Kinematic and Centre of Pressure (COP) Parameters in Golf Putting

In fulfilment of the requirements for
Doctor of Philosophy (PhD)

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Abstract

The aims of the present study were to: develop a portable and reliable field-based system for assessment of centre of pressure movement during the putting task; identify different putting techniques used by experienced golfers; identify the relationship between handicap and putting performance; identify the relationship between putting performance and putting stroke kinematics; identify the relationship between putting performance and movement of the centre of pressure; and to assess the effect of a 3 week balance biofeedback training program on subsequent putting performance and centre of pressure movement during the putting task.

In order to enable data collection to occur on the golf course, a portable rubber mat containing 256 individual capacitance pressure sensors (novel pliance®, Munich, Germany) was validated for standing COP output against an AMTI force platform. Assessment of the equality of the output from both systems was assessed using the non-central F test. The peak-to-peak amplitude of movement of COP data in the medio-lateral (COPx, p=0.023) and antero-posterior (COPy, p=0.023) directions were found to be significantly the same.

In-field testing required each participant (n=38) to complete five putts at a hole 4m away, and five putts at a hole 8m away. Testing was conducted on the practice putting green of a private golf course. The result of each putt was

assessed by recording the distance the ball finished from the hole, as well as other descriptors of direction (left, right, centre) and length (short, long, holed out). Participants (n=38) completed these putts whilst standing on the previously validated mat. Video of each putt was recorded using a 50Hz video camera located perpendicular to the line of the putt. The video was later used to track the path of the putter head. The movement of the putter head was used to establish the key events and phases in the putting stroke – backswing, downswing, ball contact and follow through.

Putting performance was assessed using exact putt result, absolute putt result and number of holed out putts. Players were initially grouped according to handicap such that there were low (0-9), middle (10-18) and high handicap groups (19-27). On putting performance, the low handicap group were significantly more likely to achieve a holed out putt at both the 4m and 8m putting tasks ($p<0.05$). On the other measures some trends were evident but there were no significant differences between groups.

In order to determine whether putting techniques existed, analysis of kinematic and COP data was completed using cluster analysis techniques. Ultimately, a two cluster solution was indicated as optimal for both tasks meaning there are two distinct putting techniques used by the golfers. At the 4m task these two putting techniques were identified as:

1. Less movement (relative to cluster 2) of COPx in the backswing and downswing phases with velocity of COPx at ball contact closer to zero (on average). Low COPx velocity.
2. Larger movement (relative to cluster 1) of COPx in the backswing and downswing phases with velocity of COPx at ball contact non-zero. High COPx velocity.

In the 8m putting task, these two techniques were identified as:

1. Short, sharp with minimal COPx movements – a technique that involves comparatively smaller movements of the putter head and the COPx throughout the putting stroke relative to cluster 2. Velocity of the COPx at ball contact is minimal but is a heterogeneous mixture of movements away and towards the hole. Low motion.
2. Long, slow with greater movements of the COPx – a technique that incorporates larger displacements of the putter head and COPx throughout the putting stroke relative to cluster 1. Velocity of the COPx at ball contact is higher than cluster 1 but is homogeneous. High motion.

On both tasks, players in cluster 1 had significantly lower handicaps than cluster 2 (4m task – cluster 1 = 12.4±5.9; cluster 2 = 16.4±6.6; $p = 0.002$; $d = 0.63$: 8m task – cluster 1 = 11.9±5.5, cluster 2 = 18.3±7.6; $p < 0.001$; $d = 0.91$) so would be classified as more skilled, however, no putting technique was significantly better than the other on putting performance. Importantly, all a player's putts were not necessarily classified into the same technique grouping. This highlighted the importance of treating each putt as an individual trial rather than using averaged data in the cluster analysis method.

At the 4m putting task, the mean putt distance data were not significantly different for both exact putt result (cluster 1 = 14.0±44.5cm; cluster 2 = 25.7±44.5cm; p=0.22; d=0.26) and absolute putt result (cluster 1 = 36.8±28.5cm; cluster 2 = 39.5±32.3cm; p=0.66; d=0.09). Techniques were not significantly different ($\chi 2 = 0.08$, p = 0.78) in their ability to produce a holed putt. At the 8m putting task, both the measures of exact putt result (24±77cm vs. 2±71cm; p = 0.7; d = 0.29) and absolute putt result (60±54cm vs. 56±43cm; p = 0.11; d = 0.08) reveal non-significant differences between the techniques. Again, techniques were not significantly different ($\chi 2 = 0.04$, p = 0.85) in their ability to produce a holed putt.

All players involved in the field based study were offered the opportunity to participate in a follow up study using real time biofeedback training to improve putting technique. Of the current sample, 7 players chose to participate in a three week training program followed by a re-testing session. The biofeedback training was aimed at minimizing COP movement during stance and the putting stroke.

On re-testing, the sample of players showed no improvement in putting performance or COP related parameters. The effect of the training program on

some players was to, in fact, produce a poorer putting performance and greater movement of the COPx during the stroke. On both putting tasks, there was a significant increase in movement of COPx during the backswing on re-testing. The effect of biofeedback training for improved putting performance was, at best, limited.

A new field-based method for assessment of COP has been validated and established. Putting performance data provides evidence to suggest that handicap level and putting performance are related if performance is measured solely by the number of putts holed. Cluster analysis is shown to be a very suitable method for differentiating putting techniques. The movement of the COP was highly influential in distinguishing putting techniques at both tasks, but had no influence on putting performance.

Putting techniques have not been described previously in the published scientific literature. Further field-based assessment of putting performance, especially during golf competition is required, along with a more detailed understanding on how far from the hole players of different handicap levels hit their first putts.

I, Patrick McLaughlin, declare that the PhD exegesis titled “Kinematic and centre of pressure (COP) parameters in golf putting” is no more than 100,000 words in length including quotes and excluding tables, figure, appendices, bibliography, references and footnotes. This exegesis 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 exegesis is my own work.

Signed Date

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1 Introduction

> *"Once on the green…the game is almost exactly the same for the pros as it is for every other golfer. There is nothing at all any of them can do there with a putter which any other player, no matter what his handicap, is not capable of doing also"*
>
> *(Cochran and Stobbs, 1968; p. 186).*

There are many aspects to the game of golf. What a player lacks in distance off the tee or from the fairway can be compensated for by taking as few putts as possible on the green. Ultimately, the aim of the game is to get the ball in the hole. So, whilst the average player may not be able to hit the ball as far or as accurately as the elite performer, when it comes to putting, the task is the same for all participants – roll the ball across the surface of a specially prepared playing area into a hole four and a quarter inches in diameter.

Consider the scoring system in golf. On each hole, playing to "par" allows the golfer two putts per hole – a total of 36 putts over an 18-hole round, or about half the total number of shots allocated for par. Considering that players have 13 other clubs in their bag, and would tend to use most of them at some stage, the putter is the most often used piece of equipment that a player possesses. This makes the putting stroke the singularly most used shot in the game. Whilst this simplistic logic may be an exaggeration for the elite golfer, data indicates that even at the elite level, around 42% of all strokes are putts (Pelz, 2000).

At the elite level, the best putters average 1.7 putts per green hit in regulation – that is 30.6 putts per round (www.pgatour.com, 2007). Fairweather and Sanders (n.d.) asked spectators at the British Open to putt at three different length holes (3, 12 and 24 feet). At the longest distance the amateur golfer took an average of 2.3 putts to get the ball into the hole, compared to 1.2 putts from 3 feet and 2.0 putts at 12 feet.

The average golfer would do well then to implement a putting stroke that provides them with an opportunity to decrease their number of putts per round. In fact, decreasing one’s score by one or two strokes per round would be considered a significant practical improvement for the average golfer. Improving one’s putting is one way to reduce one’s score and handicap. However, for a number of years an over abundance of anecdotal magazine and internet copy has focused on hitting the ball further, hitting the ball straighter and having the right equipment to achieve this. Whatever the reason, putting gets comparatively little attention in golf magazines and internet advice sites – and golf practice facilities are mainly designed and used for hitting lots of golf balls with a full swing, not putting. It seems the golf swing is considered more important than the putting stroke.

An investigation of the scientific literature provides a similarly biased picture. Whilst in recent years there has been a gradual increase in the number of scientific publications on the golf swing, very little regard has been given to putting. Apart from a few notable exceptions, as an area of scientific learning, the putting stroke has been largely ignored as a research topic. Cochran and Stobbs (1968) provided a detailed analysis of putting performance at a professional tournament in England. These authors detailed the success rate of professional golfers at different length putts. Also, if the first putt was missed, the authors measured how far the ball finished from the hole. This secondary aspect has been mentioned in many anecdotal putting articles since, but Cochran and Stobbs (1968) was published 40 years ago and similar work has not been produced since. This highlights the dearth of research on golf putting performance.

A few authors have investigated putting kinematics, but have tended to focus on the kinematics of a successful putt (Delay et al., 1997; Paradisis and Rees, n.d.; McCarty, 2002). Some of these authors excluded putts that were not successful, whilst others classified players into accurate and less accurate groups based on the finishing distance of the ball from a “hole” (though none of these authors conducted research outside of the laboratory setting). The analyses conducted by these authors assumed that successful or accurate putting was achieved by a common putting stroke. But as Pelz (2000) points out, there have been many different putting techniques used by professionals over the years. And even though Pelz advocates a type of technique called the pure in-line pendulum stroke, successful putting is achievable in a number of ways.

The author aims to provide detailed biomechanical analysis of the putting stroke with regard to the interaction between the putter head and the balance of the golfer during the stroke (as measured by movement of the centre of pressure). Within this process, the author intends – using cluster analysis methods - to define if more than one putting technique truly exists in a sample of golfers of different handicap levels. Similarly, the author will seek to determine whether the theory of good putting – the so called pure in-line pendulum putting stroke advocated by Pelz (2000) – is actually used by club level golfers, and whether movement of the centre of pressure during the putting stroke is a distinguishing factor between good and bad putting performance.

“Balance” is often referred to in coaching literature but what does it mean in relation to putting technique? Only one author has addressed this issue (McCarty, 2002) and the outcomes were unclear. In-field testing of a player’s COP movement will be employed to explain this relationship in more detail. To achieve these aims, an in-field method for assessing putting kinematics and COP movement will be validated. Following in-field testing, a group of players will be exposed to a biofeedback training program focused on minimizing movement of the centre of pressure during the putting stroke. The same players will be retested on the same putting tasks to determine whether the biofeedback training program has any effect on putting technique and putting performance.

2 Literature review

Golf putting is a target skill that effectively has no time constraints on its execution. Although putting is a common pastime, the scientific literature on this topic is sparse. Whilst the interested player could readily find advice in a golf magazine, the researcher is required to search much harder for papers published in scientific journals or on science-based web pages. As a result, the literature covered here will incorporate papers published through journals, world wide web sites, and two books – one dubbed the bible of putting (Pelz, 2000), the other the bible of the golf swing (Cochran and Stobbs, 1968). This is necessary to provide detail on both the theory of (good) putting and the results of the limited research that has been completed.

2.1 The theory of (good) putting

Putting is a target skill and as such there is a certain framework within which each player must work. Logic suggests that to hit the ball in a desired direction whilst standing perpendicular to the ball's intended path, the player must be able to contact the ball with the putter club face perpendicular to, and traveling on, that intended path. Taking the putter straight back on the downswing and straight through in the forward swing on the same line as the intended initial direction of ball motion is the goal, as illustrated in Figure 2.1.1 (Pelz, 2000).

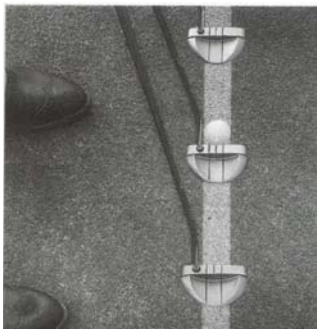


Figure 2.1.1: Diagram from Pelz illustrating putting technique of straight back and straight through (Pelz, 2000; p. 59).

When standing perpendicular to the path of the ball, it is difficult to maintain a perfectly straight (in-plane with the ball's intended path) backswing, forward swing and follow through of the putter. It is much more natural for the golfer to provide momentum through rotations in the transverse plane around a vertical axis (e.g. pelvic and trunk rotation) coupled with translation of the body laterally, as occurs in the full golf swing (Cochran and Stobbs, 1968). However, the pure in-line pendulum putting stroke advocates rotation of the shoulders in the frontal plane about a sagittal or antero-posteriorly oriented axis as the key component of the optimal putting method (Pelz, 2000). The simplicity of this type of putting stroke makes it highly repeatable - a key ingredient for optimal performance of any skill.

According to Pelz, the pendulum putting method requires a stable base of support, the ability for the hands to hang directly underneath the shoulders and for the golfer to maintain a "triangle" between the two arms and a line between the shoulders, as demonstrated in Figure 2.1.2.

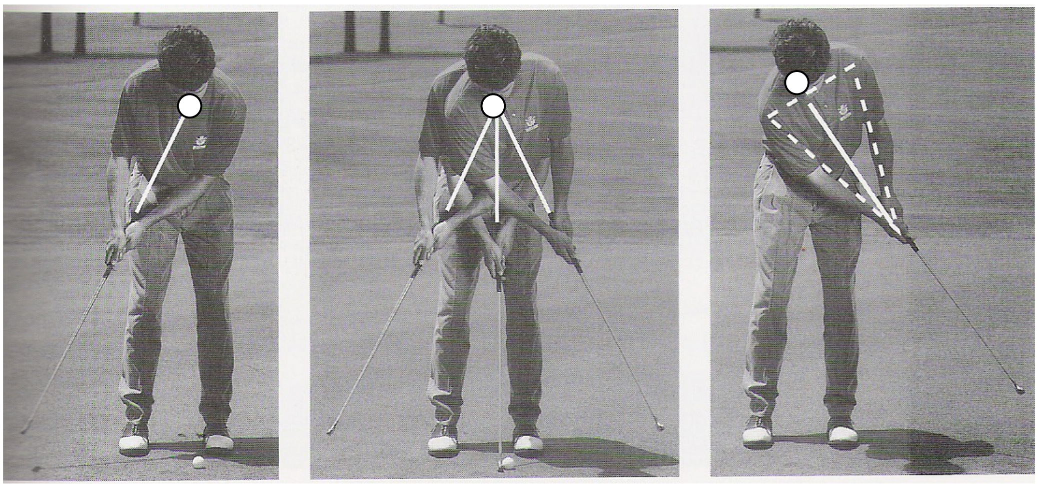


Figure 2.1.2: Modified diagram from Pelz illustrating pendulum putting technique of a triangle between the two arms and a line between the shoulders. The axis of rotation of the shoulders is also marked. The middle diagram also indicates equidistant backswing and follow through lengths utilized in this technique (Pelz, 2000; p. 71).

The hands grip the club at the bottom of the triangle, and when putting, the player rotates the triangle away from the ball (backswing) using only shoulder rotation in the frontal plane about the fixed sagittal or antero-posterior axis (as indicated in Figure 2.1.2), then lets gravity take the triangle through the ball (downswing and follow through) (Pelz, 2000). This movement of the shoulders, according to Pelz (2000), distinguishes the putting action from the golf swing.

The pendulum theory dictates the backswing/downswing and follow through are of equal length either side of the ball. The putter head speed at contact is determined by the distance of the backswing. The distance of the follow through is also dictated by the distance of the backswing. The forward swing is created by the force of gravity (Pelz, 2000). Contact is made at the bottom of the pendulum swing (although Pelz suggests ball contact should be slightly forward of this position so that the putter head is on a slightly upward path at contact to create topspin on the ball). The result of this combination of factors is a pendulum putting stroke that is not susceptible to interference from movement of the wrists or forearms – in golfing terms it is called a “dead-hands” stroke (Pelz, 2000), from a biomechanics perspective the arms, wrists and hands are locked or fixed into position and do not change position during the stroke. It is a stroke whose backswing length is determined by the required putting distance – longer putts, longer backswing; shorter putts, shorter backswing.

This method of putting is in opposition to a variety of putting methods that Pelz suggests have been popular with amateurs and professionals alike. Whilst there is no research indicating these styles exist, anecdotally these styles are worthy of consideration in order to provide a comparison to the pendulum putting technique. These styles, taken from Pelz (2000), include:

- Body Putting – where the arms, wrists and forearms are locked into the body and the putter is swung by rotation of the body around the spine. Relies on consistent body motion, which when putting, most golfers tend to want to avoid. This motion of the body occurs in the transverse plane around a vertical axis in a similar fashion to the golf swing. The putter head path follows a curved, rather than straight line as a result of this motion.
- Power stroke – power comes from the muscles of the hands, wrists or forearms. The weakness of this technique is the tendency to provide too much power when anxious or excited. Pelz suggests that Arnold Palmer

and Tiger Woods are power putters, and indicates that both could be better putters if they changed this technique to the in-line pendulum method.

- Pop Stroke – short, straight back swing, putter stops immediately after impact. Very much a jab at the ball. Putter face stays on line, but uses the muscles of the hands and arms for power. This technique used by Gary Player and Johnny Miller, two leading golfers in the 1970s.
- Hook stroke – supposedly used by Bobby Locke between the 1930's and 1950s, so named because the putter head traveled on a path from inside the line of the putt, to outside the line post contact with the ball.
- Cut stroke – opposite to the hook stroke, the putter head travels from outside the line to inside the line, cutting across the ball. This technique was used by tour professional Chi Chi Rodriguez for many years.
- Wrist stroke – the arms are locked against the trunk/stomach and the only movement comes from hinging at the wrists. As with the power stroke, Pelz suggests that techniques relying on muscles of the forearms are far more difficult to control and reproduce consistently.
- Block stroke – Lee Trevino was a professional golfer who was renowned for aiming to the left but hitting the ball down the middle of the fairway. Pelz suggests that his putting style was similar. He would aim to the left and "block" the ball to the right, requiring him to estimate the amount of "blocking" required.

- Blend stroke – this is considered to be a combination of the power stroke and the in-line pendulum stroke as it incorporates some wrist extension on the backswing and flexion on the downswing. Pelz provides a short list of current and past PGA tour players who have used this method.
- Push stroke – “or right hand push” has been used successfully by Jack Nicklaus for many years. The position of Nicklaus’ flexed right arm behind the left allows him to push the putter down the line of the putt through impact. Pelz suggests this is an excellent technique when executed well as it takes out the wrist and forearm issues of other techniques.
- Long putter – a very simple method because it eliminates wrist, hand and arm motion. The club acts as a pendulum providing it is fixed on some point of the body, like the chin, during the swing.

The pure in-line pendulum putting technique eliminates all of these issues, according to Pelz (2000), if it is performed correctly. The author names a variety of elite level players (Norman, Charles, Mickelson and Weibring amongst others) who use this technique and who Pelz considers were (and currently are) the best putters in professional golf.

The effect of gravity on a pendulum is such that at the lowest point of the pendulum, gravity will create the greatest velocity (when the putter head is closest to the ground on the forward swing). Pelz suggests there is no need for the golfer to provide extra force or torque to the stroke as the club head velocity at contact is set by the length of the backswing. Standard pendulum calculations by the current author, combined with Pelz (2000) “arms” triangle can be used to highlight the effect of gravity on the putter head. For example, a putter of standard length (86.4cm) held at the mid point of the grip (72.9cm above the ground) by a player with arms 60cm in length and measuring 40cm from shoulder to shoulder, produces an overall pendulum length of 129.3cm (Figure 2.1.3). This is the distance from the axis of rotation of the shoulders to the end of the putter.

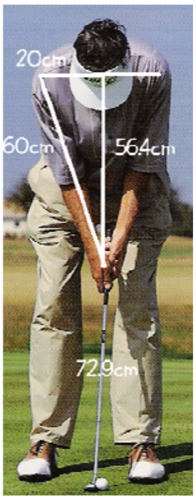


Figure 2.1.3: Diagram of player with 60cm arm length, 40cm shoulder width and gripping the putter at the midpoint of the grip (72.9cm above the ground).

If the backswing takes the putter back 30° to the vertical, then using the formula,

$$v = \sqrt{2gl(\cos\theta - \cos\theta_0)}$$

where θ is the angle of the shaft of the pendulum during the motion, θ_0 is the initial angular displacement of the pendulum, g is acceleration due to gravity and l is the length of the pendulum, velocity data for the putter head can be calculated. The maximum velocity value of this pendulum, given the 30° starting position, occurs at 0° or the vertical position of the pendulum and is equal to 1.84m/s (figure 2.1.4).

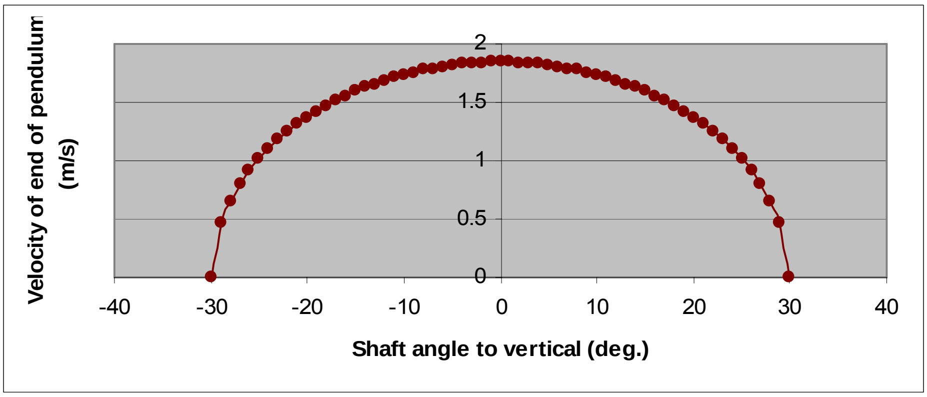


Figure 2.1.4: Velocity of a pendulum 129.3cm in length taken back 30°to the vertical during backswing.

Using this formula and different backswing positions (initial angular displacements) (θ), it is possible to calculate the velocity of the putter head at contact for any given length of pendulum (putter length plus arms effectively). Using the same pendulum length as above the following data can be compiled (Figure 2.1.5a and b). Thus for a backswing length of 50cm, angular displacement on the backswing is 23°, and velocity of the putter head at ball contact is 1.42m/s.

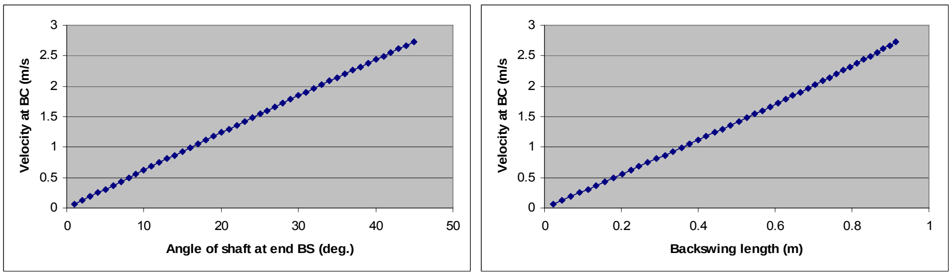


Figure 2.1.5a and b: (a) The relationship between angular displacement of the pendulum and putter head velocity at ball contact, and (b) the relationship between backswing length horizontally and putter head velocity at ball contact when pendulum length is 129.3cm.

Pelz’s putting theories are acknowledged throughout the golfing community, and Pelz claims many professional golfers apply them (Pelz, 2000). From a (bio)mechanical point of view, the in-plane pendulum putting stroke is attractive because of its simplicity. Of course, in a sport with a large number of variables, it is not a guarantee of putting success. As golf greens are seldom truly flat, other factors such as the ability to read the slope and speed of the green, and then using that information to align the ball path become important.

Pelz suggests that the optimal holing speed of any putt would result in the ball finishing 17 inches (approx 42cm) past the hole. Obviously, if the ball does not have enough speed to reach the hole, it is not going to go in. Pelz advocates learning how to strike the ball at the appropriate speed to allow the ball a chance of going in the hole, but also ensuring that if the ball does not go in, the next putt is a successful one (as the ball is left quite close to the hole). Being able to strike the ball at the optimal speed is the most important characteristic of successful putting according to Pelz (2000).

To highlight the importance of backswing length to the preferred pendulum putting stroke, Pelz provides two graphs plotting backswing distance against putt length. The data on 150 amateur golfers was collected at the DuPont World Amateur tournament (no year or other methodological data provided). This testing was conducted in the evening, after each player had completed their round. As far as is possible to detect, the testing was completed on an artificial putting surface, indoors, to a fixed length hole. However, the author does not provide the exact details of this putting task in the text.

The data in Figure 2.1.6 indicates that whilst backswing length varied approximately 15cm (6 inches) across the group of players (n=150), the length of putt produced varied by approximately 7.2m or 24 feet. This is a range of 6 feet to 30 feet in putt lengths. Figure 2.1.6 indicates that very small changes in backswing length had a large effect on putt length for this sample of golfers. For every small change in putt length (in this example 90cm or 3 feet) the backswing length changes only minimally (in this case 2.5cm or 1 inch). Unlike the pendulum putting stroke, where a small change in backswing length equates to a small change in the distance the ball travels, these data presented by Pelz suggest a small change in backswing length can equate to a small, medium or large change in the distance the ball travels depending on the level of tension or excitement the player is experiencing at the time.

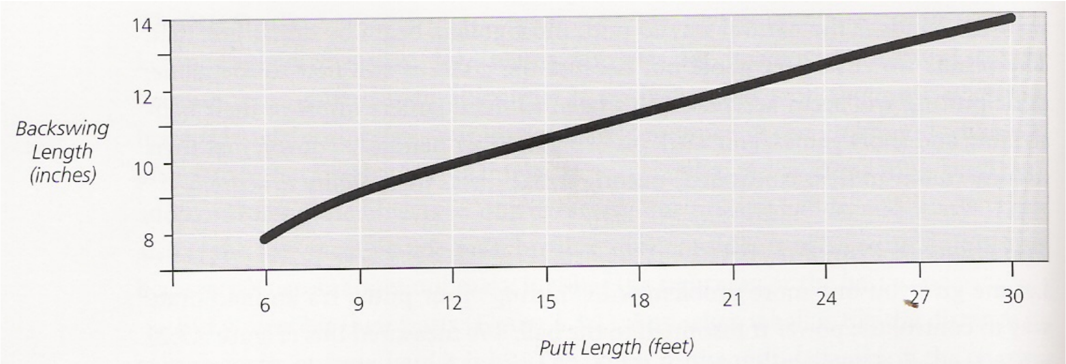


Figure 2.1.6: Graph plotting backswing length against putt result for 150 amateur golfers. Taken from Pelz (2000, p.118).

In contrast to these players, Pelz provides data from his own putting performance and from a robot device ("Perfy") that creates the perfect pendulum stroke (Figure 2.1.7). When combined with the data previously presented from the amateur players (Figure 2.1.6), there is a clear distinction between the relationship of backswing length and putt length as described by a pure pendulum motion (Perfy), and that produced by the human version of a putting pendulum (Pelz) and those producing different kinds of putting strokes (amateurs).

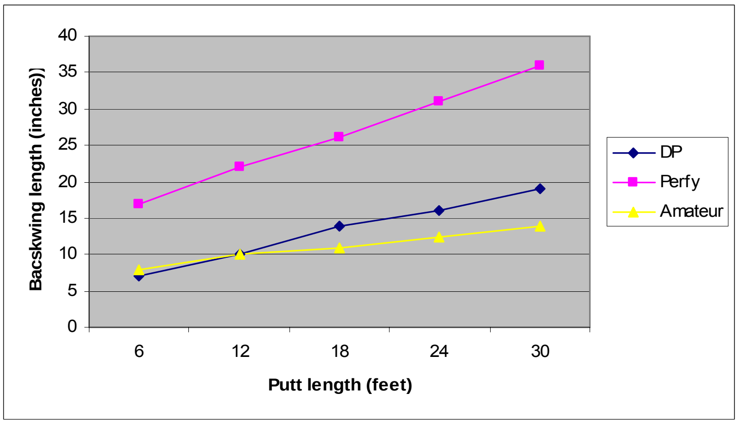


Figure 2.1.7: Graph plotting backswing length against putt result. Combining two sets of data taken from Pelz (2000; pp.118 & 120).

These data indicate that when compared to the robot device, both Pelz himself, and the amateur players are able to produce large changes in putt length without large changes in backswing length. Both Pelz and the amateur players use a backswing length of around 7 inches to produce a putt of 6 feet. The robot device uses a backswing length approximately two and a half times that for the same length of putt. As the putt length increases, the change in the robot's backswing changes by a greater distance than either Pelz or the amateur players. For each 6 foot increase in putt length, the robot's backswing length increases by 5 inches. For the same increase n putt length, the amateur players' backswing length increases by 1 to 1.5 inches. Pelz own backswing length changes by between 3 and 4 inches.

Whilst Pelz is able to provide evidence that he has a pendulum like putting technique, the data from the mechanical putting robot is a closer representation of a true pendulum putting action. The robot was constructed to allow the putter to be manually taken into the backswing position then released. It would not be possible for any interference in the pendulum putting motion from other inputs (such as muscle, rotation about longitudinal axes or sagittal plane motions like wrist extension and flexion). Therefore, the purest form of the pendulum putting technique is only possible where all of these inputs are maintained constant. Thus, Pelz argues, the pendulum putt is more reliable and repeatable than other techniques as the player who produces a pendulum putting stroke can use the length of the backswing to dictate putter head velocity at contact. The appropriate putter head speed at contact and a sweetly struck ball, provide the player with a more reliable putting stroke, and more chance of getting the ball in the hole.

Whilst Pelz is a source of useful theory and discussion it is also a source of frustration because of a lack of attention to research method, proof or other aspects of the stroke that the author believes are not so important. Similarly, the author claims to be a researcher, but published very little in the peer reviewed literature. For example, at the end of a section dedicated to the stance, the author suggests,

> “My measurements also show that many of the world’s best putters create a stable lower body by placing slightly more than half – 55 to 60 percent – of their weight on their forward foot” (page 104).

A statement such as this can be taken to mean a number of things to the amateur golfer –

- Should I stand at address with my weight more on my left foot?
- Should I maintain this posture throughout the stroke or just while I am addressing the ball?
- How do I know if I am at 55 to 60 percent?
- Should my weight be shifting during the putt or do I maintain this relationship throughout the stroke?

Alternatively –

- Were these golfers placed on a force platform for actual measures or was some other method used to come up with this figure (e.g. Questionnaire or self stated)?
- If measurements were quantitative, were they made throughout the putt or just at address?

- Did the author assess centre of balance or pressure movement during the putting stroke – if so, how far did it move?
- Is their a relationship between putting accuracy or putt speed and body weight transfer?
- How many golfers were measured on this factor?
- How many trials? etc.

Whilst Pelz does not address these specific issues dealing with the centre of pressure or weight transfer during the putt, the author does stress the importance of maintaining a stable base of support, not sliding or moving the hips towards the hole and having no movement of the lower body during the stroke (2000). The question of whether control of movement of the COP is an indicator of putting remains unanswered.

2.2 Putting research

The putting research of interest to this study can be broken down into biomechanical research and putting performance research. The biomechanical research is largely lab-based studies completed indoors and assessing putter head kinematics (and in one case force platform parameters). The putting performance research is a body of literature that assesses the performance of professional and or amateur players based on their performance (number of putts) in tournament or simulated tournament conditions.

2.2.1 Putting performance

In terms of putting performance, how often does the ball actually go in the hole in one stroke? Tournament play data from Tierney and Coup (1999) suggests that when putting from 3ft (0.9m) elite professional golfers hole out 93.86% of the time, putting from 12ft (3.6m) they have a success rate of 34.46% and from 24ft (7.2m) they hole out only 11.8% of the time. In an earlier publication, Cochran and Stobbs (1968) performed an analysis of putting results from the 1963 British Open. In this study, the professional golfers holed out 99% of the time from 0-3ft, 74% of the time from 3-6ft, 38% of the time from 9-12ft, and 11% of the time from 24-30ft. Based on these tournament play data, the putting performance of the professional had not changed substantially over the years.

The Cochran and Stobbs (1968) ground breaking study provides slightly more detail than simply the success rate of putts. The research team also had the opportunity to measure the distance the ball was left from the hole after an unsuccessful putt. This data helps to understand the ability of the professional golfer to get the ball close enough to the hole on the first putt (if the ball does not go in on the first stroke) to ensure success in the following putt. Remembering that under the scoring system of golf two putts are standard on each hole, the data from Cochran and Stobbs reveals an average number of strokes per hole of 1.75 (equates to 31 putts per round) for the professional golfer. This value suggests that whilst getting the ball close to the hole is important, striking the ball with enough speed to go into the hole is more important, as only then is there a possibility of the score improving. A putt that is 1cm short of the hole is a good result as the subsequent putt is simple, a putt that finishes 1cm past the hole is better as it had the potential to go in the hole. Only those first putts at each hole made with enough velocity to go in can result in one-putt greens.

If the professional misses the first putt, how far do they leave the ball from the hole for the subsequent putt? This information was also provided by Cochran and Stobbs and is summarized in Table 2.2.1.1. Whilst the holed out data decreases as distance increases (not with standing the anomaly in the data for putts of greater than 9m in length), the professional golfer was still able to leave the vast majority of putts within 1 ½ ft (45cm) if the first putt was not successful. The subsequent success rate was high as judged by the average number of putts to hole out. Whilst Cochran and Stobbs data did not provide information on whether the ball had traveled past the hole, finished short of the hole or was left or right of the hole, what it does highlight is the importance of imparting an appropriate amount of velocity to the ball at the point of contact.

Table 2.2.1.1: Putting results for different length putts taken from Cochran and Stobbs (1968, p.187) and converted to metric distances. Data based on measurements from 1963 British Open.

Putt distance (m)	**0-0.9**	**0.9-1.8**	**1.8-2.7**	**2.7-3.6**	**3.6-4.5**	**4.5-5.4**	**5.4-6.3**	**6.3-7.2**	**7.2-8.1**	**8.1-9.0**	**+ 9.0**
Total # of putts	692	205	120	80	152	111	93	83	70	52	58
Holed out (%)	99	74	48	38	23	12	11	4	4	4	8
Missed but w/in 45cm (%)	100	100	100	98	100	99	96	91	87	80	77
Average # to hole out	1.013	1.259	1.517	1.62	1.78	1.91	1.94	2.00	2.11	2.15	2.05

The data on the putting ability of amateur golfers reveals a different tale. The data in Table 2.2.1.2 indicates the average number of strokes required to hole out from a variety of putt lengths. The data on these non-elite golfers was collected by Fairweather and Sanders (n.d) and is based on 1,748 male putters and 120 female putters. The data for elite players is based on expected values (no information provided on how this was calculated).

Table 2.2.1.2: Average number of putts taken to get the ball into the hole. Taken from Fairweather and Sanders (n.d).

Distance	Elite Players	Males	Females
3 feet (0.9m)	1.06	1.23	1.14
12 feet (3.6m)	1.66	1.97	1.95
24 feet (7.2m)	1.91	2.31	2.34

These data indicate that as the distance of the putt increases, the difference between elite and club level golfers increases. However, it also suggests that at relatively short distances, there is not a great deal of difference between elite and club level golfers. The average for the 24ft (7.2m) putt suggests that most elite players can most often hole out in two putts or less, whilst the amateur golfers are more likely to require three putts. This 0.4 stroke per hole difference is important in the context of an 18 hole round (7.2 extra strokes per round), and is magnified if it can be assumed that the amateur golfer will, on average, be required to hit more longer putts than the professional throughout a round.

The validity of the data presented by Fairweather and Sanders (n.d) can be assessed when compared with the 1968 data of Cochran and Stobbs (previously presented in Table 2.2.1.1). Cochran and Stobbs indicated that elite players needed, on average, two putts (2.00) to get the ball in the hole from around the 7.2m distance. Fairweather and Sanders (n.d) calculated value of 1.9108 strokes to hole out from the same distance is comparable.

Fairweather and Sanders collected the data from volunteers in the spectator gallery at the 2000 British Open at St Andrews. Participants were provided with a putter and ball and after a short warm-up completed the task of holing out at each of the three holes (3, 12 and 24ft – metric equivalent is 0.9m, 3.6m and 7.2m). It is assumed that the player did not use their own putter and using unfamiliar equipment would tend to over estimate the number of strokes per hole. Each result represents one trial only at each hole. No kinematic data were provided, however the authors suggest video footage was collected of the initial putt at each hole but has not yet been analysed.

2.2.2 Biomechanics of putting

2.2.2.1 Putter head kinematics

Several authors have conducted putting studies with the aim of analyzing putting stroke characteristics and putt result (Delay et al., 1997; Paradisis and Rees, n.d; McCarty, 2002; Haltom, 1994; Zafiroglu, 1994). All of these investigations were conducted indoors and most did not use an actual hole as the target, such that the task was different to that confronting the player on a normal putting green. In these lab based situations (apart from the Paradisis and Rees paper), the players involved were required to either putt to a desired length (stop the ball on a line drawn across the putting surface at a set length) (Zafiroglu, 1994; Haltom, 1994) or putt to a round target (stop the ball on the exact position of the hole as drawn on the carpeted putting surface) (McCarty, 2002; Delay et al. 1997).

Although not tested or validated, the putting task, requiring players to stop the ball at a certain distance changes the way the putting task is performed compared to putting the ball into a hole. All players are aware that the ball can enter the “hole” at a variety of speeds. This gives the player a range of club head velocities at ball contact that will still result in the ball going into the hole. The task requested of the players in these studies takes away form the player this possibility. This limitation ignores the importance of the player striking the ball with enough velocity to leave it 42cm past the hole – the standard advocated by Pelz (2000) for optimizing velocity. Notwithstanding these limitations, the papers provide insight into putter head kinematics, COP movement and variability and will be discussed further here.

One common theme amongst all putting papers was the separation of players into groups based on handicap level. The question of interest seemingly “how do the elite/expert/low handicap golfers compare to the novice/high handicap golfers?” All authors assumed that putting performance was related to handicap level. On putting performance alone this was not definitively supported. Also, the authors often analysed only putts that were successful - that is putts that went in the hole (Paradisis and Rees, n.d.) or stopped over the target (Delay et al., 1997; Haltom, 1994; Zafiroglu, 1994).

Whilst the methodology of these papers that analysed successful putts only required the players to strike enough putts to achieve a minimum number of successful putts, most did not report how many putts each player took to achieve this aim. McCarty (2002) did provide data on the accuracy of the different putting groups, as this author recorded the ball finishing position for each putt as the radial distance from the hole. Initially, players were grouped according to handicap (less than or greater than 14) for 2m and 4m putts. Each player (12 low handicappers, 11 high handicappers) hit 25 putts at each of the “holes”. The results reflected a significant difference between handicap groups for the 4m putts (25.6±14.7cm vs. 32.9±18.6cm for low and high handicap groups, p=0.001, calculated d=0.44, power = 0.992), non significant differences were present for the 2m putts (20.8±13.3cm vs. 23.2±15.8cm for low and high handicap groups respectively, p=0.17, calculated d = 0.165, power = 0.297). The minimal difference found between groups at the 2m putting task forced McCarty to group players based on accuracy.

Whilst this data subsequently produced significant differences in putting performance, the groups were not significantly different in handicap (p=0.98 at 2m task, p=0.06 at 4m task), and players were not necessarily in the accurate group for 4m putts if they were in the accurate group for 2m putts, and vice versa. The data reported by Fairweather and Sanders (n.d.) (Table 2.2.1.1 above) also indicated relatively small differences between amateur and professional golfers at short putting tasks, with the differences increasing progressively with increasing putting task length.

All of the above authors suggest that as the length of the putting task increases, certain kinematic parameters also increase. Specifically, McCarty (2002) reported greater putt length required significantly greater backswing length ($p<.001$) significantly greater putter head velocity at ball contact ($p<.001$) and significantly greater follow through lengths ($p<.001$) between 2m and 4m putts. The time taken to complete the task did not (from start of downswing to ball contact) change with increased putting length ($p=.33$, calculated $d = 0.006$, power = 0.153). The time to move the putter head from its most backward position to ball contact remained the same even though the displacement of the putter head was greater – thus the increased velocity required to move the ball further was achieved. Many authors commented that this temporal parameter appeared to be fixed for each individual, but none went on to assess the significance of equality of this parameter between different putt lengths.

These data were supported by Delay et al. (1997) who also analysed putts of different lengths, and who suggested that at putts of 2m, 3m and 4m movement time on the downswing was not significantly different ($p>0.05$). This study of 10 professional golfers and 10 novices suggested that as the movement times were not significantly different from each other, even though the backswing lengths were different for the different lengths, there was an isochrony of movement. That is, the movement time is fixed, irrespective of the displacement required to successfully complete the task. So, as putt length increased and putter amplitude increased, movement time remained relatively constant. Whilst it was not possible from the reported data to calculate whether the data were significantly equal, rather than not being significantly different, further calculation by Delay et al. indicated the isochrony of movement for this putting task was confirmed when all players' data were combined. There was a non-significant tendency for the elite players to be more isochronic than the novice players. This was calculated by relating the mean movement velocity to movement amplitude.

Whilst all papers provided kinematic data suitable for comparison to further research in this area, the most interesting findings were based on the so-called pendulum putting theory advocated by Pelz (2000). Both Paradisis and Rees (n.d) and Delay et al. (1997), report that when comparing the overall displacement of the putter head between novice and expert golfers, it was the novice player who produced a stroke most resembling a pendulum. For the expert players, ball contact was made after one third of the entire forward swing of the club had been completed. The novice players made contact with the ball after half of the forward swing had been completed (Figure 2.2.2.1). This novice position at ball contact also resembles the pendulum putting stroke produced by a variety of robot putting devices (Delay et al., 1997; Hurrion et al., n.d; Pelz, 2000), where ball contact was made in the middle of the forward pendulum swing.

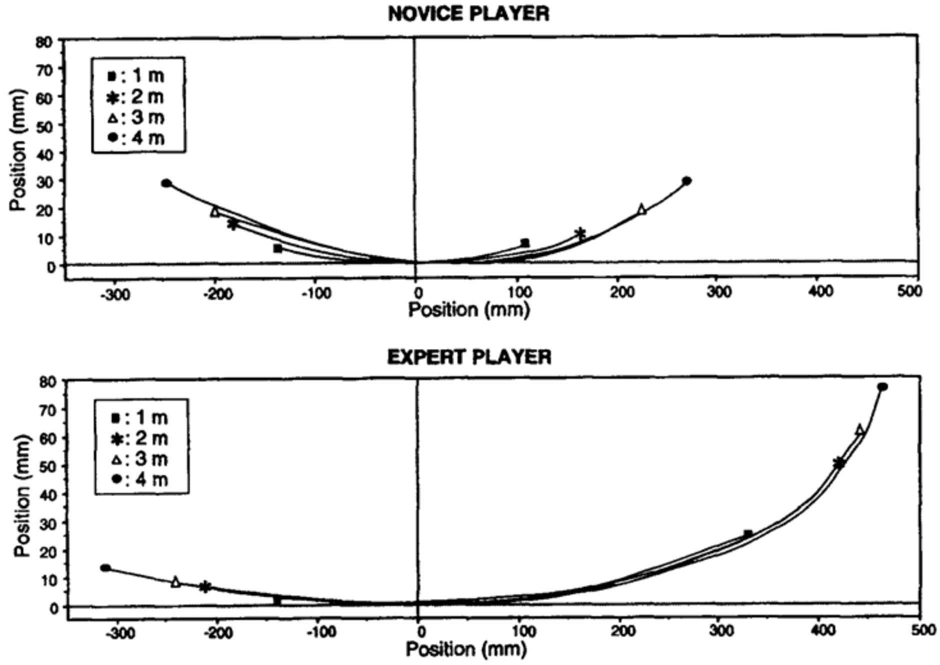
Closer analysis of the data reported by Delay et al. (1997) indicates that the novice player was less likely to hit the ball in the true midpoint of the downswing as the putting task got longer (table 2.2.2.1). The difference in putter head displacement between the first part of the downswing (up to contact) and the second part (from contact to end of follow through) gradually increased as the putt length changed from 1m to 2m, 2m to 3m and from 3m to 4m. Temporal data for these phases and players displays the same pattern. This difference data further highlight the tendency for the novice golfer to be more pendulum like (in terms of displacement) than the expert golfer.

Table 2.2.2.1: The difference in putter head displacement between the first and second parts of the downswing. A positive value indicates a longer second part of the downswing. (Putter head displacement in second part of downswing as a percentage of putter head displacement in the first part of the downswing for successful putts). Data calculated form values reported in Delay et al. (1997).

Difference (mm)	1m	2m	3m	4m
Novice	-2 (99%)	42 (119%)	63 (123%)	67 (121%)
Expert	115 (184%)	219 (212%)	306 (231%)	367 (233%)

The putter head paths depicted below (from the same study), and the data presented on displacement suggest that on first experience the pendulum putting stroke may in fact be the easiest (unskilled) technique to employ. The first graph also indicates that there is variability on the novices putter path with the putter path starting low during the backswing and finishing high after ball contact and vice versa for the four different length putts. Alternatively, the expert player graph illustrates the flatter trajectory and more consistent putter path of the expert player in the putting stroke. Whilst this graph may initially suggest the tendency for the novice to be more likely to use a pendulum putting technique, it also highlights an inconsistency in putting technique of the novice player.

Figure 2.2.2.1: Putter head trajectories during the downswing for novice and expert players at 1m, 2m, 3m and 4m putt lengths. These trajectories all represent successful putts. (Taken from Delay et al. 1997, p. 606).



Delay et al. also compared the novice and expert data to the kinematic parameters produced by robot like pendulum putting device. Based on their data, the authors concluded that the novice golfers spontaneously reproduced a pendulum putting stroke, whilst the expert player reproduced a pendulum like motion in the early part of downswing, but modified the stroke after the point of peak velocity was achieved. Importantly, unlike the novice subjects and pendulum device, the expert players did not achieve peak velocity at the time of ball contact but in the middle of the downswing. Velocity of the putter head was then controlled for the rest of the downswing until ball contact.

Similarly, Sanders (n.d.) suggests that elite putters, like Jack Nicklaus, were consistent because of the ability to develop and maintain optimal club head velocity prior to and during ball contact. Sanders' (n.d) case study of Nicklaus suggests that the hands (moving about the wrist joint) are 'active' during the middle part of the downswing to generate the desired putter head velocity, but then 'switch off' before impact to allow the putter head to 'coast' at a constant speed as it strikes the ball. As a one off case study, Sanders provides some interesting analysis of the torque profile at the wrist. This data demonstrates Nicklaus' ability to turn the hands "on" during the early part of the downswing, and then "off" just before ball contact is made. When the hands are "on" there is a positive torque at the wrist as the putter rotates around the wrist joint (left wrist extension). When the hands are switched off, there is zero torque at the wrist and the wrist joint is fixed (no change in position). The hands are moving towards the hole during the stroke, and also acting as a pivot point for the putter during the first part of the downswing.

To the average golfer, it would seem that the ability to allow gravity to initiate the downswing, then to incorporate torque from the hands, then to switch the hands "off again" is exactly the scenario that Pelz (2000) is labeling poor technique. Fairweather and Sidaway (1994) suggests that rather than focus on controlling spatio-temporal parameters as advocated by Pelz, the golfer should focus on force control in the downswing. Interestingly, Pelz (2000) claimed that Nicklaus' putting stroke (push stroke) did not incorporate a hinge at the wrist (flexion and extension occurring at the wrist joints), and rated it highly because of this. It would seem that the anecdotal analysis of Pelz and the scientific analysis of Sanders (n.d) classify Nicklaus' putting technique quite differently.

The theory behind Pelz pendulum putting stroke also relies on another key factor – sweetness of ball strike. It is possible that for the same backswing length, and the same "dead hands" stroke that the ball will travel different distances once struck. This is because the point of contact on the putter face can influence the amount of force imparted to the ball.

