	TO - TO (frame no.)	No. frames per stride	Frame no. at which MTC occurred	MTC_{time}
1	1 to 52	51	10	17.6%
2	52 to 104	52	61	17.3%
3	104 to 155	51	112	15.7%
4	155 to 206	51	164	17.6%
			$MTC_{time(mean)}$	***17.1%***

It can be seen in Table 6.4 that, for the four strides examined, MTC occurred a mean of 17.1% of the stride (i.e. $MTC_{time(mean)}$ = 17.1%). Once $MTC_{time(mean)}$ has been determined, a new value of MTC can be calculated based on mean (normalised) timing of MTC data ($MTC_{(normalised)}$). This is achieved by applying $MTC_{time(mean)}$ to the raw vertical co-ordinates of PTP. For the example of young subject y14, using raw PTP data and identified TO events, the timing of $MTC_{(normalised)}$ is assumed to occur at 17.1% ($MTC_{time(mean)}$ of each stride.

No difference was found in the timing (i.e. frame number) of MTC and $MTC_{(normalised)}$ for young subject y14. In this case, there is no difference in the value of MTC and $MTC_{(normalised)}$ (calculated as vertical co-ordinate of PTP less the ground reference previously digitised in Peak Motus). Timing of $MTC_{(normalised)}$ (i.e. frame number) was calculated for 40 accurate strides in order to compare with timing of MTC (frame number). For 40 strides, $MTC_{time(mean)}$ was calculated at 16.95% compared with 17.1% for four strides. It was found the timing of only one $MTC_{(normalised)}$ (i.e. frame number) varied from that of MTC timing showing that, for this example, accuracy of $MTC_{(normalised)}$ timing (i.e. frame number) is reasonably accurate.

It is important to note that the example given for young subject y14 was for MTC data where all identified MTC points within the Qbasic program were deemed to be correct. PTP trajectories for this subject, as can be seen in Figure 6.26, were very regular with little variability between strides. Young subject y14 had $median_{MTC}$ of 1.98cm with IQR_{MTC} of 0.22cm, the smallest intra-individual variability of all subjects. It appears for this subject, with regular PTP trajectories, the normalisation method of determining MTC is reasonably accurate.

In comparison to the example of young subject y14, PTP trajectory data for elderly subject e16 is examined. The MTC identification in the Qbasic program was not successful for elderly subject e16. The 20 minutes of normal undistracted walking for elderly subject e16 resulted in 74% (i.e. 699 strides) of the 945 ground clearances (strides) deemed to be correct (i.e. 246 strides or 26% of the data set were incorrect). It is, therefore, important to examine the accuracy of obtaining $MTC_{(normalised)}$ in such subjects.

The process of calculating $MTC_{time(mean)}$ using data where no MTC occurred is not as straightforward as the previous example of young subject y14. Unlike for young subject y14, it was not possible to obtain a large number of consecutive strides with accurate MTC for elderly subject e16. Forty strides with accurate MTC were selected in order to calculate $MTC_{time(mean)}$ and other descriptive statistics. MTC_{time} was calculated for these forty strides and then $MTC_{time(mean)}$ was calculated and found to be 13.98%, approximately 3% earlier in the stride compared with young subject y14.

A series of six consecutive strides that included two accurate MTC and four strides where no MTC occurred are shown in Figure 6.27. $MTC_{(normalised)}$ was calculated for these six strides based on the $MTC_{time(mean)}$ of 13.98% of the stride.

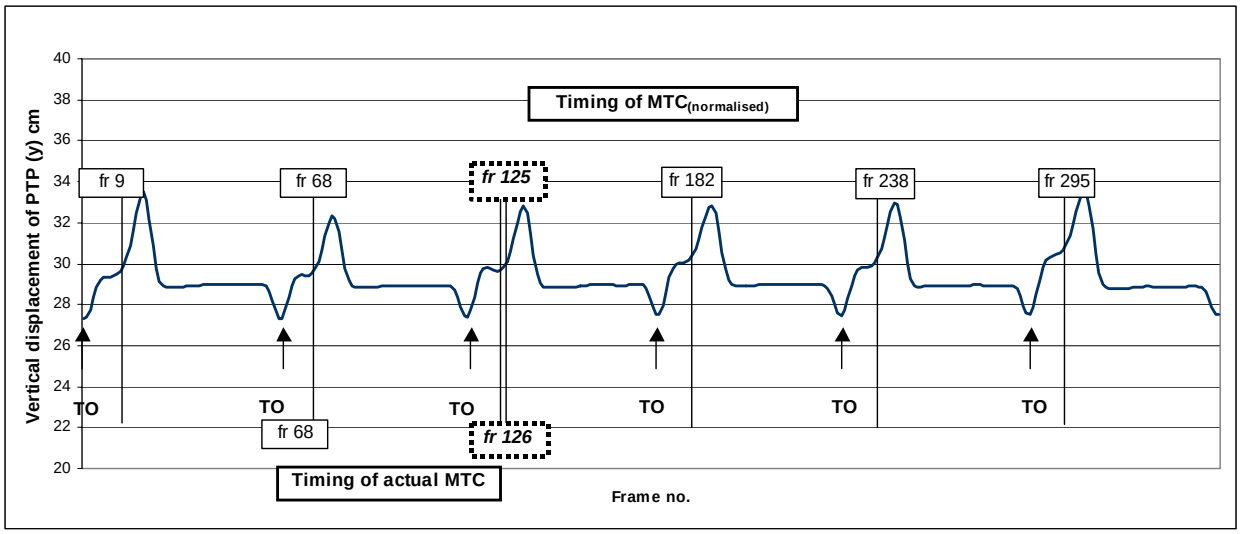


Figure 6.27: Example of calculation of $MTC_{(normalised)}$ timing (i.e. frame number) for one subject with no identifiable MTC (elderly subject e16).

Timing of $MTC_{(normalised)}$ (i.e. frame number) is shown at the top of the chart in Figure 6.27. It can be seen that only two actual MTC occurred (frame 68 and frame 126, shown at the bottom of the chart). The timing of the second $MTC_{(normalised)}$ coincides

with the accurate MTC (frame 68) whilst the timing of the third $MTC_{(normalised)}$ (frame 125) occurs one frame prior to the accurate MTC (frame 126).

Timing of $MTC_{(normalised)}$ was the same as timing of MTC for 16 of the 40 ground clearances whilst 21 varied by one frame and three varied by two frames. The mean difference in timing with respect to frame number was 0.18s. This difference in timing using the two methods resulted in a mean difference in vertical co-ordinate of PTP of 0.02cm, a very small difference indeed. Whilst timing of $MTC_{(normalised)}$ is relatively accurate compared with MTC timing, other important differences between the two methods can be observed in descriptive statistics. Descriptive statistics of the forty strides for elderly subject e16 are shown in Table 6.5.

Table 6.5: MTC and $MTC_{(normalised)}$ for 40 strides for one elderly subject (e16).

Variable	MTC	$MTC_{(normalised)}$	Difference (%)
mean (cm)	2.53	2.55	0.9
median (cm)	2.53	2.55	1.0
sd (cm)	0.34	0.35	1.8
IQR (cm)	0.37	0.38	1.5
Q1 (cm)	2.34	2.35	0.6
Q3 (cm)	2.71	2.73	0.7
PC1 (cm)	2.11	2.11	0.3
PC5 (cm)	2.53	2.55	1.0
min (cm)	1.80	1.83	1.9
max (cm)	3.37	3.49	3.7
range (cm)	1.57	1.66	5.6
S	0.19	0.37	97.2
K	0.42	0.66	58.2

It can be seen in Table 6.5 that most descriptive statistics for MTC and $MTC_{(normalised)}$ for the forty strides are relatively similar. For example, median for $MTC_{(normalised)}$ was only 1.0% greater, and IQR was 1.5% greater than for MTC. Max was 3.7% greater in $MTC_{(normalised)}$, with greater range (5.6% greater). Most noticeably was the greater S of

97.2% in $MTC_{(normalised)}$ and greater K (58.2% greater). Although the method of obtaining $MTC_{(normalised)}$ appeared to be relatively accurate with respect to timing compared with MTC, it is clear that the large differences in S and K make this method unsuitable for analysing such descriptive statistics. Given that these descriptive statistics vary considerably using the two methods, there is good justification for discarding subjects with large numbers of strides with no MTC.

The young and elderly subject described here varied in the timing of $MTC_{(normalised)}$ ($MTC_{time(mean)}$) by 3%. Although not found in this research, it may be possible for some individuals to have data sets where no identifiable MTC can be observed. In these cases it is impossible to calculate individual $MTC_{time(mean)}$ as described and the group mean $MTC_{time(mean)}$ could be used to predict $MTC_{(normalised)}$. Future research should investigate the reasons for the unusual gait where there is no identifiable MTC. Further investigation into alternative methods of calculating ground clearance during swing phase is an important area for future research into foot clearance and tripping in elderly populations.

6.3.5 Dual-task methodology

The dual-task methodology employed for this research includes attentional switching between the primary and secondary tasks. This methodological issue is discussed in detail in the literature review chapter but, briefly, it is postulated that where the primary task performance (MTC in this research) is not held constant it is difficult to evaluate the effect of the secondary task (e.g. Marsh and Geel, 2000; Abernethy, 1988). Other researchers, however, have defended the usefulness of such methodologies (e.g.

Woollacott and Shumway-Cook, 2002; Shumway-Cook and Woollacott, 2000) since it is useful to examine how individuals react to challenging divided attention conditions, including changes to the primary and/or secondary tasks. In this research the influence of a range of prolonged and short 'real life' distractions on the primary task (MTC while walking) is examined. Changes to the foot trajectory (MTC) during periods of normal everyday distractions are observed and implications for tripping risk are discussed. Therefore, whilst not pure dual-task methodology, it is argued the rationale for this methodology is warranted given the usefulness the findings have for tripping and falls research. That is, the types of distractions employed can be related to normal everyday tasks that elderly may undergo and the effect these have on walking is of vital interest to falls research. Additionally, the types of distractions that most influence MTC and possibly increase the likelihood of tripping are of particular interest and are discussed in the following sections.

6.3.6 Limitations of the study

The major limitation of this study was the lengthy data analysis method, which required many hours to digitise and then to draw out the pertinent data. This research also studied healthy elderly females for whom walking on a treadmill for over 30 minutes was an achievable task. Since the treadmill is the only means of obtaining the large numbers of strides required, the technique might not be suitable for certain pathological samples, e.g. high risk fallers. These factors limit the usefulness of the technique as a screening tool in its current form.

The second part of this research was to examine the effect of distractions on MTC and it was considered important to measure MTC in response to the first presentation of the distraction. Future studies could benefit from examining multiple sets of distracted MTC.

Chapter 7: Conclusion

The objective of this research was to examine the control of the foot trajectory (MTC) during distracted and undistracted walking among healthy young and elderly females. This would extend the existing body of literature on specific age related changes to gait (i.e. MTC) and demonstrate the different strategies to implement MTC in order to prevent tripping. This research also extends the work on declines in divided attention ability and its relationship to falls by utilizing distractions that can be related to everyday life and evaluating the contribution to tripping risk. The need for research investigating such real-life distractions has been highlighted in the literature.

One of the major differences with this research to other gait analysis studies is the size of the data sets analysed. Typically only small numbers of strides (e.g. up to 10 strides) are analysed and these are often collected overground and therefore not continuous. This research collected large data sets of approximately 1,000 continuous strides per subject during treadmill walking, which is currently the only means available for collecting large numbers of continuous strides. The large data sets allowed important inferences to be made about the intent of the locomotor system in implementing MTC and the accuracy in this task. Other meaningful descriptive statistics (e.g. skew and kurtosis) could be calculated and enabled a comprehensive understanding of the strategies employed by young and elderly subjects during normal undistracted and distracted walking. Skew and kurtosis of the MTC distributions are useful descriptors and, indeed, must be modelled in order to obtain an accurate probability of tripping.

Skew and kurtosis are never reported in other gait studies and the distributions are assumed to be normal.

A second major focus in this research was the selection of appropriate measures of central tendency and variability. Typically mean and standard deviation are reported as measures of central tendency and variability, however, these descriptive statistics assume normality of the data. As seen in this research, the MTC data are typically positively skewed and leptokurtic which results in erroneously high mean and standard deviation. It has been shown that median and IQR are more accurate representations of these measures for such data. Future investigations should determine the nature of the distribution prior to selecting descriptive and statistical measures.