Hurrion et al. (n.d) investigated this factor using a "robot" as the putting subject so that each backswing length was perfectly repeatable. The authors manufactured the "robot" so that a fixed backswing was taken on each stroke, however, they aligned the robot slightly differently so that putts were struck on the heel, mid point or toe of the putter. Those putts that were struck in the middle of the club face had the greatest initial ball velocity, whilst those putts struck off centre not only generated less ball velocity but also contributed to the ball deviating from its intended path – the club face opened during impact when the ball was struck from the toe of the putter and closed during impact when the ball was struck from the heel of the putter. Delay et al. (1997) and Pelz (2000) both discuss the importance of the "sweetness" of contact without providing any supporting evidence.

2.2.2.2 Movement of the COP during the putting stroke

Of the putting research papers, only McCarty (2002) incorporated force plate data collection into their lab-based study. McCarty's thesis provides information on the distribution of weight during the putting stroke. McCarty focused on the location of the COP at specific events in the putting stroke (address, end of backswing, ball contact, end of follow through). The author used one AMTI force platform (sample rate = 240Hz) and tracings of the outline of each player's feet to calculate COP in relation to left/right loading. This required the player to repeat the stance position for each putt (n=50 putts with 25 at hole 2m away, 25 at hole 4m away). As the goal of the task was to stop the ball on a target and feet placement was not self selected (after the first putt), this study imposed some unusual constraints on the putting task.

McCarty's data on the COP sheds light on the issue of COP movement during the putting stroke. Although the author did not provide grouped COP data for handicap levels or putting techniques, data were presented for accurate and less accurate putts. COP data were analysed in the medio-lateral direction only. During the backswing, both groups displayed movement of the COP away from the hole for both 2m and 4m putts. From the start of downswing until ball contact, group values indicated movement of the COP back towards the hole. Compared to the starting position of the COP at address, at ball contact the more accurate players moved the COP closer to the hole, whilst the less accurate players moved the COP to a position further away from the hole. By the end of follow through all groups had moved the COP closer to the hole than at address. Thus, the greatest displacements of the COP in the medio-lateral direction during the backswing were in the less accurate groups ($p<.001$ for both 2m and 4m putts). However, the minimal difference in position of the COP at address for the 2m putts ($p=0.43$), meant that non-significant differences were found for COP location at the end of backswing ($p=.990$), whilst significant differences were present for COP location at the end of backswing for the 4m putts ($p<.001$) after significant differences were present at the address position ($p=0.02$).

The data presented on COP location and movement in the first part of the putting stroke highlights differences between the groups for these parameters (remembering that group membership is not the same for each putting task). For the 2m putting task, the accurate group start with the COP located closer to the right foot (-0.09±2.80cm), whilst the less accurate group started with the COP located closer to the left foot (0.14±3.8). At the end of the backswing phase, the

COP location for each group was almost identical (-0.46±2.70 vs. -0.45±3.70; p=0.99), but movement of the COP during the backswing phase was significantly greater, therefore, in the less accurate group (-0.36±0.8 vs. -0.59±0.58; p<0.001). The less accurate group had moved the COP further away from the hole, but the COP location at end of backswing was (on average) the same between groups.

In the 4m putts, the less accurate group again produced greater movement of the COP away from the hole during the backswing (-0.53±0.65 vs. -1.00±1.10; p<0.001), and the COP location at end of backswing was significantly different between the groups (0.20±2.60 vs. -0.95±3.20; p<0.001). However, the position of the COP at address was opposite to that produced in the 2m putting task, with the COP located closer to the left foot (0.73±2.70) in the accurate group and closer to the midpoint of stance (0.07±3.40) in the less accurate group (p=0.02). This difference in starting position of the COP for the 4m putts was different to that employed by the accurate group in the 2m putting task.

At ball contact in the 2m putts, the COP location was again not significantly different between the accurate and less accurate groups (0.02±2.70 vs. -0.09±3.80; p=.710), whilst significant differences were evident at ball contact in the 4m putting task (0.89±2.70 vs. -0.13±3.20; p<0.001). By the end of the follow through the COP had moved to a non-significantly different position for all groups across both tasks. The large standard deviations reported for all parameters suggest a variety of techniques were employed both within and between the accuracy groups. In all data reported by McCarty (2002) for COP location by group and point in time during the putting stroke, the mean plus or minus one standard deviation indicates a range of values that would incorporate a zero crossing within the group. Some players had a COP location closer to the left foot, some had a COP location closer to the right foot, and some with a COP location around the middle of stance, irrespective of the point in time of the putting stroke. This, more than any other data, indicates a variety of techniques employed during the putting stroke to control movement of the COP.

A variety of kinematic techniques have been utilized in previous studies. The advantage of testing indoors is that it allows researchers the ability to use passive marker systems (Delay et al. 1997; McCarty, 2002) to collect data at medium to high sample rates (60-200Hz), and also to control the testing environment. Some studies were also completed with standard video techniques sampling at between 25 and 60Hz (Paradisis and Rees, n.d; Haltom, 1994; Zafiroglu, 1994) using manual digitizing after marking the subject and/or club head prior to filming. In all of these studies, subjects performed the putting task indoors, had reflective or other markers attached to them, they were asked to wear black lycra clothing, had to putt at a mark on the ground rather than a hole, and were asked to stop the ball at a certain distance in order to complete the task successfully. These scenarios are arguably not indicative of normal putting practice or conducive to producing typical putting performance. At least, no assessment was made of the field validity of their research.

2.3 Posturography

Researchers have long had an interest in assessing the amount of movement of the body in seemingly static standing situations. Measurement of the body's propensity to sway when the subject is standing upright involves measuring movement of the centre of mass (COM) using a variety of kinematics methodologies that calculate the COM using known segmental length and mass properties. Alternatively, the ability to measure the location of the centre of pressure (COP) has allowed researchers to focus on that position where the interaction between the subject and the supporting surface takes place. Changes in the position of the centre of pressure in the horizontal plane are calculated over time allowing this parameter also to be used as an indicator of the body's propensity to sway. However, Palmieri et al. (2002) suggests that the use of the term "COP" as a direct measure of body (COM) sway is incorrect.

The location and tracking of the centre of pressure (COP) is often reported in the literature in relation to gait and stability analyses (Winter, 2005). Whilst some authors suggest that COP movement is indicative of movement of the total body centre of mass, others have shown this to be incorrect (Winter, 2005). The movement of the COP is not of the same magnitude as movement of the COM of the body. The COP is indicative of weight transfer and adjustments of the body in relation to movement of the COM. Numerous researchers have published data on the COM and/or the COP of standing subjects, some have used the terms interchangeably, and some have used a further term, the centre of balance to explain movement of the COP. Most interest in the posturography literature is on the measurement and assessment of standing COP, noting that all golfers must putt from a standing position. The present study will not be tracking the movement of the COM, but will be using the COP as a measure of weight transfer during the putting stroke.

The COP is a measure that requires the calculation of a central point of application of the overall ground reaction force vector. It is a dynamic indicator of weight distribution between the feet. Typically, this calculation requires the use of a force platform, and indeed this is the most common methodology for assessing COP. As a cross section of the papers published in the posturography literature, Table 2.3.1 provides a guide to the types of studies completed in the area. Although the task of standing upright is not directly relevant to the putting stroke, these papers are able to assist in providing detail on methodological issues (see Table 2.3.1, over page).

As the table suggests there is little uniformity in methodology or parameters used to assess movement of the COP. All authors did agree however, that sway in the antero-posterior (AP) direction is always greater than sway in the medio-lateral (ML) direction during quiet standing.

Assessment of data frequency and filtering from past papers again highlights a number of variations. Whilst not all authors performed filtering techniques or reported detail on frequency content, others went into considerable detail. Consensus on power for double leg stance static tests with eyes open suggests that data fall below 5Hz and even less than 3Hz for younger subjects (Baloh et al., 1994; Era and Heikkinen, 1985).

In the only previous putting study conducted where COP movement was assessed, the author chose a 6Hz low pass Butterworth filter for both kinematic and force plate data (McCarty, 2002). No justification of this cut-off frequency was provided by the author.

The Master’s research work conducted by Ball (1999) also provides great detail of the smoothing process that the force plate data channels were passed through before any data analysis was completed. The shooters were attempting to stand still, therefore minimizing movement of the COP. This allowed the researcher to be confident that filtering could be conducted at a relatively low frequency, as all shooters demonstrated (more or less) the same consistency of movement of the COPx,y. Thus, Ball chose a cut off value of 4Hz and used a recursive filter to smooth the raw COP data. Compared to elite level shooters, it is possible that there will be greater COP movement in club level golfers and a higher cutoff frequency may be required. Therefore, pilot study testing will be used to determine the precise cut-off level to be used in the present study.

Author, year	Platform type	Methods	Parameters
Baloh et al., 1994	Custom made, footplates	Fixed stance width, one off 10 s tests, no sample rate listed, velocity data filtered only	Mean sway velocity of COP in AP and ML direction (mm/s)
Colledge et al., 1994	Custom made, load cells	Feet slightly apart, one test of 1 min, no sample rate listed, filtered at 10Hz	COM (sic) path length (cm), quotients comparing surface and eye conditions to determine the effect of eyes open/closed
Ekdahl et al., 1989	AMTI	Feet close together, repeated (3) tests of 30 secs, 10 Hz, not filtered	Means sway amplitude x,y (cm), mean velocity (cm/s), length of sway path (cm), area within path (cm^2)
Era & Heikkinen, 1985	Custom made, transducers	Feet slightly apart, one off tests of 8s at 10Hz, not filtered	Extent of postural sway AP & ML (mm), Frequency-amplitude distribution
Geurts et al., 1993	Custom made, transducers	Fixed stance width, 3 x 20s or 2 x 30s tests, at 20Hz or 60Hz. Multiple sessions over 5 weeks, filtered at 30Hz	Mean frequency (Hz), peak-to-peak amplitude of COP displacement, mean velocity, coefficient of variation
Shumway-Cook et al., 1988	Custom made	Standard foot placement, 4 x 30s tests at 33Hz, not filtered	Medio-lateral displacement of sway, total sway area

Table 2.3.1: Summary of selected papers published in the area of COP motion while standing.

Research into the use of the COP as a means of indicating performance level has occurred in rifle and pistol shooting. Ball et al. (2003) investigated the relationship between movement of the COP (the authors referred to body sway) and aim point accuracy during rifle shooting. As there were no discernible events in the activity other than the point of shot, data were analysed at set time periods prior to the shot.

As with the putting stroke, shooters are required to stand with both feet on the ground whilst performing the skill. Like putting, there are no time restrictions on performance completion, and the task is performed across the body, meaning that the performer stands parallel (one foot closer to the target than the other) to the intended line of the shot or stroke. However, the shooting task requires the ability to limit movement of the rifle, unlike the gentle swinging movement of a club.

Ball et al. suggest that performance of the shooting skill was related to individual COP movement analysis, but not to the overall group performance. Individual analysis was performed by correlating multiple trials to COP movement. For four of the six shooters the COP data were related to shooting performance, but when averaged across all shooters there was no relationship between COP movement and shooting performance. Ball et al. measured many parameters that have been highlighted in the posturography literature, and focused on the velocity of the COP in specific directions (ML and AP) (rather than as a 2D value) and also highlighted the importance of the position of the COP at specific points in time (using time prior to shot to create common temporal landmarks).

Shumway-Cook et al. (1988) (listed in Table 2.3.1) incorporated the use of balance biofeedback training in the rehabilitation of hemiplegic patients. Their real-time biofeedback system used the COP information from a standard force platform displayed onto a video screen. The position of the COP was represented as a cross, and the patients were required to maintain the cross in a certain part of the screen in line with limits of postural sway for the normal elderly population. The nature of hemiplegia is such that weight bearing for this population is unequal, and the biofeedback provided information on symmetrical weight bearing. Shumway-Cook et al. were thus interested in the medio-lateral displacement of the COP. After intensive rehabilitation incorporating short biofeedback sessions of 2 x 1 minute trials per day, the treatment group had a significantly decreased lateral displacement of the COP ($p<0.01$) when compared to a matched group undergoing standard rehabilitation protocols ($n=8$ subjects in each group).

Shumway-Cook et al. were one of the first groups to utilize this type of biofeedback system to assist in balance (re-) training. There have been a number of subsequent studies in the area, mainly focusing on the display of the COP in a dynamic way to assist in the recovery of patients suffering a range of neurological conditions (e.g. Nichols, 1997; Cattaneo and Cardini, 2001; Rougier, 2004). This basic type of balance assessment and feedback relies on making the patient aware of the specific factor of interest (the location of the COP as displayed on the screen), and how to control it. For biofeedback to work, the signal should be easy to understand, feedback instantaneous, and movement of the COP mark on the screen proportional to the movements produced by the patient (Cattaneo and Cardini, 2001).

A biofeedback approach to rehabilitation, whilst present in the literature, has become an area of great commercial interest. What may have started as researchers searching for the best way to provide biofeedback has become a commercial arm of many of the manufacturers of biomechanics equipment (see www.amtiweb.com, www.kistler.com, and www.onbalance.com).

Whilst one of the aims of the present study is to initially measure, and then provide biofeedback information to a group of players on the location and control of the COP whilst performing putting movements, it is not possible to do this on-site (that is, at the golf course) with any currently available balance testing system. All systems rely on a force platform type arrangement to collect data. This makes the system large, heavy and not very portable. Portable force plates also raise the subject off ground level meaning that putting could only occur at the same “level” through the construction of an artificial surface – this is one of the reasons putting research is generally conducted indoors. In order to satisfy the criteria of the present study then, a “balance” measuring and biofeedback system must be created that is, lightweight, portable, can be placed on the putting surface, does not raise the player off the ground, can provide instantaneous and easily understandable biofeedback, and is highly accurate. The development and assessment of this tool forms an early part of the present study.

2.4 Cluster analysis

The basis of the present study, whilst being the first-field based study of putter kinematics and COP parameters, is to investigate if different styles of putting techniques exist. The publication of Pelz (2000) especially and to a lesser degree Sanders (n.d) indicates the prevalence of different putting styles in the elite levels of the sport. At the level of the club golfer it is expected that similar numbers of techniques are prevalent. The identification of these putting styles amongst multiple kinematic and COP parameters require the use of cluster analysis. This statistical technique has been used for many years in a range of scientific areas, especially in the biological/taxonomical sciences. The use of cluster analysis in biomechanical studies is not so common, although there are previously published works in the field dating back more than 20 years (Wilson and Howard, 1983).

In most of the papers in the biomechanics field, cluster analysis has been used to describe movement patterns in sports such as swimming (Wilson and Howard, 1983), gymnastics (Forwood et al., 1985) and weightlifting (Grabe and Widule, 1988) or to describe gait patterns based on kinetic (Vardaxis et al., 1998) or kinematic data (Kawamoto et al., 2003).

The basis of cluster analysis is the grouping of like items based on defined parameters. These parameters are the measured or collected data from the movement of interest. Like patterns become grouped together and should be distinct from the other patterns or groupings. In the case of Wilson and Howard (1983) the backstroke starting technique of 10 swimmers was assessed using cine analysis. For each frame of film, the swimmers posture was defined based on 2D segmental angles. Using cluster analysis techniques, swimmers who moved through similar “postures” were closely related and thus grouped into a separate cluster. Wilson and Howard eventually defined 6 distinct clusters. Importantly, some of these clusters contained many members, whilst others contained only one or two members.

This separation into large and small groups is often the case in the application of cluster analysis techniques, and creates one of many issues for researchers. The question is whether those subjects’ in small groups (in some cases forming a group by themselves) are outliers that could be eliminated from analysis, or indicative of a true cluster group of their own.

Perhaps of greatest interest in the biomechanics literature is the finding of Grabe and Widule (1988) that the same subject could appear in different clusters. In their weightlifting study, repeated performances from the same lifter were not always classified into the same cluster. This classification of performances into different clusters always occurred when the lifter had one successful and one unsuccessful attempt (n=5), and also occurred on two of seven occasions where both lifts were successful. This finding suggests that averaging trials across subjects may not necessarily be the best way of identifying techniques when a measure of the quality of the performance (e.g. success of lift, faster time) is available in the methodology. Each putt in the main part of the present study will be analysed individually, as a measure of the quality of performance, putt result, will be available to each player during completion of the putting tasks.

Further analysis of the clustering techniques will be conducted in the theoretical analysis chapter of this paper.

2.4.1 Clustering techniques

There is not one, easy to use cluster analysis method. There are a number of ways of defining clusters, but in this paper the focus will be on two of these only, as they are the most common and are freely available in any number of statistical analysis software packages. These two techniques – hierarchical and k-cluster - are different in their method of cluster creation. The hierarchical method is agglomerative, meaning that at the start of the process all N number of subjects/items are considered N clusters, and in each stage the number of clusters is reduced by 1 when the two most like items join together. This process continues until all subjects/items are part of one large cluster. On the other hand, the k-cluster method is a partitioning process, and revolves around a user-selected number of clusters being created from the data. The cluster centre points (centroids or seeds) can be randomly selected, or provided by the user from previous analysis. As such, it is possible to use the hierarchical method to provide the cluster seeds for the k-cluster method to create the optimal solution.

The hierarchical methods, and the joining together of like items, relies on some initial measure of dissimilarity or likeness. These measures define how far apart, or close together the items are. An *n* x *n* data matrix containing a distance or similarity measure for each pair of items is created initially. This matrix contains no data on each *n* items score on *p* parameters, but provides only its similarity or difference to every other item under investigation. Typically, the dissimilarity measure is Euclidean distance calculated as the distance between two points in *p*-dimensional space, whilst the similarity or likeness measure is Pearson's correlation co-efficient. Using the dissimilarity measure, the further apart two items are, the greater the Euclidean distance between them, and therefore the higher their dissimilarity score.

Thus the (squared) difference between two items (r, s) in the dissimilarity matrix can be calculated by:

$$d_{r,s}^{2} = \sum_{j=1}^{p} \left(x_{rj} - x_{s,j} \right)^{2}$$

Once this matrix has been calculated (and in this paper the dissimilarity measure will be used), the researcher must decide on the method and measure of proximity to be used in each step of the cluster creation process.

The k-cluster analysis requires the expected number of clusters to be selected by the user. Hair et al. (1995) suggests that by calculating a hierarchical solution initially, the cluster seed data (which is simply the average of each parameter for each cluster group) can be used as the initial cluster seeds in the k-cluster solution. The final solution contains clusters with a Euclidean distance measure between their midpoints (centroids). However, the k-cluster process requires the continuous calculation of cluster solutions based on the seed data until all Items are eventually clustered around the cluster centre they are closest to.

2.4.1.1 Proximity measures used in hierarchical clustering techniques

There are a number of ways of utilizing dissimilarity data in the creation of clusters. In the agglomerative clustering process, each step requires the calculation of distances between the new clusters formed at each step and the remaining unclustered items and the other clusters created previously. Figure 2.4.1.1.1 is used to explain two of these proximity measures.

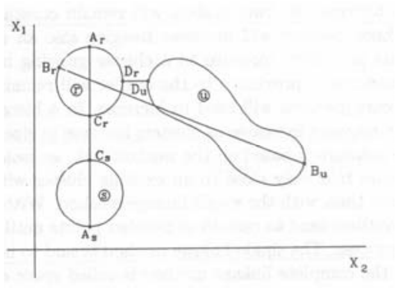


Figure 2.4.1.1.1: Using two distinct distance measures to calculate proximity between groups: nearest neighbour (single linkage) and furthest neighbour (complete linkage). Diagram taken from Jobson (1992, p. 523).

The figure provides details of three distinct clusters labeled **r**, **s** and **u**. Four distance measures have been calculated and presented in the figure. Two of these measures (Br, Bu) and (Ar, As) are calculating the greatest distance between any two points in the three clusters. The measures (Dr, Du) and (Cr, Cs) are calculating the shortest possible distance between the clusters. Importantly, if the greatest distance proximity measure (called furthest neighbour or complete linkage) is used to calculate the next step in the process, clusters **r** and **s** are closer together than **r** and **u**. If the shortest distance proximity measure (called nearest neighbour or single linkage) is used, then clusters **r** and **u** are closer together. The choice of proximity measure influences the final cluster groupings.

Alternatives to these two measures, but not illustrated in the diagram, are using the average distance (average linkage method) between all pairs of objects in the two clusters (when one item is taken from each pair). Ward's method and the Centroid method both use the squared Euclidean distance between cluster centroids to calculate proximity. The difference between them being that Ward's method employs a minimum within sum of squares distance between all pairs of clusters, whilst the Centroid method calculates a distance between cluster centroids.

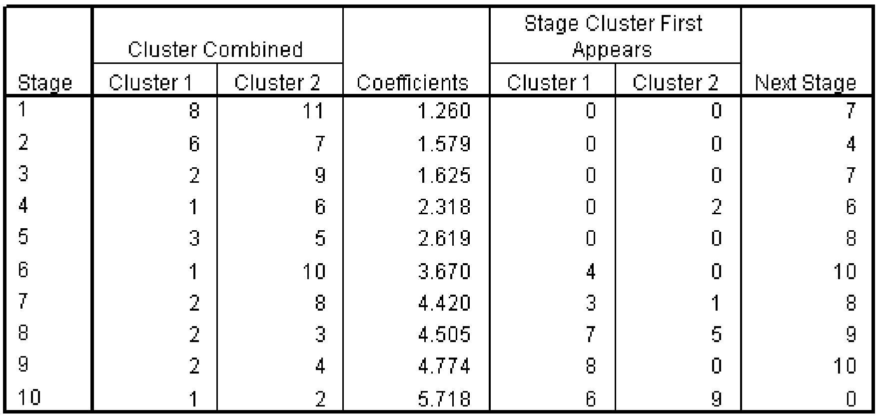
Previous biomechanical studies have employed a variety of proximity measures in their individual clustering procedures (where listed), but the justification for the selection of the criteria was never provided. Suffice to say, Wilson and Howard (1983) and Forwood et al. (1985) used the nearest neighbour method, whilst Grabe and Widule (1988) used the average linkage method.

2.4.2 Stopping rules

Unlike other parametric statistical techniques, cluster analysis does not provide definitive solutions. There is no single agreed upon criteria (commonly termed stopping rule) for determining the optimal number of clusters in a data set. A review of biomechanics studies that have used cluster analysis indicates that no stopping rules were used (Forwood et al., 1985; Kawamoto et al., 2003; Grabbe and Widule, 1988), the authors used one stopping rule (Vardaxis et al., 1998), or the authors used their expert knowledge of the skill (Wilson and Howard, 1983) to ultimately decide on the number of clusters.

During the hierarchical clustering process, details are compiled on the items being clustered and the derived proximity (usually a measure of distance) of the two items clustered is recorded at each step in the agglomeration schedule. As the process continues from step 1 to step (N-1), items that are becoming less and less similar will necessarily be grouped together (or an item that was dissimilar to a group of other items will be clustered with that group), as the ultimate goal is to group all items into one cluster. This results in the gradual increase of the proximity measure as the number of cluster approaches 1.

Assessing this proximity measure in the agglomeration schedule (labeled the "co-efficient of distance" or "co-efficient" in SPSS output) provides an initial indication of the optimal cluster solution, as any large change in the derived proximity measure will indicate that an item or items that were not similar have been clustered. The optimal cluster solution therefore, may lie at the previous stage in the process. In table 2.4.2.1, the agglomeration schedule suggests an optimal solution of six clusters, as the greatest jump in the co-efficient occurred between stages 5 and 6. This information is also presented graphically in the dendogram (Figure 2.4.2.1). The dendogram illustrates the size of the difference between items clustered. The dendogram and agglomeration schedule are combined to make an early assessment of the appropriate number of clusters in the solution.



Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	8	11	1.260	0	0	7
2	6	7	1.579	0	0	4
3	2	9	1.625	0	0	7
4	1	6	2.318	0	2	6
5	3	5	2.619	0	0	8
6	1	10	3.670	4	0	10
7	2	8	4.420	3	1	8
8	2	3	4.505	7	5	9
9	2	4	4.774	8	0	10
10	1	2	5.718	6	9	0

Table 2.4.2.1: Example of the agglomeration schedule output from SPSS. Taken from SPSS Version 12 on-line help.

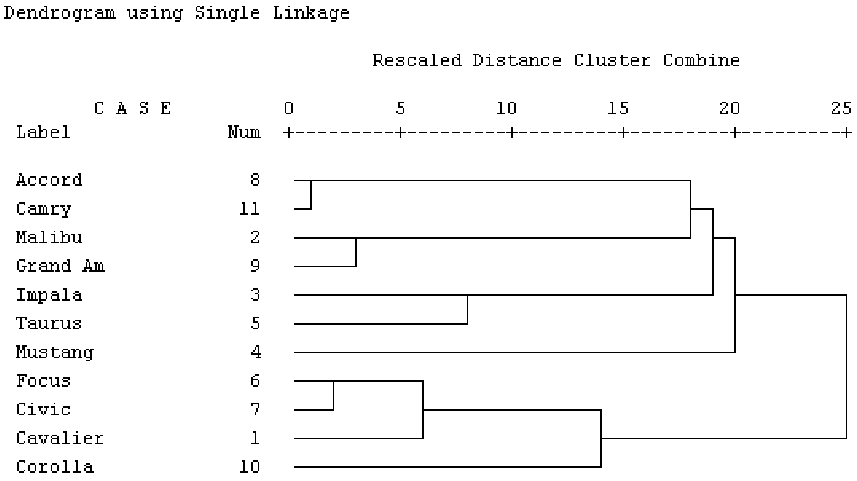


Figure 2.4.2.1: Example of the dendogram output from SPSS. Taken from SPSS Version 12 on-line help.

The following step in the decision making process uses stopping rules, effectively statistical ways of determining the optimal number of clusters. Many of the stopping rules are based on the concept of sum of squared differences used in the calculation of ANOVA and others are forms of the F statistic. Two of these types of stopping rules are the Variance Ratio Criterion (VRC) developed by Calinski and Harabasz (1974) (also known as the *pseudo-F statistic*) and the R

Ratio of Chen and Shiavi (1990). These ratios can be calculated for both the hierarchical and non-hierarchical clustering methods, as there is a direct relationship between the Euclidean distance matrices used in the calculation of clusters in the hierarchical methods, and the distance from cluster centroids used in non-hierarchical procedures. Other stopping rules that will be considered, not based on the sum of squares criteria, include the C-Index (Hubert and Levin, 1976) and Point Biserial correlation (Jobson, 1992).

Apart from the R Ratio value (which was developed after publication of Milligan and Cooper, 1985), the other stopping rules were demonstrated by Milligan and Cooper (1985) to be in the top 10 best stopping rules (out of 30) for indicating the correct number of clusters in a data set with known cluster groupings. However, it should be noted that the Point Biserial correlation has a tendency to underestimate the number of clusters (Milligan and Cooper, 1985).

2.4.2.1 Variance Ratio Criterion

Cluster analysis is based on the grouping of like items or in the case of the present study, putts. Using the concept that,

$$\text{Total sum of squares (TSS)} = \text{Within Group sum of squares (WGSS)} + \text{Between Group sum of squares (BGSS)} \qquad (1)$$

and that for all cluster combinations, total sum of squares is constant, the Euclidean distance between subjects is used as the basis for the calculation of all sum of squares parameters. Thus,

$$TSS = \frac{1}{2}(n-1)\overline{d^2}$$

(2)

where $\overline{d^2}$ is the overall mean of all n(n-1)/2 squared distances in the dissimilarity matrix consisting of all items. When the items are divided into their respective clusters, within group sum of squares can be calculated using:

$$WGSS = \frac{1}{2}\left((n_1 - 1)\overline{d}_1^2 + (n_2 - 1)\overline{d}_2^2 + \ldots. + (n_k - 1)\overline{d}_k^2\right)$$

(3)

where $\overline{d}_{1,2\ldots k}^2$ is the mean squared distance within each cluster and *n* represents the number of items within each cluster. Given (1) above, BGSS can simply be calculated by the subtraction of WGSS from TSS.

Calinski and Harabasz (1974) thus devised the following stopping rule:

$$VRC = \frac{BGSS}{k-1} / \frac{WGSS}{n-k}$$

(4)

where *k* is the number of clusters and *n* the number of items. The VRC examines the relationship between a minimum WGSS at each clustering stage, and the maximum BGSS at the same stage. Whilst the BGSS will naturally increase as k increases, and minimum WGSS will decrease, marked changes in the ratio between the two measures is reflected by an increase in the VRC. Calinski and Harabasz recommend choosing the highest VRC value, or the place where there is a comparatively rapid increase.

Importantly, this rule can also be adapted to the (non-hierarchical) k-cluster method. The output of this method in SPSS version 12 software is the distance of each item from the cluster centre. Calinski and Harabasz state that "…the dispersion of a group of n points is measured by the sum of the squared distances of the points from their centroid." (p. 8). This provides the WGSS part of the equation. Gower (1967) provides the between group sum of squares by illustrating that the sum of squares of distances between two data sets X and Y with n and m members respectively is given by

$$(nm/N)\sum_{i=1}^{n}(\bar{x}_i - \bar{y}_i)^2 \tag{5}$$

Where n + m = N, $\bar{x}_i$ is the centroid of set X and $\bar{y}_i$ is the centroid of set Y. Taking this formula and the output from SPSS to create a WGSS value for the VRC calculation, it is necessary where there are more than two clusters, to calculate the distance between each pair of clusters separately (this data is also provided by SPSS output) and the sum of all between group sum of squares provides an overall between groups sum of squares value.

In a 1985 study that assessed the ability of 30 stopping rules to correctly identify the optimal number of clusters in a data set with a known number of cluster solutions, the VRC was rated as the best stopping rule (Milligan and Cooper, 1985).

2.4.2.2 R Ratio

Milligan and Cooper (1985) recommend the use of a number of stopping rules to help the researcher make a final decision on the number of clusters in a set of data. Whilst the majority of rules (3 of 4) used in the present study will be those rated by Milligan and Cooper, it also seems appropriate to assess the suitability of at least one rule that has been developed in the time since Milligan and Cooper's paper. For this reason, the R Ratio rule (Chen and Shiavi, 1990) will also be used.

This rule uses similar parameters to the VRC to calculate a measure of the reduction of within group variability between consecutive cluster solutions. Thus,

$$R = \left[\frac{e(N,K)}{e(N,K+1)} - 1 \right] (N - K + 1) \tag{6}$$

where e(N,K) is defined as the WGSS component for N items and K clusters. The authors recommend that the solution is optimal where the R Ratio is largest, this demonstrating homogeneity within clusters. The R Ratio can also be adapted for use with the k-cluster output data from SPSS as it takes the same WGSS values in the VRC calculations.

2.4.2.3 C Index

The C-Index developed by Hubert and Levin (1976) uses Euclidean distance dissimilarity data to determine a measure of the "tightness" of data within clusters.

$$C - Index = \left[\frac{d_w - \min(d_w)}{\max(d_w) - \min(d_w)} \right] \tag{7}$$

Where the initial d_w value is the total sum of all within-cluster distances, and the other d_w terms relate specifically to a group with the smallest within-group distance ($\min(d_w)$) and the group with the largest within-group distances ($\max(d_w)$). With this index, the lower the value the better for determining the optimal cluster solution. This index was ranked third by Milligan and Cooper (1985) for correctly identifying the optimal cluster number. As this index relies on dissimilarity data, it is not possible to calculate for the k-cluster solutions, so will be used as a guide in the overall solution based entirely on the hierarchical solution.

2.4.2.4 Point Biserial correlation

The correlation type measures of cluster quality (that is, stopping rules), are based on the comparison of the original proximity matrix (using Euclidean distance) and the cluster group location of each item at each level of the agglomerative process. At each step in the agglomerative method, it is possible to determine whether items that are in the same cluster grouping are more closely related than items that are in different clusters. Thus pairs of objects are described as *within pairs* if both items are in the same cluster, or *between pairs* if the items are in different cluster groups (Jobson, 1992).

The correlation can be determined using the expression:

$$r_b = \left(\bar{d}_b - \bar{d}_w\right)\left(n_b n_w / n_d^2\right)^{1/2} / s_d \tag{8}$$

where *b* and *w* correspond to groups of pairs between (*b*) and within (*w*). The means of the original proximities for the two groups are coded $\bar{d}_b$ and $\bar{d}_w$, the number of pairs in each group n_b and $n_{w.}$

The total number of pairs $n(n-1)/2 = (n_b + n_w)$ is denoted by n_d and the standard deviation of the original proximities is denoted by s_d. A high correlation value indicates that the pairs in different clusters are relatively dissimilar, and the pairs in the same clusters are relatively similar.

Whilst this index was evaluated by Milligan and Cooper (1985) to be ranked number seven of all stopping rules used within the study, the authors did indicate a tendency for this index to underestimate the number of clusters. Given this information, and the suggestion by other authors that indices should be assessed by investigating changes in trends or slopes as much as the value itself (Calinski and Harabasz, 1974), all of the proposed stopping rules will be applied in the present study to determine an optimal solution that satisfies most criteria, but also provides a clear biomechanical delineation of the groups.

3 Aims

3.1 General aims

3.1.1 To analyse and assess putting performance of experienced golfers on two putting tasks in a realistic golf setting by

- Measurement of putt result
- Analysis of the putter head kinematics
- Analysis of the movement of the centre of pressure

3.1.2 To provide biofeedback on the location of the COP to a group of players in order to teach them to maintain a stable COP position whilst putting. To retest these players and compare their putting performance, putter head kinematics and COP data against their initial trial data.

3.2 Specific aims

3.2.1 Identify different putting techniques used by experienced golfers

3.2.2 Identify the relationship between handicap and putting performance

3.2.3 Develop a portable and reliable field-based system for assessment of centre of pressure movement during the putting task

3.2.4 Identify the relationship between putting performance and movement of the centre of pressure

3.2.5 Assess the effect of a 3 week balance biofeedback training program on subsequent putting performance and centre of pressure movement during the putting task.

3.2.6 Identify the relationship between putting performance and putting stroke kinematics

3.3 Novelty

This study is novel in that there has been:

- No reported analysis of putting mechanics in a field-based setting
- No reported assessment of a large sample size whilst performing repeated putting tasks.
- No reported assessment of the centre of pressure in a field-based setting for golf or any other sporting activity.
- No reported use of balance biofeedback training in golf
- No reported use of cluster analysis processes to determine if different putting techniques or styles exist

4 Methodology I – Pilot studies

In order to achieve the aims of the study, the first step in this project was to establish whether differences in putting kinematics and COP data exist between golfers of different skill levels when testing in the laboratory setting. As the second step in the process, the validity of a field based testing system needed to be established to enable the ultimate collection of in-field data. This included the validation of a novel system for measuring COP in the field, and the use of appropriate video technology for the simultaneous and synchronized collection of video footage. This chapter sets out the lab based procedures used in this validation.

4.1 Pilot study I – putting data

A pilot study was conducted to develop testing procedures and determine sample size requirements for a larger study on putting, and also provide an indication of the relationship between handicap and putting performance. This first phase of testing was conducted indoors at the Biomechanics Laboratory of Victoria University. Participants were students and staff at Victoria University. All participants signed consent forms prior to participation.

Subjects (n=7, 3 skilled with handicaps 2-14, 4 less skilled novices) were required to putt whilst standing on an AMTI force plate measuring 120cm x 60cm (Advanced Medical Technology Instruments, Amherst, MT, USA). A Redlake video camera (Redlake, Arizona, USA) was located 4m from, and perpendicular to, the plane of the putt. This produced a field of view of approximately 1m which is relatively small but suitable for this activity as only movement of the putter head was of interest. Data collection occurred using standard 2D video techniques (Bartlett, 1997). The Redlake camera was synchronized through an AMTI software project (AMTI Technologies, NSW, Australia) with the force plate data. The force plate data were sampled at 500Hz and a video frame was collected at every second sample (250Hz). Ball contact was recorded as a separate channel in the AMTI project using a microphone connected to a PEAK event synchronization unit (PEAK Performance Technologies, Colorado, USA).

Subjects putted at two circles marked on the floor of the laboratory to represent holes – one at 4.2m and the second at 8.4m. The subjects were required to putt the ball at the “hole”, but not required to stop the ball on the “hole”. If the ball passed through the centre of the “hole” it was classified as a “holed putt” providing it stopped within 42cm past the centre of the hole. This value was used based on the recommendation from Pelz (2000) that a putt struck with sufficient velocity to enter the hole should finish within 17 inches of the hole if it misses. The surface of the laboratory floor was considered suitable for the testing as it is a carpeted surface, low in friction and relatively flat. Although no stimpmeter readings were taken to measure the speed of the surface, the experienced subjects felt that it closely replicated a fast putting surface. The testing protocol required the subject to walk up to and mark the location of the ball after each of five putts at each of the two holes. This was to ensure that the subject did not stay in a fixed standing position during data collection and ensured that each putt was slightly different in terms of the players' initial position. Players were allowed a number of practice putts prior to the start of testing to familiarize themselves with the putting task and the procedure employed to record video and force plate data. These putts were from the same position and over the same distance as the putting tasks. The distance each putt finished from the hole and a general description of its location (left, right, and centre) was also recorded. In all, 44 putts at the 4.2m hole were analysed and 27 putts at the 8.2m hole.

Redlake video was downloaded to PEAK Motus software for analysis. A 1 metre scaling rod was earlier filmed within the field of view to allow scaling of the data. Reflective tape placed on the toe of the putter head was used to automatically digitize putter head movement. Event data depicting start of backswing, start of downswing and ball contact was included manually (detailed below). Raw data were subsequently filtered using the Jackson Knee optimisation method contained within the PEAK software, and putter head displacement and velocity data calculated. For no trial was the cut off frequency greater than 5Hz.

The AMTI software module calculated the COPx and COPy co-ordinates from the force plate data. These were downloaded into Microsoft Excel format (Microsoft 2000, USA). Synchronisation with the video data allowed the precise location of the start and end of the putting task to be identified, and COP analysis was confined to the time during movement of the club head.

All putt results, including kinematic and kinetic data, were included for group analysis. Each putt was treated as an individual trial, with no individual means calculated. T-test and Cohen's *d* for independent groups were calculated to assess between group differences, with a greater emphasis on effect size in order to calculate subject and putt number size required for subsequent studies. Where unequal variances were present between groups, appropriate adjustments were made to reflect the non-parametric nature of the data. No kinetic data were smoothed at this stage of the project. The number of putts analysed for each parameter was affected by some minor technical problems. For example, there is a putt result for each trial but on occasion there was no force plate data collected because the force platform did not trigger at the correct time.

4.1.1 Results

In order for analysis of the putting task to be completed, the stroke was broken down into phases based on specific temporal events. Thus, two events were used to define each of three distinct phases:

Phase 1 - Backswing

- Frame prior to first movement of the putter away from the ball from the address position

- Frame prior to first movement of the putter back toward the ball in order to strike it

These two events defined the backswing and are depicted by Figures 4.1.1.1a and b.

Phase 2 - Downswing

- Frame prior to first movement of the putter back toward the ball in order to strike it
- Frame prior to point of contact between the putter head and the ball

These two events defined the downswing and are depicted by Figures 4.1.1.1b and c.

Phase 3 – Follow through

- Frame prior to point of contact between the putter head and the ball
- Most distal horizontal displacement of the putter head after it had made contact with the ball

These two events defined the follow through and are depicted by Figure 4.1.1.1c and d.

Figure 4.1.1.1a-d: Events in the putting stroke: (a) start of backswing; (b) start of downswing; (c) ball contact; (d) end of follow through. These images taken from lab based pilot testing.

The putt results indicate that both groups (on average) hit the ball past the hole 79% of the time. The skilled group mean data indicated they were able to leave the ball closer to the hole than the less skilled for both putt lengths, though there were no significant differences between the groups for the putting task (Table 4.1.1.1), suggesting that at this early stage of the study, skill level – as defined by handicap - is not a distinguishing feature of putting performance.

Using Cohen's conventions, effect sizes up to 0.5 are considered small, between 0.51 and 0.8 are considered medium, and greater than 0.8 considered large. Effect size data indicated small effects present for this parameter for this group of participants.

Table 4.1.1.1: Mean (SD) putt result data by putt length and group (S = skilled group, L = less skilled group, p = significance of independent t-test, d = effect size).

	Distance past the hole (cm)			
	S (n=14)	**L (n=30)**	***p***	***d***
4.2m putts	70 (71)	87 (96)	0.56	0.19
	S (n=14)	**L (n=13)**	***p***	***d***
8.4m putts	56 (105)	75 (179)	0.74	0.13

For temporal analysis, the skill was broken into backswing (BS) and downswing (DS) phases using the events depicted earlier. This data is presented in Table 4.1.1.2. It was not possible to assess follow through due to the variety of techniques employed in the novice group as some players did not have a definable end point in their technique.

Table 4.1.1.2: Mean (SD) timing data by putt length and group (S = skilled group, L = less skilled group, p = significance of t-test, d = effect size).

	Phase time (ms)			
4.2m putts	**S (n=14)**	**L (n=30)**	***p***	***d***
Backswing	662 (113)	684 (83)	0.53	0.23
Downswing	307 (15)	336 (78)	0.05	0.44
8.4m putts	**S (n=14)**	**L (n=14)**	***p***	***d***
Backswing	700 (90)	743 (110)	0.27	0.42
Downswing	322 (16)	381 (56)	<0.01	1.17
Combined	***All 4.2m (n=44)***	***All 8.4m (n=28)***	***p***	***d***
Backswing	*677 (93)*	722 (101)	0.09	0.45
Downswing	*327 (66)*	352 (50)	0.76	0.08

Temporal data indicates that the less skilled group took a significantly longer time to complete the downswing phase for both putting tasks, although the small effect for the 4.2m putting task indicates that the magnitude of the difference is not as large as that indicated for the 8.4m putting task. A similar trend occurred for the timing of the backswing.

The temporal data also suggest some similarity between the downswing phases for the skilled group for the different length putts. Based on the literature published by Delay et al. (1997) who suggested a fixed movement time in the downswing phase, further analysis was conducted to detect whether non significant differences were preset for this parameter between the putting tasks. Parametric analysis indicated that for the present sample there was in fact a significant difference between the downswing times for the skilled players between putting tasks (t_{16}=3.44, p=0.003, d=0.83). This significant difference in downswing lengths for the different putts was not present when all data were combined and differences in the phase times for both putting tasks were calculated (p=0.76, d=0.08). The large variability in the less skilled group's timing data attributing to this lack of significance.

Putter head displacement (range) was measured only in the horizontal plane in line with the path of the club head (Table 4.1.1.3). A significant difference was evident in the backswing and downswing length between groups for the shorter putts. Medium to large effect sizes were determined for these parameters also. Non-significant differences with small to medium effect sizes were reported for putter head displacement data on the longer putts. Significant differences were present when comparing the combined group data for backswing length and downswing length across putts. Logically players used a significantly longer backswing (p=0.00, d=1.04) and downswing (p=0.00, d=0.87) on the 8.4m putts than on the 4.2m putts.

Table 4.1.1.3: Mean (SD) putter head displacement for backswing and downswing phases.

	Displacement (cm)			
4.2m putts	**S (n=14)**	**L (n=28)**	***p***	***d***
Backswing	18.8 (2.1)	22.0 (6.2)	0.02	0.60
Downswing	19.9 (2.4)	24.6 (5.9)	<0.01	0.86
8.4m putts	**S (n=14)**	**L (n=8)**	***P***	***d***
Backswing	26.2 (2.7)	28.3 (6.4)	0.39	0.48
Downswing	26.9 (3.0)	30.6 (7.9)	0.24	0.68
Combined	***All 4.2m (n=42)***	***All 8.4m (n=22)***	**P**	***d***
Backswing	20.9 (5.4)	27.0 (4.4)	<0.01	1.04
Downswing	23.1 (5.5)	28.3 (5.4)	<0.01	0.87

It is also important to point out to the reader that it is possible to have a longer downswing than backswing. This is because the golfer does not necessarily place the putter head right next to the ball in the address position. There is no rule that states that the club must start within a certain distance of the ball at the address position. Thus, if the player chooses to start the backswing with the putter head placed 5cm away from the ball, there will be a 5cm difference in the length of the backswing when compared to the downswing.

Table 4.1.1.4 presents putter head velocity at instant of ball contact. At a sample rate of 250Hz there is a visible effect of impact on the velocity data in the unfiltered data. But with this task, noisy data, the variability in the timing of maximum putter head velocity and the comparatively slow moving implement also played a role in determining how to manage this effect. As demonstrated in Figures 4.1.1.2a-c it is possible for the velocity curve to indicate a maximum value; (a) post impact, (b) at impact, or (c) pre impact. These graphs are a sample of 50 frames either side of impact for three different trials with the filtered and unfiltered velocity$_{x,y}$ data v time presented. In summary, the filtered velocity values one frame prior to impact were used in this section of the analysis.

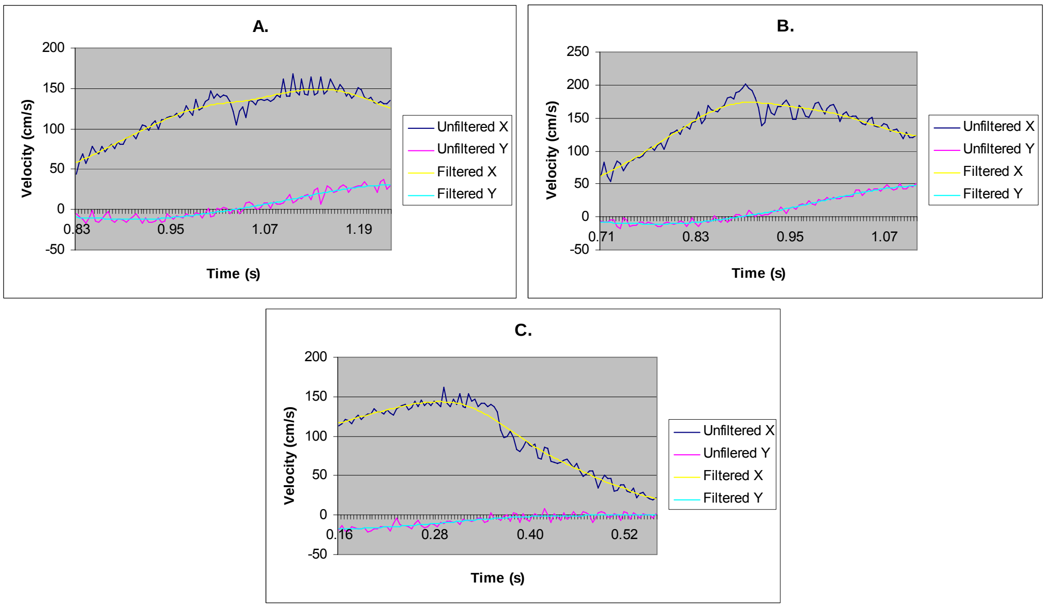


Figure 4.1.1.2a-c: Three examples of putter head velocity profile depicting different locations of maximum velocity relative to ball impact. Data details 50 frames either side of ball impact (sample rate 250Hz).

The smaller standard deviation values for the skilled golfers in both tasks indicate the homogeneity of this group of players. Based on these values, it would be assumed that the distance from the hole data would reflect the tendency for the less skilled group to strike the ball with greater velocity. This was not the case however, and may be explained in part by the variability in sweetness of strike. As Pelz (2000) and Hurrion et al. (n.d.) have indicated, the nature of contact between the ball and the clubface plays a role in determining the impulse momentum imparted to the ball. Hurrion et al. presented data that indicated a twisting moment is created in the putter head when the ball makes contact off centre or off the sweet spot, limiting the impulse imparted to the ball, and deviating the ball slightly from the line of the putter path. It is beyond the scope of the present study to investigate this aspect of the putting stroke at this time.

Table 4.1.1.4: Mean (SD) putter head velocity data at ball contact.

	Velocity (cm/s)			
4.2m putts	**S (n=14)**	**L (n=28)**	***P***	***d***
	106.3 (10.4)	126.0 (18.5)	<0.01	1.05
8.4m putts	**S (n=14)**	**L (n=13)**	***P***	***d***
	146.9 (16.6)	161.9 (26.5)	0.09	0.66
Combined	**All 4.2m (n=42)**	**All 8.4m (n=27)**	**P**	**d**
	119.8 (18.7)	154.1 (22.7)	<0.01	1.31

Other factors that may also play a role in clouding the relationship between horizontal putter head velocity at impact and the distance the ball travels may include putter type and style and tightness of grip of the player on the putter. However, these factors will not be analysed in the larger study, but each player will be allowed to strike the ball with their own putter. This will help to limit the effect of the type of putter (because each player will be familiar with their own) and grip (as it will be assumed that each player has developed the best combination for them of grip type and grip strength). A final factor, the vertical velocity of the putter head at ball contact may also influence these data, as the ball struck with downward putter head velocity will tend to be pushed into the putting surface. This would limit the transfer of impulse to the ball and result in a diminished ball velocity post impact.

The other consideration in this data is the relationship between the backswing/downswing length and club head velocity at ball contact. These data indicate the increase in club head path length with increased putt distance, and subsequent increased club head velocity at ball contact. Correlation data for both short (r=0.54, p=0.00) and long putts (r=0.568, p=0.01) suggest a significant positive relationship between backswing length and putter head velocity at contact for this group of players.

Movement range of the COP was measured in both the medio-lateral (COPx) and antero-posterior (COPy) directions and reflects total COP range (peak-to-peak amplitude) during the putt. The COPx vs. COPy data were plotted to verify the quality of the data, and an example of one novice player's output is given below (Figure 4.1.1.3). The data taken from each of these force plate outputs were averaged and presented according to group in table 4.1.1.5.

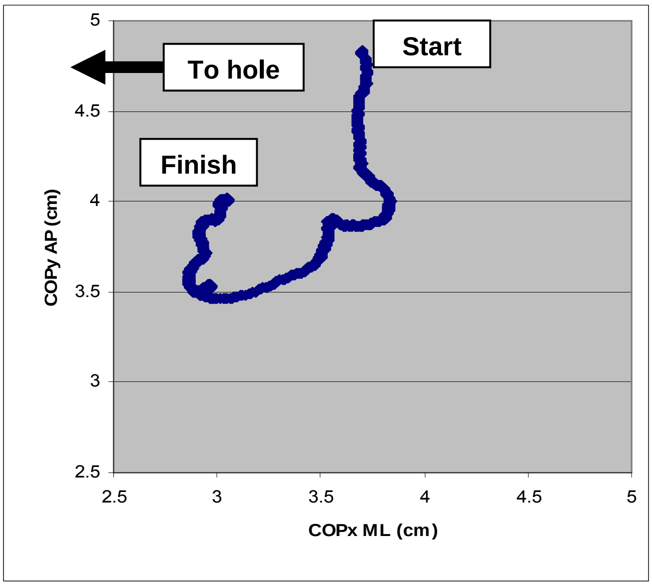


Figure 4.1.1.3: Example output of COPx v COPy from AMTI force plate for one putting trial at 4.2m distance (COPx range 0.98cm, COPy range 1.22cm) (Novice player).

Table 4.1.1.5: COP peak-to-peak amplitudes during the putting stroke.

	Peak-to-peak amplitude (mm)			
4.2m putts	**S (n=14)**	**L (n=30)**	***P***	***d***
COPx 4.2m	15.8 (6.8)	35.2 (13.8)	0.00	1.29
COPy 4.2m	12.5 (5.2)	18.7 (7.7)	0.00	0.83
8.4m putts	**S (n=14)**	**L (n=13)**	***p***	***d***
COPx 8.4m	20.6 (10.8)	30.9 (12.3)	0.03	0.82
COPy 8.4m	11.7 (4.6)	21.1 (11)	0.01	1.00

These data indicate significant differences between the groups for all measures in Table 4.1.1.4 and the possibility that control of the amplitude of movement of the COP is a distinguishing factor by skill level within this group of subjects. Large effect sizes verify these differences. These findings alone warrant further investigation of the role of balance in putting.

COP velocity data show the skilled performers have not only significantly less COP movement (in antero-posterior and medio-lateral directions; table 4.1.1.5) but also significantly slower COP movements at ball contact than the less skilled golfers (table 4.1.1.6). The latter could be another important discriminating parameter between skill levels in putting.

Table 4.1.1.6: Mean (SD) COPx velocity at ball contact and the absolute maximum COPx velocity during the putt.

	Velocity (mm/s)			
4.2m putts	**S (n=14)**	**L (n=30)**	***p***	***d***
Ball contact	-5.3 (16.1)	56.1 (50.5)	0.00	1.2
Maximum	38.8 (8.3)	88.3 (30.3)	0.00	1.44
8.4m putts	**S (n=14)**	**L (n=12)**	***p***	***d***
Ball contact	6.2 (19.2)	30.5 (49.3)	0.13	0.65
Maximum	35.7 (13.3)	96.7 (37.9)	0.00	1.43

Analysis based on skill level reveals a homogenous COPx velocity profile for the skilled golfer reflected by low mean intra-individual standard deviation values for COPx velocity at ball contact (table 4.1.1.7). The skilled golfers demonstrated the ability to bring the magnitude of COPx velocity closer to zero at ball contact compared to the less skilled golfer. Though this is not significant for the longer putts, the medium and large effect sizes reported for this parameter indicate that a higher N (putts x subjects) may be required to prove this point.

Table 4.1.1.7: Mean of intra-individual SD values for COPx velocity at ball contact.

	SD (cm/s)			
	S (n=3)	**L (n=4)**	***p***	***d***
4.2m putts	0.52	2.53	0.02	1.5
8.4m putts	0.81	2.13	0.01	1.7

Based on the data calculated above, sample size calculations were completed. The rationale was that the parameters of most interest were those associated with movement of the COP during the putting stroke. Known data on COP displacement during the putting stroke was sourced from McCarty (2002) and the present pilot study. The main part of the present study intends to break the playing group into three distinct groupings (k=3) based on handicap (0-9, 10-18 and 19-27).

The known effect size data is based on two distinct (k=2) groupings only (skilled vs. less skilled or novice). In order to convert these effect size data used in t-test analysis (d) to effect size measures (f) used for ANOVA analysis (k>2), it is necessary to convert using formulae provided by Cohen (1988). The other assumption made in this calculation is that there will be an even spread of group means between the k=3 groupings. Thus, converting **d** to **f** requires the following calculation:

$$f = \frac{d}{2}\sqrt{\frac{k+1}{3(k-1)}}$$

That is, given k=3 and an even spread of means between the three groups:

$$f = 0.408d$$

The table below (4.1.1.8) contains the calculated effect size values from McCarty (2002) and the present pilot study for putts in the range of 4m and 8m on COPx,y displacement data with the calculated f value based on the above formula, and the required number of putts in each group to achieve 80% power given these data and an alpha value of 0.05 using power tables in Cohen (1988; p.313).

Table 4.1.1.8: Sample size calculations for 80% power, k=3, p=0.05.

Source	**d**	**f**	**n**
McCarty (2002) 4m putts COPx displacement in backswing 4m putts	0.87	0.357	27
McLaughlin pilot study COPx displacement in backswing 4.2m putts	1.29	0.526	14
McLaughlin pilot study COPx displacement in backswing 8.4m putts	0.83	0.340	27
McLaughlin pilot study COPy displacement in downswing 4.2m putts	0.82	0.335	27
McLaughlin pilot study COPy displacement in downswing 8.4m putts	1.00	0.408	21

Thus a minimum of 27 trials in each group will be required to achieve a power level of 80%. This analysis is based on data from novice vs. skilled golfers. As a result, the effect size expected in in-field testing using experienced golfers of varying handicap levels will be somewhat less but to an unknown degree. It is possible, as previous research has shown that there is in fact no difference in putting performance between players of different handicap levels. Therefore alternative methods of grouping players, such as cluster analysis, will also be used in the major part of this study.

4.2 Pilot study II – testing of portable system

A pilot study was designed to assess the pliance® mat (novel $_{gmbh}$, Munich, Germany) as a suitable tool for the measurement of the COP in a field setting.

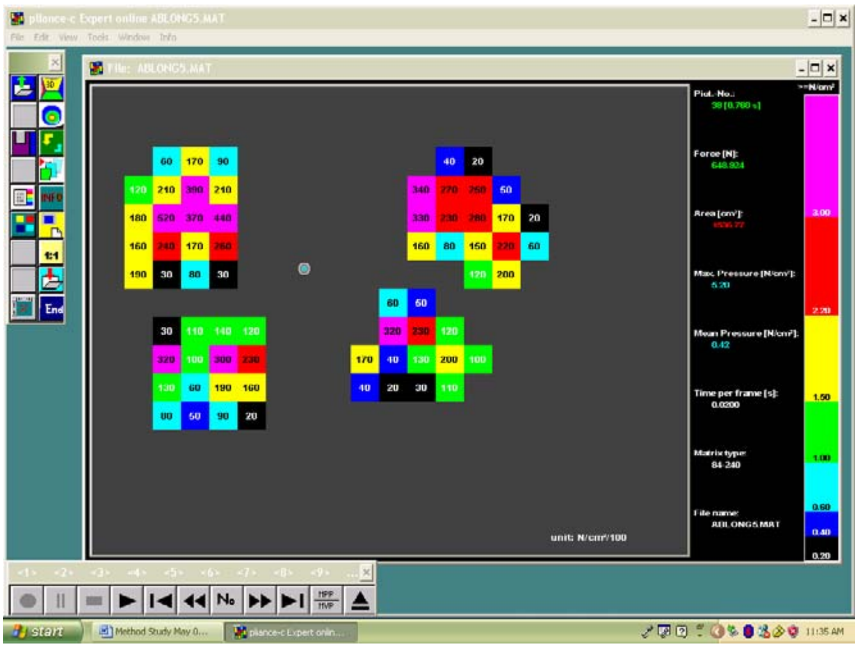
The COP output from a novel pliance® mat was compared to the COP output from an AMTI force platform located in the Biomechanics Laboratory at Victoria University. To achieve this direct comparison, the pliance® mat was placed over the top of the AMTI force plate and data collected simultaneously from both systems whilst participants stood quietly (erect posture) or moved (golf putting) according to the requirements of a putting stroke. Participants were students and staff at Victoria University. All participants signed consent forms prior to participation.

Data from the AMTI force plate were recorded through an AMTI system that provided COP*x,y* co-ordinates, whilst the pliance® mat data were recorded on a separate PC running novel pliance® 8.3-C software. COP*x,y* co-ordinates from both systems were calculated after the files were converted to ASCII format and analysed in MS Excel. Data on maximal excursion (peak-to-peak amplitude) of COP*x,y* during all trials were then calculated and assessed for equality using the non-central *F* distribution via The R Foundation for Statistical Computing Version 1.9.0 software package.

4.2.1 Pliance® mat

The pliance® mat is a rubber mat containing a 16 x 16 matrix of capacitive pressure sensors in an area of 392 x 392 mm. This combination of sensors and area provides a resolution of $6cm^2$ per sensor. The hardwired limit on sample rate was 10,000 samples per second. With all sensors activated this provided one sample each 26ms (approx 38.5Hz).

The pliance® mat was initially developed as a tool for the measurement of seated pressure. Its rubber composition allows it to conform to the three-dimensional curves of a variety of different surfaces. Most commonly this type of mat is used in the research and design of seats for the automotive and air transport industries. As such, the system used in the present study was not designed specifically for the assessment of COP in standing posture, but as its basic configuration allows the dynamic calculation of the COP based on surface area contact, it was surmised that it was possible for this system to collect COP data from a standing subject. The central image in Figure 4.2.1 depicts the output from the pliance® software for a putting trial – the left and right feet represented by the coloured squares with the COP location in between the feet (the solid circle). The heel of each foot is towards the bottom of the image.



Pict. No.:
38 [0.760 s]

Force [N]:
648.924

Area [cm²]:
[illegible]

Max. Pressure [N/cm²]:
5.20

Mean Pressure [N/cm²]:
0.42

Time per frame [s]:
0.0200

Matrix type:
84-240

File name:
ABLONG5.MAT

Figure 4.2.1: Example of pliance® 8.3 software screen output.

As opposed to testing of seated posture, the testing of upright posture in this study was conducted on a flat, level surface. For the purpose of this study, the pliance® mat was placed over the top of the AMTI force plate. The edges of the mat were taped down with Micropore tape (3M, USA). To ensure consistent placement of the mat on the plate between testing days, the outside edges were traced onto the surface of the plate. Figure 4.2.2 shows the pliance® mat located on the top of the AMTI force plate and connected to the pliance®-M analyser box.

Figure 4.2.2: Photograph of the pliance® pressure mat placed over the top of the AMTI force plate.

4.2.2 AMTI force plate

The AMTI force plate is a strain gauge force plate with dimensions of 120cm x 60cm mounted into the floor of the Biomechanics Laboratory at Victoria University. Data were sampled at 500Hz using a specially developed AMTI module. The AMTI interface also co-coordinated the collection of various analog signals including an output pulse from the pliance® system when it started to record. This provided the method for synchronisation of the two systems.

The AMTI system automatically saved data files in chronological order. Redlake video data was also recorded in trials where the subjects hit golf putts. A number of COP measurement trials of static and dynamic standing posture were also recorded as a further means of verification of the pliance® mat, but no video was collected of these trials. The output from the AMTI system produced time coded *Fx,y,z* data, *COPx,y* data, ball contact event data in putting trials and pliance® "start recording" event data for all trials.

For all trials, the *COPx,y* range data were calculated for both force plate and pliance® mat output. This was for the time from start of backswing to time of end of follow of through in putting. In the non-putting trials, the time from pliance® "start recording" to pliance® "end recording" was used and *COPx,y* co-ordinates calculated from each system. The time between pliance® start recording and end recording was approximately 5 seconds in total but varied depending on the time each player took to strike the ball.

All raw data from both systems were then filtered using a low pass digital filter at 5Hz (explained in further detail in section 4.2.4.1). From the matched data files (matched for length of time of pliance® data collection) the maximum and minimum COPx and COPy values were obtained and COPx range and COPy range data calculated from both systems. Absolute error was recorded as the difference between the range value calculated from the AMTI system and the range value calculated from the pliance® system – using the AMTI platform as the standard. Relative error for COPx,y was calculated as the difference between the two systems divided by the AMTI range value. These eight parameters (COPx range for pliance® and AMTI, COPy range for pliance® and AMTI, absolute error in COPx,y and relative error in COPx,y) were determined for each trial and then the mean and standard deviation values calculated prior to analysis.

4.2.3 Test of equality – non central F distribution

The aim of this pilot study was to, hopefully, demonstrate the equality of the output from the two systems. The statistical technique employed was based on a test for significant equality as described by Londeree, Speckman and Clapp (1990). These authors suggested that rather than ensuring that data were not significantly different (e.g. T-test, ANOVA) or significantly related (eg. Correlation co-efficient), a more stringent test was to determine if data were significantly equal. In this present study, it was expected that the output from the two systems would pass a test of being not significantly different, and would also pass a test of being significantly related, using conventional methods. However, the more stringent assessment using the test of equality was required to validate the pliance® system output and indicates that the system was able to provide accurate COP data when used in the field.

The test of equality relies on the adaptation of the F distribution commonly used in ANOVA techniques, and requires the selection of a minimum practical difference for the calculation of what is effectively a grouped data effect size score (d);

$$d = \frac{\left|\text{Practical difference}\right|}{\sigma\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}}$$

Where the practical difference (PD) is a value representing the minimum acceptable difference between the outcome measures for the two systems, σ is the combined or grand standard deviation of the data from both systems and n_1 and n_2 are the number of samples measured in each group.

From d, a noncentrality parameter, ϕ, is then calculated and used in the calculation of significance;

$$\phi = \frac{d}{\sqrt{2}}$$

The practical difference between the two systems was calculated as 5% of the grand mean – this was considered an acceptable amount of error in the pliance® system and equates to 0.51mm of error in the COP medio-lateral (COPx) peak-to-peak amplitude value, and 0.64m of error in the COP antero-posterior (COPy) directions. The grand mean value was calculated from the data collected in this part of the pilot study (n=19 trials).

The noncentrality parameter (ϕ) was calculated in MS Excel. The R Foundation for Statistical Computing Version 1.9.0 software package calculated the significance level of the calculated F value based on,

- the *F* score (1st value in sequence below)
- degrees of freedom (group and error) (2nd and 3rd values in sequence below)
- noncentrality parameter (4th value in sequence below)

One-way ANOVA using SPSS software was used to determine the F score for each parameter. An example of the syntax entered into the R software is detailed below. The notation **"pf"** is the syntax for calculation of probability of the *F* distribution in the R program. The significance of the data is calculated and listed immediately below the entered values (p=0.1815923 in this example).

```
> pf(0.088, 1, 161, 0.51246)
[1] 0.1815923
```

Where pf is the notation in the R software for the non-central F test, in brackets are the four values entered based on parameters listed above, and the calculated *p* value or output of the analysis next to the notation [1]**.**

4.2.4 Pilot study II results

The data used in this system testing study came from trials where subjects were in:

- Quiet standing with eyes open
- Putting a ball at a hole 4.2m away

A total of 19 trials were recorded and used in this stage of the project.

4.2.4.1 Spectral analysis and filtering

The raw data output for each trial for each system was initially graphed using MS Excel. The raw data output from each system was then assessed for signal content. This was completed to ensure that the lower sample rate of the pliance® system was not eliminating any signal content. Although postural sway studies have been published using sample rates down to 10Hz (Era & Heikkenen, 1985; Ekdahl et al., 1989), it was important to the reliability and validity of the study to be able to provide further proof of the quality of the output of the pliance® system. This exercise also proved valuable in determining the correct filtering frequency for all pliance® data collected in the future.

The data were processed for signal content using Sigview 32 Analysis application software v 1.9.1.0. This is a signal analysis package with filtering and analysis features based on the Fast Fourier Transform algorithm.

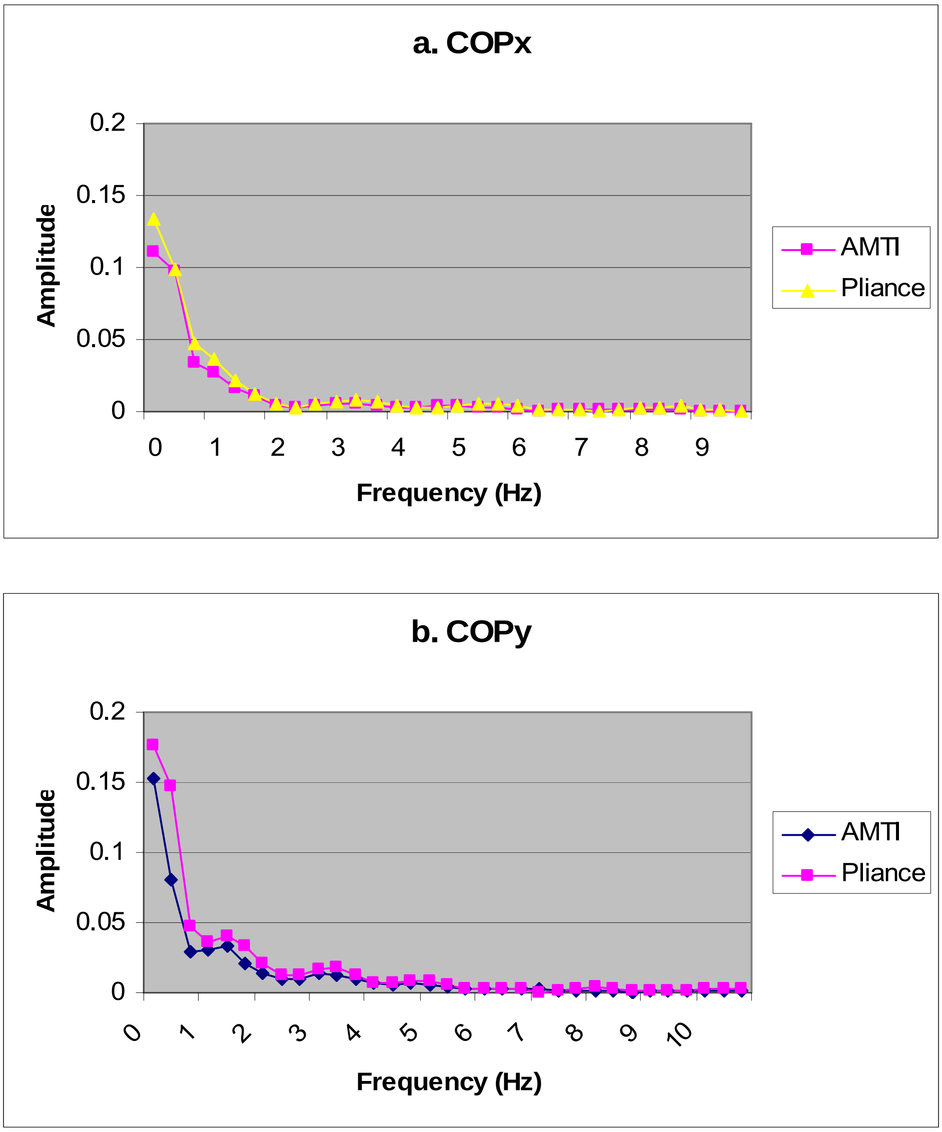
Output of the FFT process indicated that the majority of the COPx,y signal content (between 80-90%) fell in the region below 5Hz for both the pliance® and AMTI systems. This information was calculated by summing the ASCII output from the FFT. This sum was then used as the basis for percentage content calculations for each frequency step in the output. Assessment of the signal content for each 1Hz step (up to 10Hz) indicates small differences between the two systems (Table 4.2.4.1.1). Further analysis of the equality of the systems is discussed below.

Table 4.2.4.1.1: Example of frequency content breakdown for COPx,y for each system into 1Hz bins.

	COPx % signal content			**COPy % signal content**	
Hz	**Pliance®**	**AMTI**		**Pliance®**	**AMTI**
<1	58.9	58.1		51.4	66.9
1 to 2	14.7	16.5		15.4	14.1
2 to 3	3.9	6.5		8.5	3.2
3 to 4	3.8	6.1		5.1	3.9
4 to 5	2.7	3.6		3.2	2.9
5 to 6	2.3	1.9		1.9	2.0
6 to 7	0.9	1.4		0.5	0.7
7 to 8	2.2	0.7		1.4	1.1
8 to 9	1.0	0.5		0.8	0.6
9 to 10	0.8	0.5		1.5	0.3
<10	**90.2**	**95.8**		**89.7**	**95.7**

Figures 4.2.4.1.3a and b provide the FFT output from the same example trial. These graphs indicate that when the two systems are compared at the lower

frequencies, they are similar in their signal content. In Figure 4.2.4.1.3a, the COPx signal content from each system is compared, and in figure 4.2.4.1.3b the COPy signal content from each system is compared. The vertical axis indicates signal amplitude.



Figures 4.2.4.1.3a and b: FFT output of AMTI and pliance® COPx and COPy for trial putt4_1 data.

The shooting study of Ball et al. (2003) used a cut-off frequency of 4Hz when filtering COPx,y data from an AMTI platform, whilst McCarty (2002) used a 6Hz cut off frequency for filtering of force plate data in the only other putting study to have utilised this method of data collection. Using this as a guide, and combined with the results of the spectral analysis, it was decided that a cut-off level of 5Hz was appropriate when filtering the data from both the AMTI and pliance® systems, given the slightly more dynamic nature of golf putting compared to shooting, and the decision to take a slightly more conservative approach to filtering than McCarty (2002). Subsequently, both the AMTI and pliance® COPx,y co-ordinate data were filtered using a low pass digital filter set at 5Hz. The maximum and minimum values in COPx,y were then calculated for both systems and peak-to-peak amplitude calculated in each direction. (Graphical output for each trial and summary page of peak-to-peak amplitude data contained in Appendix A).

Figures 4.2.4.1.5a, b, c and d represent the output for one putting trial, with the COPx vs. COPy AMTI output on the left (a and c), and the COPx v COPy pliance® output on the right (b and d). The effect of the filtering protocol described above was to reduce the noise in the signal from both systems, but more noticeably from the pliance® system. The higher concentration of values in the left hand images represents the higher sample rate of the AMTI system.

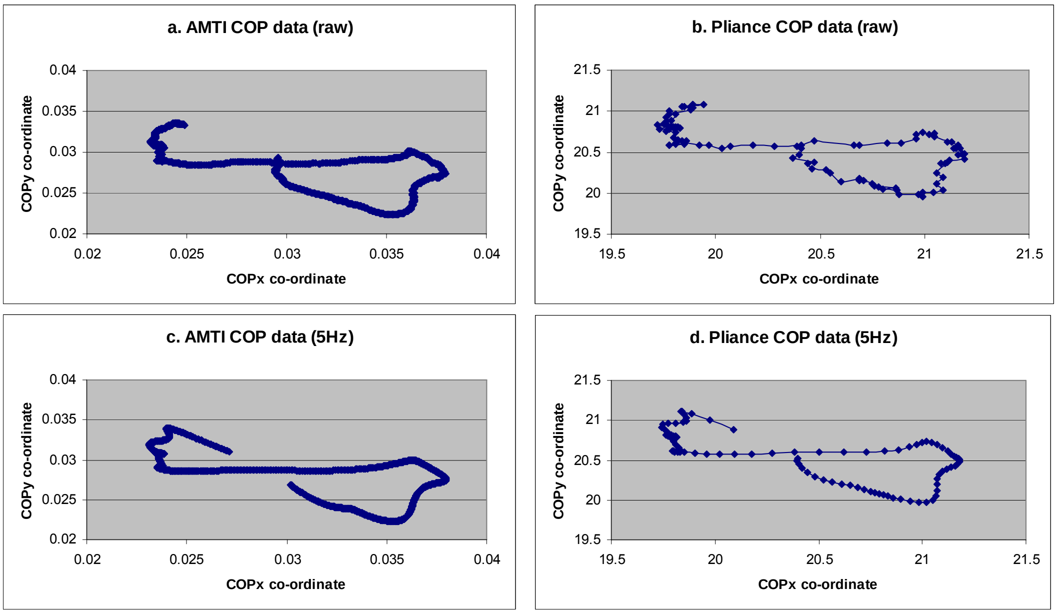


Figure 4.2.4.1.5a and b: Example COPx v COPy output for one putting trial:(a) AMTI raw; (b) pliance® raw; (c) AMTI filtered at 5Hz; (d) pliance® filtered at 5Hz.

4.2.4.2 Test of equality

Table 4.2.4.2.1 compares the mean COP range values (peak-to-peak amplitudes) for the two systems based on filtered data. These data were initially a part of a much larger group of trials where participants deliberately swayed, were required to lean to one side or to stand with eyes closed. It was felt that tests involving subjects performing different tasks, as well as quiet standing, was reflective of the future use of the system. However, different trial types created large standard deviation values which can distort the output of the test of equality. The trials with COPx,y amplitudes less than the mean values presented in the pilot study (COPx = 29.0±15.0mm; COPy 16.8±7.5mm) for 4.2mputts were used for final calculations.

Table 4.2.4.2.1: Descriptive data on all trials (n=19).

Combined data for all trials	***COPx pliance (mm)***	***COPx AMTI (mm)***		***COPy pliance (mm)***	***COPy AMTI (mm)***
Mean	10.2	10.3		12.7	12.8
SD	6.2	6.1		9.8	9.2

Table 4.2.4.2.2 expresses the data in terms of the averaged inter-trial differences between the two systems. These difference values are expressed in terms of mean exact error (in mm) and mean percentage error when using the AMTI output as the standard. These values use each trials difference data to calculate the overall difference mean values. These data indicate mean peak-to-peak amplitude differences of the magnitude of 0.07mm in the medio-lateral direction, and 0.11mm in the antero-posterior direction between the two systems.

Table 4.2.4.2.2: Error data (exact and relative) in each COP direction using AMTI data as standard on all trials (n=19).

Combined Error data for all trials	***COPx exact (mm)***	***COPx relative (%)***		***COPy exact (mm)***	***COPy relative (%)***
Mean	0.07	1.2		0.11	2.14
Stdev	0.32	2.4		0.81	3.8

Table 4.2.4.2.3 expresses the data involved in the calculation of significance of equality. The sample mean (M) and standard deviation (SD) values are presented along with the practical difference of 5% (PD), effect size (d), non-centrality parameter (ϕ), F score from one way ANOVA, and finally the significance of equality of the two datasets (p).

Table 4.2.4.2.3: Calculations to determine equality of pliance® and AMTI systems on all trials (df $_{1,36}$) after data filtered at 5Hz.

Statistical parameters	***M (mm)***	***SD (mm)***	***PD (mm)***	***d***	ϕ	***F calc***	***p***
COPx (ML)	10.24	6.06	0.51	0.26	0.18	0.001	0.023
COPy (AP)	12.75	9.37	0.64	0.21	0.15	0.001	0.023

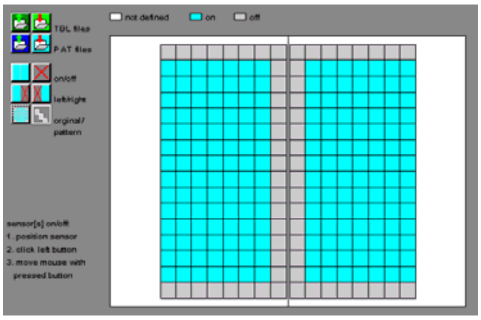
Analysis of the data revealed that COPx and y range data were statistically significantly equal at a practical difference level of 5%. The COP range data from the mat is equal to the AMTI plate at an acceptable level of tolerance.

4.2.4.2.3 Other practical changes arising from the pilot testing

Pilot testing indicated that some participants had a tendency to stand on the outer edges of the pliance® mat when putting or standing. That is, they would tend to stand with one foot over the edge of the sensor area of the mat, but within the limits of the entire mat area. This lead to problems with data collection for those particular trials, as for these participants it was unclear whether the entire foot was on or off the mat. This was not because the mat was too narrow, but because the edges of the mat were not clearly defined. In subsequent tests, it was important to clearly mark the outer edges of the mat and to verbally and physically ensure that participants did not stand on these edges (although this did not ensure 100% compliance from all participants).

It was also evident during pilot testing that two columns of sensors in the middle of the mat, and two rows at the front and back edges were not needed as all players stood with their feet apart, and no person had feet that covered the entire length of the mat. Thus, 56 sensors were deactivated via the novel pliance®

software. The resulting configuration given below in Figure 4.2.4.2.3.1 (active sensors in blue) allowed the sample rate to be increased to 50Hz in all subsequent trials. This also made synchronization with the PAL video system (used in the field) more straightforward and improved the accuracy of the system.



sensor[s] on/off
1. position sensor
2. click left button
3. move mouse with pressed button

Figure 4.2.4.2.3.1: Pliance® mat sensor configuration with 56 sensors (the grey squares) de-activated.

4.2.4.2.4 50Hz v 250Hz kinematic information

To validate the use of a standard 50Hz PAL video camera in field-based testing, 10 putts recorded on a high speed Redlake camera were digitised using PEAK Motion Analysis. Initially, the footage was digitised at the original sample rate of 250Hz, then the same video clip was digitised at 50Hz by digitizing every 5th field.

The putter head was the only point of interest in the footage and thus represented the only point digitised. Data were initially filtered using the Jackson Knee method prescribed in the PEAK system manual. For all 10 putts, the Butterworth cut-off frequency was automatically derived by the software and calculated at either 4 or 5Hz. There were no exceptions. Linear displacement (x,y) and velocity data (x,y) were calculated after filtering and compared across the two sampling frequencies of 50Hz and 250Hz.

As with the analysis of the COP output, the non central F distribution was used to assess equality between the derived kinematic data methods. For these data a practical difference of 5% was used. Data are presented in Table 4.2.4.2.4.1. The data are denoted by X for horizontal displacement of the putter head (positive in the direction of the putt) and Y for vertical displacement of the putter head (positive in the upwards direction).

Table 4.2.4.2.4.1: Calculations to determine equality of video data from 250Hz and 50Hz data (df $_{1,8}$). Displacement data were calculated in cm, velocity data in cm/s.

Statistical Parameters	***M***	***SD***	***PD***	***d***	ϕ	***F calc***	***p***
Minimum displacement X	*14.4*	*11.4*	*0.72*	*0.14*	*0.09*	*0.001*	*0.024*
Maximum displacement X	*71.1*	*12.6*	*3.56*	*0.63*	*0.45*	*0.002*	*0.028*
Minimum displacement Y	*7.75*	*0.58*	*0.39*	*1.49*	*1.06*	*0.01*	*0.046*
Maximum displacement Y	*14.9*	*3.63*	*0.75*	*0.49*	*0.35*	*0.003*	*0.036*
Minimum velocity X	*-58.0*	*20.5*	*-2.9*	*-0.32*	*-0.22*	*0.000*	*0.005*
Maximum velocity X	*155.5*	*25.5*	*7.78*	*0.68*	*0.48*	*0.003*	*0.034*
Minimum velocity Y	*-16.7*	*7.6*	*-0.83*	*3.39*	*-0.17*	*0.003*	*0.039*
Maximum velocity Y	*21.6*	*11.6*	*1.08*	*0.21*	*0.15*	*0.003*	*0.04*
Velocity at ball contact X	*146*	*29.2*	*7.29*	*0.56*	*0.39*	*0.000*	*0.009*

Results from Table 4.2.4.2.4.1 suggest that the data sampled at 50Hz is significantly equal to the data sampled at 250Hz for this particular skill. As with the validation of the pliance® mat, these kinematic data provided sufficient evidence for the researchers to use a standard PAL 50Hz digital video camera in subsequent field-based testing.

5 Methodology II – field based study

Having established the validity of the methodologies and calculated the required sample size, the basic data collection in the field occurred over a two week period.

5.1 Field testing – pre intervention

Verification of the pliance® mat enabled the collection of in-field data at a golf course in metropolitan Melbourne. After agreement from the club management and approval from the University Ethics Committee, two testing sessions were conducted, one fortnight apart.

5.1.1 Participants

A total of 38 players participated in the testing sessions. These players were members of a private suburban golf club in Melbourne and all were experienced golfers. The average age of the sample was 55.3 (±17.8) years and average handicap 15.3 (±6.9). This sample provided a good spread of ages and skill level when using handicap as an indicator.

Testing took place on two Wednesday mornings a fortnight apart as this day of the week was the men's competition day, and attracted the largest group of potential participants to the course.

5.1.2 Apparatus

The pliance® pressure mat was used for all testing. Fifty six (56) of the 256 sensors were deactivated through the proprietary software to provide a total of 200 active sensors. This allowed the system to sample at 50Hz.

The pressure mat was connected to a Toshiba Tecra M2 laptop running novel® pliance®-C 8.3 software. Data were stored directly on-line to the hard drive of the laptop.

A Panasonic F-15 PAL video camera was placed 12 metres away, off the edge of the putting green perpendicular to the plane of the putt. The plane of the putt was the assumed path of the putter head during the putting stroke (assumed that the club moved in line with the hole). Sample (frame) rate was 25Hz (50 fields per second) with a shutter speed of 1/2000th of a second. The footage recorded was used to establish events within each putt and for further analysis using PEAK 2D Motus software.

The PEAK Event Synchronisation Unit (ESU) was used to overlay a sync output pulse from the pliance® system onto the video footage. The cable connection between the pliance system and the ESU passed through a specially designed (novel$_{gmbh}$) interface box that, when combined with the novel software, was able to create Transistor-Transistor Logic (TTL) signal pulses that can be detected by other hardware systems. For this data collection protocol, the pliance® software was set to send 10 high signal pulses followed by 10 low signal pulses continuously during pliance® data collection. At the “start recording” event this meant that a white synchronization marker produced by the ESU on the video screen would disappear for 10 fields, reappear for 10, disappear for 10, and so on whilst the pliance® system was in recording mode. Time code information was also overlayed onto the video footage to aid in trial identification.

Figure 5.1.2.1 is a photograph taken during the second testing session. The camera in the foreground is perpendicular to the plane of the putt, the player is standing on the pliance® mat which is placed on the putting green, the operator at the table is co-coordinating the data collection by instructing the participant and activating the pliance® system, and the camera in the left background was used to record an overview of the session but was not used for specific putting analysis.

Figure 5.1.2.1: Photograph of in-field data collection set up.

5.2 Procedures

On the day of testing, the testing apparatus was set up at one end of the practice green adjacent to the first tee, and immediately in front of the club pro shop.

Subsequently, volunteer participants approached the researchers at the practice green. Each potential participant was provided with an information to participants sheet and any questions they had were answered by either the researcher or two assistants. The objectives of the study and the putting procedure were explained and informed consent provided before testing commenced.

Each participant completed five putts at two holes cut into the green at set distances from the front of the middle of the mat– the first at 4m, the second at 8m. These distances were slightly modified from the lab testing as the only flat part of the putting green was limited to just more than 9.5m from the point of ball contact, and with the expectation that some putts would travel past the hole the decision was made to use 4m and 8m putting distances.

The requirement to offset the holes slightly from each other did not affect the player's ability to align themselves with the hole. There was enough room for the player to move their stance slightly forward on the mat to align themselves for the 8m putting task. It is acknowledged that the presence of a hole at the 4m distance when putting for the 8m distance was unusual (and in fact one player accidentally landed the ball in the 4m hole when putting at the 8m task), but logistically this was the best way of collecting data for two putting tasks from the one set up. Detailed in figures 5.2.1 are two separate holed out putt sequences for the same player at each hole. The left hand image is at address. These images are presented to support the argument that the offset putt lines had no effect on the players positioning on the pliance® mat and the accuracy of kinematic data collected using one perpendicular camera.

Figure 5.2.1: A rear view sequence of images of a successful putt at each hole by the same player. Top five images at 4m hole, bottom four images from 8m hole (includes research assistant picking ball out of hole to indicate hole position).

Each putt followed the same procedure, and all participants were dressed in their golf clothing (including golf shoes – metal spikes were banned at this club so only soft spike shoes were worn). Firstly, the participant stood on a synthetic grass mat immediately behind the pliance® pressure mat. The pressure mat was zeroed each time prior to the participant stepping onto it. The participant was then advised to step onto the mat and get ready to putt. When the participant looked settled (that is, not shifting their weight from side to side and putter head at the address position), the pliance® recording software was started. This “record” command also initiated the sync output pulses to the video footage. After the pliance® system started recording, the participant was told to "putt whenever you are ready". Once follow through was completed the pliance® recording software was stopped. The player was asked to step back onto the synthetic mat whilst the pressure data file was saved and the mat zeroed for the next putt.

During this time, the finishing position of the ball in relation to the hole was measured and recorded by one of the assistants. The results were recorded by hand onto a previously prepared sheet containing each participant's name, handicap and self reported average number of putts per round. Putts were recorded as short or long, left, right or centre and "holed out" in addition to the radial distance in cm they came to rest from the centre of the hole. These descriptors and an indication of the radial measurement technique used (for example, short, left and 25cm from the hole) is detailed in Figure 5.2.2.

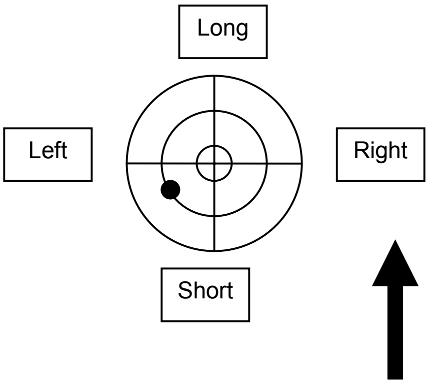


Figure 5.2.2: Diagram of the putt result recording method.

All 10 putts (2 sets of 5) were completed within a time span of approximately 5 minutes. No participants were given practice putts on the exact line of the putts taken for the study. However, all players had taken practice putts on the surrounding parts of the practice green before being involved in this study.

Data were entered and stored into novel database pro I4 software. The researcher developed a specific data entry method that allowed all relevant data to be input and linked through the database. This included all subject demographic details, individual putt results and links to data files in novel, ASCII (CSV) and Excel format.

5.2.1 Video analysis

The pliance® mat acted as the known length required for calibration. The mat has a width of 50.5cm and was perpendicular to the camera. The lateral edges of the mat are clearly discernible. The PEAK software required the corners of the mat to be digitized 10 times to create a scale factor value. The scale factor varied slightly between filming sessions as the camera was not set in exactly the same position on both days.

Each putt was analysed from a point at least 20 fields prior to the start of the backswing, to a point 20 fields past the end of the follow through. This was to ensure that end point errors would be avoided when filtering was applied. As described previously, the following events were used to denote common points in time in the putt and extracted from the video:

- Field prior to first movement of the putter away from the ball from the address position.

- Field prior to first movement of the putter back toward the ball in order to strike it.

These two events defined the backswing phase and are depicted by Figures 5.2.1.1a and b.

- Field prior to first movement of the putter back toward the ball in order to strike it.
- One field prior to the point of contact between the putter head and the ball.

These two events defined the downswing phase and are depicted by Figures 5.2.1.1b and c.

- One field prior to the point of contact between the putter head and the ball.
- Most distal horizontal displacement of the putter head once it had made contact with the ball.

These two events defined the follow through phase and are depicted by Figure 5.2.1.1c and d.

Figure 5.2.1.1a-d: Events in the putting stroke: (a) start of backswing; (b) start of downswing; (c) ball contact; (d) end of follow through. These images taken from one in-field testing trial.

Apart from being used as the basis for analysis of the movement of the putter head, the event fields extracted from the video were also used as part of the analysis of the accompanying pressure data. The pliance® system was able to control the video camera through a master-slave relationship with the pliance® system acting as the master. This meant that both systems generate a sample at the same point in time as determined by the pliance® sync pulse.

Synchronisation of the pressure and video data enabled the pressure data to be broken down with respect to the same events and phases. This was achieved through the overlaying of a synchronization pulse onto the video image. In figure 5.2.1.2, a small white square (circled) is the event synchronization pulse from the Peak system ESU. This event is created via the hardwired connection between the pliance® and video systems via a coaxial cable running from the sync out connection of the pliance® box, to the sync in connection of the ESU. When the pliance® system started recording pressure data, this square disappeared from the screen for 10 fields, reappeared for 10 and so on, until the pliance® system stopped recording pressure data. When recording from the pliance® system stopped, this sequence was immediately interrupted and the white square disappeared from the video. With the time code information also on the video (time code is visible directly above the white square in Figure 5.2.1.2), and matched sample rates of 50Hz between the video system and the pliance® system, it was possible to use the temporal phase data to break up the pressure information with respect to the events and phases detailed above.

Figure 5.2.1.2: Image capture from video indicating the Peak synchronization event used to synchronise the pliance® and video systems.

As data collection occurred outdoors on a practice green, a number of trials were lost because of another person walking in front of the camera during the putt. If the complete movement of the putter head was not visible, the trial was removed from the analysis.

During data collection, the pliance® system was manually put into record mode shortly after the subject stepped onto the mat. It then took a number of seconds for the subject to settle into position, and putt. In the first part of the video analysis process, approximately 10 seconds of video was temporarily captured into the PEAK Motus system. This period of time was required to ensure that it was possible to detect the pliance® “start recording” pulse during the digitization process and the time of synchronization noted. However, no video was digitized between this point and the point 20 fields prior to the start of the backswing.

5.2.1.1 Digitisation

The outdoor setting for data collection necessitated the use of manual digitization for this part of the study. To ensure reliability for this particular part of the study, 10 randomly selected putts were digitized twice at least one week apart. The x,y co-ordinate data of the putter head from these trials were assessed across all frames using intra-class correlation coefficient (ICC) in SPSS software Version 12. Separate ICC values were calculated for each of the 10 sets of data (putter head$_{x,y}$) and the mean ICC results are presented in Table 5.2.1.1.1. The data indicate a high level of reliability of the manual digitizing in this study.

Table 5.2.1.1.1: Intra-class correlation coefficient data and confidence intervals for manual digitising reliability for 10 random trials.

		95% CI				**95% CI**	
X co-ordinate	**ICC**	**Upper**	**Lower**	**Y co-ordinate**	**ICC**	**Upper**	**Lower**
	0.9976	0.9967	0.9984		0.9899	0.9849	0.9933

The toe end of the putter head was digitized in each field. Event fields were noted visually during the digitization process and marked on the data file throughout the putting sequence. These event field numbers were also used to calculate temporal data for each putt.

At the completion of the final digitized field in the process, raw data were then filtered via the Butterworth digital filter method using Jackson-Knee optimisation contained within the PEAK Motus software. For all trials, the filter process was visually assessed by comparing the raw and filtered output at the unscaled data level (that is pixel vs. time) (example trial in Figure 5.2.1.2.1). For no trial was the filter rate higher than 5Hz.

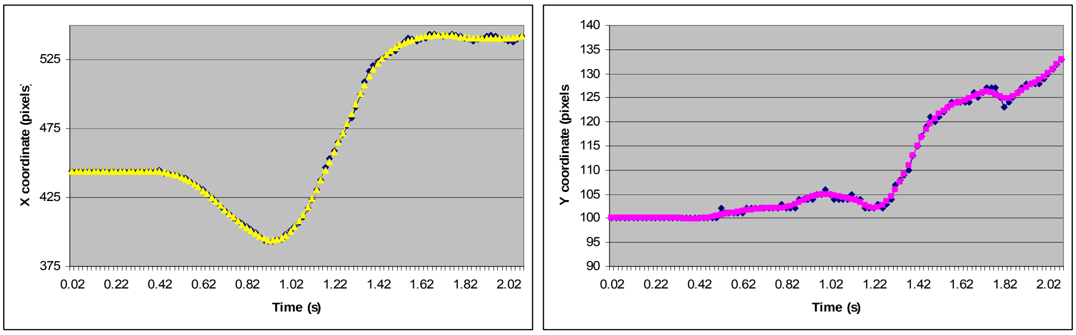


Figure 5.2.1.1.1a and b: Raw and filtered coordinate (pixels) of putter head vs. time for (a) X coordinate, and (b) Y coordinate for one putting trial.

Filtered co-ordinate data (pixels) were then scaled and converted to centimeters using the scale factor. Putter head velocity data were calculated within the PEAK software from this filtered and scaled data.

A total of 188 short putt and 188 long putt files were exported in comma separated ASCII format to Microsoft Excel for further analysis.

5.2.1.2 Putter head parameters

5.2.1.2.1 Putter head displacement

For each subject, a Microsoft Excel file was created that contained the putter head displacement data for each of the five trials at each distance. Short and long putts were treated separately.