The use of the treadmill for collecting reliable data generalisable to overground walking has received considerable interest in the literature with some conflicting findings. It is argued in this research that the treadmill, like any other walking terrain such as paved, grassed, or gravel surfaces for example, is a different terrain and may or may not produce different gait kinematics. In real life, one might typically be confronted with many different surface terrain changes.

There are some methodological issues concerning the use of the treadmill that have been addressed in this research. For example, determination of preferred walking speed (PWS) varies in the literature but is suggested in this research, consistent with some other authors (e.g. Dingwell and Marin, 2006; Alton *et al.*, 1998), that subjective experience of the subjects be incorporated into the protocol. Indeed, no standard protocol currently exists for determining PWS and method of familiarization with the

treadmill. These are areas that warrant further research in order to improve the consistency and reliability of results in future investigations.

There is currently no standard protocol for screening elderly subjects prior to participating in gait analysis studies. Screening methodology employed in this research demonstrated the need for extensive screening of elderly subjects and a need for a standard protocol of screening items. This would improve the reliability of future investigations into age-related changes in gait.

The main findings of this research show that healthy elderly females have smaller MTC while walking without distractions on a treadmill compared with healthy young females. This finding is supported by the smaller $median_{MTC}$ in the elderly (young = 2.16cm vs. elderly = 2.01cm, p=.076). Additionally, variability as measured by IQR_{MTC} is significantly higher (p=.003) in the elderly subjects (young = 0.28cm vs. elderly = 0.41cm). The elderly group also had significantly lower measures in the lower end of the MTC distribution, namely min_{MTC} (young = 1.42cm vs. elderly = 1.08, p=.021), $PC1_{MTC}$ (young = 1.68cm vs. elderly = 1.35cm, p=.008) and $PC5_{MTC}$ (young = 1.81cm vs. elderly = 1.50cm, p=.006). Keeping all other factors constant, these conditions contribute to an overall high risk of tripping on unseen obstacles that occur at the point of MTC in the elderly compared with the young subjects.

The lower $median_{MTC}$, low MTC measures and higher IQR_{MTC} in the elderly individuals potentially increases the risk of tripping on unseen obstacles while walking. However, some strategies that might compensate for this were found in the significantly higher S_{MTC} (young = 0.33 vs. elderly = 0.60, p=.029) in an attempt to

reduce the frequency of MTC in the lower portion of the MTC distribution and is accompanied by a greater UQR_{MTC} (young = 0.82cm vs. elderly = 1.31cm, p=.019). S_{MTC} was highly positively correlated with UQR_{MTC} in both groups but to a greater extent in the elderly group (r=.863, p<001). It therefore appears the elderly in particular adopted a strategy of increased S_{MTC} and UQR_{MTC} in order to theoretically minimize the frequency of MTC in the lower portion of the distribution.

The calculated probability of tripping (PT) is significantly higher in the elderly individuals between MTC(y) = 0.9cm to 2.0cm. Moreover, it was found that at $median_{MTC}$, an individual had approximately 50% chance of tripping on an unseen obstacle that occurred at the point of MTC. This supports the notion that individuals who walk with smaller $median_{MTC}$ are at a greater risk of tripping than individuals with higher $median_{MTC}$. When also combined with lower min_{MTC} and higher IQR_{MTC}, the elderly are, indeed, at a greater risk of tripping compared with the young. The higher risk of tripping in the elderly is a great concern given they are least likely to recover successfully from a trip, leading to a potential fall.

It is well established that the elderly have significantly more difficulty in tasks requiring divided attention (e.g. Bloem *et al.*, 2001; Shumway-Cook *et al.*, 1997b; Chen *et al.*, 1996; McDowd, 1986). The results of this research show some significant differences between young and elderly groups in $median_{MTC}$ (refer Figure 6.17) for four of the six distraction tasks, namely, *cough* (young = 2.47cm vs. elderly = 2.06cm, p=.001), *video* (young = 2.26cm vs. elderly = 1.89cm, p=.004), *3s* (young = 2.21cm vs. elderly = 2.01cm, p=.029) and *RTP&delay* (young = 2.41cm vs. elderly = 2.13cm, p=.037) tasks with elderly subjects having lower $median_{MTC}$ during all walking

conditions. Elderly subjects generally had lower min_{MTC} and higher IQR_{MTC} compared with the young for all walking conditions. Keeping all other factors constant, the combination of low MTC and increased stride-to-stride variability in MTC increases the risk of the foot contacting small unseen obstacles for the elderly group.

Observed changes in group $median_{MTC}$ show that shorter discrete distractions (namely *pouch*, *cough*, *head turn* and *RTP&delay* tasks) elicit higher $median_{MTC(distr)}$ compared with $median_{MTC(norm)}$ as opposed to prolonged distractions (namely *3s* and *video* tasks). Although not significant, there was a decrease in MTC during the *video* task in the elderly (norm = 2.01cm, video = 1.89cm). This was the only task to show a group $median_{MTC(distr)}$ lower than the $median_{MTC(norm)}$, seen in the elderly only, and is indeed an interesting finding. Age-related differences were statistically significant for both prolonged distraction tasks (*video:* p=.004; *3s:* p=.029). In comparison to the short distractions, $median_{MTC}$ and min_{MTC} was smaller in the two prolonged distractions. These factors contribute to an increased likelihood of tripping on unseen obstacles during the prolonged compared with short distractions for both young and elderly, but particularly the elderly group.

Although $median_{MTC}$ was not significantly different between young and elderly during *normal* and *head turn* condition, the *head turn* condition in the young group was the only task significantly different to $median_{MTC(norm)}$ (young norm = 2.16cm vs. young head turn = 2.61cm, p=.005). There was an increase in $median_{MTC(headturn)}$ of approximately 19% from $median_{MTC(norm)}$ for the young group while the increase was only approximately 13% in the elderly. Initial examination might suggest the influence was greater in the young subjects. The *head turn* task was the only task producing

IQR_{MTC} greater than during undistracted walking (young $IQR_{(norm)}$ = 0.28cm vs. $IQR_{(head\ turn)}$ = 0.39cm; elderly $IQR_{(norm)}$ = 0.41cm vs. $IQR_{(head\ turn)}$ = 0.44cm). The greater stride-stride variability in MTC increases the chance of hitting small unseen obstacles while walking. It also seems that the young responded more efficiently to the *head turn* task by increasing MTC. This situation demonstrates a failure in the elderly to adopt the protective strategy of increasing MTC. Given that a volitional head turn while walking is an activity typically performed everyday, this clearly is an area that would gain favourably by further examination.

The variability as measured by IQR_{MTC} for the *video* task was negligibly smaller compared with $IQR_{MTC(norm)}$ for the young group (~0.01cm) but significantly lower for the elderly group (*norm* = 0.41cm vs. *video* = 0.28cm, p=.004). Low MTC measures (i.e. $PC5_{MTC}$) was higher during the *video* task compared with normal but not significantly different. There were, however, significant age effects for $PC5_{MTC}$ during the *video* task (p=.002) with the young significantly higher (young = 1.94cm vs. elderly = 1.56cm). It seems with the significantly lower $median_{MTC}$ and $PC5_{MTC}$ in the elderly the trade-off was to ensure variability was minimized in order to prevent any smaller MTC which might further increase the risk of tripping. It is reasonable to suggest the low MTC in the elderly combined with directing vision upwards and not at the travel terrain would predispose elderly to tripping on small obstacles since any obstacles appearing at the point of MTC would not be seen.

It can be concluded that the *head turn* task caused the greatest increase in MTC and *video* task produced the smallest MTC. The larger MTC seen in the *head turn* task might indicate the difficulty in the task and the precision in the locomotor system erring

on the side of safety by increasing MTC. The smaller MTC seen in the *video* task increases the risk of tripping on small unseen obstacles. Moreover, this risk is higher in the elderly given their smaller MTC compared with the young. Interestingly, these two tasks involved vision to be directed to the required task as well as maintaining balance. It appears that distractions such as *head turn* and *video* have the potential of causing a disruption to gait and individuals should, therefore, exercise caution under these circumstances.

Future research should concentrate on:

- examining control of the foot trajectory in pathological elderly populations as well as healthy elderly;
- real-life distraction situations while walking and the contribution to tripping risk;
- reasons for unusual walking patterns with no identifiable MTC and suitable methods of dealing with it;

Further studies in these areas will make an important contribution to the established body of research into tripping and falls. This information could be used to construct prevention programs targeted at at-risk individuals.

REFERENCES

Abernethy, B. (1988). Dual-task methodology and motor skills research: Some applications and methodological constraints. *Journal of Human Movement Studies,* **14,** 101-132.

ABS (2005). *Population Projections, Australia, 2004 - 2101*. Cat. no. 3222.0. Commonwealth of Australia.

Adams, J.M. and Perry, J. (1994). Gait Analysis: Clinical Application. In *Human Walking* (Rose, J. and Gamble, J.G. eds.), pp. 139-164. Williams & Wilkins, Baltimore, Maryland.

Afifi, A.A. and Clark, V. (1990). *Computer-Aided Multivariate Analysis*. Van Nostrand Reinhold, Singapore.

AGS (2001). Guideline for the prevention of falls in older persons. In *Journal of the American Geriatrics Society*, Vol. 49, pp. 664-672.

Alexander, N.B. (1996). Differential diagnosis of gait disorders in older adults. *Clinics in Geriatric Medicine,* **12,** 689-703.

Allum, J.H., Adkin, A.L., Carpenter, M.G., Held-Ziolkowska, M., Honegger, F. and Pierchala, K. (2001). Trunk sway measures of postural stability during clinical balance tests: effects of a unilateral vestibular deficit. *Gait Posture,* **14,** 227-237.

Alton, F., Baldey, L., Caplan, S. and Morrissey, M.C. (1998). A kinematic comparison of overground and treadmill walking. *Clinical Biomechanics (Bristol, Avon),* **13,** 434-440.

Anacker, S.L. and Di Fabio, R.P. (1992). Influence of sensory inputs on standing balance in community-dwelling elders with a recent history of falling. *Physical Therapy,* **72,** 575-581; discussion 581-574.

Anderson, P.G., Nienhuis, B., Mulder, T. and Hulstijn, W. (1998). Are older adults more dependent on visual information in regulating self-motion than young adults? *Journal of Motor Behavior,* **30,** 104.

Ashton-Miller, J.A. (1999). Effects of age on obstacle avoidance during human locomotion. In *International Society of Biomechanics XVIIth Congress Abstracts*, Calgary, Canada, August 8-13, p. 92.

Austin, G.P., Garrett, G.E. and Bohannon, R.W. (1999). Kinematic analysis of obstacle clearance during locomotion. *Gait & Posture,* **10,** 109-120.

Bailey, I.L. and Lovie, J.E. (1976). New design principles for visual acuity letter charts. *American Journal of Optometry and Physiological Optics,* **53,** 740-745.

Begg, R., Best, R., Dell'Oro, L. and Taylor, S. (2007). Minimum foot clearance during walking: strategies for the minimisation of trip-related falls. *Gait & Posture,* **25,** 191-198.

Begg, R.K. and Sparrow, W.A. (2000). Gait characteristics of young and older individuals negotiating a raised surface: implications for the prevention of falls. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **55,** M147-154.

Berg, W.P., Alessio, H.M., Mills, E.M. and Tong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and Ageing,* **26,** 261-268.

Best, R.J. (1996). *Javelin Aerodynamics, Flight Simulation and Optimisation of Javelin Release.* PhD Thesis. University of Salford, U.K.

Best, R.J. and Begg, R.K. (2002). Personal communication.

Best, R.J., Begg, R.K., Ball, K. and James, L. (2000). Minimum foot clearance variability in walking: a case study. Accepted for presentation at the *3rd Australia and New Zealand Society of Biomechanics Conference*, Queensland, January 31 - February 1.

Best, R.J., Begg, R.K. and James, L. (1999). The probability of hitting an unseen obstacle while walking. In *Proceedings of the International Society of Biomechanics XVII Congress*, Calgary, Canada, August 8 - 13, p. 234.

Blake, A.J., Morgan, K., Bendall, M.J., Dallosso, H., Ebrahim, S.B., Arie, T.H., Fentem, P.H. and Bassey, E.J. (1988). Falls by elderly people at home: prevalence and associated factors. *Age and Ageing,* **17,** 365-372.

Bland, J.M. and Altman, D.G. (1995). Statistics notes: Multiple significance tests: the Bonferroni method. *British Medical Journal,* **310,** 170-.

Bloem, B.R., Valkenburg, V.V., Slabbekoorn, M. and Willemsen, M.D. (2001). The Multiple Tasks Test: development and normal strategies. *Gait & Posture,* **14,** 191-202.