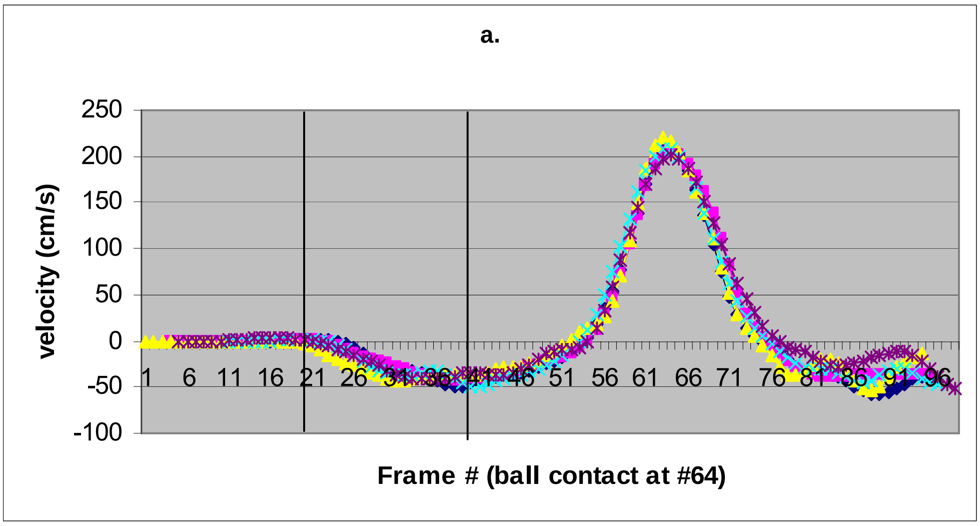
For each putt, displacement data in the *x* (horizontal) and *y* (vertical) directions were calculated using the field event numbers and the maximum and minimum values within each phase. Therefore, the maximum and minimum putter head *x* and *y* co-ordinates were used to calculate range of putter head displacement during each of the three phases. A summary page for each subject at each putt distance grouped the data and contained the following parameters:

- Range of horizontal movement of the putter head during the backswing (cm)
- Range of vertical movement of the putter head during the backswing (cm)
- Range of horizontal movement of the putter head during the downswing (cm)
- Range of vertical movement of the putter head during the downswing (cm)
- Range of horizontal movement of the putter head during follow through (cm)
- Range of vertical movement of the putter head during follow through (cm)

Also calculated was the combined downswing and follow through displacement of the putter head in both the x and y directions. This list of parameters logically represents the movement of the putter throughout the stroke and has previously been reported in the literature (Paradisis and Rees, n.d.).

5.2.1.2.2 Putter head velocity

All velocity data were calculated in PEAK Motus software and exported to Microsoft Excel. Two summary pages were created in each file to summarise *x* and *y* putter head velocity data for the group of five putts. In order to create graphs that could be used for comparison between all five trials, time was normalized to time of ball contact. No normalized data were extracted from this process, it was simply a method employed to view all velocity data files from the same subject in a standardised way. Examples of one subject's putter head velocity summary page for horizontal and vertical velocity are given below (Fig. 5.2.1.2.2.1a & b) – start and end of backswing as marked, with ball contact occurring at frame number 64.



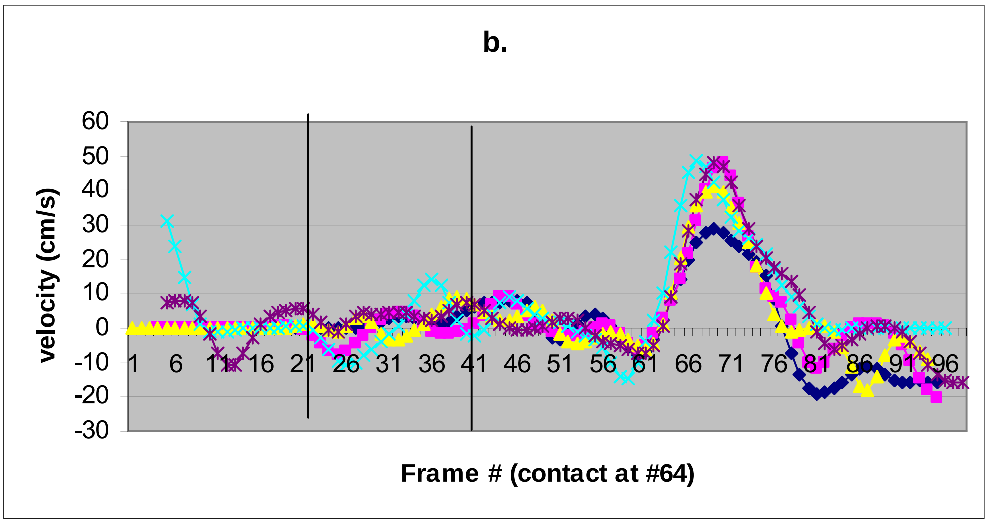


Figure 5.2.1.2.2.1a and b: Putter head velocity$_{x,y}$ summary graphs for a sequence of five putts from one subject at the 8m hole; (a) Horizontal putter head velocity, (b) Vertical putter head velocity.

The parameters detailed below were extracted from the data. Note that the term ‘forward swing’ is used to indicate a combined downswing and follow through. This is to record any maxima or minima that occurred post ball contact, therefore outside the limitations of the downswing. For example, it is possible that the maximum horizontal velocity of the putter head occurred after ball contact. In this instance, the time of occurrence was reported as a positive time (ms) post contact:

- Horizontal putter head velocity at ball contact (cm/s)
- Vertical putter head velocity at ball contact (cm/s)
- Maximum horizontal putter head velocity during the forward swing (cm/s)
- Maximum vertical putter head velocity during the forward swing – upward velocity (cm/s)
- Time of maximum horizontal putter head velocity during the forward swing (ms)
- Time of maximum vertical putter head velocity during the forward swing – upward velocity (ms)
- Minimum vertical putter head velocity during the down swing (maximum downward velocity)(cm/s)
- Time of minimum vertical putter head velocity – downward velocity (ms)

The velocity of the putter head at ball contact and maximum putter head velocity are standard parameters used in all other studies of putting kinematics (Sanders, n.d.; Paradisis and Rees, n.d.; Delay et al., 1997; McCarty, 2002). The timing of these maxima and minima indicate where in the putting stroke velocity peaks (in both the upward and downward direction when referring to y), and allows the researcher to understand how the player controls putter head velocity during the stroke. The velocity profile of the putter head during the back swing was ignored in the present study as there is no evidence to suggest that backswing velocity has any effect on forward swing velocity.

5.2.2 Pliance® mat

The number of pliance® trials was not the same as the number of video trials. Although specific instructions were provided to players on stance position and the edges of the mat were clearly marked with the words “DO NOT STAND HERE’ (figure 5.2.3.1) some players chose to place the ball on the ground and position themselves accordingly, rather than position themselves first and place the ball accordingly. It is possible that the width of the mat was not large enough to enable the taller payer to stand comfortably without contacting the edges of the mat. Also, some data were lost due to a weak connection between the synchronization box of the pliance® system and the ESU. Ultimately, 112 short putts and 126 long putts from the pliance® system were included in the analysis.

Figure 5.2.2.1: Pliance® mat highlighting the markings warning participants away from standing on the edges.

Each pliance® trial was transformed through novel® proprietary software into an ASCII file that included information on the co-ordinates of the total mat centre of pressure. This data file also contained header details, time and total force information. An abbreviated example of this file is provided below (Figure 5.2.2.2).

file name: XXXXXX1.fgt	date/time 01.12.04 11.09		
mat type 84-240			
force time integral[N*s]: 5213.050			
pressure time integral[kPa*s]: 371.720			
total times [secs]: 6.800	time per frame [secs]: 0.02000	scanning rate [Hz]: 50	
time[secs]	force[N]	x[mm]	y[mm]
0.02	751.513	202.18	193.87
0.04	746.111	202.71	193.25
0.06	741.909	203.08	192.1

Figure 5.2.2.2: Abbreviated example of the ASCII file output from the pliance® system indicating header information, time force and COPx,y co-ordinates.

Using the information from the video analysis on the difference between the time of “start pliance” recording pulse and the start of backswing, each pliance® file was trimmed so that the first data point was twenty samples prior to the sample associated with start of backswing. The synchronization of the two systems, the low frequency content of the data and the common sample rate (50Hz) ensured this was completed with a high level of accuracy.

In order to filter the data, each pliance® file was then transformed into a tab separated text file. This file contained the time information, raw COPx and raw COPy data. These data were loaded into Sigview32 Version 1.9.1.0 Signal Analysis Application software. This software separated the data file into COPx vs. time and COPy vs. time graphs.

The raw co-ordinate data were initially assessed for signal frequency content using a Fast Fourier Transfer algorithm (FFT). This was to verify that the content of the signal was consistent with that measured in the pilot study. Following the methodology developed in the pilot study, data were then filtered using Sigview software with a low pass digital filter set at 5Hz.

Each filtered COPx,y vs. time graphs were assessed against the raw data vs. time graph for each putt. This assessment was conducted visually using the Sigview software, and ensured that the applied filtering had not created an abnormal set of filtered COPx,y data. An example of the output is contained in Figure 5.2.2.3a & b.

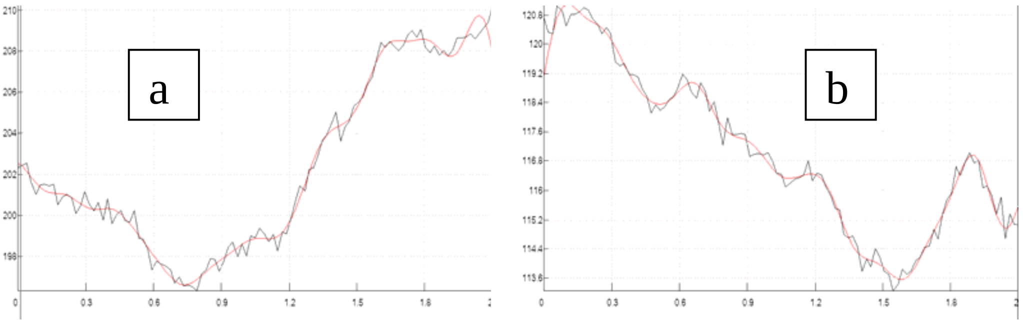


Figure 5.2.2.3a & b: Examples of raw and filtered pliance® COP data files; (a) COPx and, (b) COPy. The vertical axes are the COP co-ordinate data values, and the horizontal axes the time data.

The filtered COPx,y data were saved into separate files, copied to Microsoft Excel then combined again to form a single file containing the time line, filtered COPx and filtered COPy data in consecutive columns. COP velocity data were subsequently calculated (method provided later) and saved in this file.

In this paper, medio-lateral movement of the COP (COPx) relates to that movement along, or parallel to the intended line of the putt (left to right movement), whilst antero-posterior movement of the COP (COPy) relates to movement perpendicular to the intended line of the putt.

The orientation of the pressure mat was such that in relation to COPx, movement away from the hole, or towards the back foot, was positive (+), and COPy movement towards the heels was positive (+). The following figure (Fig. 7.2.3) provides the orientation of the pliance® mat in the set up used for data collection. This is viewed from above with the left toe located closest to COPx,y = 0,0.

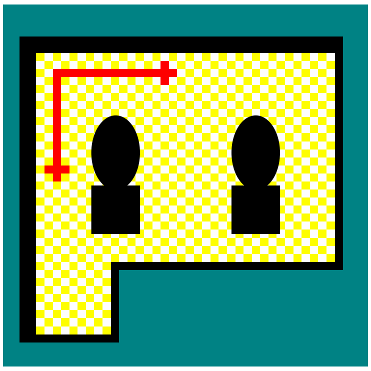


Figure 5.2.2.4: Pliance® mat orientation indicating origin of COP directions during data collection with left and right feet represented accordingly.

In order to orient the movement of the COPx with the movement of the putter head, the COPx data were transformed post data collection (multiplied by -1) so that the positive direction was towards the hole or towards the front foot.

5.2.2.1 COP parameters

5.2.2.1.1 COP range of movement

The process for displacement parameter extraction of COPx,y data was the same as for putter head displacement. In order that the same event numbers were used, the COPx,y data were copied into the putter head displacement file and saved as a separate file. This allowed the calculation of COP range data for the same phases. Thus the following parameters were extracted for each file:

- Range of medio-lateral movement of the COP during the backswing (COPx, mm)

- Range of antero-posterior movement of the COP during the backswing (COPy, mm)
- Range of medio-lateral movement of the COP during the downswing (COPx, mm)
- Range of antero-posterior movement of the COP during the downswing (COPy, mm)
- Range of medio-lateral movement of the COP during the follow through (COPx, mm)
- Range of antero-posterior movement of the COP during the follow through (COPy, mm)

These data were calculated by initially determining the maximum and minimum COPx,y coordinates for each phase of the putting stroke. The range was then calculated using these two values.

5.2.2.1.2 COP Position

As the phases within the stroke were determined from movement of the putter head, these phases may not be in sync with movement of the player. It cannot be assumed that the player will shift the COP at the same time as changing the direction of the putter head. The variables listed above provide range of movement of the COP during a phase. It is also important to determine the location of the COP in relation to its starting position (position at address) at the end of each phase. In Figure 5.2.2.1.2.1 the movement of the COPx,y for the complete putting stroke is provided, with the start and end of temporal phases indicated.

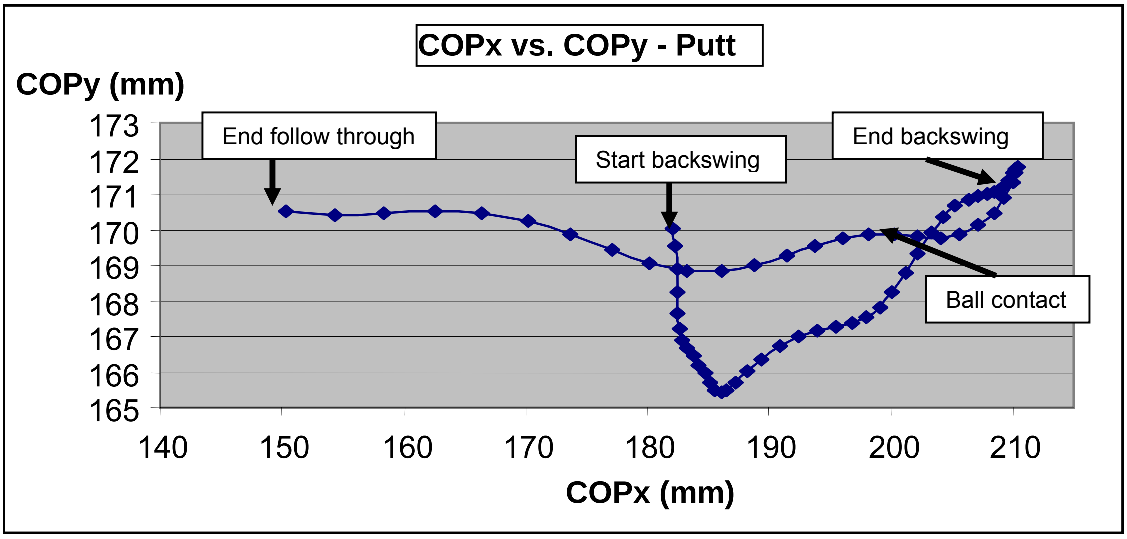


Figure 5.2.2.1.2.1: COPx vs. COPy plot for one subject's putting trial.

In order therefore to obtain the location of the COP during the putting motion four positional parameters were calculated. These were based on the location of the COPx,y at the end of backswing and at ball contact compared to the position of the COPx,y at the address position.

- Position of COPx at the end of the backswing relative to COPx at address
- Position of COPx at ball contact relative to COPx at address
- Position of COPy at the end of the backswing relative to COPy at address
- Position of COPy at ball contact relative to COPy at address

These position parameters are different to the range parameters as they define the location of the COPx,y at the end of each phase, compared to reporting on the range of movement of COPx,y during each phase.

5.2.2.1.3 COP velocity

The velocity of the COP in x and y was calculated using a central difference approximation equation presented by Nakamura (1993; p.176). This equation is:

$$\chi_i = \left(\frac{-(\chi_{+2}) + (8\chi_{+1}) - (8\chi_{-1}) + (\chi_{-2})}{12t} \right)$$

These data were calculated and copied into the putter head velocity files previously created so that the same event numbers were used. The file was then saved as a COP velocity file. Each file contained summary pages for both COPx and COPy and included graphs of each COP velocity trace with time normalized to ball contact. An example of one trial’s COP co-ordinate and velocity data for COPx and COPy is provided in Figures 5.2.2.1.3.1a and b.

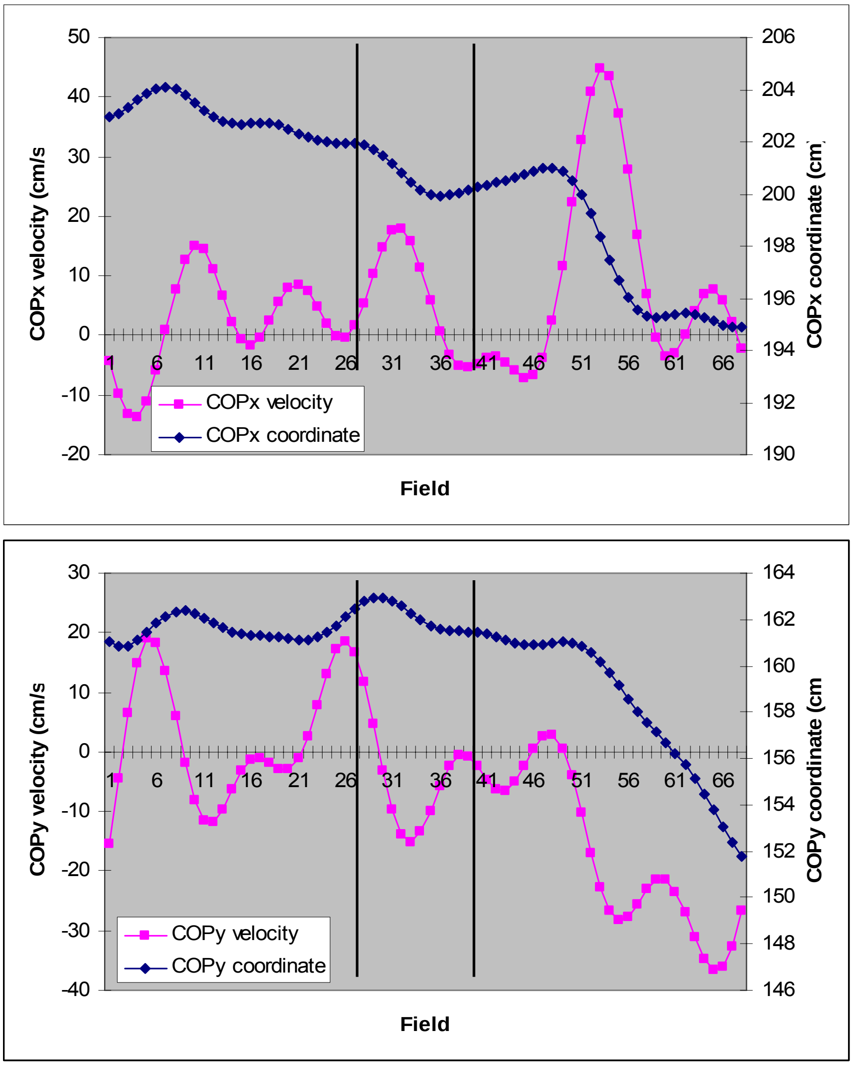


Figure 5.2.2.1.3.1a and b: (a) COPx coordinate and COPx velocity vs. field number, (b) COPy coordinate and COPy velocity vs. field number for one putting trial. Start of backswing at field zero, start of downswing (field #28) and ball contact (field #40) as marked, end of follow through at right hand edge of graph.

The following parameters were extracted from the data:

- Medio-lateral velocity of the COP at start of backswing (COPx, mm/s)
- Antero-posterior velocity of the COP at start of backswing (COPy, mm/s)

- Maximum medio-lateral velocity of the COP during the backswing phase (COPx, mm/s) and time maximum occurred prior to start of downswing (seconds)
- Maximum antero-posterior velocity of the COP during the backswing phase (COPy, mm/s) and time maximum occurred (seconds)
- Minimum medio-lateral velocity of the COP during the backswing phase (COPx, mm/s) and time minimum occurred (seconds)
- Minimum antero-posterior velocity of the COP during the backswing phase (COPy, mm/s) and time minimum occurred (seconds)
- Medio-lateral velocity of the COP at start of downswing (COPx, mm/s)
- Antero-posterior velocity of the COP at start of downswing (COPy, mm/s)
- Maximum medio-lateral velocity of the COP during the downswing phase (COPx, mm/s) and time maximum occurred (seconds)
- Maximum antero-posterior velocity of the COP during the downswing phase (COPy, mm/s) and time maximum occurred (seconds)
- Minimum medio-lateral velocity of the COP during the downswing phase (COPx, cm/s) and time minimum occurred (seconds)
- Minimum antero-posterior velocity of the COP during the downswing phase (COPy, mm/s) and time minimum occurred (seconds)
- Medio-lateral velocity of the COP at ball contact (COPx, mm/s)
- Antero-posterior velocity of the COP at ball contact (COPy, mm/s)
- Maximum medio-lateral velocity of the COP during the follow through phase (COPx, mm/s) and time maximum occurred (seconds)

- Maximum antero-posterior velocity of the COP during the follow through phase (COPy, cm/s) and time maximum occurred (seconds)
- Minimum medio-lateral velocity of the COP during the follow through phase (COPx, mm/s) and time minimum occurred (seconds)
- Minimum antero-posterior velocity of the COP during the follow through phase (COPy, cm/s) and time minimum occurred (seconds)
- Medio-lateral velocity of the COP at end of follow through (COPx, mm/s)
- Antero-posterior velocity of the COP at end of follow through (COPy, mm/s)

In order to incorporate as many variables as possible into the analysis, all minima and maxima for each phase were included in the analysis of movement of the COP. This type of analysis thus provides eight data points within each phase of the stroke (COPx maximum and minimum velocity; timing of COPx maximum and minimum velocity – repeat for COPy).

Thus, the total number of parameters analysed was 62. This combines

- 4 Length of phase parameters
- 8 Putter head displacement parameters
- 8 Putter head velocity parameters
- 10 COP displacement and position parameters
- 32 COP velocity related parameters

Data from previous authors (for example, Delay et al., 1997) and the pilot study indicated that skill level – as measured by handicap – was not an indicator of putting performance. The grouping of players into skill levels based on handicap is an incorrect assumption. In order to assess the data and determine whether different putting techniques exist – not based on skill level - cluster analysis was performed.

A number of other parameters (putt result, age, handicap, number of putts per round) were excluded from the cluster analysis so that the derived putting techniques (clusters) could be assessed against each other based on these parameters.

5.2.3 Treatment of the putt result data

The exact putt result data collected in using this method is the radical distance from the hole. This means that only one measure of distance, rather than a measure left or right and a measure of short and long, was taken. This raises the issue of how to treat this data as it is questionable whether the data is continuous.

Previous research in the area provides some insight. McCarty (2002) had recorded radial distance from the hole (or mark on the ground) as the only measure of accuracy. The author treated the accuracy data from this study as continuous parametric data reporting on differences between groups – based on handicap and then classifying based on accuracy – using parametric statistics.

In this paper a similar approach will be taken, however this approach will be based on data already collected. Using the exact putt result data and the putter head velocity at ball contact data for the same putt, correlation coefficients were calculated for the 4m ($r = 0.69$) and 8m ($r = 0.56$) data respectively to determine whether there was a significant relationship between these two parameters ($n=188$). In both cases, the data indicated a significant relationship ($p<0.001$) between the parameters. The paired data is presented in Figures 5.2.3.1a and b. The strength of this relationship combined with the clear trend in the figures provided indicates that the exact putt distance data can be treated as continuous. However, normality tests will be conducted on all data before statistical analysis occurs and where mean and overall data is reported, values with and without holed putts will be provided to account for the zero value attributed to holed putts. It will also be necessary to conduct analysis of frequency data, as the putt results were also recorded based on descriptors (long, short, holed and left, right). In these cases, chi square analysis will be completed to determine whether significant differences are present.

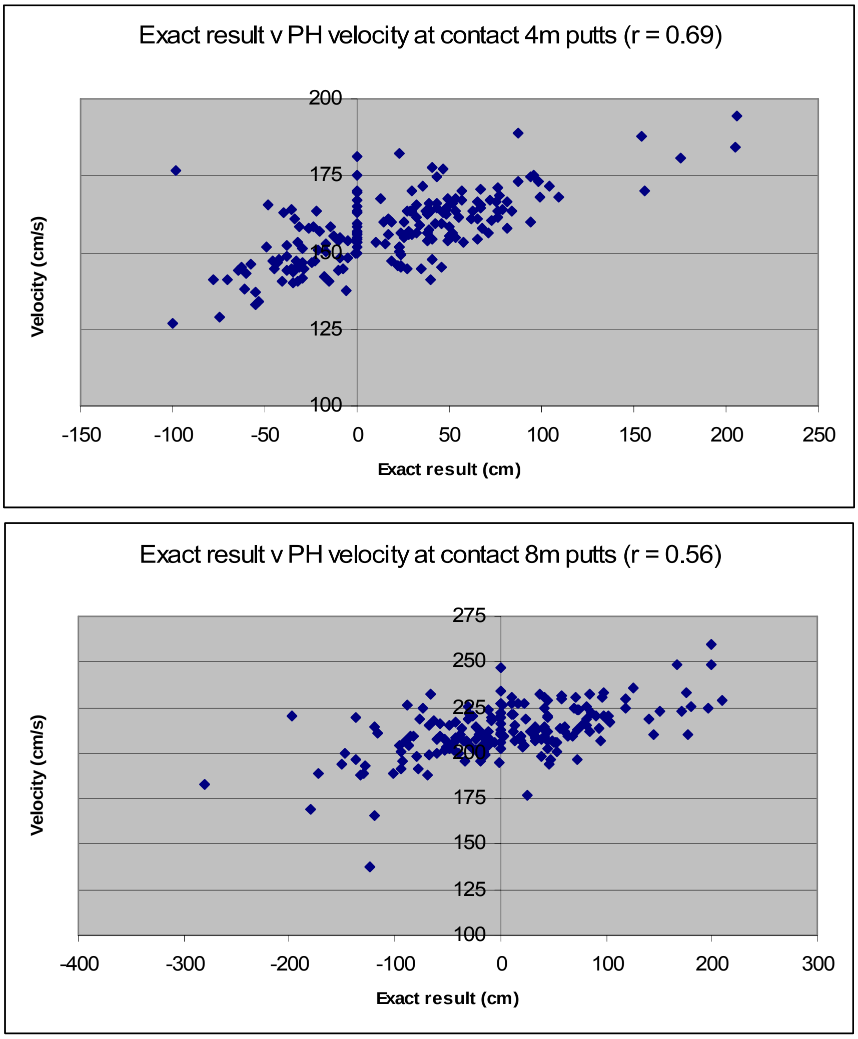


Figure 5.2.3.1a and b: Scatterplot of exact putt result versus putter head velocity at ball contact for (a) 4m putts, and (b) 8m putts.

5.3 Biofeedback training sessions

Putt result data were provided to all participants within two weeks of data collection. This included the mean putt result for both the 4m and 8m putts, and a ranking between 1 and 38 within the sample for putting performance. At this time volunteers were called to participate in a follow up biofeedback study that would last four weeks, with week 4 being a retesting session on the putting green. Twelve participants agreed to take part in the biofeedback training study.

The following week, ten participants completed the first training session. The second and third week, nine participants completed the training sessions. In week four, seven participants completed the retesting on the putting green. The data from these seven participants were used in all analysis of the biofeedback group.

Biofeedback training was completed in the committee room of the golf club. This was a room measuring 6m x 4m, with a white wall suitable for projecting the image from the pliance® software out of the laptop via a video projector. Each participant completed the training immediately prior to the completion of their round of golf on three consecutive Wednesdays. No participant was required to change their normal routine in order to complete the training sessions.

The apparatus used in the biofeedback training sessions included:

- Pliance® mat used in data collection (Figure 5.3.1a)
- Pliance® X data collection box (Figure 5.3.1b)
- Panasonic video projector
- Toshiba Tecra M2 laptop.

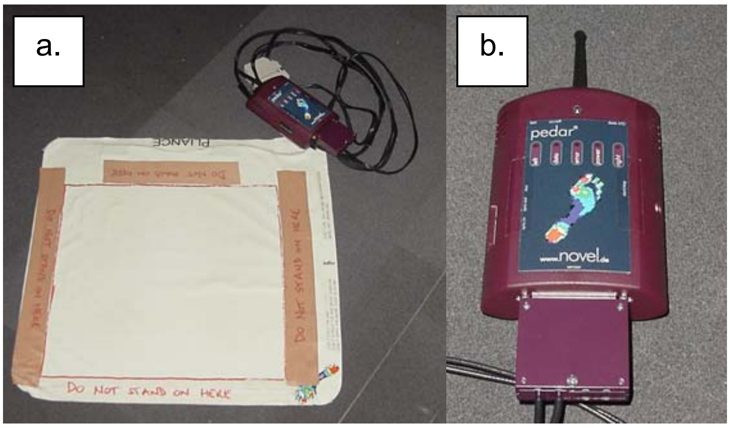


Figure 5.3.1a & b: (a) Pliance® mat system, and (b) the updated pliance® X analyzer box used during biofeedback training.

The software used for these training sessions was novel pliance® 10.2.22. The pliance® X box is an updated version on of the data collection unit used during data collection with a higher hardwired sample rate (20,000 sensor samples per second). This combination of apparatus allowed the real-time projection of the pliance® information directly onto the wall facing the participants as each stood on the pliance® mat. The pliance® 10.2.22 software allows the mat to be divided into left and right sides in real time. This can then be displayed in real time. This feature is not available in the pliance® 8.3-C software, however the pliance® X hardware was not available when the pliance® mat was being validated against the AMTI plate, so was not used during data collection.

The real time display is depicted in figure 5.2.2. A number of options were possible. Initially the participants were introduced to the concept of understanding the signal output as suggested by Cattaneo and Cardini (2001) via the display of real-time 2D pressure pictures as depicted in the left hand side of Figure 5.3.2. The images on the left hand side of the screen depicting the left and right foot are in the orientation provided to the participant. The information on the right side of the screen represents peak pressure, force and area v time curves. These curves were not referred to or used during the biofeedback sessions. Small images on the extreme right of these figures represent recently opened or stored data files. This information was also ignored during the biofeedback sessions.

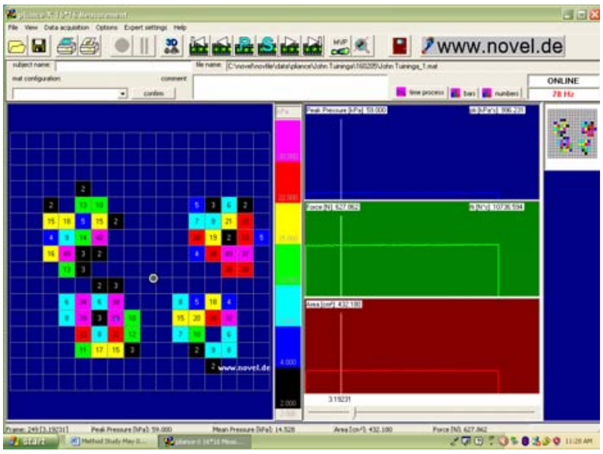


Figure 5.3.2: Print screen capture of pressure information as viewed by each participant in the biofeedback training group. Left hand side of the image provides a 2D representation of the left and right foot (heel at bottom of the image). The circled dot in the middle of the picture is the location of the COP.

In the first week of the biofeedback training program participants were shown how to interpret the pictures by firstly placing one foot on the mat whilst watching the screen, then the other foot. Whilst this was happening, the researcher was pointing out the relevant images of the outline of the feet, the position of the COP (the blue dot with white and black border around it), and how the position of this COP is influenced by movement and weight distribution (see Figure 5.3.3). All participants were asked to ignore the right hand side of the screen at this stage of training.

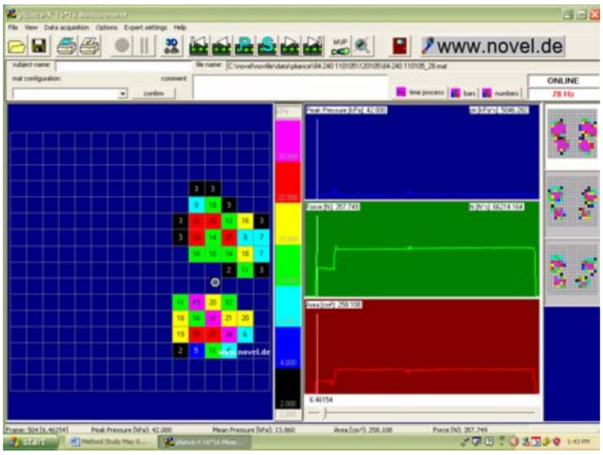
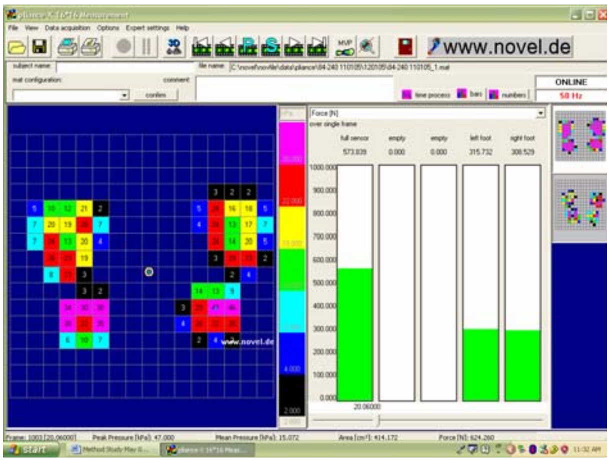


Figure 5.3.3: Print screen capture of pressure information as viewed by each participant in the biofeedback training group when only the right foot is placed on the mat.

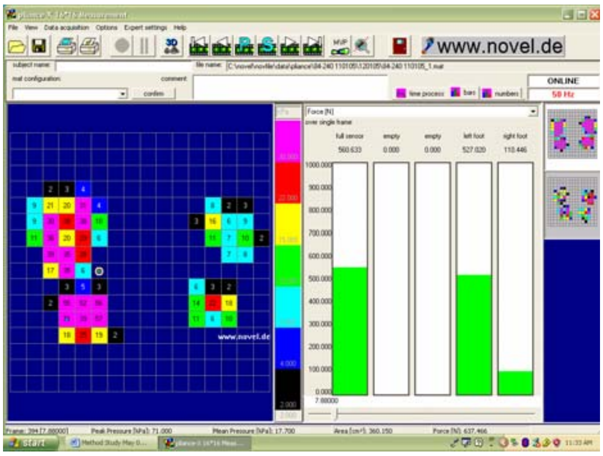
Subsequently, participants spent 5-10 minutes becoming familiar with the mat and the display. During this time all participants were fully clothed and wearing standard street shoes or golf shoes. Following this familiarization process, the participants were asked to step off the mat, the mat was zeroed, then they stepped back on and were asked to concentrate on keeping the COP as still as possible by concentrating on it's position on the screen. The protocol used for each participant included one minute of focus on the COP, one minute of eyes closed and trying to stay as balanced as possible, another minute of focus on the COP, another minute of eyes closed, and one final minute of focus on the COP. At the end of this time, the researcher asked the participant if they felt comfortable with their eyes closed, and whether they could feel a difference between the eyes open and closed conditions. This was to orient them to the feeling of being relatively stable. They were then asked to step off the mat.

Using the pliance® 10.2.22 software, the left and right sides of the mat were then masked (a term used by novel to indicate the breaking down of an area into smaller parts) so that the information pertaining to the left and right foot could be displayed as individual columns (or bars) on the screen. A balanced, symmetrical position (Nichols, 1997) was explained to each participant as keeping each of the two columns on the far right of the screen at the same height (Figure 5.3.4). If the load under the foot was more centred on one side, for example the left side, then the COP and bar heights would represent this asymmetrical loading (Figure 5.4.5). The same procedure of alternating one minute with eyes open, one minute with eyes closed protocol was completed. On completion of this exercise the participant was free to leave. The session took approximately 15 minutes to complete.



Frame: 1003 [20.06000] Peak Pressure [kPa]: 47.000 Mean Pressure [kPa]: 15.072 Area [cm²]: 414.172 Force [N]: 624.260

Figure 5.3.4: Print screen capture of pressure information as viewed by each participant in the biofeedback training group where the load under each foot is presented in column form on the extreme right hand side of the image. This image indicates relatively equal loading of each foot.



Frame: 394 [7.88000] Peak Pressure [kPa]: 71.000 Mean Pressure [kPa]: 17.700 Area [cm²]: 360.150 Force [N]: 637.466

Figure 5.3.5: Print screen capture of pressure information as viewed by each participant in the biofeedback training group where the load under each foot is presented in column form on the right hand side of the image. This image indicates a greater load on the left foot.

Using the same equipment set up described for week 1 above, the week 2 biofeedback training session started with each participant repeating the exercises completed in week 1 (alternating minutes of eyes open, eyes closed with 2D representation of the feet, then columns). Whilst standing on the pliance® mat each participant was then asked to mimic their putting address position. Once comfortable they were then asked to look at the screen to note the position (and stability) of the COP location (using the 2D representation).

When each participant was able to maintain the COP in a relatively stable position, they were then asked to make a “phantom” putting movement whilst looking at the screen. This was to highlight to them how their COP moved when they made the putting stroke. The researcher then explained to each participant that Pelz (2000) putting theory includes the ability to maintain balance during the putting stroke by focusing on movement of the shoulders rotating about the trunk in a vertical fashion (keeping the triangle shaped depicted in Figure 2.1), as opposed to movement of the arms on a fixed trunk. The participant was then encouraged to repeat the phantom putting procedure and focus on developing a feel for the putting motion that kept the COP in the most stable position. All participants agreed that the shoulder putting method was the most suitable for this. At the completion of this set of exercises the participant was free to go, but they were encouraged to emulate what they had “felt” in their round of golf.

Each participant was asked to bring their putter with them for the week 3 training session. The exercises alternating eyes open, eyes closed were completed initially. Then holding the putter as per normal, and standing in their putting address position, each participant watched the screen to determine the location and stability of the COP. Then making their standard putting stroke (apart from looking up at the screen), participants observed the movement (or lack of movement) of their COP. These participants were reminded of the need to putt with their shoulders and arms moving as one unit about their trunk. All participants spent 3-5 minutes performing this task, using the feedback from the 2D COP location projected onto the screen. After this exercise was completed, participants were free to leave, but were asked to emulate the feeling of the putting stroke they had just achieved in their round of golf.

The following week, seven players were re-tested using the same procedures outlined in section 5.2.

6 Data analysis – pre intervention testing

This chapter presents data on the putting performance measures of this sample of players on each of the two putting tasks (n=190). Each putt is treated separately. Putts that successfully achieved a “holed out” result were removed from some parts of this analysis. Where removal from the sample is the most logical way of treating these putts, this is pointed out to the reader.

It was not assumed in the analysis of putting performance that holed out putts would have traveled past the hole. It is possible for the ball to drop into the hole; that is, distance past the hole = 0cm. However, as the velocity of the ball when it dropped into the hole was not measured, holed out putts are treated separately to putts that finished past the hole.

6.1 Overall data analysis of putt results

Putt result data indicates that of the 380 putts taken at the two holes 8.7% (33 of 380) resulted in the ball finishing in the hole. Overall, 38.4% of putts finished short of the hole and 61.6% of putts reached or finished past the hole. At the individual task level, 19 putts (10%) were holed at the 4m task, and 14 putts (7.4%) were holed at the 8m task.

The majority of putts that missed traveled past the hole for both the 4m task (107/171 = 62.6%) and the 8m task (93/176 = 52.8%). Tables 6.1.1 and 6.1.2 provide frequency data for putt results based on putt result classification.

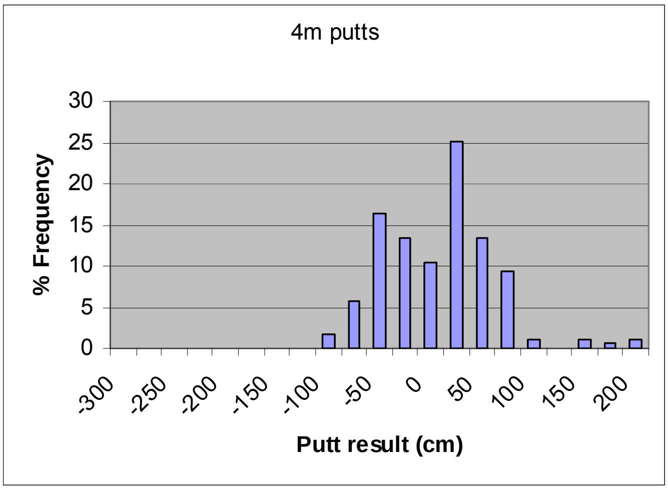
Table 6.1.1: Frequency data for 4m putts based on classification of result.

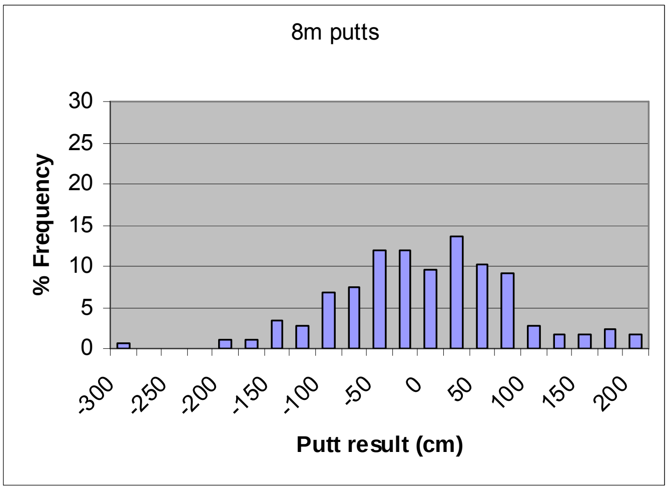
Putt result	n	% of all (n=190)	% of missed (n=171)
Holed out	19	10.0	
Long left	18	9.5	10.5
Long right	89	46.8	52.6
Short centre	3	1.6	1.7
Short left	17	8.9	9.9
Short right	44	23.2	25.1
Total	190	100.0	100.0

Table 6.1.2: Frequency data for 8m putts based on classification of putt result.

Putt result	n	% of all (n=190)	% of missed (n=176)
Holed out	14	7.4	
Long left	57	30.0	32.4
Long right	36	18.9	20.4
Short centre	0	0	0
Short left	30	15.8	17.0
Short right	53	27.9	30.1
Total	190	100.0	100.0

The exact finishing distance from the hole was recorded as “long/short”, “left/right/centre” and “distance from the hole”. In this study, exact finishing distance from the hole equates to the radial distance from the hole. Overall data for the exact finishing distance of the putt indicates a spread of values around zero although there are numerous outlying values in both (see Figures 6.1.1a and b below). This data, with all holed out putts eliminated from calculations, produce skewness (4m putts = 0.45, standard error (SE) = 0.186; 8m putts = -0.106, SE = 0.183) and kurtosis values (4m putts = 0.867, SE=0.369; 8m putts = 0.344, SE=0.364) which suggest that the 4m putt data is skewed slightly to the putts that finished a long way from the hole and past the hole with a more peaked than normal curve (Figure 6.1.1a), whilst the 8m putt data is relatively symmetrical, and still more peaked than normal but less so than for the 4m putts (Figure 6.1.1b).





Figures 6.1.1a and b: Histogram representation of putt results by exact distance (cm) (a) 4m putts (n=171), (b) 8m putts (n=176). This data excludes holed out putts. Negative sign (-) indicates putt finished short of the hole.

Having eliminated the holed out putts, the kurtosis values suggest that the data is still grouped in a small area of the curve for the 4m putts. The skewness data suggest that the 4m putting task was more likely to produce a “too long” putt result. There may be a number of factors that could explain this result. Players may have considered the 4m task to be easier than the 8m task so were more likely to attempt to hit the ball into the hole as they believed that they could get the ball in the hole. Even though all players were encouraged to hit the ball into the hole for both tasks, hitting the ball into the hole from 8m away may have been considered a less realistic task. The 4m task is easier and players were less likely to leave the ball “too short” of the hole. The more equal spread of “too short” and “too long” putts at the 8m task creates a more symmetrical distribution in the data compared to the 4m task results.

All putts that missed produced an overall average 4m putt result of the ball finishing 21.2cm past the hole with a median of 27cm and inter-quartile range (IQR) of 76cm. For the 8m putts, the average result for the missed putts was 7cm past the hole with a median of 11.5cm and IQR of 107.75cm. In these calculations, putts that finished in the hole have been deleted, such that final sample numbers are 171 for 4m putts and 176 for 8m putts (Tables 6.1.3 and 4). The data for all putts (n=190) is presented for reference.

Table 6.1.3: Descriptive data on 4m putts using exact putt result data (cm).

	n	%	Min	Max	Mean	Median	IQR
Putts short of hole	64	37.4	-100	-1	-34.80	-32.5	
Putts past hole	107	62.6	10	206	54.64	47	
All misses	171	100	-100	206	21.16	27	76
All putts	190		-100	206	19.05	23	67.5

Table 6.1.4: Descriptive data on 8m putts using exact putt result data (cm).

	n	%	Min	Max	Mean	Median	IQR
Putts short of hole	83	47.2	-280	-1	-63.84	-49	
Putts past hole	93	52.8	1	210	70.24	58	
All misses	176	100	-280	210	7.01	11.5	107.75
All putts	190		-280	210	6.49	0	99.25

These small central tendency values for all missed putts are affected by the scoring method used in this study. The putts that finished short of the hole were recorded as negative values and those that finished past the hole as positive. Tables 6.1.3 and 6.1.4 provide data on putt result based on the exact putt result (short of, or past, the hole). With the putts that finished in the hole deleted, there is a clear tendency for players to hit the ball past the hole at the 4m distance

The frequency data for direction of 4m putts (Table 6.1.5) indicates a clear trend towards putts being hit to the right of the hole (70% right vs. 18.4% left). Chi square analysis of direction of putt (left, right or on-line) reveals a significant difference between these classifications ($\chi 2 = 57.2$, $p < 0.01$). This calculation used the actual number of putts on line as the expected value (that is, n= 22 expected for on line putts), then distributed the remaining putts evenly between the left and right sides (that is, for right and left the expected number of putts = 84). This method of equal expected distributions for left and right putts produced a significant result as the right side is well above expected values and the left side is well below expected values.

Table 6.1.5: Classification of 4m putts by direction.

Putt result by direction	n	%
Left	35	18.4
Right	133	70.0
On-line	22	11.6
Total	190	100.0

When this trend is assessed across the order of putts, the ability of players to learn from the previous putt and find the correct line improves with more putts but never achieves equity between left and right (Table 6.1.6). Combining all first putt data, 30 putts were hit to the right of the hole and 4 putts to the left on the first attempt. By the fifth putt, 22 putts were hit to the right of the hole compared to 11 hit to the left.

Table 6.1.6: Frequency data for 4m putts based on putt number by putt result.

		Putt#					Total
Result		1	2	3	4	5	
Holed out	Count	3	3	5	4	4	19
	% within putt#	7.9%	7.9%	13.2%	10.5%	10.5%	10.0%
Long left	Count	4	2	2	5	5	18
	% within putt#	10.5%	5.3%	5.3%	13.2%	13.2%	9.5%
Long right	Count	21	17	19	16	16	89
	% within putt#	55.3%	44.7%	50.0%	42.1%	42.1%	46.8%
Short centre	Count	1	0	0	1	1	3
	% within putt#	2.6%	.0%	.0%	2.6%	2.6%	1.6%
Short left	Count	0	5	1	5	6	17
	% within putt#	.0%	13.2%	2.6%	13.2%	15.8%	8.9%
Short right	Count	9	11	11	7	6	44
	% within putt#	23.7%	28.9%	28.9%	18.4%	15.8%	23.2%
Total	Count	38	38	38	38	38	190
	% within putt#	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

It should be noted that after each putt each player was asked to step off the mat whilst the mat system was zeroed. The player was then asked to step back on to the mat and ready themselves for the next putt. The players were not constrained in their stance and alignment during this task, and all players were able to see the result of each putt. The results therefore are surprising as it was assumed that the result of the previous putt would be used to inform the performance of the subsequent putt on this task. It is possible that the putt results are influenced by the set up used for the putting task, but the knowledge of result of the previous putt was expected to produce a more even spread of results than has been recorded here. It appears that many players were expecting the ball to move from right to left as it traveled towards the hole, and even though it did not do this throughout the putting task, what they perceived to be the correct line (slightly to the right of the hole) was incorrect and with trial and error minimal corrections were produced. Both putting tasks in this study were straight putts. Assessing the frequency data for trends in length of putt reveals that at the 4m putting task the ball was hit with enough velocity to reach or pass the hole the majority of the time (66.3%) (Table 6.1.7). This represents approximately two thirds of all putts at the 4m hole and supports the higher than normal skewness value reported for this putting task. Players were more likely to hit the ball past the hole than leave it short at this task. This tendency is a technique advocated by Pelz (2000) as it increases the chance that the ball will go into the hole. Analysis of the overall trend of putt length indicates that there is a significant difference between putt length classifications ($\chi 2 = 20.3$, $p < 0.01$).

Table 6.1.7: Classification of 4m putts by length.

Putt result by length	n	%
Short	64	33.7
Long + Holed out	126	66.3
Total	190	100.0

Using the data presented in Table 6.1.6, the putt by putt details indicate that the biggest change in putt result by length occurred between the first and second putts. On the first putt, 28 putts reached or past the hole compared to 10 left short. On the second putt 22 putts reached or past the hole compared to 16 left short (the number of holed out putts did not change between putt numbers). The second putt data is the only putt number where the 2:1 ratio of long to short putts is not evident. However, the overriding trend in this data indicates players were more likely to hit the ball with enough velocity to reach or pass the hole on this putting task.

The same analyses as above were performed on the 8m putt frequency data. The assessment of putt direction indicated that the overwhelming trend of hitting the ball to the right of the hole in the 4m task was not evident in the 8m task. The data in table 6.1.8 indicates that there is an even distribution between the left and right classifications. Chi square analysis performed with the assumption of equal expected distributions between the left and right sides, and using the actual number of on-line putts as the expected distribution for that classification, indicates non-significant differences between the classifications ($\chi2 = 0.02$, $p = 0.99$).

Table 6.1.8: Classification of 8m putts by direction.

	n	%
Left	87	45.8
Right	89	46.8
On-line	14	7.4
Total	190	100.0

Overall data for putt length (Table 6.1.9) subsequently reveals a non-significant trend between long and holed out putts compared to short putts at the 8m task ($\chi2 = 3.03$, $p = 0.08$). Compared to the results for the 4m task, frequency data for the 8m putting task more closely resemble a normal distribution across classifications for both direction and length of putt. The more difficult putting task is revealed as the task more likely to produce an even spread of data. The perceived difficulty of the 8m task may have been more likely to produce a variety of methods within the sample in their approach to the task. One method or approach may have seen players focusing on leaving the ball close to the hole, and being careful not to leave a "too long" putt. Another method may have focused on making sure the ball got to the hole, not being afraid of hitting the ball well past the hole, as there were no consequences to a missed putt in this study. It may also be the case that the longer putting task is more difficult so the spread of data is greater. However, calculating the co-efficient of variation (CV) for the absolute distance parameters on both 4m (70%) and 8m putts (76%) reveals a slightly greater variation in the data in the 8m putting task indicating the sample of players performs relatively the same on the two putting tasks.

Table 6.1.9: Classification of 8m putts by length.

Putt result by length	n	%
Short	83	43.7
Long + Holed out	107	56.3
Total	190	100.0

The putt by putt result data presented in Table 6.1.10 allows further analysis of trends in the data. Of note is the change between first and second putts for the "long" and "short" results in the 8m putts. This data would seem to indicate that a typical response to leaving a putt short (or long) is to attempt to ensure that the same result does not occur on the following putt. This tendency across the group produces a mirror image of the first putt result on the second putt (frequency of long putts decreased on 2nd putt, frequency of short putts increased on 2nd putt). However, increasing the number of putts left short of the hole would not be considered an improvement in performance as those putts have no chance of going in the hole, but from a players perspective may be a good strategy to reduce the chance of having a 3-putt by ensuring the ball does not go “too long”.

Table 6.1.10: Frequency data for 8m putts based on putt number by putt result.

Result		Putt #					Total
		1	2	3	4	5	
Holed out	Count	4	2	3	2	3	14
	% within putt #	10.5%	5.3%	7.9%	5.3%	7.9%	7.4%
Long left	Count	17	7	11	10	12	57
	% within putt #	44.7%	18.4%	28.9%	26.3%	31.6%	30.0%
Long right	Count	10	8	8	6	4	36
	% within putt #	26.3%	21.1%	21.1%	15.8%	10.5%	18.9%
Short left	Count	3	9	4	8	6	30
	% within putt #	7.9%	23.7%	10.5%	21.1%	15.8%	15.8%
Short centre	Count	0	0	0	0	0	0
	% within putt #	0%	0%	0%	0%	0%	0%
Short right	Count	4	12	12	12	13	53
	% within putt #	10.5%	31.6%	31.6%	31.6%	34.2%	27.9%
Total	Count	38	38	38	38	38	190

Assessment of the holed out data in isolation indicates that a greater number of putts were holed at the 4m task (n=19, 10%) compared to the 8m task (n=14, 7.4%). The longer putting task is considered the more difficult, so the difference in results is not surprising. Data from Cochran and Stobbs (1968) on successful putts from a range of 3.6-4.5m indicates a success rate of 23% in the professional player. Each of the putts recorded by Cochran and Stobbs would be considered “first putts” under the classification used in the present study, as the professional player would be attempting that particular putt for the first and only time under competition conditions. Applying similar criteria to the present study, the data reveals that rather than a success rate of 10%, taking first putts only into account produces a slightly lower success rate of 7.9% (3 of 38). The sample of players used in the present study hole out much less than the professional golfers of 1967 at a 4m putting task.

The success rate of professional golfers putting from around the 8m distance was reported by Cochran and Stobbs (1968) at 4%. The overall value of 7.4% recorded in this study indicates an excellent rate of holed out putts on the more difficult task by comparison. When only first putts from the present study are assessed, the success rate overall increases to 10.5% as 4 of 38 players were able to hole out on the first putt at the 8m putting task. It is unclear why the players in the present study achieved such a – comparatively – good result. The data may be reflective of the different approach to putting at the 8m task by the professional golfers compared to the present sample. Whilst some of the players in the present study may have approached the 8m putting task with the attitude that they would strive to achieve a holed putt on the task, the professional player facing an 8m putt is probably striving to achieve a putt result that leaves the ball close to the hole for the subsequent putt.

Alternatively, it could be considered that the excellent results produced in the present sample are partly due to the methodology employed. All players had hit five putts at the 4m hole by the time they hit their first putt at the 8m hole. This gave these players the opportunity to assess the speed of the green and the initial four metres of the path to the 8m hole. This allowed the present players practice at the task that is not possible for the professional player, and could subsequently have contributed to the better performance reported in this data at the 8m putting task.

6.2 Putting performance – grouped analysis (analysing individual putt performance in groups according to handicap)

To assess whether there were differences between groups of players according to handicap, each player was assigned into a low (1-9, n=10), middle (10-18, n=14) or high (19-27, n=13) handicap group. The low handicap group was selected as those with a single figure handicap (an important milestone for the club golfer) and then subsequent divisions based on a factor of nine up to and including the maximum male handicap of 27. These classification groups have been used previously in golfing literature (e.g. McLaughlin and Best, 1994) and also reflect the grading of players in golf club competitions (A grade = 0-9, B grade = 10-18, C grade = 18+).

6.2.1 Results of 4m putts analysis

The data in Table 6.2.1.1 presents 4m putt results by handicap group and putt direction. The analysis detailed in the previous section highlighted the significant difference between the direction of putts when the overall data were assessed. Breaking this data down into handicap groups reveals non-significant differences between groups and classifications ($\chi 2$ = 5.5, p = 0.24). The data on left and right putt direction indicate that across the handicap levels, little if any trend is apparent. However, when the holed out putts are assessed across groups, the trend is for the low handicap group (18%) to produce the best result, the middle handicap group the next best (10.7%) and the high handicap group to produce the poorest result (3.1%).

Table 6.2.1.1: 4m putt by direction and handicap groups.

Putt result by direction	Low	Middle	High
Left	9 (18.0%)	13 (17.3%)	13 (20%)
Right	31 (62.0%)	54 (72.0%)	48 (73.8%)
On-line (holed + short centre)	10 (20.0%)	8 (10.7%)	4 (6.2%)
Total	50 (100%)	75 (100%)	65 (100%)

Using Cochran and Stobbs (1968) reported success rate for putts from 3.6-4.5m of 23% as a benchmark to calculate expected results, chi square analysis reveals that the differences in holed out putts between groups are significant ($\chi 2 = 6.3$, $p = 0.04$). Both the low and middle handicap groups were significantly better at holing putts than the high handicap group, and the low handicap group was significantly better than the middle handicap group. As a measure of game related performance, the number of holed out putts may be the most relevant in the assessment of group differences.

Assessment of the length of putts by handicap reveals non-significant differences between the groups ($\chi 2 = 1.03$, $p = 0.6$). The data in table 6.2.1.2 indicate an even spread of values across the groupings that falls into line with the approximately 2:1 ratio of long to short putts indicated in the previous section. No handicap group was significantly more likely to achieve a long putt than any other group although the trend in the data indicates a greater proportion of putts from the low to high handicap groups are to increasingly finish short of the hole.

Table 6.2.1.2: 4m putts by length and handicap groups.

Putt result by length	Low	Middle	High
Long + holed out	34 (68%)	52 (69.3%)	40 (61.5%)
Short	16 (32%)	23 (30.7%)	25 (38.5%)
Total	50 (100%)	75 (100%)	65 (100%)
Ratio long:short	2.13:1	2.26:1	1.6:1

When group data were assessed using distance measures, the general similarity between groups was, for the most part, maintained. The exact putt result (cm) and the absolute putt result (cm) data were assessed across groups using the Kruskall-Wallis non parametric technique. As reported previously, the exact result data had a data set skewed to the longer putt results (skewness = 0.45). By generating an absolute result for each putt, this further skewed the data. Both sets of data failed the tests of normality required for parametric analysis of data (table 6.2.1.3).

Table 6.2.1.3: 4m putt result data assessed for normality.

Parameter	Kolmogorov-Smirnov		Shapiro-Wilk	
	Statistic	p	Statistic	p
Exact 4m putt result	0.08	<0.01	0.97	<0.01
Absolute 4m putt result	0.12	<0.01	0.86	<0.01

Kruskall-Wallis analysis revealed non-significant differences between groups when the groups were assessed for exact putt result (table 6.2.1.4). However, assessment of the absolute putt result data indicates a significant difference was present between the high handicap group and the other two groups ($\chi 2 = 6.62$, $p = 0.04$). The high handicap group achieved a significantly higher mean absolute putt result than the other two groups. This indicates the less skilled golfer was significantly more likely to leave the ball further away from the hole than the middle or low handicap golfer. This would likely lead to an increased number of putts, by comparison, during an 18 hole round of golf. The data revealed no significant difference between the low and middle handicap groups. When the 19 holed putts were removed from the analysis, non significant results were recorded for both parameters across all groups. Whilst all mean values increased with the removal of the holed putts, the effect on the absolute distance means was to bring all group values closer together, thus non-significant results were recorded. Therefore, with holed out putts removed players of all skill levels leave the ball a similar distance from the hole on missed putts. These mean values equate to a distance from the hole that has been termed a “good miss” result (Cochran and Stobbs, 1968; Pelz, 2000). Previously published data suggests that at short distances (0.9m - 2m), players of all skill levels are equally likely to hole a putt (Delay et al., 1997; McCarty, 2002; Fairweather and Sanders, n.d.), so the mean absolute distance of around 0.5m would not have an effect on the number of putts per round for the less skilled golfers. This data again points to the logical choice of the number of holed out putts being most indicative of skill level.

Table 6.2.1.4: Putt distances by handicap groups, exact and absolute distance values.

Result (cm)			**4m putt (all putts) n = 190**			**4m putt (no holed putts) n =171**	
Group	**n**	**Mean H’cap**	**Exact distance mean (cm)±SD**	**Absolute distance mean (cm)±SD**	**n**	**Exact distance mean (cm)±SD**	**Absolute distance mean (cm)±SD**
Low	**50**	6.2	20.2±50.5	38.6±38.1	**41**	24.7±54.9	47.1±36.9
Middle	**75**	13.8	15.9±47.6	39.3±30.9	**67**	17.8±50.0	44.0±29.4
High	**65**	22.7	21.8±56.5	49.2±34.9	**63**	22.5±57.3	50.7±34.3
Overall	**190**	14.5	19.1±51.3	42.5±34.4	**171**	21.2±53.7	47.2±33.1
$\chi 2$			***0.45***	***6.62***		***0.45***	***2.12***
p			***0.8***	***0.04***		***0.8***	***0.35***

McCarty (2002) reported that of the two putting tasks (2m and 4m) completed in his study, handicap was more closely related to performance on the longer task (4m) which is in contrast to the present study. McCarty reported absolute putt result values (on an indoor putting task on synthetic grass) of 25.6±14.7cm vs. 32.9±18.6cm for low (<14 handicap) and high handicap (>14) groups respectively on a 4m putting task. With at least 275 putts in each group, a mean difference of 7.3cm was enough to produce a significant difference between groups in the McCarty study. McCarty's data comes from a slightly different methodology to that used in the present study. In the McCarty study, players were required to stand in the same position for every putt – as the outline of their feet was traced onto the floor - so reproducing the same alignment and stroke would have been easier than in the present study. Also, McCarty asked the players to stop the ball on the "hole" marked on the carpeted surface. This resulted in a far smaller proportion of putts traveling past the hole (43.8% overall). Taking a slightly different view, the ability of the low handicap group to hole out more often from the 4m distance may be the defining difference between the groups in the present study. The number of holed out putts has been reported in only one previous study and that data were collected from players putting in tournament conditions (Cochran and Stobbs, 1968).

In order to assess the presence of any effects between groups, Cohen's *d* was calculated between pairs of groups. Using Cohen's conventions, effect sizes up to 0.5 are considered small, between 0.51 and 0.8 are considered medium, and greater than 0.8 considered large (Cohen, 1988). This data, reported in Table 6.2.1.5, confirms small differences between the handicap groups, and confirms the assessment from the data that apart from the holed out putts and the absolute putt result when all putts are included, no statistically significant differences exist within this sample of players based on putting performance for the 4m putting task.

Table 6.2.1.5: Effect size data for 4m putt distance based on handicap groups.

Analysis results	Cohen's d (all putts)	n = 190		Cohen's d (no holed putts)	n =171
Group	Exact mean	Absolute mean		Exact mean	Absolute mean
1 v 2	0.09	-0.02		0.13	0.09
1 v 3	-0.03	-0.31		0.04	-0.11
2 v 3	-0.11	-0.29		-0.09	-0.21

Further analysis of putt result was performed by categorizing the data based on result divisions (Table 6.2.1.6). In this analysis, putt result was broken down into 50cm divisions and coded accordingly based on exact putt result. Frequency data categorized into 50cm divisions highlights the grouping of the putts around the hole. With the holed out putts included, 70% of all putts at the 4m hole finished within a 50cm radius and 95.8% finished within a 1m radius. These data contributed to a highly kurtotic (1.253) distribution curve when all holed out putts were included or excluded (0.867).

Of the putts that missed the hole, two-thirds (66.7%) finished within a 50cm radius, with 55% of these finishing past the hole. Similarly, 95.3% of missed putts finished within a 1m radius of the hole, with 57.9% of these passing the hole. The percentage of putts finishing past the hole represents those putts that at least had the potential to go into the hole.

Table 6.2.1.6: Frequency data by 50cm divisions of putt result at the 4m hole by group (n=190).

		Low	Middle	High	Total
200+	Count	0	1	1	2
	% within group	.0%	1.3%	1.5%	1.1%
151-200	Count	2	0	1	3
	% within group	4.0%	.0%	1.5%	1.6%
101-150	Count	2	1	0	3
	% within group	4.0%	1.3%	.0%	1.6%
51-100	Count	9	10	17	36
	% within group	18.0%	13.3%	26.2%	18.9%
1-50	Count	12	32	19	63
	% within group	24.0%	42.7%	29.2%	33.2%
Holed out	Count	9	8	2	19
	% within group	18.0%	10.7%	3.1%	10.0%
-1 - -50	Count	14	16	21	51
	% within group	28.0%	21.3%	32.3%	26.8%
-51 - -100	Count	2	7	4	13
	% within group	4.0%	9.3%	6.2%	6.8%
Total	Count	50	75	65	190
Summary					
50cm radius	Count	35	56	42	133
	% within group	70%	74.7%	64.6%	70%
100cm radius	Count	46	73	63	182
	% within group	92%	97.3%	96.9%	95.8%

Cochran and Stobbs (1968) reported on the putting performance of professional players during a competition round of golf. The authors reported that when a professional player was putting in the range of 3.6-4.5m and missed a putt, the ball would finish within 45cm (1 ½ feet) of the hole 100% of the time. These data were reported in Table 2.2.1.1 in this thesis. This value is different to the values recorded in the present study irrespective of handicap groupings and reflects not only a possible difference in skill level, but also a possible difference in approach to the task. The professional player being more likely to take a careful approach to the task and ensure that he does not leave a “too long” result in the context of the competition and/or environmental conditions (speed of greens, weather conditions) he/she is faced with at the time.

For each putt the professional player takes – or any player in a competition – there is a possible consequence of a missed putt. A missed putt is not the best possible outcome, but leaving the ball close enough to hit in on the next stroke is the next best possible outcome. Cochran and Stobbs (1968) reported that on 99% of occasions when the ball finished within 45cm of the hole, the professional player was able to hole the subsequent putt. The professional player, aware of the consequences, would complete the 4m task accordingly. By comparison, the players in the present study did not need to hit any subsequent putts from a missed putt, and were free to strike the ball without fear of the penalty of a badly missed putt.

A total of 82 putts at the 4m task finished in the hole or within 50cm past the hole (43.1%). This distance equates to the 42cm range advocated by Pelz (2000) as indicative of a putt struck with enough velocity to reach the hole and also to the 45cm used by Cochran and Stobbs (1968) to assess the success of subsequent putts. It is considered by Pelz (2000) and supported by data from Cochran and Stobbs (1968) to be the same two putt range. Of this study’s 82 putts, 48.8%

were achieved by the middle handicap group, 25.6% by the low handicap group, and 25.6% by the high handicap group. As a percentage of the number of putts in each handicap group, these values equate to 42% of the low handicap group's putts, 53% of the middle handicap group's putts, and 32% of the high handicap group's putts. With equally expected results on this parameter from each of the handicap groups, these data reveal a significant difference between the middle handicap group and the other two groups ($\chi2 = 8.81$, $p = 0.01$). The middle handicap group were more likely to achieve a holed out or up to 50cm past the hole putt result than the other two groups.

All handicap groups left at least 30% of all putts short of the hole. This is also in line with the reported spread of overall data. Surprisingly, both the low and high handicap groups recorded higher frequencies in this result group than in the corresponding category past the hole. The lower percentage of putts in the "up to 50cm short" range for the middle handicap group (21.3%) compared to the low handicap group (28%) is unexpected. But as indicated above, analysis of data using 50cm divisions of results highlights the better performance of the middle handicap group compared to the other two groups when length of putt is the only criteria. However, it is also possible to argue that the ultimate measure of performance – the number of holed putts – illustrates the higher performance level of the low handicap group on this putting task. In the author's opinion, most golfers would take the increased number of holed out putts.

It is possible to take all this information on putt length result, combine it with previously published data and turn it into game relevant data for this sample of players. However, these calculations are based on the assumption that over the course of 18 holes, each player takes their first putt at each hole from 4m.

Cochran and Stobbs (1968) provide data on completion of a 3.6 – 4.5m putting task, and the success rate of putts from 45cm and on putts between 1.8 and 2.9m. Fairweather and Sanders (n.d.) provide completion rate data for putts from 0.9m for players of various handicap levels. Using this information, the data on holed putts calculations were made on the total number of putts per round for this sample of players based on the following:

- The number of holed out putts for each group as reported in table 6.2.1.6. (Putts per hole = 1).

All other putts classified as missed

- The success rate of putts within 50cm of the hole is 100% for all groups (Cochran and Stobbs, 1968). (Putts per hole = 2; original plus subsequent putt).
- The success rate of putts between 50cm and 100cm from the hole is 76.3% (Fairweather and Sanders, n.d.). (Putts per hole = 2.231).
- The success rate of putts greater than 1m from the hole is 48% (Cochran and Stobbs, 1968). (Putts per hole = 2.52).

The break down for each handicap group and Cochran and Stobbs (1968) sample is provided in Table 6.2.1.7.

Table 6.2.1.7: Breakdown of putt result by handicap groups and radial distance of ball finishing position for the 4m putting task. Pro group data from Cochran and Stobbs (1968).

	Pro	Low	Middle	High
Holed out	23%	18%	10.7%	3.1%
Within 50cm	77%	52%	64%	61.5%
50-100cm from hole	0%	22%	22.6%	32.4%
100cm plus from hole	0%	8%	2.6%	3%

Based on these results and using the assumption that a player starts with a 4m putt at every one of the 18 holes on the course, the total number of putts per 18 hole round and the average number of putts per hole indicates the (hypothetical) level of performance for each of these groups (Table 6.2.1.8).

Table 6.2.1.8: Calculated 18 hole putting results based on the performance of the present sample. Pro group data from Cochran and Stobbs (1968).

	Pro	Low	Mid	High
Total number of putts	31.86	34.4	35.23	37.07
Average per hole	1.78	1.91	1.96	2.06

Based on this data, the approach of the professional player – to not leave a too long putt – has a clear effect on the total number of putts taken per round. These players achieve the lowest number of putts per round by ensuring that if they did miss the hole, they comfortably holed the putt out on the next putt. Fairweather and Sanders (n.d.) presented data on a putting study conducted at the 2000 British Open where spectators (who had a golf handicap) were asked to complete three putting tasks. The data presented by these authors indicated a mean number of strokes to get the ball in the hole on a 3.6m putting task was 1.966 strokes, with only marginal differences between the lower and higher handicap groups. The data presented in Table 6.2.1.8 are similar to this data for the three handicap groupings in the present study (overall mean of 1.97), and appear to provide evidence of a distinction between the low and middle handicap group compared to the high handicap group in terms of putting performance. These data also indicate that if all players hit the ball to the same distance from the hole (4m), the scorecard would slightly favor the low handicap player over the middle handicap player, with a clear margin to the high handicap player.

It is unlikely that this situation would arise, of course, and one would assume that as handicap increased, the ability to hit the ball close to the hole would likely decrease. The data on the average number of putts per round of golf provides some insight into this. On average, the low handicap players indicated they took 30.5 putts per round, compared to 35.2 and 36.1 putts per round for the middle and high handicap groups respectively. This data would necessarily be influenced by the putt location which is determined by the skill of the player on approach shots to the green. The greater ability of hitting the ball close to the hole places the low handicap player in a more likely location to hole a putt, and in a less likely location from where they will make a three putt compared to the middle and high handicap player.

6.2.2 Results of 8m putts analysis

The 8m putt direction data were broken down into handicap group classifications to assess for the influence of group membership on putt alignment (Table 6.2.2.1). The overall data presented above had indicated a far more even distribution of putts between left and right for the 8m putting task, and the group data reflects this trend. Across the left and right classifications, the breakdown indicates near enough equal distribution of putts. However, in the on line (Holed plus short and centre, although for this task there were no short and centre) classification, there is a clear distinction between the high handicap group and the other two groups. This is confirmed by chi square analysis using Cochran and Stobbs (1968) success rate of 4% at this distance as the expected frequency benchmark ($\chi2 = 6.02$, $p = 0.049$).

Table 6.2.2.1: 8m putt by direction and handicap groups.

Putt result by direction	Low	Middle	High
Left	22 (44%)	34 (45.3%)	31 (47.7%)
Right	21 (42%)	35 (46.7%)	33 (50.8%)
On-line (holed + short centre)	7 (14%)	6 (8.0%)	1 (1.5%)
Total	50 (100%)	75 (100%)	65 (100%)

The low and middle handicap groups perform significantly better than the high handicap group in holing out putts on the 8m task. The low handicap group performs significantly better than the middle handicap group. Based on expected values in the chi-square calculation, the high handicap group performs below expectations, the middle handicap group performs to expectation, and the low handicap group performs above expectation.

Previously published data has compared the ability of elite and amateur golfers (Fairweather and Sanders, n.d.) or low handicap and high handicap golfers (McCarty, 2002) on putting tasks. The indication from these publications was that as the task increased in distance (and therefore difficulty) significant differences between groups were more likely. In the present study, the performance of each handicap group could be distinguished on both putting tasks based on the number of putts holed out. This suggests that, like the 4m distance, the number of holed out putts from 8m is a factor that influences individual handicap level. However, the implications of these data for the high handicap golfer are that they are significantly less likely to achieve a one putt result from 8m. Also of note, is they would be more likely to be putting from 8m than the other handicap levels if they are unable to hit the ball as close to the hole. The high handicap player may be more likely to be putting from a longer range than the other golfers and, if so, holing out rate at the 8m putting task would accentuate the difference in handicap levels when these data are related back to game score performance. The same reasoning would apply to the middle handicap group when compared to the low handicap group.

The length of putt by handicap group indicates that the low handicap group was able to maintain a ratio of long to short putts of close to 2:1 as presented for the 4m putting task (1.78:1 to be exact for the 8m putting task). As the overall data for the 8m task suggested a more even distribution of short (43.7%) and long putts (56.3%), the data for the low handicap group suggests the other two groups are less likely to achieve a similar ratio. Table 6.2.2.2 indicates that as handicap level across groups increases from low to high, the number of putts that reach the hole decreases (or the number of putts that are left short of the hole increases). However, this is a non-significant trend as chi square analysis reveals no difference between handicap group when all 8m putt length data is combined

($\chi 2$ = 3.33, p = 0.19), or when broken down into long putts by group ($\chi 2$ = 2.94, p = 0.23) or short putts by group ($\chi 2$ = 1.46, p = 0.48).

Table 6.2.2.2: 8m putts by length and handicap groups.

Putt result by direction	Low	Middle	High
Long + holed out	32 (64%)	44 (58.7%)	31 (47.7%)
Short	18 (36%)	31 (41.3%)	34 (52.3%)
Total	50 (100%)	75 (100%)	65 (100%)
Ratio long:short	1.78:1	1.42:1	0.91:1

The data on 8m putt results had suggested a closer to normal distribution of data compared to the 4m putt data. Analysis of the exact putt result data for normality indicated that these data were parametric. The absolute putt result data were assessed as non-parametric because of significant results on the Kolmogorov-Smirnov and Shapiro-Wilk statistics (Table 6.2.2.3). As a result, the exact distance data were assessed for between group differences using one-way ANOVA, and the absolute distance data were assessed using the Kruskall-Wallis non-parametric technique.

Table 6.2.2.3: 8m putt result data assessed for normality.

Parameter	Kolmogorov-Smirnov		Shapiro-Wilk	
	Statistic	p	Statistic	p
Exact 8m putt result	0.04	0.2	0.99	0.26
Absolute 8m putt result	0.12	<0.01	0.9	<0.01

The mean values for exact putt result suggest that all groups performed better on the 8m putting task than the 4m putting task (Table 6.2.2.4). This is more to do with the scoring system used in the study than a true reflection of performance. This result occurs because many more putts did not get to the hole producing a negative putt result. The high handicap group record a negative mean value overall and also when the holed out putts were excluded. Despite this difference, analysis of variance tests (both parametric and non-parametric) indicate that there were no significant differences between groups based on these putting performance measures. To indicate the non significant relationship between handicap and putting performance, when holed out putts were removed from the mean value calculation the low handicap group actually recorded the highest absolute mean result, making them the worst performing group on this measure. Again, this is suggestive of an anomaly in the method and calculation rather than a true reflection of performance.

Table 6.2.2.4: Putt distances by handicap groups, exact and absolute distance values for 8m putts.

Result (cm)			**8m putt all putts (n=190)**			**8m putt no holed putts (n=176)**	
Group	**N**	**Mean H'cap**	**Exact distance mean (cm) ±SD**	**Absolute distance mean (cm) ±SD**	**N**	**Exact distance mean (cm) ±SD**	**Absolute distance mean (cm) ±SD**
Low	**50**	6.2	8.1±79.3	62.1±49.3	**43**	9.4±85.6	72.2±45.6
Middle	**75**	13.8	13.2±76.2	59.5±49.0	**69**	14.3±79.4	64.7±47.6
High	**65**	22.67	-2.4±88.1	65.6±58.3	**64**	-2.5±88.8	66.6±58.2
Overall	**190**	14.5	6.5±81.1	62.3±52.2	**176**	7.0±84.3	67.2±51.1
F or χ2			***F = 0.65***	***χ2 = 0.12***		***F = 0.68***	***χ2 = 1.81***
P			***0.52***	***0.94***		***0.51***	***0.40***

Effect size data based on the values reported in table 6.2.2.4 are presented in table 6.2.2.5 and highlight the lack of differences between groups. The mean value data suggests that the 8m putting task is less distinguishing of skill level than the 4m task as values are closer together and no trend in effect sizes is evident. As no previously published research has assessed putting at this task length, it is difficult to compare data in the present study to others. However, the results presented here contrast the work of previous authors who suggest that as the task length increases, differences between skill levels become more apparent (McCarty, 2002; Fairweather and Sanders, n.d.). The comparison between elite or low handicap players and social or novice golfers that is common in the literature does not provide insight into the differences between handicap levels of golfers who are regular players.

Table 6.2.2.5: Effect size data for 8m putt results based on handicap groups.

Analysis results	Cohen's d (all putts)	N = 190		Cohen's d (no holed putts)	N =176
Group	Exact average	Absolute average		Exact average	Absolute average
1 v 2	-0.06	0.05		-0.06	0.15
1 v 3	0.13	-0.07		0.14	0.11
2 v 3	0.19	-0.12		0.2	-0.04

When broken down into 50cm divisions around the hole (Table 6.2.2.6), the putt result data reveals that all handicap groups leave around half of all putts within 50cm of the hole (51.6%) and around 80% within 1m of the hole. Cochran and Stobbs (1968) reported that when putting from around 8m, professional players left the ball within 45cm of the hole 87% of the time. Comparatively the missed putts in this study were left within 50cm of the hole only 47.7% of the time, with the high handicap group recording the only value greater than 50% for this measure. These data suggest a clear distinction between the professional and the players in the present study in terms of putting strategy. At the longer distance putts, it is possible that the professional does not seek to get the ball into the hole, but within a certain radius or target area of the hole. As mentioned earlier, some players in the present study may have approached the 8m putting task with the attitude that they would strive to achieve a holed putt on the task, resulting in a “too long” putt. There was no penalty for the “too long” putt in this method. In comparison, the professional player facing an 8m putt is probably striving to achieve a putt result that leaves the ball close enough to the hole to ensure a maximum of two putts is taken on that green. It is possible that some of the players in the present study also took this attitude at this task and the resultant even spread of data is evidence of this. The difference between the professional player and the sample of players in the present study may also – and most likely – be because the professional players are better putters.

In short, previously presented data indicate the low handicap group are more likely to hole putts at the 4m task (p=0.04) and are more likely to hole putts at the 8m task (p=0.049). As a measure of performance that most affects a golfer score, these data distinguish the low handicap group as the best putters in the present study.

Table 6.2.2.6: Frequency data by 50cm divisions of putt result at the 8m hole by group (n=190).

		Group			Total
Distance from the hole (cm)		Low	Middle	high	
201+	Count	0	0	1	1
	% within group	.0%	.0%	1.5%	.5%
151 - 200	Count	1	4	3	8
	% within group	2.0%	5.3%	4.6%	4.2%
101 - 150	Count	5	2	1	8
	% within group	10.0%	2.7%	1.5%	4.2%
51 - 100	Count	7	17	9	33
	% within group	14.0%	22.7%	13.8%	17.4%
1 - 50	Count	12	15	15	42
	% within group	24.0%	20.0%	23.1%	22.1%
Holed out	Count	7	6	1	14
	% within group	14.0%	8.0%	1.5%	7.4%
-1 to -50	Count	8	16	18	42
	% within group	16.0%	21.3%	27.7%	22.1%
-51 to -100	Count	4	11	10	25
	% within group	8.0%	14.7%	15.4%	13.2%
-101 to -150	Count	4	3	4	11
	% within group	8.0%	4.0%	6.2%	5.8%
-151 to -200	Count	2	1	2	5
	% within group	4.0%	1.3%	3.1%	2.6%
-200 and more	Count	0	0	1	1
	% within group	.0%	.0%	1.5%	.5%
Total	Count	50	75	65	190
	% within group	100.0%	100.0%	100.0%	100.0%
Summary					
50cm radius	Count	27	37	34	98
	% within group	54%	49.3%	52.3%	51.5%
100cm radius	Count	38	65	53	156
	% within group	76%	86.7%	81.5%	82.1%

A hypothetical analysis of the number of putts per 18 hole round of this sample of players was based on the following:

- The number of holed out putts for each group as reported in table 6.2.2.7. (Putts per hole = 1).

All other putts classified as missed

- The success rate of putts within 50cm of the hole is 100% for all groups (Cochran and Stobbs, 1968). (Putts per hole = 2 - original plus subsequent putt).
- The success rate of putts between 50cm and 100cm from the hole is 76.3% (Fairweather and Sanders, n.d.). (Putts per hole = 2.231).
- The success rate of putts greater than 1m from the hole is 48% (Cochran and Stobbs, 1968). (Putts per hole = 2.52).
- The break down for each handicap group and Cochran and Stobbs (1968) sample is provided in Table 6.2.2.5.

Table 6.2.2.7: Breakdown of putt result by handicap groups and radial distance of ball finishing position for the 8m putting task. Pro group data from Cochran and Stobbs (1968).

	Pro	Low	Middle	High
Holed out	4%	14%	8%	1.5%
Within 50cm	83.3%	40%	41.3%	50.8%
50-100cm from hole	12.7%	22%	37.4%	29.2%
100cm plus from hole		24%	13.3%	18.4%

Based on these results and using the assumption that a player starts with an 8m putt at every one of the 18 holes on the course, the total number of putts per 18 hole round and the average number of putts per hole indicates the (hypothetical) level of performance for each of these groups (Table 6.2.2.8).

Table 6.2.2.8: Calculated 18 hole putting results based on the performance of the present sample on the 8m putting task. Pro group data from Cochran and Stobbs (1968).

	Pro	Low	Mid	High
Total number of putts	35.81	36.64	37.36	38.64
Average per hole	1.99	2.04	2.08	2.15

Fairweather and Sanders reported putting data on a 7.2m putting task and reported that the average number of putts to get the ball into the hole was 2.31 strokes across all handicap levels. The data in the present study indicate a higher success rate and may be due to the repeated nature of the task in the present study compared to that used in the Fairweather and Sanders study. Table 6.2.2.8 data indicate a two stroke advantage to the low handicap player over the high handicap player if all putts were taken from the 8m range. As mentioned previously, these are hypothetical results based on all players having their first putt on the green from the same distance. Interestingly, the professional golfer of 1963 performed at a similar level to the low handicap golfer for the 8m putting task. The data indicate a difference in approach to the task – the professional having a small percentage of holed putts, but a high percentage of putts finishing close to the hole. The low handicap player striving to hole the putt, but leaving only half as many putts within 50cm of the hole.

The calculated data for the present sample in 4m and 8m putting tasks is summarized in Table 6.2.2.9. The trend in the data is for the low handicap group to perform best and the high handicap group to perform worst. Assuming that first putt distance for each of the handicap groupings will most likely be different (that is, the low handicap group will have more putts from a 4m range than the middle handicap group and the middle handicap group will have more putts from the 4m range than the high handicap group), the results of this analysis magnify the potential effect of putting performance to the score achieved in an 18 hole round of golf.

Table 6.2.2.9: Calculated average number of putts per hole for 4m and 8m putting tasks by handicap groups.

	Low	Mid	High
Average per hole at 4m task	1.91	1.96	2.06
Average per hole at 8m task	2.04	2.09	2.15

6.3 Handicap vs. putt result at an individual level

With respect to the relationship between handicap and putting performance on an individual level, each player's performance was assessed in a number of ways, with each method based on a summary of the individual's five putts. After the exact and absolute average data were calculated, it was decided to rank each player's performance based on their absolute average for each putting task – possible rankings for each putting task from 1 to 38. Descriptive outputs, ranked performance data, age and number of putts per round were then related to handicap using Pearson's correlation co-efficient.

This output (table 6.3.1) revealed a significant correlation between the absolute average on 4m putts and handicap ($r = 0.390$, $p = 0.016$) and ranked performance on the 4m putting task ($r=0.372$, $p=0.022$). Effectively, these two measures are the same for both the 4m ($r=0.98$, $p<0.01$) and 8m ($r=0.98$, $p<0.01$) putting tasks, so the ranking variable has been eliminated from the analysis. When controlling for age, the correlation between handicap and absolute average on 4m putts decreases only slightly ($r=0.388$) and remains significant (p=0.018). Thus, as handicap increased the absolute average increased (that is, the average result and ranking was worse). However, this parameter accounts for a maximum of 15% of the variability in the data.

Table 6.3.1: Pearson's product moment correlation co-efficient: handicap v number of putts, age and all averaged putt result data for each player (n=38).

	Putts per round	**Age**	**4m exact mean**	**4m abs mean**	**8m exact mean**	**8m abs mean**
r	0.69	0.68	0.09	0.39	-0.15	0.11
p	0.00	0.00	0.61	0.02	0.36	0.52

Other relationships of note with handicap include 4m putts exact average (r = 0.09, p = 0.61), 8m putts exact average (r = -0.15, p = 0.36) and 8m putts absolute average (r = 0.11, p = 0.52). All these combinations recorded non-significant values. Age was correlated strongly to handicap, but was not significantly correlated to any of the performance parameters presented here.

Interestingly, handicap was significantly related to number of putts per round (r = 0.666, p < 0.001). This was a question asked of players before testing – how many putts do you normally have per round of golf? This correlation result suggests that higher handicap players reported that they are less skilled putters than the middle and low handicap groups (of course, it also suggests that low handicap players reported that they are better putters than the middle and high handicap groups). Alternatively, in line with previous analysis, this may be reflective of the different starting positions of first putts between skill levels. The high handicap player has more putts because they do not hit the ball close to the hole from the fairway. The low handicap player has fewer putts because they are more skilled at getting the ball close to the hole from the fairway. This difference in skill level on the approach shot has an effect on the number of putts hit by a player in a round of golf.

So, is handicap an indicator of putting performance? Based on the data presented here and by previous authors, it would appear a tenuous link at best if using continuous parametric data to assess. The method of assessment of putting performance (exact and absolute distance measures) needs further thought. The data presented throughout this chapter has highlighted the ability of the low handicap group players to get the ball in the hole more often than either of the other two groups on both putting tasks. This would appear to be the most suitable measure of performance as it has the greatest effect on golf score.

The variability in mean continuous values in all groups suggests a spread of data that indicates an overlapping of performance, and possibly, technique between players. The following chapter will explore the putter head kinematics and COP data collected on this sample during the in-field testing part of this study to determine whether different putting techniques exist in this sample.

7 Data analysis - clusters

A total of 62 parameters were assessed further using cluster analysis. As highlighted in the literature review cluster analysis is used to group like items/subjects based on similarities in technique.

Putts that contained incomplete data have been excluded, thus 112 putts at the 4m distance and 125 putts at the 8m distance were initially assessed.

In the present study, each individual putt has been treated as a separate item. This is because the methodology employed in this study allowed the participant knowledge of results whilst performing the technique. Unlike gait or other repetitive skills where there is little or no feedback on performance, this task allowed athletes to make adjustments in their technique between putts. As a result, the researcher assumed that a player who hit the ball 200cm past the hole would adjust their technique on the next putt with the possibility of producing an improved performance.

A number of steps were completed to achieve the final cluster solutions for the 4m and 8m putts. The following section details these steps, and a chart summarizing the process is provided at the end of this section.

7.1 Data preparation and clustering processes

7.1.1 Standardisation of raw data

The following standardisation procedure was performed. Initially, data for all included putts and 64 variables were standardised. This process used the group range of data values (maximum minus minimum values) for each of the 64 parameters. Thus,

$$Z = \frac{X}{Max - Min}$$

where Z is the standardized value and X the raw value. Milligan and Cooper (1985) suggested that division by the range was the best method of standardization.

Standardisation was completed because of the different scales of measure within the parameters. It is possible that unequal scales can produce bias with the final cluster solutions in favor of those scales that are larger (Hair et al., 1995). For example, measurements of movement of the COP can be around 1-2 mm, timing parameters can be up to 700ms, and velocity values can be around 250cm/s for the putter head horizontal velocity. Standardizing the values helps to eliminate these numerical discrepancies. The raw and standardized input for both 4m and 8m putts are included in Appendix B.

7.1.2 Assessment of inter-parameter similarity and collinearity

The second step in the preparation for cluster analysis was to assess all parameters for similarity and collinearity.

According to Hair et al. (1995), the most effective way to assess similarity between parameters is by using Euclidean distance measures of dissimilarity. In a matrix that assesses each pair of variables, the lower the value the closer is the relationship between the pair. All standardized data were exported into SPSS V.12 software and using the Linear Regression options, Euclidean distances between each pair of variables were calculated (dissimilarity matrix). In order to determine a Euclidean distance cut-off value for exclusion based on a parameter being “too” similar to another, a similarity matrix was also created using Pearson’s correlation coefficient as the measure.

All pairs of standardised parameters with a correlation value greater than 0.9 and a Euclidean distance measure of less than 3 were denoted as closely related. Both of these conditions needed to be satisfied for one of the related parameters to be removed from the study. These cut-off values are relatively conservative in that they reflect a high level of similarity between parameters. However, in order to achieve the aims of the study, it was not deemed necessary to trim the list of parameters to an excessive level so the exclusion of only those parameters that were highly related was a suitable approach. The matrices for both short putts and long putts are presented in Appendix C.

Simultaneously, collinearity was assessed using the measures of Tolerance and Variance Inflation Factors (VIF) commonly used in regression analysis. These two parameters provide information on the linear relationship between independent variables when a dependent variable is being explained. Essentially, can the relationship of an independent variable to the dependent variable be explained by another independent variable? As cluster analysis weights each parameter equally throughout the process, this step in the screening process allows the researcher to ensure that the parameters used in the analysis are not going to create a solution weighted towards a specific group of variables. According to Hair et al. (1995), the collinearity measures, combined with the similarity measures, can be used to assess the suitability of parameters for inclusion into cluster analysis, and the researcher should eliminate parameters considered too closely related to another or likely to lead to a solution weighted to a specific group of parameters.

Using the SPSS software, Tolerance and VIF values were calculated for all parameters using putt result (exact distance) as the dependent variable. High VIF values and low (close to or equal to zero) tolerance values indicate a parameter is highly related to other independent variables (all VIF and collinearity results are presented in Appendix D).

Analysis of the VIF and Tolerance data for the 4m putting task indicated that the relationship of three parameters to the dependent variable could be explained by other parameters. These parameters were automatically detected by the collinearity software:

- Swing time to ball contact

- Combined downswing and follow through displacement x (cm)

Assessment of the similarity/dissimilarity data revealed the following pairs of data were considered closely related (r = correlation co-efficient value; ED = Euclidean distance):

- Combined downswing and follow through displacement x (cm) – follow through displacement x (cm) (r=0.92, ED=2.82),
- Follow through displacement y (cm) - combined downswing and follow through displacement y (cm) (r=1, ED=0.13),
- Backswing displacement (x) cm – downswing displacement (x) cm (r=0.98, ED=0.87).

With a third pair of variables - swing to BC (ms) and backswing time (ms) (r=0.96, ED = 3.15) – on the threshold of exclusion, but only satisfied one of the exclusion criteria. Combining these screening processes, and considering the relationship between parameters it was decided to exclude:

- Swing time to ball contact (ms) – can be explained using backswing time (ms)
- Combined downswing and follow through displacement x (cm) – can be explained using follow through displacement x
- Combined downswing and follow through displacement y (cm) – can be explained by follow through displacement y

- Downswing displacement x – can be explained through backswing displacement x. This was considered only after ensuring that all players in the sample started the backswing with the putter head close to the ball.

For the 8m putting task, VIF and Tolerance calculations did not automatically detect any parameters that could be excluded from the analysis based on their relationship to other variables and the independent variable (exact distance). Similarity data suggested the following parameters were highly related, based on correlation (r) and Euclidean distance (ED) measures:

- Swing time to ball contact (ms) – backswing time (ms) (r=0.96, ED=2.68)
- Combined downswing and follow through displacement x (cm) – follow through displacement x (cm) (r=0.91, ED=2.98)
- Combined downswing and follow through displacement y (cm) - follow through displacement x (cm) (r=0.92, ED=2.61)
- Downswing displacement y (cm) – backswing displacement y (cm) (r=0.91, ED=1.01)
- Combined downswing and follow through displacement y (cm) – follow through displacement y (cm) (r=0.98, ED=0.93)
- Putter maximum velocity y (cm/s) - follow through displacement y (cm) (r=0.9, ED=2.09)

Considering these data, the following parameters were excluded from the cluster analysis process in the 8m putting task

- Swing time to ball contact (ms) – can be explained by backswing time (ms)
- Follow through displacement y (cm) AND combined downswing and follow through displacement y (cm) – can be explained by relationship to maximum upward velocity of the putter head (m/s)
- Combined downswing and follow through displacement x (cm) – can be explained by follow through x (cm)
- Backswing displacement y (cm) – can be explained by downswing displacement y (cm)

It should be noted that Hair et al. (1995) suggest the cut off values used by SPSS are too lenient, allowing the inclusion of parameters with too high VIF and too low tolerance values. As many of the variables in the present study are logically related, it was expected that this screening process may produce a higher than normal number of parameters sensitive to variations in other variables (as according to Hair et al.). However, as this study is investigating parameters that have not previously been analysed, it was again decided that the more lenient screening of the SPSS software was well suited to the inclusive nature of the study.

7.2 Creating a cluster solution

It was proposed by Hair et al. (1995) that the best cluster solution may be one where the techniques of both hierarchical (agglomerative) and k-clustering (partitioning) are combined. This approach was adopted for the present study.

7.2.1 Hierarchical clustering

The hierarchical clustering technique was performed using SPSSv.12 software. All data were input to the program, and initially, a variety of proximity measures employed. The clearest solution of the data into clusters was achieved using the complete linkage (furthest neighbour) method with Euclidean distance as the proximity measure. The agglomeration schedule and dendogram were assessed to determine at what stage in the hierarchical process the greatest changes in the co-efficient occurred.

To help determine the correct number of clusters contained in the data a number of stopping rules were also implemented. These were the Variance Ration Criterion (VRC), the R Ratio, the C-Index and Point Biserial Correlation. In order to calculate these stopping rules, a number of data outputs were used. These outputs were provided by SPSS and included:

- the cluster group membership number of each putt,

- overall dissimilarity matrix containing Euclidean distance data (for calculation of C-Index and Point Biserial Index stopping rules)
- overall dissimilarity matrix containing squared Euclidean distance data (for calculation of Variance Ratio Criterion and R Ratio stopping rules)
- a within group dissimilarity matrix using squared Euclidean distance for each cluster solution.

These data were necessary to calculate stopping rules based on group membership and Euclidean distance (C Index and Point Biserial) and stopping rules based on sum of squares principles (VRC and R Ratio).