Boulgarides, L.K., McGinty, S.M., Willett, J.A. and Barnes, C.W. (2003). Use of clinical and impairment-based tests to predict falls by community-dwelling older adults. *Physical Therapy,* **83,** 328-339.

Box, G.E. and Tiao, G.C. (1973). *Bayesian Inference in Statistical Analysis*. Addison-Wesley, Sydney.

Box, M.J., Davies, D. and Swann, W.H. (1969). *Non-linear Optimization Techniques.* Oliver & Body, Edinburgh.

Brauer, S.G. and Burns, Y.R. (2002). The influence of preparedness on rapid stepping in young and older adults. *Clinical Rehabilitation,* **16,** 741-748.

Brauer, S.G., Woollacott, M. and Shumway-Cook, A. (2002). The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. *Gait & Posture,* **15,** 83-93.

Braun, B.L. (1998). Knowledge and perception of fall-related risk factors and fall-reduction techniques among community-dwelling elderly individuals. *Physical Therapy,* **78,** 1262-1276.

Broglio, S.P., Tomporowski, P.D. and Ferrara, M.S. (2005). Balance performance with a cognitive task: a dual-task testing paradigm. *Medicine and Science in Sports and Exercise,* **37,** 689-695.

Brown, L.A., Shumway-Cook, A. and Woollacott, M.H. (1999). Attentional demands and postural recovery: the effects of aging. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **54,** M165-171.

Buzzi, U.H., Stergiou, N., Kurz, M.J., Hageman, P.A. and Heidel, J. (2003). Nonlinear dynamics indicates aging affects variability during gait. *Clinical Biomechanics,* **18,** 435.

Campbell, A.J., Borrie, M.J. and Spears, G.F. (1989). Risk factors for falls in a community-based prospective study of people 70 years and older. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **44,** M112-117.

Campbell, A.J., Borrie, M.J., Spears, G.F., Jackson, S.L., Brown, J.S. and Fitzgerald, J.L. (1990). Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study. *Age and Ageing,* **19,** 136-141.

Chang, J.T., Morton, S.C., Rubenstein, L.Z., Mojica, W.A., Maglione, M., Suttorp, M.J., Roth, E.A. and Shekelle, P.G. (2004). Interventions for the prevention of falls in older adults: systematic review and meta-analysis of randomised clinical trials. *British Medical Journal,* **328,** 680.

Chen, H.-C., Ashton-Miller, J.A., Alexander, N.B. and Schultz, A.B. (1994a). Age effects on strategies used to avoid obstacles. *Gait & Posture,* **2,** 139-146.

Chen, H.C., Ashton-Miller, J.A., Alexander, N.B. and Schultz, A.B. (1991). Stepping over obstacles: gait patterns of healthy young and old adults. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **46,** M196-203.

Chen, H.C., Ashton-Miller, J.A., Alexander, N.B. and Schultz, A.B. (1994b). Effects of age and available response time on ability to step over an obstacle. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **49,** M227-233.

Chen, H.C., Schultz, A.B., Ashton-Miller, J.A., Giordani, B., Alexander, N.B. and Guire, K.E. (1996). Stepping over obstacles: dividing attention impairs performance of old more than young adults. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **51,** M116-122.

Chou, L.S. and Draganich, L.F. (1997). Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. *Journal of Biomechanics,* **30,** 331-337.

Chou, L.S., Draganich, L.F. and Song, S.M. (1997). Minimum energy trajectories of the swing ankle when stepping over obstacles of different heights. *Journal of Biomechanics,* **30,** 115-120.

Chou, L.S., Kaufman, K.R., Brey, R.H. and Draganich, L.F. (2001). Motion of the whole body's center of mass when stepping over obstacles of different heights. *Gait & Posture,* **13,** 17-26.

Choy, N.L., Brauer, S. and Nitz, J. (2003). Changes in postural stability in women aged 20 to 80 years. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **58,** 525-530.

Coakes, S.J. and Steed, L., G. (1999). *SPSS: analysis without anguish: versions 7.0, 7.5, 8.0 for Windows.* John Wiley & Sons, Milton, Queensland.

Craik, R. (1989). Changes in locomotion in the aging adult. In *Development of Posture and Gait Across the Life Span* (Woollacott, M.H. and Shumway-Cook, A. eds.), pp. 176-201. University of Southern California Press, Columbia.

Cripps, R. and Carman, J. (2001). *Falls by the elderly in Australia: Trends and data for 1998. Injury Research and Statistics Series: Adelaide*
(AIHW cat no. INJCAT 35). Australian Institute of Health and Welfare, Canberra.

Cumming, R.G., Salkeld, G., Thomas, M. and Szonyi, G. (2000). Prospective study of the impact of fear of falling on activities of daily living, SF-36 scores, and nursing home admission. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **55A,** M299-M305.

Cunningham, D.A., Rechnitzer, P.A., Pearce, M.E. and Donner, A.P. (1982). Determinants of self-selected walking pace across ages 19 to 66. *Journal of Gerontology,* **37,** 560-564.

Cwikel, J.G., Fried, A.V., Biderman, A. and Galinsky, D. (1998). Validation of a fall-risk screening test, the Elderly Fall Screening Test (EFST), for community-dwelling elderly. *Disability and Rehabilitation,* **20,** 161-167.

Danion, F., Varraine, E., Bonnard, M. and Pailhous, J. (2003). Stride variability in human gait: the effect of stride frequency and stride length. *Gait & Posture,* **18,** 69-77.

Dingwell, J.B. and Cavanagh, P.R. (2001). Increased variability of continuous overground walking in neuropathic patients is only indirectly related to sensory loss. *Gait & Posture,* **14,** 1-10.

Dingwell, J.B. and Cusumano, J.P. (2000). Nonlinear time series analysis of normal and pathological human walking. *Chaos,* **10,** 848-863.

Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R. and Sternad, D. (2001). Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. *Journal of Biomechanical Engineering,* **123,** 27-32.

Dingwell, J.B. and Marin, L.C. (2006). Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. *Journal of Biomechanics,* **39,** 444-452.

Dingwell, J.B., Ulbrecht, J.S., Boch, J., Becker, M.B., O'Gorman, J.T. and Cavanagh, P.R. (1999). Neuropathic gait shows only trends towards increased variability of sagittal plane kinematics during treadmill locomotion. *Gait & Posture,* **10,** 21-29.

Dolinis, J., Harrison, J.E. and Andrews, G.R. (1997). Factors associated with falling in older Adelaide residents. *Australian and New Zealand Journal of Public Health,* **21,** 462-468.

Dubost, V., Annweiler, C., Aminian, K., Najafi, B., Herrmann, F.R. and Beauchet, O. (2008). Stride-to-stride variability while enumerating animal names among healthy young adults: Result of stride velocity or effect of attention-demanding task. *Gait & Posture,* **27,** 138-143.

Ducic, I., Short, K.W. and Dellon, A.L. (2004). Relationship between loss of pedal sensibility, balance, and falls in patients with peripheral neuropathy. *Annals of Plastic Surgery,* **52,** 535-540.

Elston, R.C. and Johnson, W.D. (1994). *Essentials of biostatistics (2nd edn.).* FA Davis Company, Philadelphia.

Eng, J.J. and Winter, D.A. (1995). Kinetic analysis of the lower limbs during walking: what information can be gained from a three-dimensional model? *Journal of Biomechanics,* **28,** 753-758.

Feise, R. (2002). Do multiple outcome measures require p-value adjustment? *BMC Medical Research Methodology,* **2,** 8.

Felson, D.T., Anderson, J.J., Hannan, M.T., Milton, R.C., Wilson, P.W. and Kiel, D.P. (1989). Impaired vision and hip fracture. The Framingham Study. *Journal of the American Geriatrics Society,* **37,** 495-500.

Fildes, B. (1994). *Injuries among older people: falls at home and pedestrian accidents*. Collins Doves, North Blackburn.

Folstein, M.F. (1975). Mini-mental state: A Practical methods for grading cognitive state of patients for the clinician. *Journal of Psychiatric Research,* **12,** 189-198.

Friedman, P.J., Richmond, D.E. and Baskett, J.J. (1988). A prospective trial of serial gait speed as a measure of rehabilitation in the elderly. *Age and Ageing,* **17,** 227-235.

Gabell, A. and Nayak, U.S. (1984). The effect of age on variability in gait. *Journal of Gerontology,* **39,** 662-666.

Gardner, M.M., Robertson, M.C. and Campbell, A.J. (2000). Exercise in preventing falls and fall related injuries in older people: a review of randomised controlled trials. *British Journal of Sports Medicine,* **34,** 7-17.

Giladi, N. (2007). Gait and mental function: the interplay between walking, behavior and cognition. *Journal of Neural Transmission,* **114,** 1241-1242.

Gillespie, L.D., Gillespie, W.J., Robertson, M.C., Lamb, S.E., Cumming, R. and Rowe, B.H. (2003). Interventions for preventing falls in elderly people. *The Cochrane Database of Systematic Reviews,* **4,** Art. No: CD000340. DOI: 000310.001002/14651858.CD14000340.

Graafmans, W.C., Ooms, M.E., Hofstee, H.M., Bezemer, P.D., Bouter, L.M. and Lips, P. (1996). Falls in the elderly: a prospective study of risk factors and risk profiles. *American Journal of Epidemiology,* **143,** 1129-1136.

Greig, C., Butler, F., Skelton, D., Mahmud, S. and Young, A. (1993). Treadmill walking in old age may not reproduce the real life situation. *Journal of the American Geriatrics Society,* **41,** 15-18.

Guimaraes, R.M. and Isaacs, B. (1980). Characteristics of the gait in old people who fall. *International Rehabilitation Medicine,* **2,** 177-180.

Hageman, P.A. and Blanke, D.J. (1986). Comparison of gait of young women and elderly women. *Physical Therapy,* **66,** 1382-1387.

Harper, C.M. and Lyles, Y.M. (1988). Physiology and complications of bed rest. *Journal of the American Geriatrics Society,* **36,** 1047-1054.

Hartley, A.A. and Little, D.M. (1999). Age-related differences and similarities in dual-task interference. *Journal of Experimental Psychology: General,* **128,** 416-449.

Harwood, R.H., Foss, A.J.E., Osborn, F., Gregson, R.M., Zaman, A. and Masud, T. (2005). Falls and health status in elderly women following first eye cataract surgery: a randomised controlled trial. *British Journal of Ophthalmology,* **89,** 53-59.

Hausdorff, J.M., Edelberg, H.K., Mitchell, S.L., Goldberger, A.L. and Wei, J.Y. (1997). Increased gait unsteadiness in community-dwelling elderly fallers. *Archives of Physical Medicine and Rehabilitation,* **78,** 278-283.

Hausdorff, J.M., Rios, D.A. and Edelberg, H.K. (2001). Gait variability and fall risk in community-living older adults: A 1-year prospective study. *Archives of Physical Medicine and Rehabilitation,* **82,** 1050.

Herman, T., Giladi, N., Gurevich, T. and Hausdorff, J.M. (2005). Gait instability and fractal dynamics of older adults with a "cautious" gait: why do certain older adults walk fearfully? *Gait & Posture,* **21,** 178.

Hill, K. (1997). *Manual for Clinical Outcome Measurement in Adult Neurological Physiotherapy.* Prepared for the Australian Physiotherapy Association Neurology Special Group (Victoria).

Hill, K., Schwarz, J., Flicker, L. and Carroll, S. (1999). Falls among healthy, community-dwelling, older women: a prospective study of frequency, circumstances, consequences and prediction accuracy. *Australian and New Zealand Journal of Public Health,* **23,** 41-48.

Hill, K.D., Schwarz, J.A., Kalogeropoulos, A.J. and Gibson, S.J. (1996). Fear of falling revisited. *Archives of Physical Medicine and Rehabilitation,* **77,** 1025-1029.

Holliday, P.J., Fernie, G.R., Gryfe, C.I. and Griggs, G.T. (1990). Video recording of spontaneous falls of the elderly. In *Slips, Stumbles and falls: Pedestrian footwear and surfaces* (Gray, B.E. ed.), pp. 7-16. American Society for Testing and Materials, Philadelphia.

Hwang, I.S., Lee, H.M., Cherng, R.J. and Chen, J.J. (2003). Electromyographic analysis of locomotion for healthy and hemiparetic subjects--study of performance variability and rail effect on treadmill. *Gait & Posture,* **18,** 1-12.