Using the sums of squares approach (used by VRC and R-Ratio), the overall dissimilarity matrix remained constant, and provided the Total Sum of Squares (TSS) value, whilst the sum of each of the within-cluster dissimilarity matrices were added to provide a total Within Groups Sum of Squares (WGSS) value. The C-Index and Point Biserial Correlation calculations used the Euclidean distance dissimilarity matrices output by SPSS. The calculation of all indices were completed using a customized Excel spreadsheet develop by Ball (2006) in the case of the C Index and Point Biserial calculations, and the same sheet was adapted by the present author in calculations of the VRC and R Ratio.

The hierarchical clustering solution stopping rules provided an initial impression on the make up of the clusters for both the 4m and 8m putts (more detail provided below). After assessment of the stopping rule data from the hierarchical clustering method, the approach was to use the mean value of each parameter by cluster group as the cluster seeds for the k-cluster analysis. This was completed for each clustering solution from 2 to 6 cluster levels. This process involves using the group membership of each cluster (that is, those putts within a cluster) to create mean values for each parameter. This is repeated for the number of possible cluster solutions being assessed.

7.2.2 K-Clustering

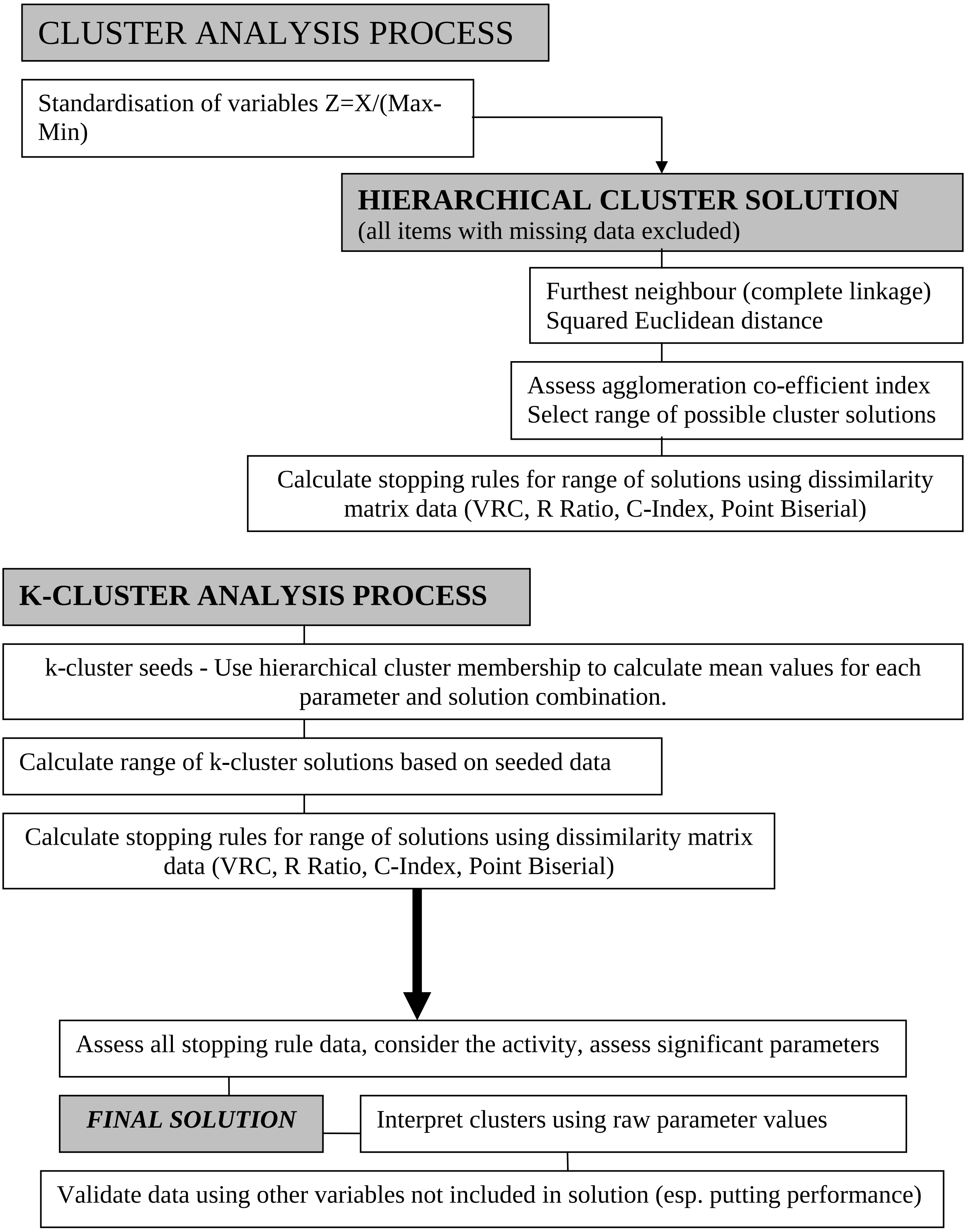
Hair et al. (1995) suggest that one of the weaknesses of k-clustering techniques is the lack of a starting point in the clustering process. With initial cluster seeds provided by the hierarchical process, one of the weaknesses of k-cluster techniques is eliminated.

Although it is possible to include items with missing values in the k-cluster program, the subsequent calculation of the stopping rules based on sum of squares principles is somewhat compromised. The pairwise deletion of parameters creates a different Total Sum of Squares value for each solution. This causes the WGSS and BGSS values used in the calculation of the VRC and R Ratio to have a different relationship across the range of solutions. The value of both these stopping rules is lost, as it becomes impossible to compare the indices across a range of solutions.

It was initially considered important to include as many items as possible in the final solutions, and missing values analysis was considered to increase the number of putts entered into the cluster analysis. However, this would have compromised the integrity of the methodology. The researcher’s intent to treat each putt individually would have been compromised if a missing value analysis (based on substituting missing values by those calculated based on normative data for that parameter) was carried out. As a result, a smaller, but complete, set of data were assessed.

The final number of clusters was based on a combination of the information provided by all of the stopping rules, the researcher’s knowledge of the area of investigation, the logical variability in the key parameters and the fit of the final solution. In the present study, the aims were based on determining the key parameters in good putting performance, specifically the role that balance plays in putting. Specifically, do good putters minimize movement of the COP during the execution of the putting stroke?

A summary of the steps in the cluster analysis process are detailed below.


CLUSTER ANALYSIS PROCESS
Standardisation of variables Z=X/(Max-Min)
HIERARCHICAL CLUSTER SOLUTION
(all items with missing data excluded)
Furthest neighbour (complete linkage)
Squared Euclidean distance
Assess agglomeration co-efficient index
Select range of possible cluster solutions
Calculate stopping rules for range of solutions using dissimilarity matrix data (VRC, R Ratio, C-Index, Point Biserial)
K-CLUSTER ANALYSIS PROCESS
k-cluster seeds - Use hierarchical cluster membership to calculate mean values for each parameter and solution combination.
Calculate range of k-cluster solutions based on seeded data
Calculate stopping rules for range of solutions using dissimilarity matrix data (VRC, R Ratio, C-Index, Point Biserial)
Assess all stopping rule data, consider the activity, assess significant parameters
FINAL SOLUTION
Interpret clusters using raw parameter values
Validate data using other variables not included in solution (esp. putting performance)

7.3 Cluster analysis of 4m putts

7.3.1 Hierarchical clustering

All standardized data were analysed using SPSSv12 hierarchical solution software options. The proximity measure used was squared Euclidean distance and the linkage method chosen was furthest neighbour.

The first attempt at the hierarchical solution revealed that four (of 112) items could be considered outliers. Data for both the agglomeration schedule and group membership progression through the last 10 stages are presented below (Tables 7.3.1.1 and 2). From the agglomeration schedule it was clear that the greatest change occurred in the second last stage when three clusters became two clusters (Table 7.3.1.1). Analysis of the cluster membership data indicated that throughout the process four items had remained separate to the rest of the clusters (Table 7.3.1.2) These four items were in three separate clusters (n=2, n=1, n=1). Two of these clusters joined together late in the process (5 cluster solution, stage 107) and joined the main cluster in the second last stage (2 cluster solution, stage 110), whilst the other cluster (n=1) remained separate from the "main" cluster until the final stage. Hair et al. (1995) recommends the removal of such items from the process and re-calculation of the solution.

Table 7.3.1.1: Abbreviated agglomeration schedule for 4m putting task cluster analysis.

# of clusters	Stage	Coefficients	Change	%Change
10	102	8.4	0.2	1.7
9	103	8.5	0.1	18.1
8	104	10.1	1.5	11.0
7	105	11.2	1.1	3.8
6	106	11.6	0.4	5.9
5	107	12.3	0.7	11.3
4	108	13.7	1.4	93.0
3	109	26.4	12.7	158.7
2	110	68.4	41.9	108.5
1	111	142.6	74.2	

Table 7.3.1.2: Final 10 steps of hierarchical clustering process indicating group membership sizes and progression of outlying data to main cluster.

10 clusters	n	n	n	n	n	n	n	n	n	n
Hierarchical	45	6	10	20	6	**2**	12	9	**1**	**1**

9 clusters	n	n	n	n	n	n	n	n	n
Hierarchical	45	16	20	6	**2**	12	9	**1**	**1**

8 clusters	n	n	n	n	n	n	n	n
Hierarchical	65	16	6	**2**	12	9	**1**	**1**

7 clusters	n	n	n	n	n	n	n
Hierarchical	81	6	**2**	12	9	**1**	**1**

6 clusters	n	n	n	n	n	n
Hierarchical	81	15	**2**	12	**1**	**1**

5 clusters	n	n	n	n	n
Hierarchical	81	15	**3**	12	**1**

4 clusters	n	n	n	n
Hierarchical	93	15	**3**	**1**

3 clusters	n	n	n
Hierarchical	108	**3**	**1**

2 clusters	n	n
Hierarchical	111	**1**

1 cluster	n
Hierarchical	112

Subsequently, four items were eliminated from the sample (items 13, 31, 32, 97) and the hierarchical clustering process repeated. On examination of the subsequent agglomeration schedule, it was evident that the greatest changes in coefficient occurred in the last 9 steps (see Table 7.3.1.3). The membership of each group in each clustering solution reflected the elimination of the four outliers from the process (Table 7.3.1.4). The agglomeration schedule indicates that the coefficient changes remained consistent with the original schedule with differences occurring because of the eliminated outliers (and subsequent elimination of steps where these outliers were clustered together).

Table 7.3.1.3: Abbreviated agglomeration schedule for the hierarchical cluster solution of 4m putts.

# of clusters	Stage	Coefficients	Change	%Change
10	98	6.9	0.0	18.1
9	99	8.2	1.3	0.1
8	100	8.2	0.0	2.8
7	101	8.4	0.2	1.7
6	102	8.5	0.1	18.1
5	103	10.1	1.5	11.0
4	104	11.2	1.1	3.8
3	105	11.6	0.4	17.9
2	106	13.7	2.1	93.0
1	107	26.4	12.7	

Table 7.3.1.4: Final 10 steps of hierarchical clustering process indicating group membership sizes and progression of outlying data to main cluster after 4 items deleted.

10 clusters	n	n	n	n	n	n	n	n	n	n
Hierarchical	34	6	5	20	6	12	5	4	11	5

9 clusters	n	n	n	n	n	n	n	n	n
Hierarchical	45	6	5	20	6	12	5	4	5

8 clusters	n	n	n	n	n	n	n	n
Hierarchical	45	6	10	20	6	12	5	4

7 clusters	n	n	n	n	n	n	n
Hierarchical	45	6	10	20	6	12	9

6 clusters	n	n	n	n	n	n
Hierarchical	45	16	20	6	12	9

5 clusters	n	n	n	n	n
Hierarchical	65	16	6	12	9

4 clusters	n	n	n	n
Hierarchical	81	6	12	9

3 clusters	n	n	n
Hierarchical	81	15	12

2 clusters	n	n
Hierarchical	93	15

1 cluster	n
Hierarchical	108

By calculating the change in coefficient between successive steps in the process, it was evident that the greatest single change (93%) occurred in the last step in the process however a large change (18.1%) occurred in the change from 10 clusters to 9 clusters. The dendogram confirmed this large change in the last step and provided an indication that a possible cluster solution was present in any of the last 10 steps (with 108 items, the dendogram covers three pages and is provided for reference in Appendix E).

The appropriate output for the four stopping rules was calculated and exported into Microsoft Excel. This included dissimilarity matrices containing Euclidean distance measures for the calculation of the C-Index and Point Biserial correlations, and the squared Euclidean distance for the VRC and R-Ratio values. The calculation of these measures has been previously described, and the following data derived (Table 7.3.1.5):

Table 7.3.1.5: Summary of stopping rule indices on hierarchical 4m putt solution.

Cluster	Point r	C Index	VRC	R Ratio
2	0.59	1.03	20.51	7.47
3	0.48	1.05	14.53	4.98
4	0.48	1.03	11.68	7.47
5	0.51	1.12	11.12	5.07
6	0.39	1.45	10.23	3.50
7	0.40	1.37	9.30	2.14
8	0.41	1.35	8.36	3.25
9	0.41	1.31	7.87	7.33
10	0.41	1.69	8.23	2.47
11	0.39	1.55	7.76	4.39

All stopping rules recorded optimal criterion values for the two cluster solution for the 4m putting data, although two stopping rules also recorded equivalent optimal values at a 4 cluster solution level. The large change at the 9 cluster solution observed in the agglomeration schedule was reflected in the stopping rule data by small changes in direction of the values C Index, VRC and R Ratio. From this data, the most likely cluster solutions were in the range of 2-4 clusters, with the strongest support for a two cluster solution as at that level all stopping rules recorded an optimal value.

7.3.2 k-cluster output for 4m putts

Cluster seed data were calculated for cluster solutions between 2 and 5 groups. These data were derived from the hierarchical membership assigned during the agglomeration process. The 5 cluster data were required in order to calculate the R Ratio for the 4 cluster solution. The cluster seed files for this next step can be found in the Appendices (F).

Each calculation of the k-cluster solution required the user to select the number of clusters. The appropriate seed file was then entered into the process, and a solution containing cluster membership details of each item (in this instance, each putt) created. The relevant Euclidean distance and squared Euclidean distance matrices were generated and stopping rules calculated as per the hierarchical process. The output from SPSS also provides an ANOVA output table detailing the parameters that have had the greatest influence on the final cluster solution. This formed the basis of the analysis of results and interpretation of the clusters.

The stopping rule data contained in Table 7.3.2.1 from the k-cluster process provided supporting evidence for a two cluster solution. However, three of the stopping rules indicate a change in direction at the 4 cluster solution level suggesting the possibility of a 4 cluster solution also.

Table 7.3.2.1: Summary of stopping rule indices on k-cluster 4m putt solution.

Cluster	Point r	C Index	VRC	R Ratio
2	0.55	1.22	26.24	9.93
3	0.42	1.44	19.08	4.86
4	0.44	1.28	14.76	5.86

7.3.3 Cluster solution for 4m putts

Based on all of the stopping rule data it was decided that the data contained two clusters. The data on cluster membership indicates two groups of unequal size. Assessment of the k-cluster creation process suggests that there is one large group present in the process and a number of smaller groups within the data. Between the three cluster and two cluster solution (the final possible solution in the k-cluster process), it would appear that one of the smaller clusters is joined to the bigger clusters to form the final two cluster solution (Table 7.3.3.1). However, between these two solutions group members changed in a more complex way. Clusters 1 and 3 were combined, but 11 putts that were in cluster 1 at the three cluster level, became part of cluster 2 at the two cluster level. These membership data will be analysed more closely in the following section.

Table 7.3.3.1: Cluster membership for 4m putt solutions.

2 clusters	n	n
K-clusters	77	31

3 clusters	n	n	n
K-clusters	57	20	31

4 clusters	n	n	n	n
K-clusters	59	8	31	10

The ANOVA table output by SPSS during the k-cluster calculation indicates the most influential parameters in the process at each selected cluster solution level. In order to assess those variables that had the most influence on the final cluster solution, the most consistently influential parameters for 2, 3 and 4 clustering solutions were assessed.

For this part of the analysis, parameters that were most influential in the clustering process at a level of p<.001 were considered across each solution level. It should be noted that larger numbers of significant parameters contribute to the cluster solution as the possible number of clusters increases, but to be included in the list of most influential parameters, the parameter had to be significant at p<.001 for each possible solution from 2-4. At the 2 cluster solution 12 of 58 parameters were significant at p<.001 whilst at the 4 cluster solution 21 parameters were significant at this cut off level. Across these solutions, 11 parameters were consistently indicated as the most influential in these cluster solutions (see Table 7.3.3.2).

Table 7.3.3.2: The consistently (p<.001) most influential parameters in formation of clusters at levels 2-5 for 4m cluster solutions. These data are ordered from most influential based on F score for the two cluster solution.

Velocity of COPx at ball contact
Maximum velocity COPx towards the hole in the downswing
Range of COPx during the downswing
Maximum velocity of the COPx away from the hole during the backswing
Maximum velocity of the COPx towards the hole during the follow through
Time of maximum velocity of COPx away from the hole during the follow through
Time of maximum velocity of COPx velocity toward the hole during the follow through
Time of maximum velocity of COPx velocity away from the hole during the downswing
Range of COPx during the backswing
Position of COPx at end of backswing
Range of COPx movement during the follow through

The velocity of COPx at ball contact was the most influential (highest ranked) parameter across these cluster solutions. The other parameters all changed “ranking” at some stage in the process, that is, the order of most influential parameters varied with the cluster solutions. It should also be noted that all of these most influential parameters relate to COPx movement or timing of movement. No parameters related to movement of COPy or putter head kinematics are included. The ANOVA outputs indicating the influence of each parameter are included in Appendix F. The parameter that indicated movement of the COPy during the downswing was only significant for the two cluster solution ($p<0.001$), so was not included in this part of the process.

In the interpretation of clusters, it is necessary to explore the differences between clusters based on the influential parameters (Hair et al., 1995). For the present study, this involved the use of the raw (non-standardised) data and the cluster membership values. Significant differences ($p<.001$) existed between groups on all of these parameters when assessed using univariate ANOVA. Partial eta squared – a measure of effect size in ANOVA techniques - and power values are also presented.

As the clustering process combines subjective and objective decision making, the next section will assess the range of cluster solutions based on differences between groups for the 11 most influential parameters. Using this process, changes in group membership can also be assessed.

Note: It is important to remember that as cluster membership was determined on the characteristics of individual putts, players could be “members” of a number of different cluster groups. Thus, for some players it is not possible to categorise all of their performances as indicative of one cluster’s characteristics.

7.4 Interpreting the 4m cluster solution

The stopping rule data calculated on the 4m putting task provided strong support for a solution at the 2 cluster level. The data also suggested that an alternate (though less likely) solution may be present at the 4 cluster level. The analysis of the most influential parameters will concentrate on the 2 cluster solution, but throughout the analysis, consideration will also be given to the formation of clusters and how the final solution was created. As a result, mean data will be presented for the range of solutions from 2-4.

7.4.1 Analysis of the backswing phase

During the backswing phase of the putting stroke, the putter head is moving away from the hole. For this sample of 108 putts, the average putter head displacement on the backswing was 22.1cm±5.2cm (n=108). The data on range of COPx displacement during the backswing indicate that there was a mean amplitude of displacement of 6.3mm±4.8 (table 7.4.1.1). As the putter head and COPx movement are not necessarily synchronous, it is also necessary to assess the location of COPx at the end of the backswing (table 7.4.1.2). These mean data indicate an average location of the COPx at 3.7mm away from the hole at the end of the backswing compared to the location of COPx at address. The large standard deviation value suggests that some players may also have moved the COPx closer to the hole from its starting position. This is confirmed by further analysis that reveals 31.2% (24 of 77) of putts in cluster 1 and 12.9% (4 of 31) of putts in cluster 2 were completed after shifting the COPx closer to the hole relative to the address position at the end of the backswing phase.

Table 7.4.1.1: Range of COPx displacement during the backswing (mm). Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	2 clusters	3 clusters	4 clusters
1	4.9 (2.7)	5.6 (2.9)	5.8 (3.1)
2	9.6 (7.0)	11.4 (8.0)	5.3 (2.6)
3		4.3 (2.1)	4.3 (2.1)
4			16.2 (8.3)
5			
Total	6.3 (4.8)	6.3 (4.8)	6.3 (4.8)
η2	0.19	0.27	0.45
Power	1.00	1.00	1.00

Table 7.4.1.2: Position of the COPx at end of backswing relative to address (mm). Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	2 clusters	3 clusters	4 clusters
1	-2.2 (4.2)	-3.8 (4.1)	-4.1 (4.3)
2	-7.4 (7.7)	-9.2 (8.4)	-3.0 (4.1)
3		0.1 (3.8)	0.1 (3.8)
4			-13.6 (8.6)
5			
Total	-3.7 (5.9)	-3.7 (5.9)	-3.7 (5.9)
η2	0.16	0.28	0.39
Power	0.99	1.00	1.00

Assessment of putter head kinematic data indicates that neither the duration of the backswing (cluster 1 = 530ms; cluster 2 = 564ms; p = 0.16; d = 0.3) nor the horizontal displacement of the putter head (cluster 1 = 21.7cm; cluster 2 = 23.2cm; p = 0.18; d = 0.29) revealed significant differences between the two final clusters. The larger COPx movement of cluster 2 (n=31) during the backswing is not associated with a longer or slower backswing compared to cluster 1 (n=77).

The maximum velocity of COPx away from the hole in the backswing phase also helps to understand the putting technique. The mean data (table 7.4.1.3) suggest that the average maximum velocity of the COPx away from the hole during the downswing is 27.9mm/s. Correlation analysis indicates that the COPx displacement and maximal velocity values are closely related (r=0.8, p=0.00, n=108) in the backswing phase. As expected then, the mean values of the two clusters reflect the differences observed in the displacement data.

Table 7.4.1.3: The maximum velocity of COPx away from the hole in the backswing. Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	-22.1 (10.6)	-26.1 (10.8)	-26.8 (12.0)
2	-42.4 (21.2)	-48.5 (22.9)	-33.0 (18.1)
3		-18.1 (10.0)	-18.1 (10.0)
4			-61.0 (19.2)
5			
Total	-27.9 (17.0)	-27.9 (17.0)	-27.9 (17.0)
η2	0.29	0.37	0.46
Power	1.00	1.00	1.00

At all cluster solution levels, there were significant differences present between the clusters for these three backswing related parameters. Effect size data (assessed using partial eta squared greater than 0.2 as large; Speed and Anderson, 2000) also indicated large to medium effects for these parameters. During the clustering process, the cluster with the highest values at the 4 cluster solution level was eventually combined with the next highest cluster (cluster 2 + cluster 4 at the four cluster level) to form cluster 2 in the two cluster solution.

The two cluster solution reveals that the majority of putts, cluster 1 (n=77), use a technique that involves (on average) less movement of the COPx and a comparatively slower velocity of COPx during the backswing. Putter head displacements during the backswing phase are relatively similar for the two clusters (cluster 1 = 21.6cm; cluster 2 = 23.2cm; p=0.18; d = 0.29) and backswing times are also similar (cluster 1 = 530ms; cluster 2 = 564ms; p=0.16; d = 0.28). Slower and lesser movement of the COPx during the backswing is a distinguishing feature of putting technique, but does not translate into a difference between the clusters in putter head backswing kinematics.

7.4.2 Analysis of the downswing phase

The downswing phase of the putting technique is necessarily quicker than the backswing. Overall mean time to complete the backswing was 540ms compared to the mean time to complete the downswing of 256ms. The movement of the putter head occurs over the same distance in a much shorter period of time in order to develop putter head velocity that is maximized around ball contact. The tendency for players to incorporate some movement of the body toward the hole to assist in the development of putter head velocity would be seen in this phase if they utilised a ‘body putting’ technique (Pelz, 2000).

The COPx displacement data in the downswing indicates similar trends and values to the data relating to the backswing regarding the clustering process (table 7.4.2.1). Ultimately, two distinct cluster means were calculated indicating differences based on amplitude of movement during this phase of the stroke. The two smaller values at the three cluster level were again the basis for clustering at the two cluster level, and the larger mean values at cluster level 4 were eventually blended into cluster two at the final two cluster solution.

Table 7.4.2.1: Range of COPx during the downswing (mm). Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	3.9 (2.6)	5.1 (3.6)	5.2 (3.7)
2	10.6 (4.8)	11.8 (4.5)	13.9 (4.8)
3		3.3 (2.1)	3.3 (2.1)
4			10.5 (4.3)
5			
Total	5.8 (4.5)	5.8 (4.5)	5.8 (4.5)
η2	0.45	0.43	0.43
Power	1.00	1.00	1.00

In the final solution, cluster 1 had a smaller mean displacement of COPx in the downswing compared to the backswing. The opposite occurred for cluster 2. As a result, the data on COPx indicates that the COPx is (non-significantly) closer to the hole in cluster 2 (mean = 2.5mm) than cluster 1(mean = 0.8mm) at ball contact . The range of COPx in the downswing in cluster 2 has caused the COPx (on average) to travel past its position at address to a point closer to the hole. The technique displayed by cluster 1 indicates (on average) a return of the COPx back to the address position.

Not surprisingly then, the data on maximum velocity of COPx towards the hole in the downswing indicates a much larger value in cluster 2 when assessing the final cluster solution (table 7.4.2.2). The mean value achieved by cluster 1 (25.6mm/s) is similar to that achieved for this parameter in the backswing phase (22.1mm/s), whilst in cluster 2 there has been a substantial increase in the maximum velocity of COPx when comparing the two phases.

Table 7.4.2.2: The maximum velocity of COPx toward the hole in the downswing. Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	25.6 (15.7)	30.7 (19.3)	31.8 (20.1)
2	71.8 (28.3)	83.8 (25.2)	91.5 (27.3)
3		24.8 (15.2)	24.8 (15.2)
4			81.9 (23.5)
5			
Total	38.8 (29.0)	38.8 (29.0)	38.8 (29.0)
η2	0.53	0.56	0.55
Power	1.00	1.00	1.00

Putter head kinematic data reveal non significant differences between the two final clusters for downswing length (results equivalent to those produced for the backswing) and downswing time (cluster 1 = 253ms; cluster 2 = 266ms; p = 0.14;

d = 0.32). The trend for cluster 2 (n=31) to move the COPx further during the downswing has no influence on the duration of the downswing phase. Therefore, the greater COPx displacement in an equal amount of time creates a higher COPx velocity for cluster 2. The smaller (and larger) mean values in the earlier clustering levels were combined as previous, suggesting a continuing trend in the clustering process and clearly delineated clusters.

The differences in mean values suggest a vastly different approach to use of the movement of the COPx during the downswing phase for these two final clusters. Cluster 1 with a controlled movement of COPx during the downswing. Cluster 2 with a more pronounced movement of the COPx during the downswing to possibly assist in the production of putter head velocity. Data on when this maximum velocity of the COPx towards the hole occurred also reveals a significant difference in technique. Cluster 1 achieved a maximum velocity of COPx much earlier in the downswing phase than cluster 2 (cluster 1 = 111ms prior to contact; cluster 2 = 61ms; p = 0.01; d = 0.68). The COPx of cluster 2 was traveling at a greater rate closer to ball contact than cluster 1. This technique did not translate into differences regarding the maximal horizontal velocity of the putter head in the downswing phase. Both groups achieve their maximal value for this parameter post ball contact (cluster 1 = 17ms; cluster 2 = 14ms; p = 0.78; d = 0.06) indicating that the movement of the COPx is not influencing the kinematics of the putter head in a way that differentiates the techniques.

The data pertaining to the timing of the maximum velocity of COPx away from the hole is presented in table 7.4.2.3. This parameter is an indicator of the point in time during the downswing when COPx velocity, as a mean value, is in the opposite direction to that produced during the rest of the downswing. The asynchrony of the phases of movement of the putter head and COPx means that during the downswing of the putter head it is possible to achieve a local minima for this COPx velocity parameter. This local minima may be a turning point in the COPx velocity value.

Table 7.4.2.3: The time pre contact of maximum velocity of COPx away from the hole in the downswing. Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	124 (118)	206 (89)	207 (88)
2	247 (39)	249 (31)	230 (21)
3		17 (42)	17 (42)
4			264 (25)
5			
Total	160 (115)	160 (115)	160 (115)
$\eta 2$	0.23	0.64	0.64
Power	1.00	1.00	1.00

The data presented for the final two clusters highlights a large variability in the data for cluster 1 (n=77) (as indicated by a standard deviation almost as large as the mean value), and a highly homogenous value for cluster 2 (n=31). Combining the values from cluster 1 and 3 in the three cluster solution contributes to this. The wide spread of mean and raw values in these groups, necessarily creates a highly variable mean and standard deviation. The 11 putts that went from cluster 1 at the three cluster level to cluster 2 at the two cluster level had a mean (±SD) value of 244±51ms. The clustering process grouped these 11 with the 20 putts from cluster 2 at the three cluster level that had a mean value (±SD) of 249±31ms. The combination of clusters 1 and 3 from the three cluster level did not produce such a homogenous group.

The values indicate an early occurrence of this parameter in the downswing for cluster 2 (after 6.8% of the downswing has been completed) compared to a later occurrence (after 50.8% of the downswing) in cluster 1. The definitive movement of the COPx in the downswing produced by cluster 2 is in line with the previously presented evidence that suggests movement of the COPx may be used to produce putter head velocity in this particular putting technique. The data for cluster 1, especially the variability in the data, suggests less movement of the COPx during the downswing phase.

7.4.3 Analysis of ball contact

At all cluster solution levels, the velocity of COPx at ball contact (BC) was the most influential factor. When the data for each of the four cluster solutions are presented for COPx velocity at ball contact (table 7.4.3.1), cluster 1 mean values are consistently the lowest. In each solution, cluster 1 has the slowest moving COPx towards the hole at ball contact, suggesting this putting technique is associated with slower movements of the COPx towards the hole. In the final two cluster solution, the difference between the mean values is more than tenfold.

Table 7.4.3.1: The velocity of COPx at ball contact. Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	5.2 (16.9)	19.0 (14.2)	20.0 (14.9)
2	58.4 (22.9)	69.2 (21.7)	81.3 (21.0)
3		-8.3 (14.8)	-8.3 (14.8)
4			63.8 (19.6)
5			
Total	20.5 (30.6)	20.5 (30.6)	20.5 (30.6)
η2	0.63	0.73	0.74
Power	1	1	1

However, of note is the large standard deviation value recorded for cluster 1. Further analysis of the cluster 1 data reveals that 28 of 77 putts recorded a COPx velocity at ball contact with the COPx traveling away from the hole at the time of ball contact. No putts in cluster 2 recorded this result. Of these 28, 23 were in cluster 3 at the three cluster level. At that cluster level, only 8 of 31 in cluster 3 had a positive COPx velocity at ball contact. Not only did the clustering process combine these 31 putts with cluster 1 at the three cluster level, the process removed 11 putts from cluster 1 at the three cluster level and placed them in cluster 2 at the two cluster level (Figure 7.4.3.1). These 11 putts recorded the highest COPx velocity values (ranging from 32.68mm/s to 45.9mm/s) in cluster 1 at the three cluster level. These changes in cluster membership between solutions had the double effect on the mean value for cluster 1 at the two cluster level of incorporating a large number of negative values, and removing all high positive values. Subsequently, the mean result is close to zero but represents a mixture of techniques in terms of this parameter.

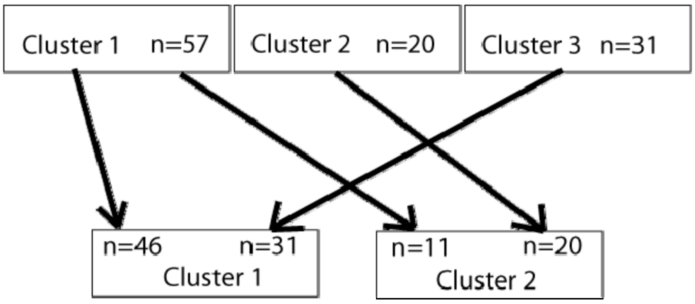


Figure 7.4.3.1: Change in cluster membership between three cluster and two cluster levels.

Does the use of the COPx in the putting stroke create a difference in putter head velocity at ball contact? Assessment of the putter head kinematic parameters around ball contact indicate that there were no significant differences between the two clusters when mean maximum putter head horizontal velocity (cluster 1 = 160.2cm/s; cluster 2 = 165cm/s; p=0.11; d=0.34), putter head horizontal velocity at ball contact (cluster 1 =154.5cm/s; cluster 2 = 158.9cm/s; p=0.052; d=0.44) and vertical velocity at ball contact (cluster 1 = 3.9cm/s; cluster 2 = 4.4cm/s; p=0.7; d=0.08) were assessed. Although the putter head velocity at ball contact was close to significantly different, the effect size data indicates small effect sizes for all differences, even though the trend in the mean values indicates higher values achieved by cluster 2 on all parameters.

Earlier in the clustering process at least one cluster mean was a negative mean value for COPx velocity at ball contact. This negative value was produced by cluster 3 at the 3 and 4 cluster level (n=31). This is indicative of another possible technique in terms of movement of the COPx during the putting stroke. The negative value suggests a movement of the COPx away from the hole around ball contact, with COPx moving towards the right foot. Correlation analysis indicates that this parameter was significantly related to putter head velocity at contact (r=0.22, p = 0.02) but was not related to putt result when measured using exact putt distance (r=0.09, p=0.34).

It is of note that the putts from these clusters that recorded negative values were ultimately blended into two clusters that produced mean values indicating (on average) movement towards the hole. However this slightly different technique (negative COPx velocity at ball contact) should be considered in future work. As this parameter was the most influential in cluster formation throughout all cluster levels, it is possible that the mean value on this parameter is a key distinguishing feature between clusters at all levels. Analysis of the other influential parameters at the three cluster level, for example, highlights that cluster 1 and cluster 3 are similar on most parameters apart from COPx velocity at ball contact.

7.4.4 Analysis of the follow through phase

The data on range of COPx during the follow through (table 7.4.4.1) shows the clustering process and the final cluster solution follow very similar patterns to the data presented previously. Ultimately, one cluster displays smaller amounts of movement of the COPx than the other cluster during the follow through (p<0.001), although in this phase the mean range of cluster 1 is greater than in the backswing or downswing phase, but still less than the value recorded by cluster 2.

For most players, the putter head travels its greatest distance in the follow through phase and this may contribute to the magnitude of COPx displacement. On average the putter head was displaced an extra 12cm horizontally when compared to the backswing and downswing phases (35cm compared to 23cm). At the two cluster level, there was a significant difference between the two cluster means for horizontal putter head displacement during the follow through (cluster 1 = 33.6cm; cluster 2 = 38.9cm; p =0.04; d = 0.45) and also for duration of follow through (cluster 1 = 385ms; cluster 2 = 450ms; p = 0.02; d = 0.51). These data suggest that the putting technique exhibited by cluster 2 produces slower, larger amplitude in the follow through stage. Previous assessment of kinematic data at the backswing and downswing phases revealed no significant differences when the two clusters were assessed on putter head kinematics.

Table 7.4.4.1: Range of COPx displacement during the follow through. Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	8.4 (8.2)	10.0 (6.0)	10.0 (5.9)
2	14.8 (8.4)	16.6 (9.8)	23.2 (5.0)
3		6.6 (10.3)	6.6 (10.3)
4			12.6 (10.8)
5			
Total	10.3 (8.8)	10.3 (8.8)	10.3 (8.8)
η2	0.11	0.15	0.22
Power	0.95	0.97	0.98

The COPx velocity data from the downswing phase and at ball contact indicated that cluster 1 players reduced the velocity of COPx at ball contact (tables 7.4.2.2

and 7.4.3.1). That is, after achieving a maximal COPx velocity during the downswing phase (25.6±15.7mm/s), players were able to reduce this COPx velocity at ball contact (5.2±16.9mm/s) to minimise the effect of movement of COPx on putter head velocity. Alternatively, the mean values for cluster 2 indicate only a small change in COPx velocity between the maximal downswing phase value (71.8±28.3mm/s) and the value at ball contact (58.4±22.9mm/s).

Table 7.4.4.2: Maximum velocity of the COPx towards the hole during the follow through (mm/s). Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	34.5 (24.6)	43.6 (23.4)	44.0 (23.2)
2	66.2 (27.8)	76.5 (29.6)	88.0 (19.3)
3		22.3 (16.6)	22.3 (16.6)
4			71.2 (36.2)
5			
Total	43.6 (29.2)	43.6 (29.2)	43.6 (29.2)
$\eta 2$	0.24	0.39	0.41
Power	1.00	1.00	1.00

In the follow through phase, the trend is for both cluster's COPx velocity means (table 7.4.4.2) to increase once ball contact has been made, with the largest increase occurring in cluster 1 (a mean change of 29.3mm/s). This large change created an overall mean value still slightly less than half that achieved by cluster 2. The maximum velocity of COPx toward the hole also occurred at a significantly (p<0.001) later time in the follow through (table 7.4.4.3) for cluster 1 (234±138ms) than cluster 2 (77±104ms). The high standard deviation values suggest a large range of values were present in both groups.

These data further highlight the difference between these two final clusters based on movement of COPx. One group minimises COPx movement range and velocity in the backswing, downswing and at ball contact, whilst the other group uses a technique that maintains a comparatively high level of displacement and velocity of COPx in those same phases. There are no significant putter head kinematic differences between these two groups.

Table 7.4.4.3: Time of maximum velocity of COPx towards the hole during the follow through. Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	234 (138)	214 (142)	211 (141)
2	77 (104)	54 (98)	33 (45)
3		230 (134)	230 (134)
4			60 (128)
5			
Total	189 (147)	189 (147)	189 (147)
η2	0.24	0.20	0.19
Power	1.00	1.00	0.99

At some point in time in the follow through phase there will be a turning point in COPx velocity where movement toward the hole ceases or starts back in the opposite direction. As mentioned earlier, both cluster means display long follow through phases in terms of both putter head displacement and time. The cluster mean values presented in table 7.4.4.4 indicate that this turning point occurs late in the follow through for cluster 2 (363±162ms), but about half way through the phase for cluster 1 (159±164ms). The value of cluster 1 is of particular note as previous analysis had revealed the maximal velocity of COPx towards the hole had occurred at a later point in time (234±138ms) for this cluster. Assessment of the mean and standard deviation for this cluster for this parameter indicates a large amount of variability for this parameter. Both groups recorded a large range of values fro this parameter (cluster 1 = 640ms; cluster 2 = 780ms) with some players achieving the maximal velocity of COPx towards the hole at ball contact, whilst others did not achieve it until the very last field of the follow through. This large variability does not allow clear distinctions between the two groups to be drawn.

Table 7.4.4.4: Time of maximum velocity of the COPx away from the hole during the follow through. Mean (SD) values for each cluster for cluster solutions 2-4 on 4m putts.

Cluster	**2 clusters**	**3 clusters**	**4 clusters**
1	159 (164)	224 (206)	226 (207)
2	363 (172)	361 (150)	365 (86)
3		112 (103)	112 (103)
4			372 (169)
5			
Total	217 (190)	217 (190)	217 (190)
$\eta 2$	0.24	0.20	0.20
Power	1.00	1.00	0.99

7.5 Profiling the 4m cluster solution

The two putting techniques identified in the previous section can be summarized as:

1. Less movement of COPx in the backswing and downswing phases with velocity of COPx at ball contact closer to zero (on average).
2. Larger movement of COPx in the backswing and downswing phases with velocity of COPx at ball contact relatively the same as that developed in the downswing.

As each putt was treated individually in this analysis, it was possible for players to be represented in both of the final clusters. With the reduction in the data analysed to a sample of 108, 4 players of the original 38 were not represented in the final analysis. Of the remaining 34, 5 players were represented by one putt only. Of interest is of the remaining 29 players with multiple putts in the analysis. Did they remain consistent in their allocation to clusters throughout?

Analysis reveals that 14 players remained in cluster 1 for all putts, 3 players remained in cluster 2 for all putts, with the remaining 12 players changing between clusters 1 and 2 during their putting trials. This equated to 13 putts that created a subsequent change from cluster 1 to cluster 2 and 11 putts that created a subsequent change from cluster 2 to cluster 1. Analysis of the subsequent cluster membership by 25cm putt result division indicates no clear distinction as to why players changed or stayed in their cluster on the subsequent putt (table 7.5.1). As an example, 7 of the 17 putts that finished further than 50cm past the hole created a subsequent change in cluster membership (that is, putting technique). On the other 10 occasions however, the subsequent putt was classified in the same cluster). There is no trend in this data.

Table 7.5.1: Breakdown of 4m putt result and the change (if any) in cluster membership as a result of that putt.

	Holed putt	-1-25cm	-25-50cm	-50-75cm	-75-100cm	+1-25cm	+25-50cm	+50-75cm	+75-100cm	+100 cm
Stayed in 1	3	3	7	4	N/A	4	12	3	4	1
Stayed in 2	2	N/A	N/A	N/A	1	1	3	2	N/A	N/A
Changed 1-2	1	3	2	N/A	N/A	1	2	2	1	1
Changed 2-1	1	1	1	N/A	N/A	3	2	2	N/A	1
Last putt	5	10	2	1	N/A	4	7	5	N/A	N/A

The three players who consistently performed the technique described by cluster 2 had a mean handicap of 14.3±10.1 and a mean age of 60.6±7.8 years. There were no significant differences between this group and those players who stayed in cluster 1 for age (51.1±16.9 years, p=0.173) or handicap (10.4±4.8, p=0.091). Similarly, there were no significant differences when compared to the group of cluster changers for age (60.6±17 years) or handicap (16.7±5.8). Further analysis revealed no significant differences between these three groups for absolute (p=0.664) or exact putt result (0.283). The ability to change putting technique, or the desire to change putting technique was not measured in this study, but may be an important factor for future analysis.

The differences in putting technique did not create significant differences between the two clusters based on putt result. The mean putt distance data were similar for both exact putt result (cluster 1 = 14.0±44.5cm; cluster 2 = 25.7±44.5cm; p=0.22; d=0.26) and absolute putt result (cluster 1 = 36.8±28.5cm; cluster 2 = 39.5±32.3cm; p=0.66; d=0.09). The exact putt result standard deviation data highlighting the spread of values across zero because of the scoring system used for that parameter.

Further assessment between the two final clusters consisted of breaking the putt result data into 25cm steps around the hole. This was in order to assess whether there were differences between the groups for the number of holed out putts and the ability of one technique to achieve a more game-friendly result. That is, does one technique produce a result that – if not holing the putt – leaves the ball close enough to the hole for success on the subsequent putt. It was earlier suggested that hitting the ball past the hole at least gives the ball a chance of going in the hole. Balanced with this is the desire to not hit the ball too far past the hole. The data presented in table 7.5.2 indicates cluster membership had some effect on putt result as described in this way. Both clusters were equally likely to hole out putts, but of the putts that missed, cluster 2 putts (70.9%) were more likely to go past the hole than putts from cluster 1 (50.6%) ($\chi2=3.86$, $p=0.05$). The technique displayed in cluster 2 is significantly more likely to produce a putting technique that allows the ball to get to the hole.

Table 7.5.2: Exact putt result by 25cm divisions and final cluster grouping for 4m putts. Data presented is count and percentage of total putts for each cluster.

	Cluster 1	**Cluster 2**
Holed out	**9 (11.7%)**	**3 (9.7%)**
25cm short	14 (18.2%)	3 (9.7%)
25-50cm short	10 (13%)	2 (6.5%)
50-75cm short	5 (6.5%)	0 (0%)
75-100cm short	0 (0%)	1 (3.2%)
Total short	**29 (37.7%)**	**5 (19.4%)**
25cm long	6 (7.8%)	7 (22.6%)
25-50cm long	19 (24.7%)	7 (22.6%)
50-75cm long	7 (9.1%)	7 (22.6%)
75-100cm long	5 (6.5%)	0 (0%)
+100cm long	2 (2.6%)	1 (3.2%)
Total long	**39 (50.6%)**	**22 (70.9%)**

The absolute putt result data were also assessed by ranking each putt and then creating four quartile segments. Top quartile represents the highest ranked (most accurate) 27 putts of the 108. The data were assessed across the two clusters to determine whether one technique was more likely to contribute to a more favorable outcome in terms of ranking of putts (table 7.5.3). As indicated there was a consistent distribution of the results throughout the rankings. The number of putts in cluster 1 makes up 71.3% of the sample and the distribution of putts across quartiles is consistent with this. Chi-square analysis revealed no significant differences between the groups for this parameter (p=0.987).

Table 7.5.3: The quartile range of putt result by cluster group for 4m putts.

	Cluster 1	**Cluster 2**
Top quartile	19 (67%)	8 (33%)
2nd quartile	20 (74%)	7 (26%)
3rd quartile	19 (67%)	8 (33%)
Bottom quartile	19 (67%)	8 (33%)
Total	**77**	**31**

The final two clusters can be distinguished on three important demographic factors – age, handicap and average number of putts per round. The mean age in cluster 1 (54.5±16.4 years) was significantly less than the mean age in cluster 2 (61.5±15.2 years) with p = 0.041 and an effect size of d = 0.43. Both clusters presented age ranges with a maximum of 84 years, but cluster 1 recorded a minimum value of 16 years (n=2) and a median of 59 years, compared to cluster 2 minimum of 33 years and a median of 64. As each putt was treated separately during this analysis, it was possible for a player to be represented in each final cluster group, however, the 16 year old player was a member of cluster 1 only.

Removing this player from the analysis creates a non-significant age difference between the groups (p = 0.67).

Handicap was considered to be a predictor of putting performance. The data pertaining to handicap reveals a significant difference between the groups (cluster 1 = 12.4±5.9; cluster 2 = 16.4±6.6; p = 0.002; d = 0.63) with a medium to large effect size present. The data relating to putt result indicated both clusters were equally likely to hole a putt, but cluster 2 were significantly (p=0.05)more likely to get the ball to or past the hole. Similarly, the number of putts taken per round was data collected by asking each participant how many putts they averaged during an 18 hole round of golf. Each player provided an answer that was subsequently averaged according to cluster membership. Cluster 1 players averaged 33.8±3.6 putts per round, whilst cluster 2 players averaged significantly more 35.5±2.6 putts per round (p=0.02; d= 0.52). The cluster with the lower handicap, (on average) younger members, who believed they were better putters and who used a technique that minimized movement of the COPx, were as likely as the other cluster to hole putts, but significantly less likely to get the ball to the hole at the 4m putting task.

7.6 *Cluster analysis of 8m putts*

7.6.1 Hierarchical clustering

The clustering process for the 8m putting data followed the process outlined in section 7.1. Four parameters were eliminated from the analysis in this section:

- Swing time to ball contact (ms)
- Follow through displacement y (cm)
- Combined downswing and follow through displacement x (cm)
- Backswing displacement y (cm)

The remaining parameters were entered into SPSSv12.0 and the first step in the clustering process was completed. The initial agglomeration schedule output from the hierarchical process indicated the greatest change occurred in the second last step in the process, suggesting a possible three cluster solution (table 7.6.1.1). Large changes were also indicated at the seven and 12 cluster stages.

Table 7.6.1.1: Abbreviated agglomeration schedule for 8m putting task cluster analysis.

# of clusters	Stage	Co-efficient	Change	% Change
12	113	6.0	0.1	12.0
11	114	6.8	0.7	2.0
10	115	6.9	0.1	5.4
9	116	7.3	0.4	4.5
8	117	7.6	0.3	0.5
7	118	7.6	0.0	11.0
6	119	8.5	0.8	1.3
5	120	8.6	0.1	8.8
4	121	9.3	0.8	8.5
3	122	10.1	0.8	21.6
2	123	12.3	2.2	10.7
1	124	13.6	1.3	

Analysis of the amalgamation of clusters and the cluster membership data indicated that 3 putts were outliers. The cluster membership data for the last 10 stages is presented in table 7.6.1.2 with the outlying values highlighted.