Ivers, R.Q., Cumming, R.G., Mitchell, P. and Attebo, K. (1998). Visual impairment and falls in older adults: the Blue Mountains Eye Study. *Journal of the American Geriatrics Society,* **46,** 58-64.

Ivers, R.Q., Norton, R., Cumming, R.G., Butler, M. and Campbell, A.J. (2000). Visual impairment and risk of hip fracture. *American Journal of Epidemiology,* **152,** 633-639.

Jack, C.I., Smith, T., Neoh, C., Lye, M. and McGalliard, J.N. (1995). Prevalence of low vision in elderly patients admitted to an acute geriatric unit in Liverpool: elderly people who fall are more likely to have low vision. *Gerontology,* **41,** 280-285.

James, L. (1999). *The probability of elderly individuals hitting obstacles during walking*. Honours thesis. School of Human Movement, Recreation and Performance. Victoria University, Melbourne, Australia.

Jamet, M., Deviterne, D., Gauchard, G.C., Vancon, G. and Perrin, P.P. (2007). Age-related part taken by attentional cognitive processes in standing postural control in a dual-task context. *Gait & Posture,* **25,** 179-184.

Jorstad, E.C., Hauer, K., Becker, C. and Lamb, S.E. (2005). Measuring the psychological outcomes of falling: a systematic review. *Journal of the American Geriatrics Society,* **53,** 501-510.

Judge, J.O., Davis, R.B., 3rd and Ounpuu, S. (1996a). Step length reductions in advanced age: the role of ankle and hip kinetics. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **51,** M303-312.

Judge, J.O., King, M.B., Whipple, R., Clive, J. and Wolfson, L.I. (1995). Dynamic balance in older persons: effects of reduced visual and proprioceptive input. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **50,** M263-270.

Judge, J.O., Ounpuu, S. and Davis, R.B., 3rd (1996b). Effects of age on the biomechanics and physiology of gait. *Clinics in Geriatric Medicine,* **12,** 659-678.

Karst, G.M., Hageman, P.A., Jones, T.F. and Bunner, S.H. (1999). Reliability of foot trajectory measures within and between testing sessions. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **54,** M343-347.

Kerr, B., Condon, S.M. and McDonald, L.A. (1985). Cognitive spatial processing and the regulation of posture. *Journal of Experimental Psychology: Human Perception and Performance,* **11,** 617-622.

Kerrigan, D.C., Todd, M.K., Della Croce, U., Lipsitz, L.A. and Collins, J.J. (1998). Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. *Archives of Physical Medicine and Rehabilitation,* **79,** 317-322.

Klein, B.E., Klein, R., Lee, K.E. and Cruickshanks, K.J. (1998). Performance-based and self-assessed measures of visual function as related to history of falls, hip fractures, and measured gait time. The Beaver Dam Eye Study. *Ophthalmology,* **105,** 160-164.

Koceja, D.M., Allway, D. and Earles, D.R. (1999). Age differences in postural sway during volitional head movement. *Archives of Physical Medicine and Rehabilitation,* **80,** 1537-1541.

Kreisfeld, R., Newson, R. and Harrison, J. (2004). *Injury deaths, Australia 2002.* AIH cat no. INJCAT 65. Australian Institute of Health and Welfare.

Kuyk, T., Elliott, J.L. and Fuhr, P.S. (1998). Visual correlates of obstacle avoidance in adults with low vision. *Optometry and Vision Science,* **75,** 174-182.

Lajoie, Y., Teasdale, N., Bard, C. and Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research,* **97,** 139-144.

Lajoie, Y., Teasdale, N., Bard, C. and Fleury, M. (1996). *Attentional demands for walking: Age-related changes*. Elsevier Science, New York.

Lamoureux, E., Sparrow, W.A., Murphy, A. and Newton, R.U. (2003). The effects of improved strength on obstacle negotiation in community-living older adults. *Gait & Posture,* **17,** 273-283.

Lamoureux, E.L., Sparrow, W.A., Murphy, A. and Newton, R.U. (2002). The relationship between lower body strength and obstructed gait in community-dwelling older adults. *Journal of the American Geriatrics Society,* **50,** 468-473.

Lee, D.N. and Lishman, R. (1977). Visual control of locomotion. *Scandinavian Journal of Psychology,* **18,** 224-230.

Lord, S.R. (2006). Visual risk factors for falls in older people. *Age and Ageing,* **35,** ii42-45.

Lord, S.R. and Clark, R.D. (1996). Simple physiological and clinical tests for the accurate prediction of falling in older people. *Gerontology,* **42,** 199-203.

Lord, S.R., Clark, R.D. and Webster, I.W. (1991). Visual acuity and contrast sensitivity in relation to falls in an elderly population. *Age and Ageing,* **20,** 175-181.

Lord, S.R., Dayhew, J. and Howland, A. (2002a). Multifocal glasses impair edge-contrast sensitivity and depth perception and increase the risk of falls in older people. *Journal of the American Geriatrics Society,* **50,** 1760-1766.

Lord, S.R., Sherrington, C. and Menz, H.B. (2002b). *Falls in older people: risk factors and strategies for prevention*. Cambridge University Press, Cambridge.

Lord, S.R., Ward, J.A., Williams, P. and Anstey, K.J. (1993). An epidemiological study of falls in older community-dwelling women: the Randwick falls and fractures study. *Australian and New Zealand Journal of Public Health,* **17,** 240-245.

Lu, T.W., Chen, H.L. and Chen, S.C. (2006). Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights. *Gait & Posture,* **23,** 471-479.

Lundin-Olsson, L., Nyberg, L. and Gustafson, Y. (1997). "Stops walking when talking" as a predictor of falls in elderly people. *Lancet,* **349,** 617.

Lundin-Olsson, L., Nyberg, L. and Gustafson, Y. (1998). Attention, frailty, and falls: the effect of a manual task on basic mobility. *Journal of the American Geriatrics Society,* **46,** 758-761.

Lyons, R.A., Sander, L.V., Weightman, A.L., Patterson, J., Jones, S.A., Rolfe, B., Kemp, A. and Johansen, A. (2003). Modification of the home environment for the reduction of injuries. *Cochrane Database of Systematic Reviews,* **4,** Art. no.: CD003600, DOI: 003610.001002/14651858.CD14003600.

Lythgo, N.D. (2003). *Age effects on the gait kinematics to negotiate surface height changes.* PhD Thesis. School of Human Movement, Recreation and Performance. Victoria University, Melbourne.

Madureira, M.M., Takayama, L., Gallinaro, A.L., Caparbo, V.F., Costa, R.A. and Pereira, R.M. (2007). Balance training program is highly effective in improving

functional status and reducing the risk of falls in elderly women with osteoporosis: a randomized controlled trial. *Osteoporosis International,* **18,** 419-425.

Maki, B.E. (1997). Gait changes in older adults: predictors of falls or indicators of fear. *Journal of the American Geriatrics Society,* **45,** 313-320.

Manchester, D., Woollacott, M., Zederbauer-Hylton, N. and Marin, O. (1989). Visual, vestibular and somatosensory contributions to balance control in the older adult. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **44,** M118-127.

Marks, R. (1997). The effect of restricting arm swing during normal locomotion. *Biomedical Sciences Instrumentation,* **33,** 209-215.

Marron, J.A. and Bailey, I.L. (1982). Visual factors and orientation-mobility performance. *American Journal of Optometry and Physiological Optics,* **59,** 413-426.

Marsh, A.P. and Geel, S.E. (2000). The effect of age on the attentional demands of postural control. *Gait & Posture,* **12,** 105-113.

Mathers, C. and Penm, R. (1999). *Health system costs of injury, poisoning and musculoskeletal disorders in Australia 1993-4.* AIHW Cat. No. HWE 12. Canberra: Australian Institute of Health and Welfare (Health and Welfare Expenditure Series no. 6).

Mathias, S., Nayak, U. and Isaacs, B. (1986). Balance in elderly patients: the "Get up and Go" test. *Archives of Physical Medicine and Rehabilitation***,** 387-389.

Matsas, A., Taylor, N. and McBurney, H. (2000). Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. *Gait & Posture,* **11,** 46-53.

McDowd, J.M. (1986). The effects of age and extended practice on divided attention performance. *Journal of Gerontology,* **41,** 764-769.

McGibbon, C.A. and Krebs, D.E. (2001). Age-related changes in lower trunk coordination and energy transfer during gait. *Journal of Neurophysiology,* **85,** 1923-1931.

McGwin, G., Jr., Gewant, H.D., Modjarrad, K., Hall, T.A. and Owsley, C. (2006). Effect of cataract surgery on falls and mobility in independently living older adults. *Journal of the American Geriatrics Society,* **54,** 1089-1094.

McIlroy, W.E. and Maki, B.E. (1995). Adaptive changes to compensatory stepping responses. *Gait & Posture,* **3,** 43 - 50.

Menz, H.B., Lord, S.R. and Fitzpatrick, R.C. (2003). Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. *Gait & Posture,* **18,** 35-46.

Menz, H.B., Lord, S.R., St George, R. and Fitzpatrick, R.C. (2004). Walking stability and sensorimotor function in older people with diabetic peripheral neuropathy. *Archives of Physical Medicine and Rehabilitation,* **85,** 245-252.

Mills, P.M. and Barrett, R.S. (2001). Swing phase mechanics of healthy young and elderly men. *Human Movement Science,* **20,** 427-446.

Moller, J. (2005). *Projected costs of fall related injury to older persons due to demographic change in Australia*. Report to the Commonwealth Department of Health and Ageing under the National Falls Prevention for Older People Initiative. Commonwealth of Australia.

Moosabhoy, M.A. and Gard, S.A. (2006). Methodology for determining the sensitivity of swing leg toe clearance and leg length to swing leg joint angles during gait. *Gait & Posture,* **24,** 493-501.

Mulavara, A.P., Verstraete, M.C. and Bloomberg, J.J. (2002). Modulation of head movement control in humans during treadmill walking. *Gait & Posture,* **16,** 271-282.

Murden, R.A., McRae, T.D., Kaner, S. and Bucknam, M.E. (1991). Mini-Mental State Exam scores vary with education in blacks and whites. *Journal of the American Geriatrics Society,* **39,** 149-155.

Murray, M.P., Kory, R.C. and Clarkson, B.H. (1969). Walking patterns in healthy old men. *Journal of Gerontology,* **24,** 169-178.

Murray, M.P., Spurr, G.B., Sepic, S.B., Gardner, G.M. and Mollinger, L.A. (1985). Treadmill vs. floor walking: kinematics, electromyogram, and heart rate. *Journal of Applied Physiology,* **59,** 87-91.

NARI (National Ageing Research Institute) (2004). *An Analysis of Research on Preventing Falls and Falls Injury in Older People: Community, Residential Aged Care and Acute Care Settings.* Report to the Commonwealth Department of Health and Aged Care Injury Prevention Section. Commonwealth of Australia, Canberra.
.

Nevitt, M.C., Cummings, S.R., Kidd, S. and Black, D. (1989). Risk factors for recurrent nonsyncopal falls. A prospective study. *JAMA: the journal of the American Medical Association,* **261,** 2663-2668.

Newell, K.M. and Corcos, D.M. (1993). Issues in variability and motor control In *Variability and motor control* (Newell, K.M. and Corcos, D.M. eds.), pp. 1-12. Human kinetics, Champaign.

Nigg, B.M., Fisher, V. and Ronsky, J.L. (1994). Gait characteristics as a function of age and gender. *Gait & Posture,* **2,** 213-220.

NIPAC (National Injury Prevention Advisory Council) (1999a). *Directions in Injury Prevention. Report 1: Research Needs*. A report from the National Injury Prevention

Advisory Council. Elkington, J. (Ed). Commonwealth Department of Health and Aged Care. Commonwealth of Australia, Canberra.

NIPAC National Injury Prevention Advisory Council (1999b). *Directions in Injury Prevention. Report 2: Injury Prevention Interventions - good buys for the next decade.* A report of the National Injury Prevention Advisory Council. Commonwealth Department of Health and Aged Care (Edited by Elkington, J.). Commonwealth of Australia.

NZNHC (New Zealand National Health Committee) (1997). *Prevention of falls and fall-related injuries among institutionalised older people*. Consultation document prepared for the National Health Committee, June 1997.

O'Loughlin, J.L., Robitaille, Y., Boivin, J.F. and Suissa, S. (1993). Incidence of and risk factors for falls and injurious falls among the community-dwelling elderly. *American Journal of Epidemiology,* **137,** 342-354.