Table 7.6.1.2: Final 10 steps of clustering process indicating group membership sizes and progression of outlying data to main cluster.

10 clusters	n	n	n	n	n	n	**n**	n	n	**n**
Hierarchical	25	17	25	11	10	8	**1**	5	21	**2**

9 clusters	n	n	n	n	n	n	**n**	n	**n**
Hierarchical	25	38	25	11	10	8	**1**	5	**2**

8 clusters	n	n	n	n	n	n	**n**	**n**
Hierarchical	25	38	25	16	10	8	**1**	**2**

7 clusters	n	n	n	n	n	**n**	**n**
Hierarchical	25	46	25	16	10	**1**	**2**

6 clusters	n	n	n	n	**n**	**n**
Hierarchical	25	56	25	16	**1**	**2**

5 clusters	n	n	n	n	**n**
Hierarchical	25	56	26	16	**2**

4 clusters	n	n	n	**n**
Hierarchical	81	26	16	**2**

3 clusters	n	n	**n**
Hierarchical	81	42	**2**

2 clusters	n	n
Hierarchical	81	44

1 cluster	n
Hierarchical	125

Although these values were eventually amalgamated into larger clusters, it was decided to eliminate these putts from the clustering process (items 26, 104, 106) based on the recommendation of Hair et al. (1995). This left a total of 122 putts in the 8m clustering process.

The hierarchical process was repeated using the edited data file. The agglomeration schedule, which had previously provided supporting evidence for a three cluster solution because of the role of two of the outlying putts, now strongly suggested a two cluster solution. Further large changes occurred at the five and 10 cluster stages (table 7.6.1.3).

Table 7.6.1.3: Abbreviated agglomeration schedule for 8m putting task cluster analysis after 3 items were deleted.

# of clusters	Stage	Coefficient	Change	% Change
10	112	6.0	0.1	12.0
9	113	6.8	0.7	2.0
8	114	6.9	0.1	5.4
7	115	7.3	0.4	4.5
6	116	7.6	0.3	0.5
5	117	7.6	0.0	11.0
4	118	8.5	0.8	9.7
3	119	9.3	0.8	4.3
2	120	9.7	0.4	28.6
1	121	12.4	2.8	

The cluster membership information indicated in table 7.6.1.4 highlights the consistency of the clustering process in the early stages of the process after the removal of the outlying values, but in the latter stages indicates that the removal of the outliers has changed the resulting cluster memberships. Rather than the creation of a cluster of n=81 as was evidenced in the original process (step from 5 to 4 clusters), the edited process produces a larger group of n=106 at the step from 3 to 2 clusters. This cluster remains the dominant group until completion of the process.

Table 7.6.1.4: Final 10 steps of clustering process indicating group membership sizes and progression of outlying data to main cluster after 3 items deleted (n=122).

10 clusters	n	n	n	n	n	n	n	n	n	n
Hierarchical	19	17	15	11	10	6	10	8	5	21

9 clusters	n	n	n	n	n	n	n	n	n
Hierarchical	19	17	25	11	10	6	8	5	21

8 clusters	n	n	n	n	n	n	n	n
Hierarchical	25	17	25	11	10	8	5	21

7 clusters	n	n	n	n	n	n	n
Hierarchical	25	38	25	11	10	8	5

6 clusters	n	n	n	n	n	n
Hierarchical	25	38	25	16	10	8

5 clusters	n	n	n	n	n
Hierarchical	25	46	25	16	10

4 clusters	n	n	n	n
Hierarchical	25	56	25	16

3 clusters	n	n	n
Hierarchical	50	56	16

2 clusters	n	n
Hierarchical	106	16

1 cluster	n
Hierarchical	122

The inclusive nature of the study required the calculation of stopping rules up to the 10 cluster level to determine the most appropriate solution (table 7.6.1.5). Optimal values were recorded at the two cluster solution level for three of the four stopping rules. The data for the point biserial index indicated a solution containing nine clusters was possible. Although this was considered unlikely – owing to the fact that each of the three other stopping rules recorded far from optimal values at this cluster solution level – cluster seeds were created for k-cluster solutions from 2 – 10.

Table 7.6.1.5: Summary of stopping rule indices on hierarchical 8m putt solution

Cluster	Point r	C Index	VRC	R Ratio
2	0.40	1.02	10.97	9.49
3	0.34	1.95	10.41	8.82
4	0.35	1.48	10.20	6.68
5	0.38	1.75	9.60	5.14
6	0.39	2.19	8.92	3.79
7	0.40	2.06	8.21	7.90
8	0.40	3.60	8.52	4.27
9	0.41	3.16	8.17	4.07
10	0.40	4.46	7.88	2.17

7.6.2 k-cluster output for 8m putts

As with the 4m k-clustering process, the cluster seed files for this step can be viewed in the appendices (Appendix F). After the calculation of 9 possible solutions using k-clustering techniques, stopping rules were again calculated to determine the most appropriate cluster solution (table 7.6.2.1). The C Index and VRC stopping rules again recorded optimal values at the two cluster solution level, however both the Point biserial ratio and R ratio provided less clear indications of the optimal solution. The point biserial values for solution levels 5-10 did not provide a distinct indication for the optimal solution as all values were within 0.02 of the optimal value recorded at the seven cluster level. The R ratio recorded an optimal value at the four cluster level. The C Index value had increased for the two cluster solution between the hierarchical process and the k-cluster process suggesting a less clear delineation between clusters. The VRC value had increased after the k-cluster solution was calculated providing stronger support for the two cluster solution.

Table 7.6.2.1: Summary of stopping rule indices on k-cluster 8m putt solution

Cluster	Point r	C Index	VRC	R Ratio
2	0.36	1.50	15.19	9.01
3	0.39	1.84	12.53	8.80
4	0.40	2.29	11.77	9.42
5	0.43	4.46	11.76	3.67
6	0.43	3.45	10.34	3.76
7	0.44	3.38	9.44	4.26
8	0.42	3.88	8.91	5.01
9	0.43	4.14	8.68	4.45
10	0.43	3.60	8.43	2.15

7.6.3 Cluster solution for 8m putts

The lack of one truly reliable and definitive stopping rule necessitated the need to again acknowledge the possibility of a range of solutions, however there was a strong leaning – due to support from C Index, VRC and agglomeration schedule – for a final two cluster solution. Analysis of the stopping rule data between the two putting tasks (comparing 4m result to 8m results) indicates that the delineation of clusters at the 8m task is not as clear. The values tend to be higher in those variables where a minimal value is desirable, and lower where a maximum value is desirable. The fact that the C Index recorded a high value (>2) for the 4 cluster solution suggested that this solution could be ignored. The lack of support for a 3 cluster solution was also evident as no stopping rule recorded an optimal value at that level. It was decided that a two cluster solution was most likely in the 8m putting data.

The k-clustering process provided membership data for the final two cluster clusters, with the optimal solution containing two unevenly distributed groups of 78 and 44 members (table 7.6.3.1).

Table 7.6.3.1: Cluster membership for 8m putt solutions

2 clusters	n	n
K-clusters	78	44

At the two cluster level 21 of 58 parameters were significant at the p<0.001 level. Many of the parameters (8 of 16) identified as significant at the 4m putting solution were again prominent in the 8m putting solution (table 7.6.3.2).

Table 7.6.3.2: The most influential parameters in formation of final cluster solution 8m putting task. These data are ordered from most influential based on F score for the two cluster solution (p<0.001).

Time of maximum velocity of COPx away from the hole during the downswing*
Time of maximum velocity of COPx towards the hole during the backswing
Downswing time (ms)
Position of COPx at end of backswing*
Velocity of COPx at the start of the downswing
Range of COPx during the backswing*
Velocity of COPx at ball contact*
Time of maximum velocity of COPx towards the hole during downswing
Time of maximum velocity of COPx away from the hole during the follow through*
Follow through time(ms)
Range of COPx during the follow through
Maximum velocity of COPx away from the hole during the backswing*
Backswing time (ms)
Maximum velocity of COPy towards the heels during the backswing
Velocity of COPx at the start of the backswing
Maximum velocity of COPx towards the hole during the follow through*
Maximum velocity of COPx towards the hole during the backswing
Maximum upwards velocity of the putter head during the putting stroke
Horizontal putter head displacement in the backswing
Vertical velocity of the putter head at ball contact
Maximum velocity of COPx towards the hole during the downswing*

* indicates these parameters were also significant in the formation of the 4m cluster solution

Significant differences (p<.001) existed between groups on all of these parameters when the raw data were assessed using univariate ANOVA. Where parameters failed the homogeneity of variance test, non-parametric tests (Kruskal-Wallis) were completed to ensure the parameter indicated significant differences between the groups. Cohen’s d for effect size is also presented to support these findings.

7.7 Interpreting the 8m cluster solution

In the list of most influential parameters, parameters related to movement of the COPx were again the most featured (14 of 21). In contrast to the 4m solution there was one parameter related to movement of COPy and there were six parameters listed that related to putter head kinematics.

7.7.1 Analysis of the backswing phase

During the backswing both the putter head and the COPx tend to move away from the hole. This phase of the stroke puts the putter head into position in preparation for the downswing and ball contact. The data from the 4m putting analysis indicated that all players produce some movement of the COPx away from the hole at this stage. Of note is that in the 8m putting analysis, a significant difference exists between clusters for the COPx velocity at the start of the backswing (table 7.7.1.1).

As the methodology associated with data collection on COP involved the analysis of 20 samples prior to the first movement of the putter head, it was possible to calculate a COPx velocity value at the time of first movement. The data suggests that of the final two clusters, cluster one is moving distinctly away from the hole, whilst the other has a mean value that represents a small movement toward the hole. It should be noted that both cluster means indicate a range of values suggesting putts in these clusters produce a variety of COPx movements at address. Cluster 2 recorded a range of values from 60.3mm/s to -41.7mm/s whilst cluster 2 recorded a range of values from 16.4mm/s to -62.6mm/s.

Table 7.7.1.1: Velocity of the COPx at the start of the backswing (mm). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	-12.3 (18.5)
2	1.4 (22.4)
Total	-7.4 (21.0)
d	0.52
Power	0.95

During the backswing, the COPx is generally displaced away from the hole. The magnitude of movement of the COPx in this phase for each of the cluster levels is presented in table 7.8.1.2. These data indicate that cluster 1 of the final cluster solution, is indicative of a technique that has minimal COPx movement during the backswing, whilst cluster 2 produces a greater amount of COPx movement.

Table 7.7.1.2: Range of COPx during the backswing (mm). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	6.7 (3.9)
2	13.2 (8.2)
Total	9.0 (6.6)
d	0.98
Power	1.00

Analysis of putter head kinematic data for the backswing phase indicates that cluster 1 has a significantly shorter backswing length (Table 7.7.1.3) and backswing time (559±113ms vs. 647±108ms; $p < 0.001$; $d = 0.74$). The two clusters are clearly distinguishable by their different techniques in backswing production – short and sharp with minimal movement of COPx compared to slow, long with greater movement of COPx.

Table 7.7.1.3: Horizontal putter head displacement during the backswing (cm). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	26.8 (5.9)
2	30.5 (5.0)
Total	28.1 (5.9)
d	0.63
Power	0.93

The larger amplitude of putter head movement during the backswing phase also translates into a significant difference between the clusters for backswing time on the 8m putting task (Table 7.7.1.4). These data indicate a slower movement of the putter head in the backswing for cluster 2. This group has also demonstrated greater amplitude of movement of the COPx during the backswing phase.

Table 7.7.1.4: Mean (SD) values for backswing time (ms) for each cluster on 8m putts.

Cluster	**2 clusters**
1	559 (113)
2	647 (108)
Total	591 (119)
d	0.74
Power	0.99

The smaller amount of movement of COPx during the backswing phase translates into a position of COPx closer to address for cluster 1 (table 7.7.1.5) at the end of the backswing phase. Whilst the variability in cluster 1 suggests that some players are even closer to the COPx address. Further analysis of cluster 1 data indicates that 21 of 78 players moved the COPx closer to the hole during the backswing whilst the remaining 57 moved the COPx away from the hole. In cluster 2, only one player moved the COPx closer to the hole compared to the remaining 43 moving the COPx away from the hole. These data indicate a more homogenous technique in cluster 2 with regards to this parameter.

Table 7.7.1.5: Position of COPx at the end of backswing (mm). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	-3.6 (5.5)
2	-11.8 (8.9)
Total	-6.5 (7.9)
d	0.23
Power	1.00

During movement of the COPx away from the hole in the backswing, a maximum velocity for the phase is achieved. Previous analysis of 4m putting data indicated that this maximum velocity was related to the amount of displacement produced in the phase (table 7.7.1.6). The 8m putting data suggests the same relationship with the mean cluster values being reflective of the amount of COPx displacement. Further, correlation analysis indicates a significant relationship in 8m putting data between the maximum velocity of COPx away from the hole during the backswing with both COPx range during the backswing ($r = 0.79$, $p < 0.001$) and the position of COPx at the end of the backswing ($r = -0.55$, $p < 0.001$) for cluster 1 players. Even stronger correlation values are evident in cluster 2 ($r = 0.89$ and -0.85, $p<0.001$ respectively), further highlighting the homogenous nature of this cluster.

Table 7.7.1.6: Maximum velocity of COPx away from the hole during the backswing (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	-29.6 (15.1)
2	-44.3 (22.2)
Total	-34.9 (19.2)
d	0.77
Power	0.99

During the backswing phase most players are moving the COPx away from the hole at some stage. In fact, analysis of the maximum velocity of COPx away from the hole data indicates that the range of values is from 2.7mm/s to 119.9mm/s, showing all players are moving at some point in time in the expected direction. As the phase of the backswing defined by the putter head and movement of the COPx is not exactly in synchrony, it is likely that at some point the COPx will be moving in the opposite direction for some players during the backswing. That is, some players will not be moving the COPx away from the hole for the whole time that the putter head is moving away from the hole. The cluster mean data (Table 7.7.1.7) suggest these values could be interpreted as a minimal positive value rather than a value that indicates a turning point in the phase. However, the result range for both groups shows a variation of techniques, as values towards the hole and away from the hole were recorded for each cluster. These values range from -20.8mm/s (away from the hole) to 69.6mm/s (towards the hole). Individual putt results indicate that of the putts classified into cluster 1, only one demonstrated a continuous movement of the COPx away from the hole during the backswing, whilst eight players in cluster 2 demonstrated this tendency. All other players demonstrated a turning point in COPx movement during the backswing.

Table 7.7.1.7: Maximum velocity of COPx towards the hole during the backswing (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	25.7 (17.1)
2	14.1 (17.3)
Total	21.5 (18.0)
d	0.64
Power	0.94

The parameter related to when this value occurs in the backswing indicates a large difference in technique when mean values are compared (table 7.7.1.8). Whilst the cluster 1 mean result indicates that this local minima occurs late in the backswing phase (at 84% of mean backswing time), the cluster 2 mean suggests that this event occurs far earlier in the backswing (at 32% of mean backswing time). Both of these means have large standard deviations and large ranges that tend to further cloud the results. However, the large effect size indicates that this parameter is distinguishing of the two clusters.

Table 7.7.1.8:Time of maximum velocity of COPx towards the hole prior to the end of backswing (ms). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	-93 (151)
2	-438 (257)
Total	-217 (256)
d	1.35
Power	1.00

Movement of the COP can also occur in the antero-posterior direction. In the 4m task cluster analysis, no parameter related to this movement has been significant in distinguishing between the clusters. The data in Table 7.7.1.9 indicate a faster movement of the COPy towards the heels in cluster 2 compared to cluster 1. The COPy range in the backswing suggests minimal differences between the clusters (5.2±3.2mm vs. 6.5±3.7mm respectively) although the range of values is large for both groups.

Table 7.7.1.9: Maximum velocity of COPy towards the heels during the backswing (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	18.5 (11.8)
2	28.8 (17.8)
Total	22.2 (15.0)
d	0.69
Power	0.97

Finally, it is of note that the values demonstrated in the backswing for the 8m putting task are generally larger than the same parameters in the 4m putting task

(Table 7.7.1.10). The overall mean values are significantly greater in backswing length, backswing time, COPx displacement in the backswing, COPy displacement in the backswing, maximum velocity of COPx in the backswing and location of COPx at the end of the backswing. Only the position of COPy at the end of backswing was similar between the two tasks when a direct comparison was made. These data indicate the 8m putting task requires larger and longer amplitude of movement of the putter head. These data follow a similar trend to that reported by Delay et al. (1997) and McCarty (2002) who also compared to different length putting tasks. The data pertaining to movement of the COPx highlights an overall difference in the amplitude of movement between the two putting tasks also. No previous literature has reported COP data on the 8m putting task.

Table 7.7.1.10: Comparison of backswing parameter means between the 4m and 8m putting tasks. Mean (SD) values for each cluster on 8m putts.

	4m mean	8m mean	p	d
Horizontal displacement of putter head	22.1cm	28.1cm	<0.01	0.95
Vertical displacement of putter head	2.2cm	3.5cm	<0.01	0.89
Time	540ms	590ms	<0.01	0.43
COPx range	6.3mm	9.0mm	<0.01	0.45
COPy range	4.7mm	5.6mm	0.02	0.3
Maximum velocity of COPx	27.9mm/s	34.9mm/s	<0.01	0.38
Location of COPx at the end of the backswing	-3.7mm	-6.5mm	<0.01	0.39
Location of COPy at the end of the backswing	0.45mm	0.45mm	0.99	0.00

When assessing the final two clusters in both tasks, it is clear that delineation between techniques based on use of, or movement of, the COPx during the backswing is possible. However, only in the 8m task are these techniques also associated with distinctive movements of the putter head.

7.7.2 Analysis of the downswing phase

As with the start of the putting stroke, there is a significant influence of the COPx velocity at the start of the downswing on cluster formation. Again the data indicate that cluster 1 is moving in the anticipated direction of movement of the putter head, whilst cluster 2 mean value indicates movement in the opposite direction at the start of this phase. Similarly, the standard deviation values suggest a range of methods for this parameter with the zero crossing indicating members of both groups are not consistent in their (group) performance.

Table 7.7.2.1: Velocity of COPx at the start of downswing (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	2 clusters
1	19.1 (22.0)
2	-9.6 (28.8)
Total	8.8 (28.2)
d	1.02
Power	1.00

The backswing kinematic parameters of time and putter head displacement were shown to be significantly different between the two final clusters. In the downswing, the time taken to complete the phase has a significant influence on cluster formation and highlights differences between the two clusters. Cluster 1 displays a significantly smaller mean value than cluster 2 (table 7.7.2.2). This finding combined with significant differences in downswing length (28.9±7.9cm vs. 32.4±4.9cm; p= 0.01; d = 0.49), backswing time and backswing length indicates that cluster 1 are producing a technique of short, sharp movements compared to the long, slow movements of cluster 2.

Table 7.7.2.2: Length of time of downswing phase (ms). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	242 (40)
2	286 (26)
Total	258 (42)
d	1.05
Power	1.00

The downswing time for both the final clusters and the overall mean values compares favorably across the putting tasks. At the 4m putting task the overall downswing time was 256±42ms, with cluster 1 recording a mean value of 253ms and cluster 2 a mean value of 266ms. As indicated in table 7.5.2.2, these mean values suggest a consistency across players for the completion of the downswing across tasks. While it is logical to assume that the putter head will travel further on the downswing for the longer putts in order to produce a greater putter head velocity at ball contact (23.5±5.3cm for 4m putts and 30.2±7.2cm for 8m putts), the time taken to complete the task does not appear to change.

Using the test of equality, the downswing times were assessed using a 5% difference as an acceptable value. A non-significant result at the 5% level (p=0.08) was indicated, but at 10% tolerance a significant result was recorded (p=0.03). The exact level of difference was calculated as 8.5%, providing a p value of 0.046 for the test of equality. Considering that the sample rate of the video was 50Hz, each field is 20ms in length. The mean downswing time for the sample is roughly 13 fields (260ms). An error of one field in identifying the start of the downswing is an error of 1/13 or 7.7%. An error of identification at both ends of the downswing would be in the magnitude of 15.4%. A tolerance of 8.5% when assessing the equality of the phase seems realistic given the method used in the identification of these phases and provides some support for the notion proposed by Delay et al. (1997) that downswing time is the same across putting tasks of different lengths.

Though not identified as a significant parameter in the cluster formation, the displacement of COPx during the downswing does indicate a significant difference between the two clusters, with cluster 1 (8.1±6.3mm) achieving a smaller mean value than cluster 2 (11.7±6.3mm; $p < 0.001$; $d = 0.55$). Smaller displacement of the COPx may be associated with a smaller maximum COPx velocity value during the downswing. This trend is indicated in the data reported in table 7.7.2.3 which indicates cluster 1 produces a lower maximum velocity of the COPx towards the hole in the downswing. Of note though, is that cluster 1 has moved the COPx further during the downswing than the backswing, whilst the opposite has occurred for cluster 2. As a result, at the end of the downswing, the COPx is located on the hole side of its position at address for cluster 1 (3.5±7.6mm), but is located further away from the hole than it was at address in cluster 2 (-1.3±9.6mm; $p = 0.00$; $d = 0.55$). The data relating to position of COPx at ball contact were not significant in the formation of clusters but add further insight into the technique differences between these clusters.

Table 7.7.2.3: Maximum velocity of COPx towards the hole during the downswing (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	50.5 (36.8)
2	76.4 (45.9)
Total	59.8 (42.0)
d	0.62
Power	0.92

The timing of the maximum velocity of COPx towards the hole in the downswing provides insight into how the velocity of the COPx is manipulated by each player around ball contact. The closer this maximum occurs to ball contact, the more likely the player will exhibit a higher COPx velocity value at ball contact (cluster 1, r = -0.26, p = 0.02; cluster 2, r = -0.39, p < 0.001). The data presented in table 7.7.2.4 indicates that cluster 1 are producing the maximum velocity earlier in the downswing compared to cluster 2. This places them in a position which is more likely to result in a slower COPx velocity value at ball contact.

Table 7.7.2.4: Time of maximum velocity of COPx towards the hole during the downswing (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	-114 (72)
2	-54 (52)
Total	-92 (71)
d	0.85
Power	1.00

As previously explained in this analysis, the timing of a local minima or turning point is highly variable. In this instance, the data for cluster 2 follows more logically than cluster 1 (table 7.7.2.5). The turning point during the downswing phase occurs early in the downswing and the maximum velocity towards the hole of COPx occurs at a later stage. The data for cluster 1 is confounding as the timing of both maximum and minimum values occurs within one field of each other (on average). However, both cluster 1 means demonstrate high standard deviation values which highlight a variety of methods employed.

Table 7.7.2.5: Time of maximum COPx velocity away from the hole during the downswing (ms). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	-112 (110)
2	-275 (30)
Total	-171 (119)
d	1.37
Power	1.00

The continuing trend for the highest cluster means to be associated with cluster 2 highlights the distinctive nature of the putting technique associated with larger COPx movements and longer and slower putter head movements. This is a consistent pattern across both the backswing and downswing phases, and offers clear evidence of a difference in technique based on the parameters used in this study on this 8m putting task.

As highlighted earlier, the time taken to complete the downswing was similar across putting tasks, to the extent that working within the error associated with identification of the length of the phase, it could be argued that the downswing time remained unchanged between tasks. It should be noted that this analysis was completed without perfectly paired data (that is five samples on each putting task for each player) owing to the large number of omitted trials from the overall analysis.

When comparing downswing parameters across putting tasks – and ignoring downswing putter head displacement as backswing displacement was already shown to be different across the tasks – significant differences are present in two parameters only. The amount of COPx displacement during the downswing indicates a larger amplitude of COPx (5.8mm vs. 9.4mm; $p < 0.001$; $d = 0.61$). Higher values were also recorded for the maximum velocity of COPx towards the hole in the 8m putting task (38.8mm/s vs. 59.8mm/s; $p < 0.001$; $d = 0.55$).

Non-significant differences were present between putting tasks for all other parameters with most interest in the parameter relating to the location of COPx at ball contact position. This parameter determined the location of the COPx compared to the COPx position at the address position. As the data presented has indicated large movements of COPx are occurring in both tasks during both the backswing and downswing phases, it was surprising to find that at ball contact the COPx is in a similar position for both tasks (1.3mm to the left of address in the 4m task vs. 1.8mm to the left of address in the 8m task; $p = 0.63$;

d = 0.06). It appears from this data that irrespective of how far the COPx is moved, at ball contact it is (on average) back at its starting position.

7.7.3 Analysis of ball contact

The velocity of COPx at ball contact is predictably lower in cluster 1 than cluster 2. The downswing data revealed that the maximum COPx velocity for cluster 1 was lower, and that it occurred earlier in the downswing compared to cluster 2. This resulted in a lower COPx velocity at ball contact, further highlighting that this technique utilizes minimal COPx movements during the putting stroke (table 7.7.3.1). The data for cluster 1 does reveal however that some putts (19 of 78) were performed with the COPx moving away from the hole (range 174.7mm/s to -57.4mm/s), whilst all players were moving the COPx towards the ball at contact in cluster 2 (201.8mm/s to 6.7mm/s).

Table 7.7.3.1: COPx velocity at ball contact (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	20.3 (41.1)
2	66.2 (47.0)
Total	36.9 (48.5)
d	0.95
Power	1.00

Further analysis was conducted to determine whether this difference in COPx velocity at ball contact had an effect on putter head kinematics. Horizontal putter head velocity at ball contact was not significantly different (211.3cm/s vs. 214.2cm/s; p = 0.21; d=0.23) between the clusters. However the maximum velocity of the putter head (217.1cm/s vs. 224.1cm/s; p = 0.02; d = 0.43) and the time at which these maximum values occurred (18ms post contact vs. 39ms post contact; p < 0.001; d = 0.58) were both found to be significantly different between clusters, though these values occurred after ball contact had been achieved. Similarly the vertical velocity of the putter head at ball contact was different between groups (1.5cm/s vs. 7.1cm/s; p = 0.00; d = 0.62) indicating that players in group 2 were contacting the ball with greater upward vertical velocity of the putter head than their counterparts in cluster 1.

The variability in COPx velocity values at ball contact produced a range that indicated some movement was occurring away from the hole on certain putts at ball contact. When the COPx velocity at ball contact and exact result data were correlated for each cluster, non-significant negative correlation trends were revealed (cluster 1, r = -0.21, p = 0.07; cluster 2, r = -0.19, p = 0.21). The scatterplots in figure 7.7.3.1a and b highlight the range of values. The values in the upper left quadrant indicate those putts struck with the COPx moving away from the hole at contact with a result of the ball finishing past the hole. Only one of 19 putts struck with this opposite movement of the COPx at ball contact finished short of the hole, whilst five putts finished in the hole using this method.

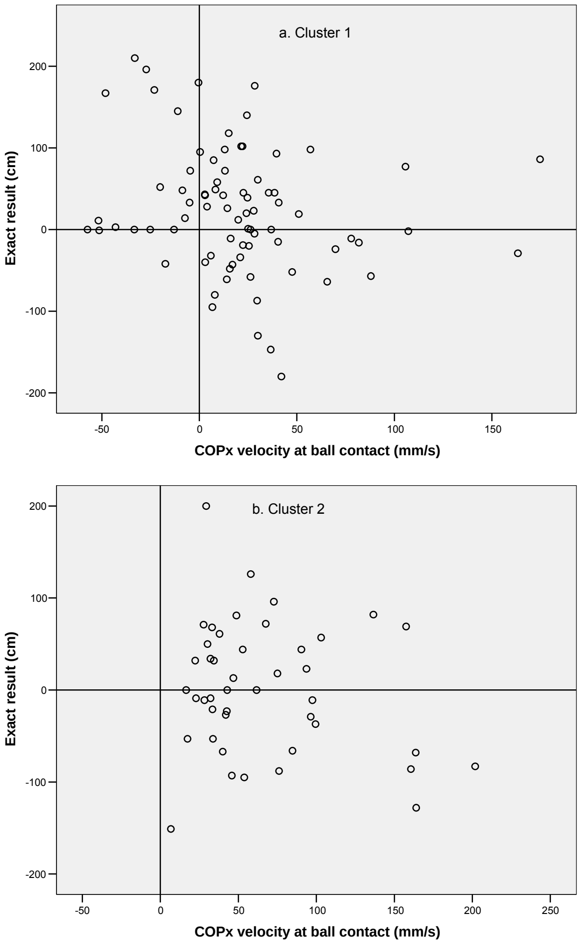


Figure 7.7.3.1: Scatterplot of exact putt result (8m) vs. COPx velocity at ball contact for each cluster: (a) Cluster 1 (r=-0.21, p=0.07); (b) Cluster 2 (r=-0.19, p=0.21). The zero lines are represented on the plot.

Of most interest is that all of these putts where COPx velocity at ball contact was away from the hole were grouped into cluster 1, modifying the mean for this parameter closer to zero as they record a negative value for this parameter.

Across the putting tasks it was expected that significant differences would be present for putter head kinematic parameters related to velocity at ball contact (155.8cm/s vs. 212.3cm/s; $p < 0.001$; d= 1.85) and maximum velocity (161.6cm/s vs. 219.6cm/s; $p < 0.001$; d= 1.77). The differences between the tasks in backswing and downswing displacement dictated that these velocity values would necessarily be different. The time at which the maximum putter head velocity occurred was not significantly different across tasks (16ms vs. 26ms; p = 0.07; d = 0.25) however these data indicate a trend for players to be developing putter head velocity around ball contact such that the maximum occurs post contact.

7.7.4 Analysis of the follow through phase

In line with the technique displayed in earlier phases of the putting stroke, the kinematic data on the follow through phase further highlights the tendency of cluster 2 to produce a short, sharp technique compared to the longer, slower movements of cluster 2. The length of time of the follow through (table 7.7.4.1) and the horizontal displacement of the putter head in the follow through (43.2±14.3cm vs. 54.3±13.2; p < 0.001; d = 0.78) both indicate significant differences between the final two clusters.

Table 7.7.4.1: Follow through time (ms). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	378 (119)
2	480 (124)
Total	415 (130)
d	0.78
Power	0.99

The movement of the COPx during the follow through is also in line with the data from previous phases (table 7.7.4.2). The follow through phase again produces the greatest magnitude of COPx displacement, as was the case in the 4m putting task. However, there is a non-significant difference between the two putting tasks for movement of COPx during this phase (10.3±8.8mm vs. 12.7±11.3mm; p = 0.07; d = 0.25).

Table 7.7.4.2: Range of COPx displacement during the follow through (mm). Mean (SD) values for each cluster for on 8m putts.

Cluster	**2 clusters**
1	10.6 (10.7)
2	16.5 (11.6)
Total	12.7 (11.3)
d	0.52
Power	0.80

Highlighting this tendency of players to continue to move the putter head towards the hole after the ball has been struck are the parameters dealing with maximum upwards velocity of the putter head (table 7.7.4.3). Whilst the mean values indicate that there is a significant difference between groups on this parameter, the data on timing of this maximum indicates both clusters achieve the maximum value well after contact (165±48ms vs. 192±54ms; p = 0.01; d = 0.52). These times are representative of points 8 to 10 fields after ball contact.

Table 7.7.4.3: Maximum upwards velocity of the putter head during the putting stroke (cm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	48.8 (20.7)
2	62.0 (18.2)
Total	53.6 (20.8)
d	0.63
Power	0.94

The urging of the ball to the hole by movement of the putter head is common across both tasks as the maximum vertical velocity of the putter head occurred at a similar time in the 4m putting task (177±62ms; p=0.762; d= 0.04) even though the maximal values were significantly different (31.3±14.8cmcm/s vs. 53.6±20.8cm/s; p = 0.00; d = 1.05). This indicates that once the ball has been struck that players are continuing to move the COPx towards the hole, the putter head displacement is large and, although none of these parameters can influence the ball, some movement towards the hole, "urging" the ball, is maintained.

With a large amount of COPx displacement taking place during the follow through phase, maximum velocity of COPx towards the hole in the follow through was expected to be greater in cluster 2 (table 7.7.4.4). The profile of both clusters is of short, sharp putter head movements with minimal movement of the COP in cluster 1 compared to long, slower movements of the outer head with larger movements of the COPO in cluster 2. In the 4m putting task, the maximum velocity of COPx towards the hole in the follow through produced significant differences between the groups, but the magnitude of the values was smaller across the board when compared to the 8m putting task data (43.6±29.2mm/s; p = 0.00; d = 0.41).

Table 7.7.4.4: Maximum velocity of COPx towards the hole during the follow through (mm/s). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	49.1 (32.4)
2	76.0 (50.0)
Total	58.8 (41.5)
d	0.65
Power	0.95

The timing of when the maximum COPx velocity towards the hole occurs highlights the variability of control of the COPx in both clusters with large standard deviation values present (table 7.7.4.5). The timing of the maximum velocity of COPx away from the hole (table 7.7.4.6) indicates that cluster 2 are more likely to stop movement of the COPx towards the hole and start moving back in the opposite direction at a point in time towards the end of the follow through. This occurs after the maximum velocity of COPx towards the hole has been achieved. Cluster 1 values reveal that the more variable nature of the movement of COPx at ball contact produces another highly variable result on these timing parameters. It appears that the large range of values on these timing parameters is confusing the true picture.

Table 7.7.4.5: Time of maximum velocity of COPx towards the hole during the follow through (ms). Mean (SD) values for each cluster on 8m putts.

Cluster	**2 clusters**
1	200 (158)
2	107 (155)
Total	167 (162)
d	0.57
Power	0.88

Table 7.7.4.6: Time of maximum velocity COPx away from the hole during the follow through (ms). Mean (SD) values for each cluster for cluster solutions 2-4 on 8m putts.

Cluster	**2 clusters**
1	184 (163)
2	335 (172)
Total	238 (181)
d	0.83
Power	1.00

7.8 Profiling the 8m cluster solution

The cluster process has produced two final clusters that are significantly different on putter head kinematic and COP movement parameters. These two clusters can be used to classify two techniques as:

1. Short, sharp with minimal COPx movements – a technique that involves comparatively smaller movements of the putter head and the COPx throughout the putting stroke. Velocity of the COPx at ball contact is minimal but is a heterogeneous mixture of movements away and towards the hole.
2. Long, slow with greater movements of the COPx – a technique that incorporates larger displacements of the putter head and COPx throughout the putting stroke. Velocity of the COPx at ball contact is higher than cluster 1 but is homogeneous.

Though there is no significant difference between these clusters for age, the putting techniques can be distinguished by handicap and perceived putting ability. Players who are a part of cluster 1 show a trend to be, but not significantly younger (53.9±14.6 years) than those players in cluster 2 (60±20.4 years p=0.06; d=0.35). Cluster 1 players have significantly lower handicaps (11.9±5.5 vs. 18.3±7.6; p = 0.00; d = 0.91) although the lowest handicap player in the study (handicap = 3) is represented in both groups. The players in cluster 1 claim that they take significantly less putts per round (33.6±3.3 vs. 35.3±2.7; p = 0.01; d =

0.81). The technique described as short, sharp and minimal appears to be favored by the better player (based on handicap).

Whilst the parameters used in this analysis can distinguish techniques, putt outcome is not significantly difference between these clusters. Both the measures of exact putt result (24±77cm vs. 2±71cm; p = 0.7; d = 0.29) and absolute putt result (60±54cm vs. 56±43cm; p = 0.11; d = 0.08) reveal non-significant differences between the techniques. Breaking the putt result down into 25cm divisions on either side of the hole and analyzing by cluster indicates that both techniques are equally likely to produce a holed out putt (table 7.8.1). A non-significant difference occurs (p=0.46) in the data between clusters, but cluster 1 putts were more likely to finish past the hole (56.4%) than short (35.9%) with a notably large proportion finishing more than 1 meter past (14.1%). Cluster 2 data indicates putts were equally likely to finish short (47.7%) or past (45.4%) the hole.

Table 7.8.1: Exact putt result by 25cm divisions and final cluster grouping for 8m putts. Data presented is count and percentage of total putts for each cluster.

	Cluster 1	**Cluster 2**
Holed out	**6 (7.7%)**	**3 (6.8%)**
25cm short	10 (12.8%)	7 (15.9%)
25-50cm short	7 (9%)	2 (4.5%
50-75cm short	5 (6.4%)	6 (13.6%)
75-100cm short	3 (3.8%)	4 (9.1%)
Less than 100cm	3 (3.8%)	2 (4.5%
Total short	**28 (35.9%)**	**21 (47.7%)**
25cm long	8 (10.3%)	3 (6.8%)
25-50cm long	15 (19.2%)	6 (13.6%)
50-75cm long	4 (5.1%)	6 (13.6%)
75-100cm long	6 (7.7%)	3 (6.8%)
+100cm long	11 (14.1%)	2 (4.5%)
Total long	**44 (56.4%)**	**20 (45.4%)**

By classifying the putts into quartiles based on ranking (absolute result), the data indicate that cluster 1 is over represented in the best and worst quartiles as these putts make up only 63.4% of the total sample but comprise around 70% (compared to the expected 66.6%) of those quartiles (table 7.8.2). Conversely cluster 2 is under represented in these quartiles. However, none of these results were significant when assessed using chi-square (p=0.36) emphasizing a lack of difference in performance outcomes between these clusters.

Table 7.8.2: The quartile range of putt result by cluster group for 8m putts.

	Cluster 1	**Cluster 2**
Top quartile	21 (70%)	9 (30%)
2nd quartile	16 (52%)	15 (48%)
3rd quartile	19 (63%)	11 (37%)
Bottom quartile	22 (71%)	9 (29%)
Total	**78**	**44**

The influence of the putt result on technique was assessed by analysing the movement of players between clusters. Of the 35 players represented in the 8m putting study, six had only one putt, 12 remained in cluster 1, three remained in cluster 2 and 14 changed between the two clusters. Breaking the putt result down by what happened on the next putt in terms of technique, the data indicates that there was little influence (table 7.8.3). Whilst leaving a putt less than 25cm short or 25-50cm long would not necessarily require a change of technique, striking a putt to further than 1 metre past the hole may necessitate a technique adjustment. However, the data in the final column highlights that even this magnitude of error did not produce a subsequent change in putting technique.

Table 7.8.3: Breakdown of 8m putt result and the change (if any) in cluster membership as a result of that putt.

	Holed Putt	-1-25cm	-25-50cm	-50-75cm	-75-100cm	Less 100cm	+1-25cm	+25-50cm	+50-75cm	+75-100cm	+100 cm
Stayed in 1	3	7	2	3	3	2	4	10	2	4	7
Stayed in 2	1	3	0	2	1	0	2	3	5	2	2
Changed 1-2	0	1	3	1	0	1	1	2	0	1	1
Changed 2-1	1	1	0	0	2	1	1	0	1	1	0
Last putt	4	5	4	5	1	1	3	6	2	1	3

7.9 Overall cluster summary

Assessment of both tasks and cluster membership reveals that of the 38 players involved in the study, 7 players produced putting performances that resulted in all their putts represented in cluster 1 for both tasks. This represented 27 of 77 putts on the 4m task and 32 of 78 8m putts. These players were consistently producing smaller movements of COPx which in the 8m putting task were combined with shorter, faster movements of the putter head. None of the remaining players consistently produced the distinct technique of cluster 2 in both putting tasks that was associated with larger movements of COPx and in the 8m task was combined with larger movements of the putter head. All remaining players produced a mixture of results.

When comparing these players' performances across tasks, non-significant differences were present in the majority of parameters, and these will not be discussed here. Significant differences between tasks for these players were present when comparing:

- Range of COPx in the downswing

- Maximum velocity of COPx in the downswing
- Velocity of COPx at ball contact
- Maximum velocity of COPx towards the hole in the follow through

In each of these parameters, the amplitude or velocity of movement of the COPx was greater in the 8m putting task (Table 7.9.1). However, no putter head kinematic parameters relating to displacement or time were significantly different for these players between tasks. These players did not achieve results that were significantly different from the rest of the sample in the 4m (p=0.39) or 8m (p=0.67) putting tasks when assessed using exact putt result.

Table 7.9.1: Parameters presenting significant differences between tasks for players represented in cluster 1 for both putting tasks (mean±SD).

	4m	**8m**	**d**	**p**
Range of COPx in the downswing	3.1 (1.8)	5.2 (3.2)	0.74	0.01
Max velocity of COPx in the downswing	20.6 (11.1)	37.8 (18.7)	0.97	<0.001
Velocity of COPx at ball contact	1.2 (17.4)	17.4 (26.3)	0.69	0.01
Max velocity of COPx in the follow through	24.9 (17.7)	39.1 (17.4)	0.76	0.01

Delay et al. (1997) suggested that downswing time may be fixed, and data from the 8m putting task offered some support for this notion. The data from these cluster 1 players was assessed for equality on this downswing parameter. The mean data for each task was 229±37ms vs. 224±36ms for the 4m and 8m tasks respectively. Whilst these values are relatively close, they are not significantly equal at a threshold of 10% (p=0.17).

Presented in table 7.9.2 is a graphical representation of each putting technique for the two tasks. These are presented in order to provide a simple reference on the differences discussed in this section based on putter head kinematics and movement of the COPx.

Table 7.9.2: Difference between clusters on each of key parameters in 4m and 8m putting tasks.

Parameter	Event	4m clusters		8m clusters	
		1	2	1	2
Putter Head	BS Displacement x	≈	≈	<	>
	BS Time	≈	≈	<	>
	DS Time	≈	≈	<	>
COPx	BS Displacement	↑	↑↑	↑	↑↑
	BS position	→	→→	→	→→→
	BS Velocity	↑	↑↑↑	↑	↑↑
	DS Displacement	↑	↑↑↑	↑↑	↑↑↑
	DS Velocity	↑	↑↑↑	↑↑	↑↑↑
	BC Velocity	≈0	↑↑↑	↑	↑↑↑
	FT Displacement	↑↑	↑↑↑	↑↑	↑↑↑
	FT Velocity	↑	↑↑	↑↑	↑↑↑

≈ almost equal to; ↑ more than zero; ↑↑ about twice as much; ↑↑↑ about three times as much; →movement to the right; →→ twice as much movement to the right; →→→ three times as much movement to the right.

8 Data analysis – biofeedback group

8.1 Putt results

The seven members of the biofeedback training group had a mean age of 65.7 years and ranged in handicap from 10-21 (mean of 15.7). Their perceived putting ability data indicated that on average these players took two putts per hole on each hole over an 18 hole round (mean = 36.1).

During the re-testing session, the procedures as outlined in Chapter 5 were followed. All testing was conducted in summer time, although all testing days were cooler than normal for that time of year (22° Celsius). As an indicator of the similarity of the green conditions, the data for putter head velocity at contact was significantly equal for the 4m putts (pre mean = 156.0cm/s vs. post mean = 156.2cm/s; $p=0.02$) but not for the 8m putts (pre mean = 213.6cm/s vs. post mean = 219.4cm/s; $p = 0.64$). In fact, on re-testing for the 8m putts, the putter head velocity at ball contact was significantly greater ($p=0.03$). Analysis of the putt result data indicates the ball was finishing short of the hole for a majority of putts (61.4% of all putts) although the putter head velocity was the same (4m putts) or greater (8m putts) on re-testing. Whilst the speed of the greens was not measured at any of the testing sessions, it appears on re-testing that the greens were slower.

Analysis of the absolute mean post training result data indicates non-significant changes to 4m (initial mean = 36.3cm; post-training mean = 28.7cm; p=0.21; d=0.3) and 8m results (initial mean = 59.0cm; post-training mean = 66.3cm; p = 0.52; d=0.15). Small effect sizes indicate little effect of the balance biofeedback training on putt result.

When the putt result data is grouped into 50cm intervals around the hole, the combined group data highlights the change in group tendency from hitting the ball past the hole, to leaving the ball short of the hole for the 4m putts (figure 8.1.1a and b).

Of the seven players involved, four achieved at least one putt that went into the hole on re-testing. This provided a total of seven holed putts or 20% of all putts at the 4m hole in the re-testing session. This was not a significant improvement in performance ($\chi 2 = 0.82$, $p = 0.37$) when compared to the initial testing session that indicated a total of four putts holed out by this group or 11.4% of the total number of putts for these seven players. A lack of holed putts (11 of 70) across initial testing and re-testing for this group of players limits the strength of this analysis. This success rate was however an improved performance compared to the total sample's performance (19 of 190 or 10%), but slightly below the level of the professional player (23% success rate) reported by Cochran and Stobbs (1968).

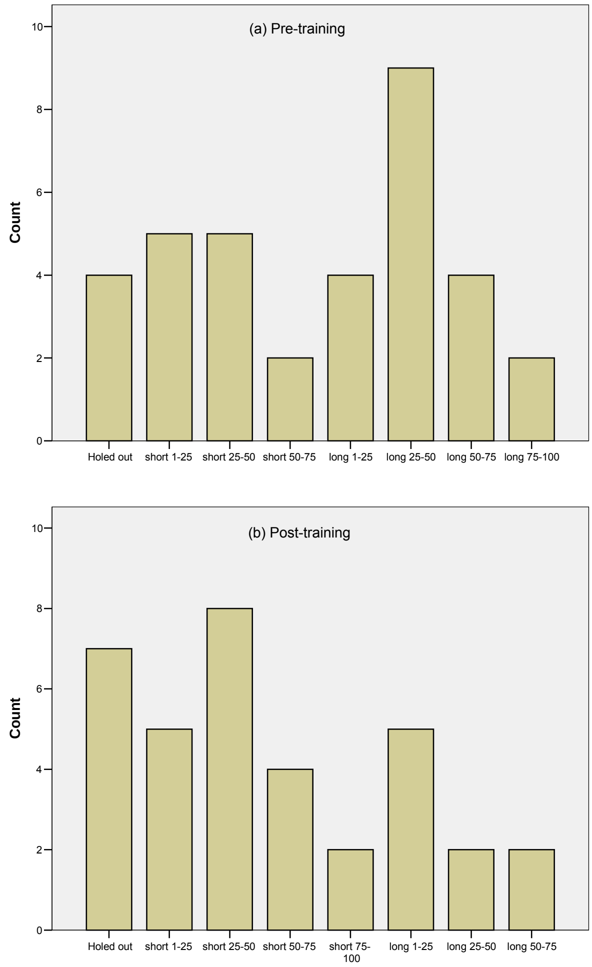


Figure 8.1.1a and b: Frequency bar chart of putt result by 25cm intervals for 4m putts (n=35) (a) pre-training, and (b) post-training. Note: no classification of long 75-100 on re-testing.

The other clear tendency was indicated by the increase in putts that fell short of the hole on retesting (54.2% up from 34.3% at initial testing). The exact result data for pre-training (16.2±40.7cm) reveals an overall trend for the ball to travel past the hole in comparison to the overall trend for the ball to finish short of the hole on re-testing (-12.3±37.6cm). This is a significantly different result across the testing sessions ($p=0.001$).

During initial testing, three players in the training group had achieved a holed out putt at the 8m distance. On re-testing, no player achieved this feat. Similar to the trend of the 4m putts, the players tended to leave the ball short of the hole on re-testing (71.4% of all putts) compared to the initial testing session (22.9%), although in the case of the 8m putts this difference is more exaggerated (figures 8.1.2a and b). The exact result data highlight the affect of this tendency, as when compared to the initial testing mean (34.3±71.9cm), the re-testing mean (-17.4±73.2cm) is significantly decreased (p=0.001).