Oreskovich, M.R., Howard, J.D., Copass, M.K. and Carrico, C.J. (1984). Geriatric trauma: injury patterns and outcome. *The Journal of Trauma,* **24,** 565-572.

Osaki, Y., Kunin, M., Cohen, B. and Raphan, T. (2007). Three-dimensional kinematics and dynamics of the foot during walking: a model of central control mechanisms. *Experimental Brain Research,* **176,** 476-496.

Ostrosky, K.M., VanSwearingen, J.M., Burdett, R.G. and Gee, Z. (1994). A comparison of gait characteristics in young and old subjects. *Physical Therapy,* **74,** 637-644; discussion 644-646.

Overstall, P.W., Exton-Smith, A.N., Imms, F.J. and Johnson, A.L. (1977). Falls in the elderly related to postural imbalance. *British Medical Journal,* **1,** 261-264.

Owen, D.H. (1985). Maintaining posture and avoiding tripping. Optical information for detecting and controlling orientation and locomotion. *Clinics in Geriatric Medicine,* **1,** 581-599.

Owings, T.M. and Grabiner, M.D. (2003). Measuring step kinematic variability on an instrumented treadmill: how many steps are enough? *Journal of Biomechanics,* **36,** 1215-1218.

Owings, T.M. and Grabiner, M.D. (2004a). Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. *Journal of Biomechanics,* **37,** 935-938.

Owings, T.M. and Grabiner, M.D. (2004b). Variability of step kinematics in young and older adults. *Gait & Posture,* **20,** 26-29.

Owings, T.M., Pavol, M.J., Foley, K.T., Grabiner, P.C. and Grabiner, M.D. (1999). Exercise: is it a solution to falls by older adults? *Journal of Applied Biomechanics,* **15,** 56-63.

Patla, A.E. (1993). Age-related changes in visually guided locomotion over different terrains: Major issues. In *Sensorimotor impairment in the elderly.* (Stelmach, G.E. and Hömberg, V. eds.), pp. 231-252. Kluwer Academic, Dordrecht, the Netherlands.

Patla, A.E. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & Posture,* **5,** 54-69.

Patla, A.E., Adkin, A., Martin, C., Holden, R. and Prentice, S. (1996). Characteristics of voluntary visual sampling of the environment for safe locomotion over different terrains. *Experimental Brain Research,* **112,** 513-522.

Patla, A.E., Prentice, S.D., Robinson, C. and Neufeld, J. (1991). Visual control of locomotion: strategies for changing direction and for going over obstacles. *Journal of Experimental Psychology: Human Perception and Performance,* **17,** 603-634.

Patla, A.E. and Rietdyk, S. (1993). Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width. *Gait & Posture,* **1,** 45-60.

Patla, A.E. and Vickers, J.N. (1997). Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport,* **8,** 3661-3665.

Pavol, M.J., Owings, T.M., Foley, K.T. and Grabiner, M.D. (1999). Gait characteristics as risk factors for falling from trips induced in older adults. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **54,** M583-590.

Pellecchia, G.L. (2003). Postural sway increases with attentional demands of concurrent cognitive task. *Gait & Posture,* **18,** 29-34.

Perneger, T.V. (1998). What's wrong with Bonferroni adjustments. *British Medical Journal,* **316,** 1236-1238.

Perry, B.C. (1982). Falls among the elderly: a review of the methods and conclusions of epidemiologic studies. *Journal of the American Geriatrics Society,* **30,** 367-371.

Pijnappels, M., Bobbert, M.F. and van Dieen, J.H. (2001). Changes in walking pattern caused by the possibility of a tripping reaction. *Gait & Posture,* **14,** 11-18.

Podsiadlo, D. and Richardson, S. (1991). The timed "Up & Go": a test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society,* **39,** 142-148.

Ponds, R.W., Brouwer, W.H. and van Wolffelaar, P.C. (1988). Age differences in divided attention in a simulated driving task. *Journals of Gerontology Series B: Psychological Sciences and Social Sciences,* **43,** P151-156.

Poulain, I. and Giraudet, G. (2008). Age-related changes of visual contribution in posture control. *Gait & Posture,* **27,** 1-7.

Prince, F., Corriveau, H., Hebert, R. and Winter, D.A. (1997). Gait in the elderly. *Gait & Posture,* **5,** 128.

Prudham, D. and Evans, J.G. (1981). Factors associated with falls in the elderly: a community study. *Age and Ageing,* **10,** 141-146.

Rankin, J.K., Woollacott, M.H., Shumway-Cook, A. and Brown, L.A. (2000). Cognitive influence on postural stability: a neuromuscular analysis in young and older adults. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **55,** M112-119.

Ray, C.T., Horvat, M., Croce, R., Christopher Mason, R. and Wolf, S.L. The impact of vision loss on postural stability and balance strategies in individuals with profound vision loss. *Gait & Posture,* **In Press, Corrected Proof**.

Redfern, M.S., Jennings, J.R., Martin, C. and Furman, J.M. (2001). Attention influences sensory integration for postural control in older adults. *Gait & Posture,* **14,** 211-216.

Richardson, J.K., Thies, S.B., DeMott, T.K. and Ashton-Miller, J.A. (2005). Gait Analysis in a Challenging Environment Differentiates Between Fallers and Nonfallers Among Older Patients With Peripheral Neuropathy. *Archives of Physical Medicine and Rehabilitation,* **86,** 1539.

Salkeld, G., Cameron, I.D., Cumming, R.G., Easter, S., Seymour, J., Kurrle, S.E. and Quine, S. (2000). Quality of life related to fear of falling and hip fracture in older women: a time trade off study. *British Medical Journal,* **320,** 340-345.

Sattin, R.W., Rodriguez, J.G., DeVito, C.A. and Wingo, P.A. (1998). Home environmental hazards and the risk of fall injury events among community-dwelling older persons. Study to Assess Falls Among the Elderly (SAFE) Group. *Journal of the American Geriatrics Society,* **46,** 669-676.

Schache, A.G., Blanch, P.D., Rath, D.A., Wrigley, T.V., Starr, R. and Bennell, K.L. (2001). A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo-pelvic-hip complex. *Clinical Biomechanics (Bristol, Avon),* **16,** 667-680.

Schrodt, L.A., Mercer, V.S., Giuliani, C.A. and Hartman, M. (2004). Characteristics of stepping over an obstacle in community dwelling older adults under dual-task conditions. *Gait & Posture,* **19,** 279-287.

Schultz, A.B., Ashton-Miller, J.A. and Alexander, N.B. (1997). What leads to age and gender differences in balance maintenance and recovery? *Muscle and Nerve. Supplement,* **5,** S60-64.

Shumway-Cook, A., Brauer, S. and Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical Therapy,* **80,** 896-903.

Shumway-Cook, A., Gruber, W., Baldwin, M. and Liao, S. (1997a). The effect of multidimensional exercises on balance, mobility, and fall risk in community-dwelling older adults. *Physical Therapy,* **77,** 46-57.

Shumway-Cook, A. and Horak, F.B. (1986). Assessing the influence of sensory interaction of balance. Suggestion from the field. *Physical Therapy,* **66,** 1548-1550.

Shumway-Cook, A. and Woollacott, M. (2000). Attentional demands and postural control: the effect of sensory context. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **55,** M10-16.

Shumway-Cook, A., Woollacott, M., Kerns, K.A. and Baldwin, M. (1997b). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **52,** M232-240.

Siler, W.L., Jorgensen, A.L. and Norris, R.A. (1997). Grasping the handrails during treadmill walking does not alter sagittal plane kinematics of walking. *Archives of Physical Medicine and Rehabilitation,* **78,** 393-398.

Simoneau, M., Teasdale, N., Bourdin, C., Bard, C., Fleury, M. and Nougier, V. (1999). Aging and postural control: postural perturbations caused by changing the visual anchor. *Journal of the American Geriatrics Society,* **47,** 235-240.

Smeesters, C., Hayes, W.C. and McMahon, T.A. (1999). Determining fall direction and impact location for various disturbances and gait speeds using the articulated total body model. In *Proceedings of the VIIth International Symposium on Computer Simulation in Biomechanics*, Calgary, Canada, August 5 - 7, p. 80-83.

Smeesters, C., Hayes, W.C. and McMahon, T.A. (2001). Disturbance type and gait speed affect fall direction and impact location. *Journal of Biomechanics,* **34,** 309-317.

Snijders, A.H., Verstappen, C.C., Munneke, M. and Bloem, B.R. (2007). Assessing the interplay between cognition and gait in the clinical setting. *Journal of Neural Transmission,* **114,** 1315-1321.

Snow, C.M. (1999). Exercise effects on falls in frail elderly: focus on strength. *Journal of Applied Biomechanics,* **15,** 84-91.

Southard, V., Dave, M., Davis, M.G., Blanco, J. and Hofferber, A. (2005). The Multiple Tasks Test as a predictor of falls in older adults. *Gait & Posture,* **22,** 351-355.

Sparrow, W.A., Begg, R.K. and Parker, S. (2006). Aging effects on visual reaction time in a single task condition and when treadmill walking. *Motor Control,* **10,** 201-211.

Sparrow, W.A., Bradshaw, E.J., Lamoureux, E. and Tirosh, O. (2002a). Ageing effects on the attention demands of walking. *Human Movement Science,* **21,** 961-972.

Sparrow, W.A., Bradshaw, E.J., Lamoureux, E. and Tirosh, O. (2002b). Ageing effects on the attention demands of walking. *Human Movement Science,* **21,** 961-972.

Spirduso, W. (1995). *Physical Dimensions of Aging.* Human Kinetics, Champaign, Illinois.

Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E.S. and Hausdorff, J.M. (2006). Dual-tasking effects on gait variability: the role of aging, falls, and executive function. *Movement Disorders,* **21,** 950-957.

Startzell, J.K. and Cavanagh, P.R. (1999). A three-dimensional approach to the calculation of foot clearance during locomotion. *Human Movement Science,* **18,** 603-611.

Stelmach, G.E. and Worringham, C.J. (1985). Sensorimotor deficits related to postural stability. Implications for falling in the elderly. *Clinics in Geriatric Medicine,* **1,** 679-694.

Stelmach, G.E., Zelaznik, H.N. and Lowe, D. (1990). The influence of aging and attentional demands on recovery from postural instability. *Aging (Milano),* **2,** 155-161.

Stolze, H., Kuhtz-Buschbeck, J.P., Mondwurf, C., Boczek-Funcke, A., Jöhnk, K., Deuschl, G. and Illert, M. (1997). Gait analysis during treadmill and overground locomotion in children and adults. *Electroencephalography and Clinical Neurophysiology,* **105,** 490-497.

Sudarsky, L. (1990). Geriatrics: gait disorders in the elderly. *New England Journal of Medicine,* **322,** 1441-1446.

Sundermier, L., Woollacott, M.H., Jensen, J.L. and Moore, S. (1996). Postural sensitivity to visual flow in aging adults with and without balance problems. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **51,** M45-52.

Sutherland, D.H., Kaufman, K.R. and Moitoza, J.R. (1994). Kinematics of normal walking. In *Human Walking.* (Rose, J. and Gamble, J.G. eds.), pp. 23-44. Williams & Wilkins, Baltimore, Maryland.

Tinetti, M.E., McAvay, G. and Claus, E. (1996). Does multiple risk factor reduction explain the reduction in fall rate in the Yale FICSIT Trial? Frailty and Injuries Cooperative Studies of Intervention Techniques. *American Journal of Epidemiology,* **144,** 389-399.

Tinetti, M.E., Richman, D. and Powell, L. (1990). Falls efficacy as a measure of fear of falling. *Journals of Gerontology Series B: Psychological Sciences and Social Sciences,* **45,** P239-243.

Tinetti, M.E. and Speechley, M. (1989). Prevention of falls among the elderly. *New England Journal of Medicine,* **320,** 1055-1059.

Tinetti, M.E., Speechley, M. and Ginter, S.F. (1988). Risk factors for falls among elderly persons living in the community. *New England Journal of Medicine,* **319,** 1701-1707.

Tobis, J.S., Reinsch, S., Swanson, J.M., Byrd, M. and Scharf, T. (1985). Visual perception dominance of fallers among community-dwelling older adults. *Journal of the American Geriatrics Society,* **33,** 330-333.

Toulotte, C., Thevenon, A., Watelain, E. and Fabre, C. (2006). Identification of healthy elderly fallers and non-fallers by gait analysis under dual-task conditions. *Clinical Rehabilitation,* **20,** 269-276.

van den Bogert, A.J., Pavol, M.J. and Grabiner, M.D. (2002). Response time is more important than walking speed for the ability of older adults to avoid a fall after a trip. *Journal of Biomechanics,* **35,** 199-205.

van Iersel, M.B., Ribbers, H., Munneke, M., Borm, G.F. and Rikkert, M.G.O. (2007). The Effect of Cognitive Dual Tasks on Balance During Walking in Physically Fit Elderly People. *Archives of Physical Medicine and Rehabilitation,* **88,** 187-191.

Verbaken, J.H. and Johnston, A.W. (1986). Population norms for edge contrast sensitivity. *American Journal of Optometry and Physiological Optics,* **63,** 724-732.

Vincent, W.J. (1999). *Statistics in Kinesiology.* Human Kinetics, Champaign, Illinois.

Vogt, L., Pfeifer, K. and Banzer, W. (2002). Comparison of angular lumbar spine and pelvis kinematics during treadmill and overground locomotion. *Clinical Biomechanics (Bristol, Avon),* **17,** 162-165.

Wang, J.J., Mitchell, P., Smith, W., Cumming, R.G. and Attebo, K. (1999). Impact of visual impairment on use of community support services by elderly persons: the Blue Mountains Eye study. *Investigative Ophthalmology and Visual Science,* **40,** 12-19.

Wass, E., Taylor, N.F. and Matsas, A. (2005). Familiarisation to treadmill walking in unimpaired older people. *Gait & Posture,* **21,** 72.

Watson, W. and Ozanne-Smith, J. (1997). *The cost of injury to Victoria, Report No.* 124. Monash University Accident Research Centre, Melbourne.

Weerdesteyn, V., Schillings, A.M., van Galen, G.P. and Duysens, J. (2003). Distraction affects the performance of obstacle avoidance during walking. *Journal of Motor Behavior,* **35,** 53-63.

Whitney, S.L. and Wrisley, D.M. (2004). The influence of footwear on timed balance scores of the modified clinical test of sensory interaction and balance. *Archives of Physical Medicine and Rehabilitation,* **85,** 439-443.

Whittle, M.W. (1993). *Gait Analysis: An Introduction*. Butterworth Heinemann, Oxford.

Williams, H.G., McClenaghan, B.A. and Dickerson, J. (1997). Spectral characteristics of postural control in elderly individuals. *Archives of Physical Medicine and Rehabilitation,* **78,** 737-744.

Winter, D.A. (1991a). *Biomechanics and motor control of human gait: Normal, elderly and pathological*. Waterloo Biomechanics, Waterloo, Ontario.

Winter, D.A. (1991b). Changes in gait with aging. *Canadian Journal of Sports Science,* **16,** 165-167.

Winter, D.A. (1992). Foot trajectory in human gait: a precise and multifactorial motor control task. *Physical Therapy,* **72,** 45-53; discussion 54-56.

Winter, D.A. (1995). *A.B.C. (Anatomy, Biomechanics and Control) of Balance During Standing and Walking*. Waterloo Biomechanics, Waterloo, Ontario.

Winter, D.A., McFadyen, B.J. and Dickey, J.P. (1991). Adaptability of the CNS in human walking. In *Adaptability of Human Gait: Implications for the Control of Locomotion* (Patla, A.E. ed.), pp. 127-144. Elsevier Science, Amsterdam.

Winter, D.A., Patla, A.E., Frank, J.S. and Walt, S.E. (1990). Biomechanical walking pattern changes in the fit and healthy elderly. *Physical Therapy,* **70,** 340-347.

Wolf, S.L. and Gregor, R.J. (1999). Exploring unique applications of kinetic analyses to movement in older adults. *Journal of Applied Biomechanics,* **15,** 75-83.

Woollacott, M. and Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait & Posture,* **16,** 1-14.

Wrisley, D.M. and Whitney, S.L. (2004). The effect of foot position on the modified clinical test of sensory interaction and balance. *Archives of Physical Medicine and Rehabilitation,* **85,** 335-338.

Yogev-Seligmann, G., Hausdorff, J.M. and Giladi, N. (2007). The role of executive function and attention in gait. *Movement Disorders,* **9999,** NA.

APPENDIX A

Initial information pack mailed to subjects, including information pack for General Practitioner

19th November, 2002

«Title» «FirstName» «LastName»
«Address1»
«Address2» «State» «PostalCode»

Dear «Title» «LastName»,

Thank you for volunteering to participate in our study investigating distracted walking and its contribution to tripping and falling in healthy older females. All volunteers in this project will live independently in the community, walk without the assistance of an aid, be free of any falls in the past year and have no conditions which might impair normal walking (e.g. hip/knee replacement, painful arthritis, ongoing back pain, painful foot problems such as ulcers and bunions, balance problems).

Enclosed is an information sheet for you to keep, and three sheets you will need to take to your General Practitioner to obtain medical approval for participation in the study. This is just a routine precaution to ensure there are no underlying medical conditions that might compromise your safety during the study. Victoria University will reimburse out-of-pocket costs for this visit to your General Practitioner (please keep your Medicare receipt).

The three sheets for your General Practitioner include: 1) a short letter briefly outlining the project and what we require the doctor to do; 2) a more detailed information sheet about the project; and 3) the 'consent form', with space for your General Practitioner's name, address and contact number. It is important that you keep this sheet once completed by your doctor and bring it with you when you come in for testing at Victoria University.

Once you have obtained approval from your General Practitioner, please contact me on **9248 1128** (Biomechanics lab) or **9887 8242** (home) to arrange a time for testing. All testing will be conducted in the Biomechanics Laboratory at Victoria University, located at basement level, 300 Flinders Street Melbourne (between Elizabeth and Queen Streets). It is anticipated you will be in the Biomechanics Laboratory for approximately 2 hours. On the day of testing please bring with you the signed 'consent form' from your doctor and your Medicare receipt (if applicable). Please also wear, or bring with you, a pair of flat, closed-toe shoes (runners are ideal). Please remember that taxis will be provided should you wish to take up this option.

Thank you again for volunteering your time for this important study. Please do not hesitate to contact me on the above numbers should you have any queries. I look forward to meeting you soon.

Yours sincerely,

Lisa Dell'Oro

Information about the Project:

Title of the Project: ***The Contribution of Divided Attention to Tripping in the Healthy Elderly***

Investigators: Dr. Rezaul Begg, Dr. Russell Best & Lisa Dell'Oro
Victoria University

Background:

Falls in old adults are a serious problem due to the high frequency of falls and the injuries sustained. Elderly females fall more often than males and are more likely to injure themselves in the event of a fall. Tripping is one of the most common causes of falling while walking. Whilst young and elderly people alike are all prone to irregular tripping, tripping and thus falling in the elderly carries more serious consequences. There is evidence that suggests concentrating on two tasks simultaneously (i.e. dividing attention) is more difficult for older adults. This project will investigate whether the ability to divide attention while walking, which is required during normal everyday walking, influences walking patterns and the risk of tripping in a group of healthy young and elderly females.

Aims:

The purpose of this research is to investigate foot motion during walking in young and older females during walking without distractions and during a divided attention tasks.

Procedure:

24 healthy young females (age range 18 - 35 years) and 24 healthy older females (age range 65 – 85 years) will participate in the research project. Older females must walk without the assistance of an aid, be relatively fit and active, have no conditions or injuries that might influence normal walking (e.g. hip or knee replacement, painful arthritis or back pain, congenital orthopaedic conditions etc), have not fallen in the past year. Measurement of body height, mass for all participants and extra screening tests for the elderly group (*'Timed Up and Go' test* - stand from a chair and walk 3m back to the chair and sit down, *'Step Test'* - place foot up and down on a 7.5cm step as many times as possible in 15 seconds then repeat for other foot, *visual acuity* - logMAR chart, *contrast sensitivity* - Melbourne Edge Test, *'Modified Falls Efficacy Scale'* - a measure of the level of fear of falling whilst completing normal everyday tasks, *'Mini-Mental State Examination'* - a measure of cognitive state or how knowledge is acquired through perception, intuition and reasoning) will be undertaken prior to actual testing of participants' foot motion. Foot motion will be video recorded using the PEAK Motus motion analysis system while walking at a comfortable speed on a treadmill for about 30 minutes. The walking task is comprised of: 1) Normal walking (20 minutes) – walking without distractions on the treadmill at a self-selected comfortable walking speed; 2) Walking with distractions (10 minutes) – walking on the treadmill whilst completing a) several instantaneous tasks (counting objects in an abstract array of shapes set up 90 degrees to the left and right, reacting to a visual probe (a red "STOP" displayed on a screen directly in front) by pressing a hand-held button, retrieving an item from a waist pouch, 'coughing' twice); and b) two continuous distractions for one minute duration each (watching a video and responding to some questions regarding its content on completion of the one minute viewing, and a simple maths task of counting backwards. Two lightweight reflective markers will be attached to the left shoe; one to the front (on the big toe) and one to the side of the shoe. A video camera will be used to record foot motion (side view camera) and another to observe where vision is focused (front view camera focused on the face). The physical risks associated with the procedures are minimal, but there is a potential that some participants may suffer from fatigue due to the treadmill walking, or some unsteadiness whilst completing the divided attention tasks. All participants will wear a safety harness during walking on the treadmill. All data collected will be identified by a code and kept confidential. Only the researchers will have access to the data files. Please be advised that you are free to withdraw from this study at anytime.

*Any queries about your participation in this project may be directed to the researcher (**Lisa Dell'Oro ph. 9248 1128, or 9887 8242 AH**).*

Dear General Practitioner,

«FirstName» «LastName» has agreed to volunteer in our study investigating the influence of divided attention while walking and the likelihood of tripping in healthy females aged 65 to 85 years. As a safety precaution, we request that participants obtain medical approval from their General Practitioner to ensure there are no underlying cardiorespiratory, or other medical conditions, which might present a health risk.

The study requires participants to walk continuously for 30 minutes at a self-selected comfortable walking pace on a treadmill. All participants will wear a safety harness and practice on the treadmill will be provided where necessary. The 30 minute walking task is comprised of 20 minutes of undistracted walking and 10 minutes where some simple distraction tasks are completed concurrently with the walking (please refer attached information sheet). The 30-minute walking task alone has been conducted previously at the University with all elderly participants managing well. All methods have been approved by the Victoria University Human Research Ethics Committee.

Mobility and vision tests will be conducted in the Biomechanics Laboratory at Victoria University. Prior to conducting these screening tests and collecting data, it is essential to ensure all participants are 'healthy' and have no medical conditions (e.g. cardiac condition) that might compromise health and safety during the study. We would appreciate it if you would examine «FirstName» «LastName» and complete the attached sheet. There is space for you to add any comments if you wish. «Title» «LastName» will return this sheet to us when she comes in for testing. If you have any queries, please do not hesitate to contact us on 9248 1128 (Lisa Dell'Oro, PhD candidate) or 9248 1116 (Dr. Rezaul Begg, Principal Supervisor).

Thank you for your time.

Regards,

Lisa Dell'Oro
Supervisors:
Dr. Rezaul Begg
Dr. Russell Best

INFORMATION ABOUT THE STUDY

About the study

Undoubtedly you are aware that falls in elderly populations is a significant concern and that females are more likely to fall, and injure themselves in the event of a fall, compared with males. Although there are many causes of falls, tripping is a frequently stated cause and this most often occurs during walking. There is also evidence that suggests the elderly have more difficulty dividing attention compared with younger subjects. Walking affords independence and a means of interacting with the environment, including socialising. However, one is confronted with the need to divide attention during walking (e.g. crossing the road and watching for cars) and, since elderly may have more difficulty in divided attention tasks, we wish to examine the influence of divided attention on gait and the likelihood of tripping.

The study will be conducted at the Victoria University Biomechanics Laboratory located at 300 Flinders Street. Participants, wearing a safety harness, will walk continuously on the treadmill at a comfortable, self-selected walking speed for 30 minutes as follows:

20 minutes	normal walking at a self-selected, comfortable walking speed on the treadmill (no distractions).
10 minutes	continue walking whilst completing several divided attention tasks (distractions):

- retrieving a handkerchief from a waist pouch, then returning it to the waist pouch
- reacting as quickly as possible (by pressing a hand-held button) to a visual probe (the word "STOP") displayed on a monitor set up in front of the participant.
- looking to the left and right to count the number of squares and triangles in an abstract array of shapes
- two 'coughs' with the hand brought to the mouth
- counting backwards by 3s for one minute
- watching a video for one minute and then respond to 2 simple questions about the video content

The distraction tasks will be randomised and the order of normal and distraction walking will be alternated for each participant. There will be a 6-minute warm-up period, chosen since recent research has shown that after 6 minutes gait kinematics collected during treadmill walking are comparable with overground walking. The motion of the lower leg, specifically the minimum foot clearance during the swing phase of the step, will be examined by videotaping the entire trial and then analysing it using motion analysis software. The 'probability of tripping' can then be calculated using mathematical modelling. This gives an indication of the likelihood of the person tripping on unseen obstacles of various heights.

All methods have been approved by the Victoria University Human Research Ethics Committee. Participants will receive training on the treadmill where necessary and are free to withdraw from the study at any time. Data collected for the elderly group (age 65 to 85 years) will be compared with a younger sample (age 18 to 35 years).

About the participants

All participants must be able to walk without the use of a gait aid and have no musculoskeletal/orthopaedic or other conditions that might impair normal walking (e.g. arthritis, back pain, hip/knee replacements, severe osteoporosis, balance/vestibular disorders, foot problems such as ulcers or bunions which are painful and/or have an affect on normal walking). Participants must also live in the community, regularly go outdoors and be generally independent in activities of daily living. Participants with vision impairment not correctable with lenses will be eliminated from the study.

Screening tests to determine level of visual function, mobility, fear of falling and cognitive state, will be conducted at Victoria University. Participants scoring poorly will be eliminated from the study. The screening tests include:

- Visual acuity (using logMAR chart)
- Contrast sensitivity (Melbourne Edge Test)
- Timed Up and Go Test (time taken to rise from a chair, walk 3 metres, turn around, walk back to the chair and sit down)
- Step Test (Number of times one can place their foot onto a 7.5cm step and return it to the floor in 15 seconds)
- Modified Falls Efficacy Scale (a questionnaire where the participant rates their level of confidence in completing some everyday activities without falling)
- Mini-Mental State Examination (a questionnaire designed to evaluate cognitive state)

These are all validated and routine tests used in similar studies, and within clinical practice, to test aspects of vision, physical performance, fear of falling and cognitive state.
If you have any queries regarding the study, please do not hesitate to contact us on 9248 1128 (Lisa Dell'Oro, PhD candidate), or 9248 1116 (Dr. Rezaul Begg, Principal Supervisor).

Participant Name: «Title» «FirstName» «LastName»

Address: «Address1», «Address2» «PostalCode»

GP Name:

Address:

Telephone:

In your opinion, is «FirstName» «LastName» of a sufficient health status to participate in the outlined study (please circle one)?

Yes No

Any comments?

.....

.....

.....

.....

.....

.....

.....

Signed: Date:

……..

……..

APPENDIX B

Informed consent form

Victoria University of Technology

Consent Form for Subjects Involved in Research

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study into...
The Contribution of Divided Attention to Tripping in the Healthy Elderly

CERTIFICATION BY SUBJECT

I**,**
of

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the experiment entitled: **The Contribution of Divided Attention to Tripping in the Healthy Elderly**

being conducted at Victoria University of Technology by: **Dr. Rezaul Begg, Dr. Russell Best and Lisa Dell'Oro**

I certify that the objectives of the experiment, together with any risks to me associated with the procedures listed hereunder to be carried out in the experiment, have been fully explained to me by **Lisa Dell'Oro** and that I freely consent to participation involving the use on me of these procedures.

Procedures:

- Walking overground for 15m to calculate normal, comfortable walking speed
- "Timed Up and Go" test (i.e. stand from a chair and walk 3m back to the chair and sit down)
- "Step test" (i.e. place foot up and down on a 7.5cm step as many times as possible in 15 seconds, then repeat for other foot)
- Measurement of certain aspects of visual function (visual acuity, contrast sensitivity) via recognised charts and procedures (LOGMAR chart, Melbourne Edge Test)
- Questionnaires including Modified Falls Efficacy Scale (a measure of the level of fear of falling) and Mini-Mental State Examination (a measure of cognitive state or how knowledge is acquired through perception, intuition and reasoning)
- Measurement of body height and mass
- Attaching two reflective markers to the left shoe
- Walking on the treadmill for a continuous 30 minute period at a self-selected, comfortable walking speed (20 minutes without distractions and 10 minutes with distractions – removing an object from a rear-opening waist pouch, counting the number of shapes in an abstract array set-up 90 degrees to the left and right, reacting to a visual "STOP" by pressing a hand-held button as quickly as possible, 'coughing' twice with the hand brought to the mouth, watching one minute of a wildlife documentary and answering 2 questions immediately after, counting backwards by 3s for one minute).

- Video recording of the face to observe where vision is directed during the entire 30 minute walking trial
- Video recording of the foot whilst walking on the treadmill for the entire 30 minute walking trial
- Standing on the treadmill and responding to a visual "STOP" by pressing a hand-held button as quickly as possible
- Standing on the treadmill and counting backwards by 3s
- A safety harness will be worn for the treadmill walking tasks to eliminate the chance of injury in the event of a fall. A staff member will stand close by to assist in the event of a fall or to stop the treadmill in the event of any unsteadiness or at the request of the participant.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this experiment at any time and that this withdrawal will not jeopardise me in any way.

I have been informed that the information I provide will be kept confidential.

Signed: **.....** **}**
}
Witness other than the experimenter: **}** **Date: .....**
}
}
.....}

Any queries about your participation in this project may be directed to the researcher (Name: Lisa Dell'Oro ph. 9248 1128). If you have any queries or complaints about the way you have been treated, you may contact the Secretary, University Human Research Ethics Committee, Victoria University of Technology, PO Box 14428 MC, Melbourne, 8001 (telephone no: 03-9688 4710).

[*please note: where the subject/s is aged under 18, separate parental consent is required; where the subject is unable to answer for themselves due to mental illness or disability, parental or guardian consent may be required.]

APPENDIX C

Folstein Mini Mental State Examination for evaluating cognitive state

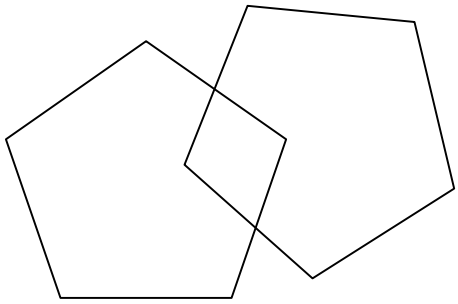
FOLSTEIN MINI MENTAL STATE EXAMINATION

Name: _____ Date:_____

Maximum Score	*Score*		
			ORIENTATION
5		( )	What is the (year), (season), (date), (day), (month)?
5		( )	Where are we? (city), (state), (country), (university), (floor)?
			REGISTRATION
3		( )	Name 3 objects (apple, table, penny) 1 second to say each. Then ask the person to name all 3 after you have said them. Give 1 point for each correct answer. Then repeat them until he learns all 3. Count trials and record. Trials_____.
			ATTENTION AND CALCULATION
5		( )	Serial 7's. Ask the person to begin with 100 and count backwards by 7's. Stop after 5 subtractions, (93, 86, 79, 72, 65). Score the total number of correct answers. If the person refuses, or is unable to perform the task, ask him to spell the word WORLD backwards. The score is the number of letters in the correct order. Eg. Dlrow = 5, dlorw = 3
			RECALL
3		( )	Ask the 3 objects repeated above. Give 1 point for each correct.
			LANGUAGE
2		( )	Show person a wrist-watch and ask him to name it. Repeat for pencil.
1		( )	Have the person repeat the following – "No ifs, ands or buts". Allow only one trial.
3		( )	Have the person follow a 3 stage command. Take paper in right hand, fold it in half, and put it on the floor. (If person unable to reach floor, select another location e.g. on to table, or give it to you).
1		( )	Have the person read the instructions (on back of this form) and do what they say. (Close your eyes).
1		( )	Have the person write a sentence. Do not dictate. Sentence must contain a verb and a subject and be sensible. Correct grammar and spelling are not required.
1		( )	Have the person copy the design on the back of the form. The result must have all 10 angles present, and 2 must intersect to score 1 point.

TOTAL SCORE /30

CLOSE YOUR EYES.



APPENDIX D

Modified Falls Efficacy Scale for evaluation level of fear of falling

The Modified Falls Efficacy Scale

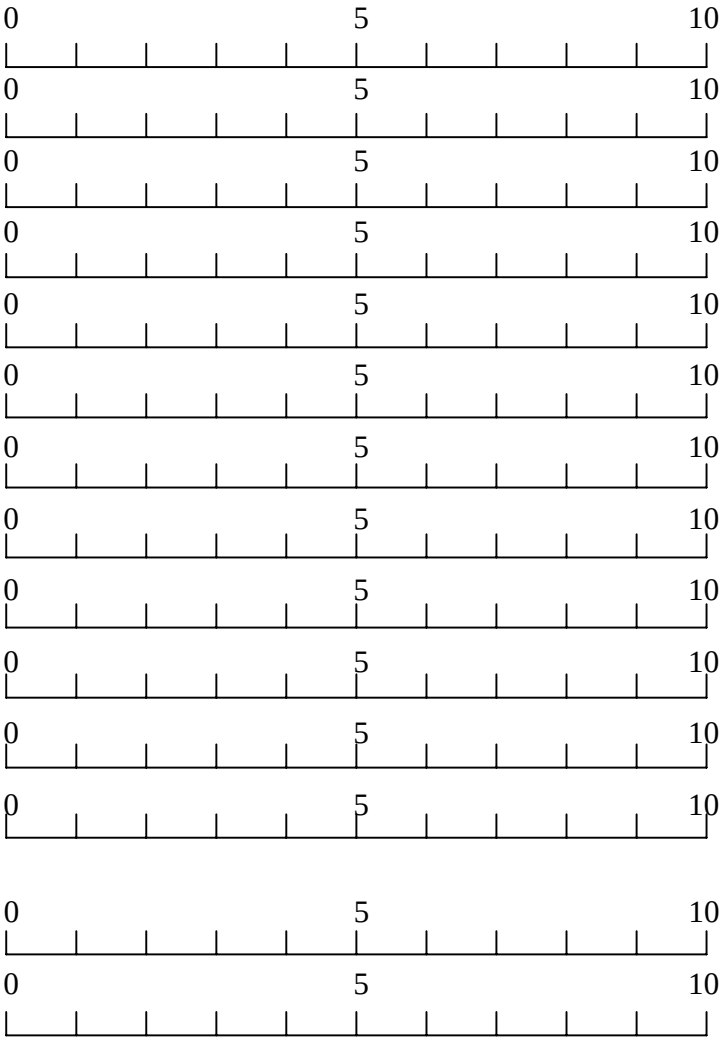
On a scale of 0 to 10, how confident are you that you can do each of these activities without falling, with 0 meaning "not confident/not sure at all", 5 being "fairly confident / fairly sure", and 10 being "completely confident / completely sure"?

NOTE: λ If you have stopped doing the activity at least partly because of being afraid of falling, score a 0;
λ If you have stopped an activity purely because of a physical problem, leave that item blank.
λ If you do not currently do the activity for other reasons, please rate that item based on how you perceive you would rate if you had to do the activity today.

Not confident at all — Fairly confident — Completely confident

0 1 2 3 4 5 6 7 8 9 10

1. Get dressed and undressed
2. Prepare a simple meal
3. Take a bath or a shower
4. Get in / out of a chair
5. Get in / out of bed
6. Answer the door or telephone
7. Walk around the inside of your house
8. Reach into cabinets or closet
9. Light housekeeping
10. Simple shopping
11. Using public transport
12. Crossing roads
13. Light gardening or hanging out the washing*
14. Using front or rear steps at home

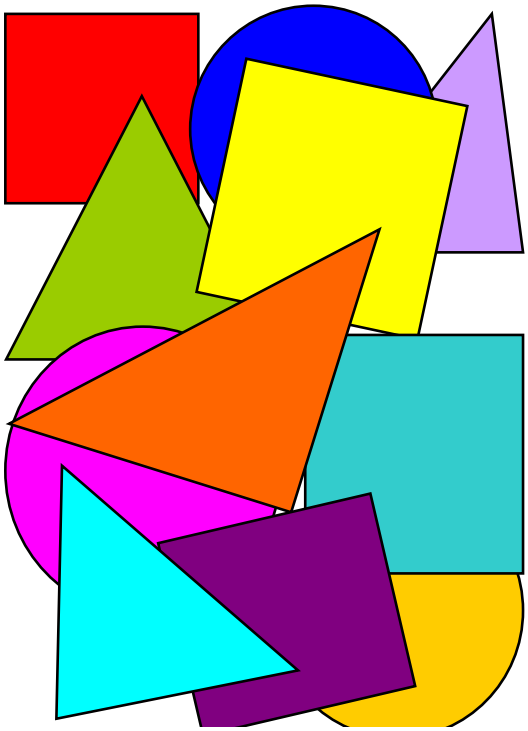


* rate most commonly performed of these activities

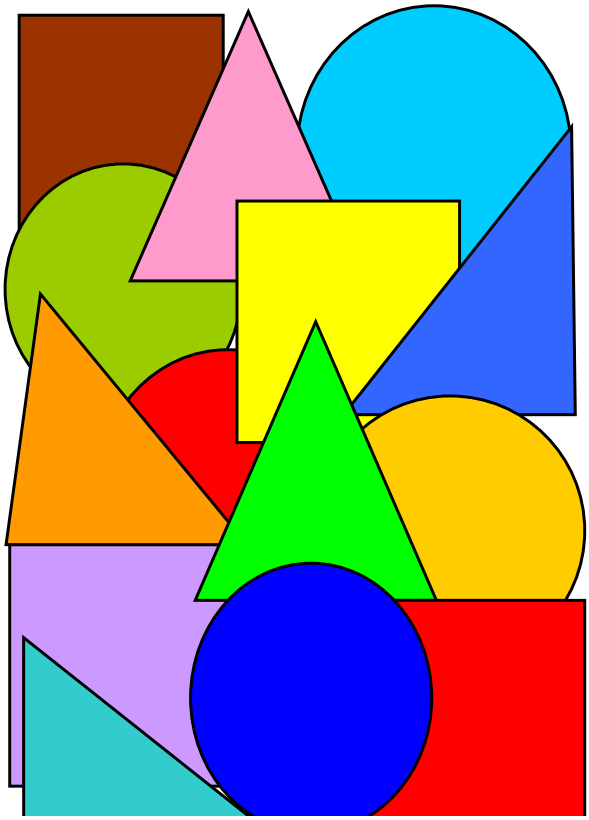
Adapted from Tinetti et al, 1990; Hill etal, 1996

APPENDIX E

Abstract array of shapes used during the *head turn* task



Shapes arrangement set up to the right of the subject.



Shapes arrangement set up to the left of the subject.

APPENDIX F

Qbasic program used to determine MTC

```
REM ****** Basic program to calculate min toe clearance data *****


DIM toeclr(4100)
DIM xyz(200, 6): REM raw data storage
DIM mintoeclr(500): REM Minimum Toe clearance w.r.t min stance Y
DIM mintoeclrg(500): REM Minimum Toe clearance w.r.t ground
reference
DIM gaitcycle(500)
DIM clrpoint(500): REM clearance point
DIM clrabsY(500): REM Clearance absolute Y value
DIM minref(500): REM min ground ref calculated from stance phase
data

FOR j = 1 TO 6
FOR i = 1 TO 200
xyz(i, j) = 0
NEXT: NEXT

minrefvalue = 9999: REM min ref value calculated from stance
phase data
PI = 3.14159: ii% = 0: noofblock = 0

PRINT TAB(8); "Type Data Filename "; nfiles%; "=";
INPUT Filename$
REM Filename$= C:walk5min_a
CLS
REM
  REM ... Read pairs of data (X(0),Y(0), etc.) to arrays X and Y ...
    OPEN Filename$ FOR INPUT AS #1: REM

INPUT "Enter Output Filename"; outfile$
OPEN outfile$ FOR OUTPUT AS #2

d1 = 11.423: d2 = 11.187: d3 = 4.375: REM d1=Toe-Fifth Met distance, d2=Fifth-PTP distance,d3=Toe-PTP
distance
Theta2 = 75.837: REM angle between d1 & d3 in degrees

REM Ground (treadmill belt height) reference
groundref = 34.52: REM Ground Y ref (cm)

 REM Reading data points
 DO: REM Do for each 4000 block
REDIM toe(4100, 2)
REDIM met(4100, 2)

 i% = 1
```

```
      DO

 INPUT #1, toe(i%, 1), toe(i%, 2), r, met(i%, 1), met(i%, 2), r


IF met(i%, 1) = toe(i%, 1) THEN angle1 = PI / 2: GOTO 100

angle1 = ATN((met(i%, 2) - toe(i%, 2)) / (met(i%, 1) - toe(i%, 1)))
REM angle2 = acos((d1 * d1 + d3 * d3 - d2 * d2) / 2 * d1 * d3)
100 angle2 = (PI / 180) * Theta2

deltaY = d3 * SIN(-angle1 + angle2)
toeclr(i%) = toe(i%, 2) - deltaY: REM values in cm

REM PRINT i%, 100 * toe(i%, 2), (180 / PI) * angle1, deltaY,
toeclr(i%)
REM PRINT #2, i%, 100 * toe(i%, 2), (180 / PI) * angle1, deltaY,
toeclr(i%)


 i% = i% + 1
     LOOP UNTIL i% = 4000 OR EOF(1)
REM CLOSE #2

REM STOP

tsamples% = i%: REM total number of samples
PRINT i%
PRINT "press a key to continue"; tsamples%: C$ = get$


REM Calculation of minimum toe clearance
REM determination of ground reference
cycle% = 1: REM no of walking cycle

REM minref = 9999: REM minimum ground ref from Toe clearance
data
counter% = 1
FOR k% = 1 TO 100: REM no of walking cycles, assume a max of
100

min = 9999
FOR j% = counter% TO counter% + 45: REM *******Samples to calculate
Ground ref
IF toeclr(j%) < min THEN min = toeclr(j%): counter% = j%
NEXT j%
REM PRINT min, counter%
minclear = 9999
```

```
FOR j% = counter% + 15 TO counter% STEP -1: REM *****Samples to look for MFC point
IF toeclr(j%) < minclear THEN minclear = toeclr(j%): counter% = j%
IF toeclr(j%) < toeclr(j% - 1) AND toeclr(j% - 2) < toeclr(j% - 3) THEN GOTO
200

NEXT j%
200 mintoeclr(k%) = minclear - min: clrpoint(k%) = counter%
mintoeclrg(k%) = minclear - groundref
clrabsY(k%) = minclear
minref(k%) = min

PRINT clrpoint(k%), mintoeclr(k%), mintoeclrg(k%), clrabsY(k%),
min

counter% = counter% + 25: REM go to the next cycle
IF (tsamples% - counter%) < 50 GOTO 300
NEXT k%
300 : extrasamples = tsamples% - counter% + 25: REM skip
cycles% = k%: REM Actual no. of walking cycles

sampletime = .02: REM sampling time (50Hz)

REM ****** Calculation for each file ********

REM ********
REM
firstpoint% = 1: secondpoint% = 2

REM Identification of Heel-contact & Toe-off events

REM FOR j = 1 TO 2: REM Two platforms
REM heel = 0: toe = 0
REM FOR i = 1 TO tsamples%
REM IF xyz(i, 3 * j) > thresh AND heel = 0 THEN heel = i
REM IF xyz(i, 3 * j) < thresh AND heel > 0 AND toe = 0 THEN toe = i

REM NEXT i

REM heelcontact1 = HC1: heelcontact2 = HC2
REM stancesamples = HC2 - HC1 + 1: REM total samples
REM sampleno = stancesamples / nsamples: REM samples per norm samples

REM temp(1, 1, 3 * j) = p(heelcontact(j), 1, 3 * j)
REM temp(1, nsamples, 3 * j) = p(toeoff(j), 1, 3 * j)
REM FOR i = 2 TO nsamples - 1: REM 2 to 99 sample
REM npoint = i * sampleno(j): REM conversion of raw samples to norm samples
REM ipoint% = npoint
REM diff = npoint - ipoint%
```

```
REM IF diff < 0 THEN ipoint% = ipoint% - 1: diff = npoint - ipoint%
REM temp(1, i, 3 * j) = p(ipoint%, 1, 3) + diff * (p(ipoint% + 1, 1, 3) - p(ipoint%,
1, 3))
REM PRINT npoint, ipoint%, diff
REM NEXT i
REM PRINT heelcontact(j), toeoff(j)
REM PRINT p(heelcontact(j), 1, 3 * j), p(toeoff(j), 1, 3 * j)
REM PRINT
REM PRINT temp(1, 1, 3 * j), temp(1, 2, 3 * j), temp(1, 3, 3 * j)
REM NEXT j

REM minrefvalue = 9999: REM min ref value calculated from stance phase data
FOR j% = 3 TO cycles% - 3
IF minref(j%) < minrefvalue THEN minrefvalue = minref(j%)
NEXT j%
PRINT "mingroundref"; minrefvalue

PRINT "Save to file? Y, N": a$ = get$

IF a$ = "N" THEN STOP


REM Save Min Toe Clearance Values Only
FOR i% = 1 TO cycles%
ii% = ii% + 1
PRINT #2, ii%, noofblock + clrpoint(i%), clrabsY(i%), mintoeclrg(i%), mintoeclr(i%), clrabsY(i%) -
minrefvalue
PRINT i%, clrpoint(i%), clrabsY(i%), mintoeclrg(i%), mintoeclr(i%), clrabsY(i%) -
minrefvalue
NEXT i%

noofblock = noofblock + clrpoint(cycles%) + extrasamples

PRINT "Minimum ground reference value="; groundref, minrefvalue,
noofblock

REM Save Original & Reconstructed Toe trajectories
REM FOR i% 2 1 TO tsamples%
REM PRINT #1, i%, 100 * toe(i%, 2), toeclr(i%)
REM NEXT i%

REM Save Original & Reconstructed Toe trajectories
REM FOR i% = 1 TO tsamples%
REM PRINT #2, i%, 100 * toe(i%, 2), toeclr(i%)
REM NEXT i%


LOOP UNTIL EOF(1): REM do all
```

```
CLOSE #1
CLOSE #2

STOP
END


REM ***************************END**************************
```

APPENDIX G

Table of individual subject characteristics

subject	age (yrs)	stature (m)	mass (kg)
y1	23.4	1.61	45.0
y2	28.4	1.57	68.8
y5	20.5	1.68	59.4
y6	21.8	1.59	49.2
y7	18.4	1.68	50.0
y9	19.2	1.69	64.2
y12	19.7	1.69	81.0
y14	32.5	1.56	56.6
y15	21.1	1.62	51.6
y16	19.6	1.73	72.4
y17	20.0	1.55	56.0
y18	22.7	1.66	62.0
y19	19.3	1.75	63.4
y20	20.9	1.57	61.4
y21	19.6	1.75	69.0
y22	19.1	1.65	55.2
y23	24.3	1.67	73.0
y24	21.4	1.64	59.0
e1	72.8	1.51	60.4
e2	65.1	1.65	65.5
e3	75.0	1.56	70.2
e4	68.6	1.63	64.2
e5	74.4	1.54	64.0
e6	69.2	1.53	53.0
e7	78.6	1.62	62.0
e8	67.2	1.62	70.6
e10	73.6	1.56	82.0
e11	65.8	1.69	75.4
e12	76.2	1.66	70.4
e13	71.2	1.65	71.2
e14	71.7	1.65	71.0
e15	71.8	1.63	65.0
e17	71.0	1.60	70.0
e19	71.7	1.54	71.5
e23	72.2	1.59	56.5
e24	67.6	1.59	73.5

APPENDIX H

Table of individual walking speed characteristics

Subject	WS m/s	RWS stats/s	Strides no.
y1	1.03	0.64	1121
y2	1.19	0.76	1253
y5	1.03	0.61	997
y6	1.08	0.68	1043
y7	1.25	0.74	1063
y9	1.03	0.61	1058
y12	1.00	0.59	906
y14	1.25	0.80	1147
y15	1.06	0.65	1031
y16	1.06	0.61	1032
y17	0.86	0.56	923
y18	0.97	0.58	1023
y19	0.94	0.54	1024
y20	0.94	0.60	1076
y21	1.06	0.60	1057
y22	0.86	0.52	992
y23	0.86	0.52	1027
y24	1.06	0.65	1096
e1	0.81	0.53	997
e2	0.83	0.50	1032
e3	0.83	0.53	981
e4	0.86	0.53	1025
e5	0.75	0.49	916
e6	1.06	0.69	1144
e7	0.78	0.48	983
e8	1.00	0.62	1107
e10	0.64	0.41	883
e11	0.83	0.49	1065
e12	0.72	0.43	954
e13	0.81	0.49	919
e14	0.78	0.47	911
e15	0.72	0.44	1121
e17	0.69	0.43	1034
e19	1.03	0.67	1203
e23	0.83	0.53	988
e24	1.00	0.63	1102