These graphs highlight the shift of frequency from the intervals indicating the ball has traveled past the hole, to those intervals indicating the ball finished short of the hole (24 putts finished short of the hole at the 8m distance in retesting compared to 8 during initial testing for these seven players). Overall, 15 putts finished further than 50cm from the hole in initial testing, whilst 20 putts finished more than 50cm from the hole on re-testing. Combined with the lack of any holed out putts on re-testing, the increased absolute mean and decreased exact mean indicates that at the 8m task players performed worse on re-testing following the training program. The data from the retesting sessions for both putting tasks, suggests that players may have changed their approach to the putting task, been adversely affected by the training program or found the tasks more difficult under slower green conditions.

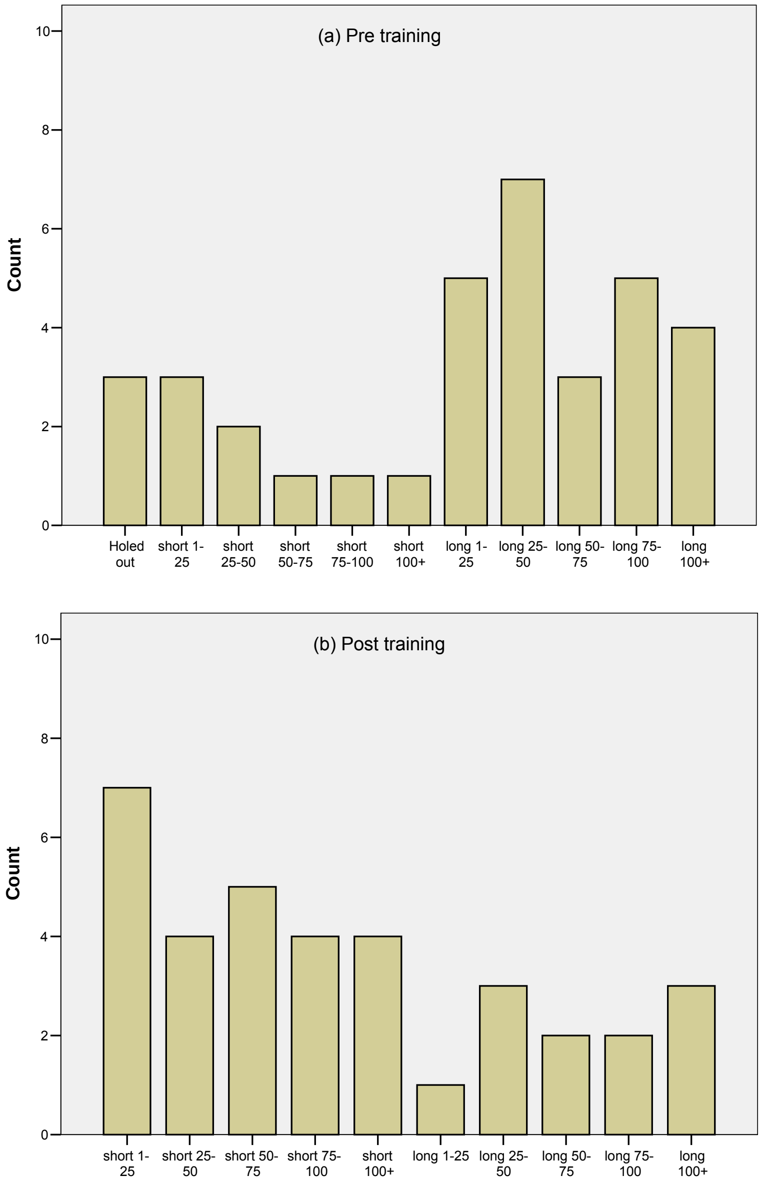


Figure 8.1.2a and b: Frequency bar chart of putt result by 25cm interval for 8m putts (n=35) (a) pre-training, and (b) post-training (no holed putts). Note: no classification of holed out on re-testing.

At the 4m putt distance, the group mean values for absolute putt result changed from 36±24cm at initial testing to 29±27cm on re-testing. This produced a no change between the testing sessions (p = 0.24). Encouragingly, five of the seven players recorded absolute mean distance results indicating the ball finishing within a smaller radius of the hole on re-testing (Figure 8.1.3a). Of these five players, four also decreased their standard deviation value on re-testing. The performance of subjects 2 and 5 was different in that they recorded results that showed the ball finishing further away from the hole (on average) on re-testing. In the case of subject 5, this increase in absolute mean (from 21cm to 50.4cm) was associated with a large increase in standard deviation (from 20.2cm to 33.4cm) as depicted in Figure 8.1.3b. This player had hit every putt up to or past the hole in initial testing (range 0 – 43cm), but reversed this trend on re-testing (range -12 to -97cm) leaving every putt short of the hole. These figures not only represent a range of results twice that in initial testing, but also leaving the ball on the “wrong” side of the hole. The majority of players recorded a smaller standard deviation value, but the overall group change in standard deviation was not significant (mean of SD values 23.8cm in initial testing, 22.7cm on re-testing, p = 0.71).

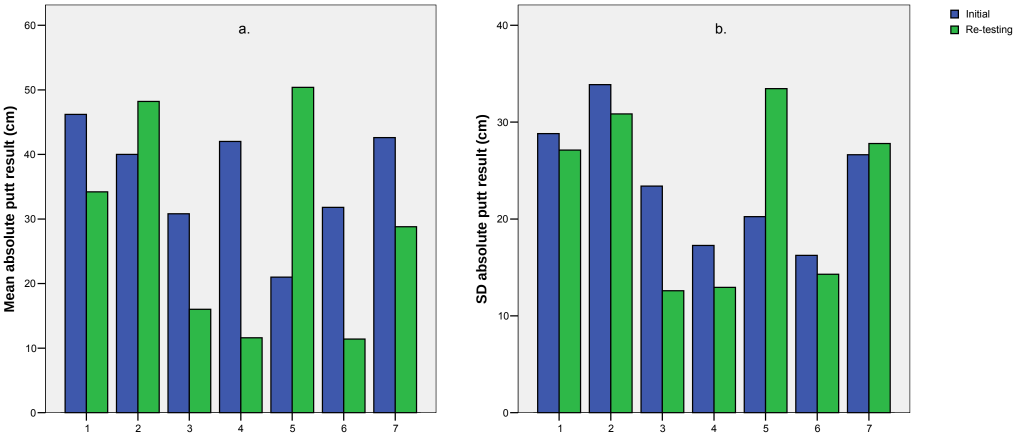


Figure 8.1.3a and b: (a) Mean and (b) standard deviation data for absolute putt distance – pre-training and post-training values - individual results at 4m.

At the 8m putt distance, the overall mean on re-testing was unchanged (63±39cm) compared to the initial testing session (59±53cm; p = 0.69) and 5 of 7 players recorded worse results (Figure 8.1.4a). Only subjects 2 (decrease from 96cm to 62cm) and 7 (decrease from 61cm to 34cm) displayed an improvement in performance at the 8m putting task based on mean absolute putt result. Of these two players, subject 2 also recorded a large decrease in standard deviation (from 82cm to 35cm), and a decrease in range of result from 3.51m to 1.8m. The trend across the players was for standard deviation values to be lower on re-testing, though player 5 again performed poorly on this parameter. This represents a positive effect of the training program for five of the seven players. The overall group results for standard deviation were not significantly different between testing sessions (initial mean of SDs = 48.7±21.7cm, re-testing mean of SDs = 36.3±12.4cm, p=0.18). With a low number of values (n=7) this result is greatly influenced by the increased value produced by player 5.

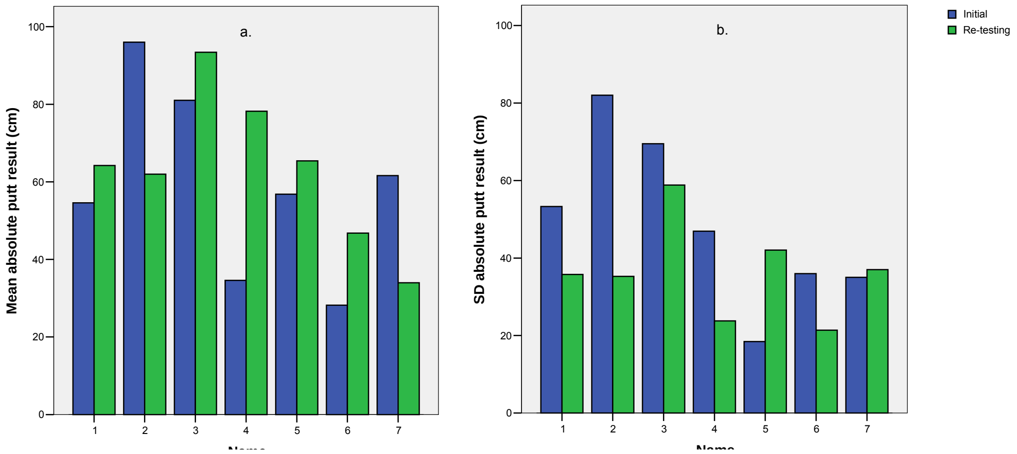


Figure 8.1.4a and b: (a) Mean and (b) standard deviation data for absolute putt distance – pre-training and post training values - individual results at 8m.

Putt result data paints a favorable picture of the effect of biofeedback training on these players as indicated by an increase in the number of holed putts (from 11.4% to 20%). This “holing” rate is twice that of the overall rate achieved with the total sample group (10%, n=190), and would help to improve players’ score over 18 holes. Based on the calculations completed in chapter 6 for number of putts per round given the categorical data on putt result, the seven players in the biofeedback group would have taken 34.9 putts for 18 holes based on their initial testing results (n=35). On re-testing this value decreased to 33.4 putts. A training technique that can improve the chances of holing putts and decrease the total number of putts per round would be highly desirable. However, the method employed here has also produced a higher proportion of putts finishing short of the hole, though this did not produce a significant change in absolute putt result at the 4m distance.

At the 8m putting distance, in initial testing the overall sample holed out on 14 of the 190 putts taken (7.4%). This included two players in the training group. On re-testing no player was able to hole out the putt and the overwhelming tendency was for the ball to be left short of the hole (71.4%). It is quite possible that some putts left more than 100cm short (20%) by this sample may result in two more putts being required to finish the hole, which would inflate the score further.

Performing the same simulation of 18 holes of putting with the biofeedback training groups initial results indicate that they would have taken 37 putts if all players putted from 8m on each of 18 holes. On re-testing this figure increased to 39.4 putts. A 2.4 putts per round increase (6.5%) is not desirable, and confirms the decreased performance on the 8m putting task by these players.

The data for putter head velocity at ball contact was presented at the start of this section. This data suggested that conditions for the 4m putting task were equal across testing days as the putter head velocity at ball contact for both sessions was significantly the same ($p = 0.02$). However, the trend in putt result indicates that the greens were slower on re-testing. An increased number of putts were holed, but an increased number of putts were left short. Conversely, putter head velocity data were not significantly equal for the 8m putting task, and players contacted the ball with a higher putter head velocity on re-testing. No players holed a putt but the tendency to leave the ball short was evident again. It is possible that slightly slower green conditions resulted in an increased putter head velocity at contact, though the putt results suggest that the increase in putter head velocity at ball contact between sessions was not large enough. Calculated values for putts per round suggest that the players improved performance on the 4m task, but performed worse on the 8m task. Balance biofeedback training without making ball contact may not contribute to an improvement in putting technique on the longer putting task but may be beneficial on the shorter putting task.

8.2 Pre v post changes in the 4m putts

Does balance biofeedback training have any affect on balance as measured during the performance of a golf putting task? The putt result data suggested that there may be some positive affect of the balance biofeedback training program when performing the 4m putting task, but does it affect those parameters related to balance? A reduction or decrease in COPx movement and/or COPx velocity would be indicative of a positive affect of the training program because the aim of the training program was to reduce movement of the COP during the putting stroke.

8.2.1 Backswing phase

The data for COPx displacement during the backswing indicates that the training program caused the players to move the COPx through a significantly greater amplitude on re-testing (pre-training mean = 5.6±3.1mm; post-training mean = 7.5±2.9mm; $p = 0.01$; $d = 0.61$). The medium effect size confirms the magnitude of the change on re-testing. Individual changes can be viewed in figures 8.2.1.1a and b. These individual data highlight the increase in COPx range during the backswing phase for the majority of players. Based on these data, the biofeedback training program had a negative effect if the goal of training was to reduce movement of the COPx during the putting stroke.

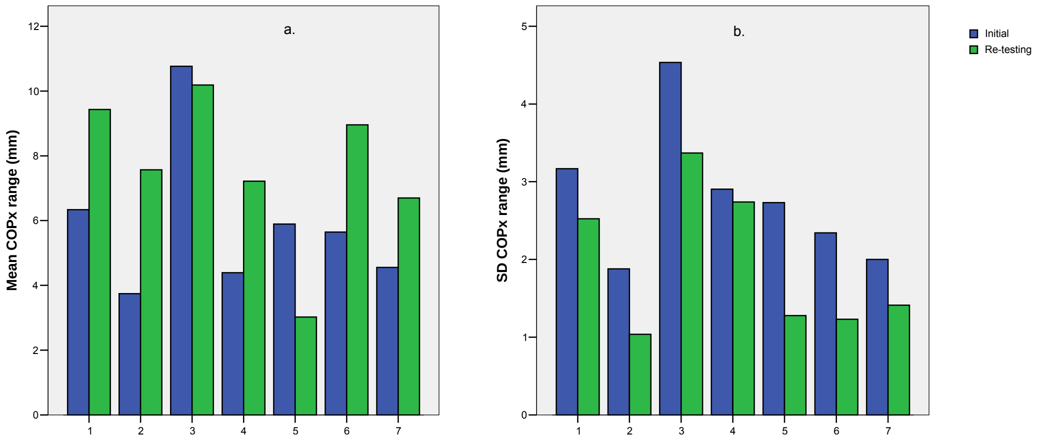


Figure 8.2.1.1a and b: COPx range during the backswing of 4m putts comparing pre-training and post-training values for (a) Mean and (b) standard deviation.

Two players (3 & 5) demonstrated the ability to reduce movement of the COP during the backswing phase on re-testing. Player 5 demonstrated the greatest change. The decreased mean value from pre-training (5.9±2.7mm) to post-training (3.0±1.3mm) in COPx movement in the backswing indicates movement of COP can be reduced by training. However, player 5 performed poorly on the putting task recording the worst putt results with both a mean increase in absolute putt result (up from 21.0cm to 50.4cm) and an increase in variability (SD up from 20.2cm to 33.5cm). The ability to reduce the movement of the COPx during the backswing phase did not assist this player in performance of the putting task.

Standard deviation values for this parameter decreased for each player. The mean of these standard deviation values decreased significantly (p=0.001, d=0.87) between the initial testing session (2.8±0.9cm) and the post training session (1.9±0.9cm). During the backswing phase, COPx was moved with improved consistency by each player, and the group as a whole, on re-testing.

The location of COPx at the end of the backswing indicates how far the COPx has displaced from its position at address. The data for this group of players indicates displacement was not significantly different on re-testing (1.2±5.0mm, 2.8±4.9mm, p = 0.21, d= 0.32). Likewise there was no significant differences in maximum COPx velocity during the backswing (from 26.3±16.3mm/s to 22.7±11.8mm/s, p=0.32, d=0.25) between testing sessions.

Assessment of the putter head kinematic data indicates that only one parameter associated with the backswing changed significantly from pre-training to post-training. The length of time taken in the backswing increased significantly from 498ms to 549ms (p=0.01; d=0.61). Putter head horizontal displacement was not significantly different between sessions (19.5±5.5cm, 19.9±4.8cm, p = 0.77, d = 0.08).

All but one (player 1) of the players in the training group had an increase in backswing time (figure 8.2.1.3). The standard deviation data indicates that player 3 produced a wide range of results. In sequence, this player produced backswing times on re-testing of 620ms, 680ms, 680ms, 840ms and 720ms. However, this players putting performance was improved between testing sessions based on absolute putt result (decrease in mean from 30.8±23.4cm to 16±12.6cm).

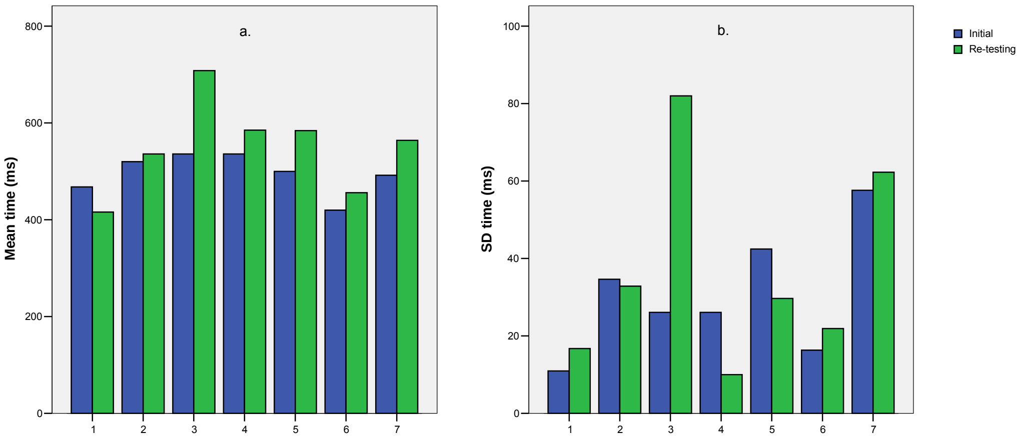


Figure 8.2.1.3: Mean backswing time for 4m putts comparing pre-training and post-training values by subject; (a) Mean, (b) SD.

8.2.2 Downswing phase

During the downswing phase, no significant changes were recorded for parameters related to COPx or putter head kinematics when comparing the initial and re-testing sessions. Grouped values for downswing time (237±46ms, 246±38ms, p = 0.35, d = 0.37), COPx range (4.9±3.4mm, 5.0±3.2mm, p = 0.91, d = 0.03), COPx position at end of downswing (1.5±5.6mm, 2.6±4.9mm, p = 0.4, d = 0.21) and maximum COPx velocity towards the hole (34.0±19.7mm/s, 32.2±18.6mm/s, p = 0.71, d = 0.09) all reveal that no significant differences were achieved across the testing sessions for these parameters.

8.2.3 Ball contact

As noted earlier there was no difference between the putter head horizontal velocity values between the testing sessions. In fact, analysis revealed that these values were significantly equal (p=0.02). The velocity of the COPx at ball contact was the most influential parameter in determining cluster membership for the 4m putting task. Between pre-training and post-training the group of seven players demonstrated the ability to reduce the velocity of COPx at ball contact from 13.3±23.2mm/s to 6.1±21.2mm/s. This was, however, a non-significant finding (p=0.2; d=0.32) with a small effect size.

The data for each player highlights that the mean value is greatly affected by player 4 whose own mean value increased, but who was moving the COPx away from the hole at the time of ball contact (figure 8.2.3.1a). The variability data indicates player 4 produced a different technique in terms of movement of the COPx at ball contact across the five trials, as he had with the movement of the COPx in the backswing (figure 8.2.3.1b), but this did not preclude this player from recording the best overall result on putting performance for this task (absolute putt results indicate this player left the ball 30cm closer to the hole on re-testing).

All but one (player 4) of the players in the study group responded with a decrease in the absolute value of COPx velocity at ball contact indicating a trend towards the group minimizing COPx velocity at ball contact. When the COPx velocity at ball contact is treated as an absolute value, non-significant differences are still recorded between the testing sessions (23.3±13.8cm/s, 16.1±14.4, p=0.09, d=0.5). Removing player 4 from the data however, indicates significant change was achieved for absolute COPx velocity at ball contact (24.7±14.2cm/s, 12.5±10.1cm/s, p=0.002, d=0.92). This trend would suggest that the training program may create a technique identified as cluster 1 in chapter 7. As previously highlighted, COPx velocity at ball contact was the most influential parameter in the 4m putting task cluster analysis process, and those players who achieved COPx velocity values close to zero at ball contact were clustered together into cluster 1.

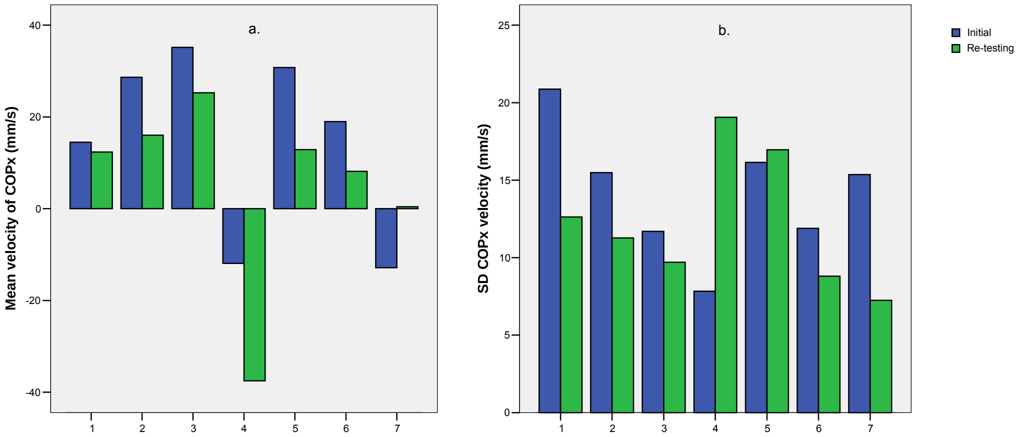


Figure 8.2.3.1a and b: COPx velocity at ball contact for 4m putts comparing pre-training and post-training values by subject; (a) Mean, (b) SD.

8.2.4 Follow through

During follow through no significant changes were recorded in COPx displacement (from 7±5.7mm to 6.8±5.7mm; p=0.9; d=0.03). Likewise, the maximum velocity of COPx towards the hole (29.0±21.7mm/s, 32.8±18.6mm/s, p = 0.45, d = 0.19), putter head kinematic values related to horizontal displacement in the follow through (32.2±10.1cm, 32.2±8.3cm, p = 0.99, d = 0.00) and follow through time (343±79ms, 354±104ms, p = 0.66, d = 0.19) produced non-significant results. The biofeedback training program caused no significant changes to the follow through phase.

8.2.5 Summary of effect of training program on 4m putting task

The final step in the assessment of the effect of the biofeedback training program was completed by including the retesting data in the k-clustering process previously described in Chapter 7. The effect of the biofeedback training on individuals was assessed by determining whether the training caused them to change the characteristics of their putting technique and, therefore, their cluster group membership.

The following steps were taken to prepare the data for analysis:

- Each player's raw re-testing data were standardized using the maximum-minimum normalization process. The maximum and minimum data required for normalization were taken from the original raw data for the total sample of 4m putts.
- Those variables that were determined to be highly related and have high collinearity in the original data were removed from the data file. The data were then stored and saved as an SPSS input file.
- SPSS k-clustering software was used to create the solution. The cluster seeds used to create the 4m putt two cluster solution were used as initial cluster centres.

The techniques defined by clustering for the 4m putting task, as detailed in chapter 7, were:

1. Less movement (relative to cluster 2) of COPx in the backswing and downswing phases with velocity of COPx at ball contact closer to zero (on average).
2. Larger movement (relative to cluster 1) of COPx in the backswing and downswing phases with velocity of COPx at ball contact non-zero. High COPx velocity.

From the results presented in chapter 7, 3 players were consistently clustered into cluster 1, the remaining players were clustered in both clusters 1 and 2 (table 8.2.5.1).

Table 8.2.5.1: Training group putt classifications from initial testing for 4m putts.

Player	**Cluster group description**
1	Mix of techniques 1 and 2
2	Mix of techniques 1 and 2
3	Mix of techniques 1 and 2
4	All technique 1
5	Mix of techniques 1 and 2
6	All technique 1
7	All technique 1

After re-calculation of the clusters based on retesting data, but using the same seeding data as that used in the original k-cluster calculation, the players were again classified into clusters, with the effect of the training obvious in that all produced a cluster 1 type putting technique on each putt.

Table 8.2.5.2: Training group putt classifications after training for 4m putts.

Player	**Cluster group description**
1	All technique 1
2	All technique 1
3	All technique 1
4	All technique 1
5	All technique 1
6	All technique 1
7	All technique 1

These data indicate that the training program had the effect of producing a more consistent putting technique from each of the four players who were originally classified across both clusters. As identified throughout the previous sections players responded to the training program in various ways. The overall mean values for parameters analysed in the previous section for the training group were similar to that achieved by cluster 1 in the initial cluster analysis.

Of special note is the performance of those players who were already classified as technique 1 (minimal movement of COPx). These players (4,6,7) were amongst the players who improved (absolute mean closer to zero) on 4m putting performance (table 8.2.5.3), but changed minimally in terms of COP parameters.

Table 8.2.5.3: 4m putts absolute putt result means (±SD) for pre- and post-training.

Subject	Pre-training	Post-training	Mean change
1	46.2±28.8	34.2±27.1	-8.0
2	40.0±33.9	48.2±30.8	+8.2
3	30.8±23.4	16.0±12.6	-14.8
4	42.0±17.3	11.6±12.9	-30.4
5	21.0±20.2	50.4±33.5	+29.4
6	31.8±16.2	11.4±14.3	-20.4
7	42.6±26.6	28.8±27.8	-13.8
Total	36.3±23.7	28.7±26.9	-7.6

For further analysis, the players were classified into two groups based on whether they had maintained group membership across testing sessions (players 4,6,7) or changed group membership across testing sessions (players 1,2,3,5). Putt result data indicate that those players who maintained their membership of cluster 1 across testing sessions performed significantly better on re-testing in terms of both exact and absolute putt result data (Table 8.2.5.4).

Table 8.2.5.4: Comparison of 4m putt result data (exact and absolute) means (±SD) across testing sessions for players who changed and classifications on re-testing against players who maintained classification on re-testing.

	Changed (n=20)	Stayed (n=15)	p	d
Initial exact (cm)	25.5±35.8	3.7±44.6	0.12	0.54
Re-testing exact (cm)	-24.9±40.3	4.5±26.4	0.02	0.78
Initial absolute (cm)	34.5±26.7	38.8±19.7	0.6	0.18
Re-testing absolute (cm)	37.2±28.7	17.3±20.0	0.03	0.74

At initial testing, there was no significant difference between these two groups based on putt result data. However, on re-testing, significant differences were apparent for both exact (p=0.02) and absolute putt result (p=0.03) and large effect sizes were evident. The putting performance of the players who changed technique classifications on re-testing was decreased compared to the payers who maintained cluster membership. These players who moved groups produced a mean exact putt result that left the ball short of the hole on re-testing (-24.9±40.3cm) after an initial mean value that indicated the ball traveled past the hole (25.5±35.8cm).

The players who maintained the same group had minimal change in exact putt result, although the standard deviation of these exact values decreased on re-testing. For absolute putt result, the players who changed groups achieved a small change on re-testing, whilst those players who maintained group membership greatly improved on this parameter, decreasing the absolute mean distance the ball was left from the hole by greater than 50% (p=0.001). Of further note; in the re-testing session, 6 of the 7 holed putts came from the players who maintained their classification.

Assessment of the absolute velocity of COPx at ball contact highlights the change in technique affected by the training program. At initial testing, these two groups of players were significantly different based on this parameter (p=0.01), with the players who changed groups producing a significantly higher absolute COPx velocity value at ball contact. On re-testing, the same analysis reveals that the two groups are similar, and non-significant differences are present (p=0.87) (table 8.2.5.5). The group of players who changed classifications achieved a significant decrease in this parameter (p=0.03) between testing sessions.

Table 8.2.5.5: Comparison of absolute COPx velocity at ball contact means (±SD) across 4m putt testing sessions for players who changed classification on re-testing against players who maintained classification on re-testing.

	Changed (n=20)	Stayed (n=15)	p	d
Initial (cm/s)	28.7±14.4	15.6±9.6	0.01	0.94
Re-testing (cm/s)	17.3±11.3	16.5±17.0	0.87	0.06

These data suggest that the velocity of COPx at ball contact is a parameter that can be reduced but will never be equal to zero. That is, COPx velocity at ball contact may be optimised but never totally reduced (minimized). Data from studies of postural stability indicate that all people produce some movement of the COP during upright stance not zero movement, implying it is optimisable not minimisable. Previously reported data on putting (McCarty, 2002) and elite rifle shooting (Ball et al., 2003) have also indicated movement of the COP is present during execution of these skills. Therefore, it cannot be expected that optimum movement and/or velocity of the COP would equal zero during the putting stroke.

The data in both tables 8.2.5.4 and 8.2.5.5 also highlight the affect of changing technique on putt result. It is possible that the training program was easier for the players who maintained their classification because their technique was already defined by less movement of the COP. The training program had no significant affect on their COP movement and their putting performance was significantly less affected compared to the other players. Conversely, those players who changed most on COP parameters performed poorest on putt result. These players were asked to change what they had been doing in terms of COP movement and their putting technique my have already produced an optimized movement of the COPx for the cluster 2 technique. In the case of these players, the training to reduce or minimise COP movement moved them away from their preferred technique, and their performance suffered. The non-specific nature of the training task did not assist these players in the short term in their putting performance.

8.3 Pre v post changes in the 8m putts

The biofeedback training program produced no improved results on the 8 putting task. As demonstrated earlier, the absolute mean putting performance increased slightly (non-significantly) on re-testing from 59cm to 66cm and no putt was holed out. Individual responses varied, as with the 4m task, but the overall trend on those factors that changed significantly was for the re-testing mean value to be greater than that achieved on initial testing.

8.3.1 Backswing phase

On re-testing, the mean backswing time (575±89ms) was slower than at initial testing (543±53ms). This was a non-significant finding (p=0.1, d=0.42), but can be considered a trend following the same trend observed in the 4m task where a similar (but significant; p = 0.01) increase in backswing time was produced on that task. One effect of the biofeedback training program appears to be to slow the movements of the putter head during the putting task.

Putter head horizontal displacement was also larger on re-testing on this task, but again, this could only be considered a trend as it was not significantly different (24.9±6.1cm, 27.9±7.1, p=0.07, d=0.44). This finding could be associated with different putting conditions. On re-testing the players were making contact with the ball with significantly greater putter head velocity (on average) (pre mean = 213.6cm/s vs. post mean = 219.4cm/s, p = 0.03).

Interestingly, this was not the case in the 4m putts where putter head velocity at ball contact was significantly equal across tasks.

The significantly equal putter head velocity at ball contact across tasks for the 4m putts did not result in exact putt distances that were equal. On re-testing the exact putt result (and putt classifications) indicated that the ball was repeatedly left short of the hole. The same amount of putter head velocity was not making the ball travel the same distance (pre mean = 156.0cm/s vs. post mean = 156.2cm/s). The speed of the greens was not measured at any of the testing sessions, but it appears that on re-testing the greens were slower.

This trend towards slower, longer movements of the putter head during the backswing on re-testing was also associated with larger movements of COPx. The data presented in Figure 8.3.1.1 indicates only one of the seven players produced a reduced COPx range in the backswing phase. The overall mean data for this parameter produced a significant increase from 7.9±5.4mm in initial testing to 11.6±5.9mm on re-testing (p=0.01, d = 0.63). There was one exception to this rule, but as with the 4m putting task, the decrease in COPx range demonstrated by player 5 did not contribute to an improved putting performance (absolute mean increased from 56.8cm to 65.4cm).

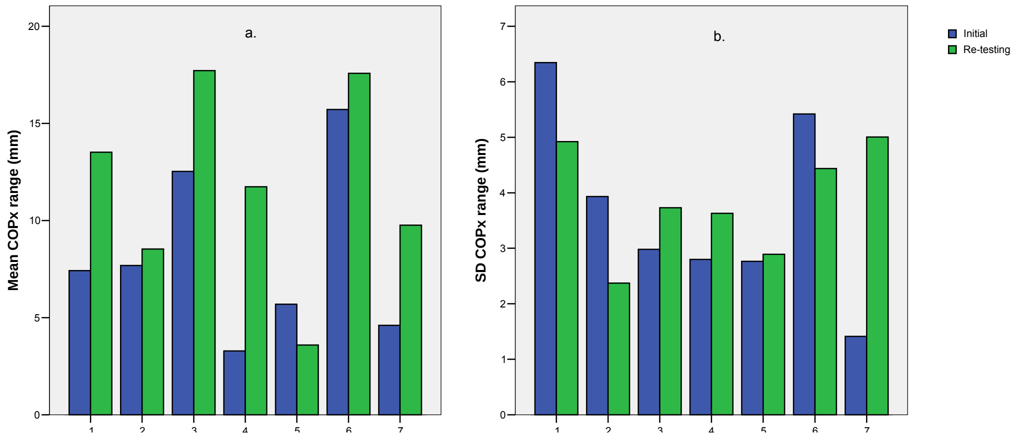


Figure 8.3.1.1a and b: COPx range in the backswing phase comparing pre-training and post-training values by subject on 8m putts; (a) Mean, (b) SD.

The increase in range of COPx during the backswing was reflected by a trend towards increased displacement of COPx at the end of backswing the position of the COPx at the end of the backswing (-4.3±6.7mm, -7.4±7.0mm, p = 0.08, d = 0.44). The most outstanding result on this parameter came from player 3 who not only achieved a large mean change in COPx position at the end of backswing (from -4.03mm to -16.7mm), but markedly decreased his variability on this parameter (from 10.1mm to 2.8mm) between initial testing and re-testing. This decreased variability indicates a more consistent performance, but the change in position is clearly in the direction opposite to that expected. This player also increased his range of COPx during the backswing, took longer to complete the backswing (740ms compared to 600ms), and moved the putter head slightly further (from 23.6cm to 22.0cm). For this player an outcome of the training program was to make a slower backswing movement, coupled with both a large COPx range and a COPx position further away from the hole during the backswing. The increased displacement and position of the COPx were not anticipated outcomes of the training program. In terms of putting performance, this player also achieved the poorest results on re-testing on both absolute mean (93.4cm) and variability (58.8cm). Re-calculation of group results with this player removed did not influence the results for this parameter (-4.3±6.3mm, -6.2±6.4mm, p = 0.29, d = 0.3).

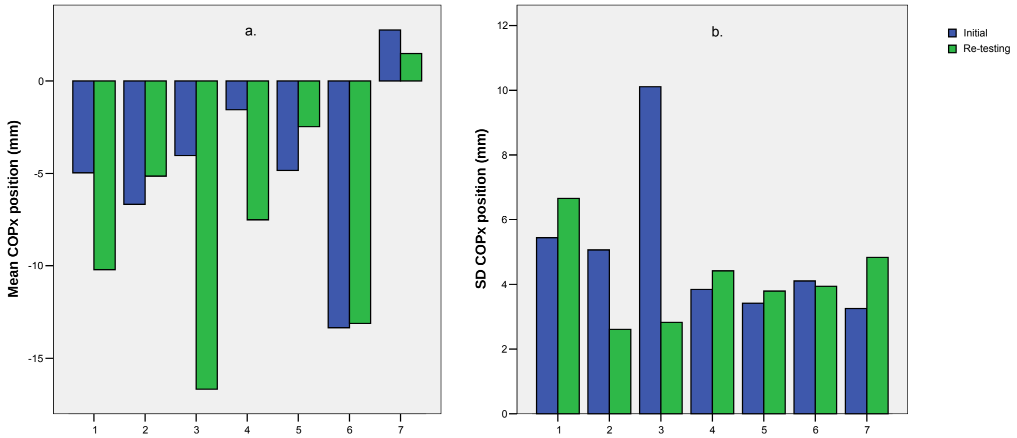


Figure 8.3.1.2a and b: COPx position at the end of backswing phase comparing pre-training and post-training values by subject on 8m putts; (a) Mean, (b) SD.

8.3.2 Downswing phase

The downswing time increased between the two testing sessions (234±43ms, 256±45ms, p = 0.05, d = 0.47) and was combined with a trend for larger displacement of the putter head to help generate more putter head velocity at ball contact (213.6±11.0cm/s, 219.4±13.2cm/s’ p = 0.06, d = 0.47). The increased downswing time is an interesting finding, as it has previously been suggested that across putting tasks the downswing time varies little irrespective of task length (Delay et al., 1997; McCarty, 2002). Though in the previous section a case was made for a slightly slower green on re-testing, theoretically this should not affect downswing time if it is, indeed, fixed. The change presented here may be more suggestive of a change in technique that was previously identified in chapter 7. Long and slow movements of the putter head were classified as cluster 2 type technique.

COPx range on downswing increased for these players – although player 6 demonstrated a small decrease between sessions (figure 8.3.2.1a and b). Overall, the group data highlights a mean change of 3.1mm (the mean change for COPx range in the backswing was 3.7mm), with an increase from 7.2±4.5mm to 10.3±6.6mm (p = 0.03, d= 0.54) on re-testing.

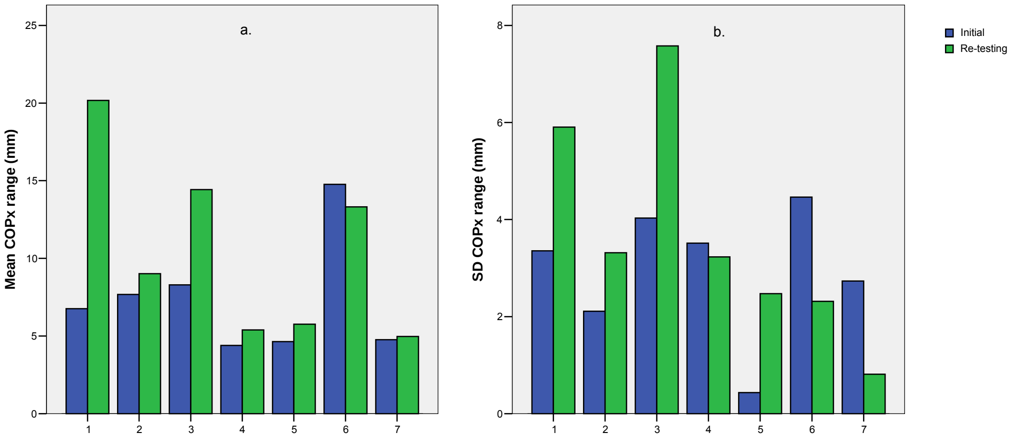


Figure 8.3.2.1a and b: Mean COPx range in the downswing phase comparing pre-training and post-training values by subject for 8m putts; (a) Mean, (b) SD.

Individual responses varied, with players 1 and 3 demonstrating the greatest increases in this parameter. These players had also demonstrated large increases in COPx range in the backswing (figure 8.3.1.1) and had produced a COPx position at the end of backswing (figure 8.3.1.2) that was further from the hole on re-testing. These two players were responding to biofeedback training in the opposite to expected direction. Along with player 5 these players also produced the greatest increases in standard deviation values which highlights the variability in their performance on this parameter.

The maximum velocity of COPx towards the hole during the downswing increased significantly ($p=0.046$) between initial testing (48.9±27.4mm/s) and re-testing (65.8±36.2mm/s). Players 1 and 3 again exerted the greatest influence on the group mean value by producing the largest changes in this parameter (Figure 8.3.2.2a and b). The other group members produced smaller changes, with players 4, 5 and 6 achieving small decreases in this parameter. However, the group mean and the responses of three of these players to increase the maximum velocity of COPx again highlights the training program produced changes away from that expected. A focus on minimizing movement of the COP during the putting stroke has, on average, had a detrimental effect on putting performance and produced increased movement of the COP in some of these players.

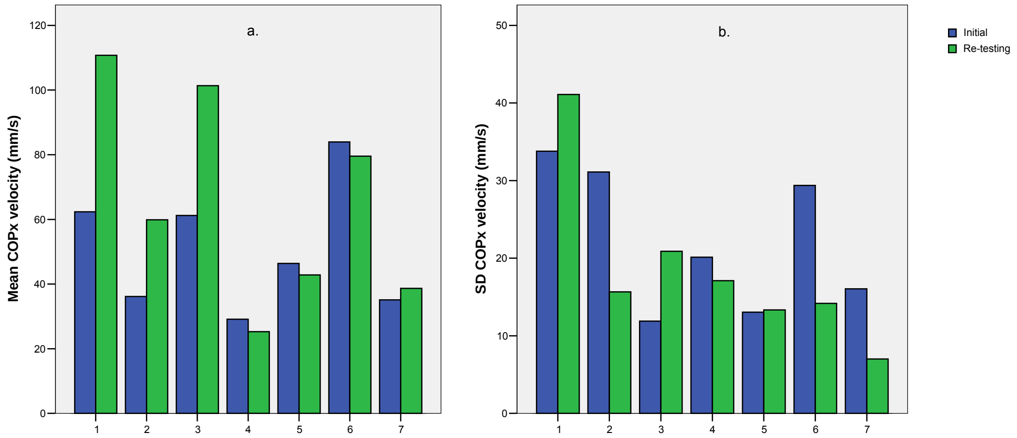


Figure 8.3.2.2a and b: Mean COPx maximum velocity towards the hole in the downswing phase comparing pre-training and post-training values by subject on 8m putts; (a) Mean, (b) SD.

8.3.3 Ball contact

No significant change in COPx velocity at ball contact occurred on re-testing (21.0±34.2mm/s, 29.5±31.6mm/s, p = 0.32, d = 0.26). Values were on average higher than in the initial testing session, though once again individual responses varied as can be seen in Figure 8.3.3.1a and b. The standard deviation data indicate that all players were significantly more consistent (p=0.001) in their production of COPx velocity at ball contact (mean of individual SDs = 26.7±11.0cm initially, 12.0±8.2cm on re-testing). This indicates a more consistent production within players of COPx velocity at ball contact. As he had done in the 4m putting task, player 4 demonstrates a different technique to the other six players, in that his COPx is moving away from the hole at ball contact. If the data is assessed in terms of absolute values, there is still a non-significant difference (33.3±21.9cm/s, 34.5±25.8cm/s, p=0.85, d=0.39). It should be noted that player 4 produced an overall increase in absolute mean putt performance, leaving the ball, on average, twice as far away from the hole on re-testing (increase on re-testing from 34.6±46.9cm to 78.2±23.8cm).

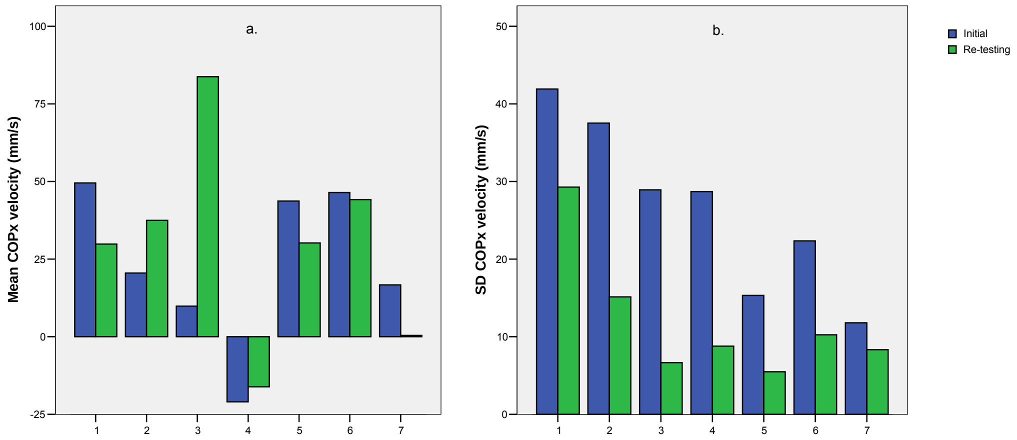


Figure 8.3.3.1a and b: COPx velocity at ball contact comparing pre-training and post-training values by subject for 8m putts; (a) Mean, (b) SD.

Of interest is that player 1 achieved a mean decrease in this parameter even though he had achieved an increase in the parameter relating to maximum COPx velocity in the downswing (table 8.3.3.1). This indicates a large change in COPx velocity was achieved between the time of maximum COPx velocity in the downswing and ball contact (a mean decrease of 80.9mm/s) even though he had not produced this same tendency in initial testing (a mean decrease of 12.8mm/s on initial testing) (figure 8.3.3.2). Alternatively, player 3 maintained a similar COPx velocity from the time of maximum velocity in the downswing to ball contact (a change of 17.7mm/s on re-testing) compared to producing a large mean change in initial testing (51.4mm/s). When averaged across the group, there was no significant difference in reduction of COPx velocity between downswing and ball contact parameter across the testing sessions (-27.9±23.4cm/s, -36.3±33.8cm/s, p = 0.27, d = 0.29).

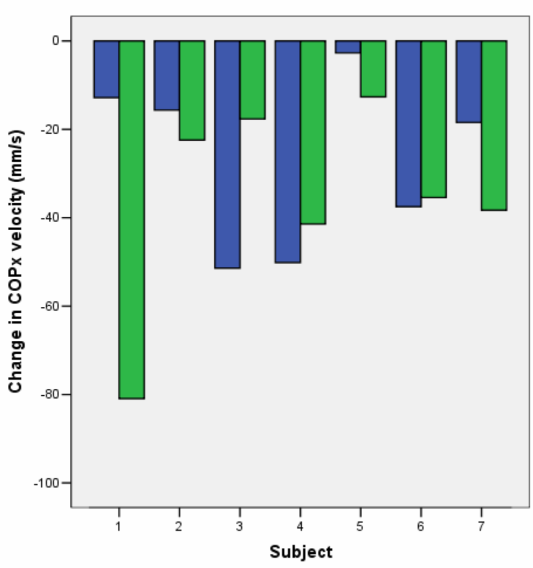


Figure 8.3.3.2: Change in COPx velocity from maximum during downswing to ball contact comparing pre-training and post-training values by subject for 8m putts; (a) Mean, (b) SD.

8.3.4 Follow through

On re-testing there were no significant changes on any parameter related to the follow through. The horizontal displacement of the putter head (41.2±11.1, 43.6±12.7, p = 0.43, d = 0.2) and time of putter head maximum velocity were not significantly different across testing sessions (26±33ms, 25±34ms, p = 0.99, d = 0.03). The biofeedback program had little effect on these putter head kinematic parameters. In terms of COPx range, no significant differences were observed between initial testing (11.1±15.3mm) and re-testing (9.4±5.2mm, p = 0.55, d= 0.15). Similarly, no significant changes occurred for the maximum velocity of COPx towards the hole (39.5±25.0mm/s, 45.3±25.6mm/s, p = 0.37, d = 0.23). The biofeedback training program had no effect on the follow through phase.

8.3.5 Summary of effect of training program on 8m putting task

The final step in the assessment of the effect of the biofeedback training program was completed by including the retesting data in the k-clustering process previously described in Chapter 7. The effect of the biofeedback training on individuals was assessed by determining whether the training caused them to change the characteristics of their putting technique and, therefore, their cluster group membership.

The following steps were taken to prepare the data for analysis:

- Each player’s raw retesting data were standardized using the max-min normalization process. The maximum and minimum data required for normalization were taken from the original raw data for the total sample of 8m putts.
- Those variables that were determined to be highly related and have high collinearity in the original data were removed from the data file. The data were then stored and saved as an SPSS input file.
- SPSS k-clustering software was used to create the solution. The cluster seeds used to create the 8m putt two cluster solution were used as initial cluster centres.

The techniques defined by clustering for the 8m putting task, as detailed in chapter 7, were:

1. Short, sharp with minimal COPx movements – a technique that involves comparatively smaller movements of the putter head and the COPx throughout the putting stroke relative to cluster 2. Velocity of the COPx at ball contact is minimal but is a heterogeneous mixture of movements away and towards the hole.
2. Long, slow with greater movements of the COPx – a technique that incorporates larger displacements of the putter head and COPx throughout the putting stroke relative to cluster 1. Velocity of the COPx at ball contact is higher than cluster 1 but is homogeneous.

From the results presented in chapter 7, 4 players were consistently clustered into cluster 1, the remaining players were clustered in both clusters 1 and 2 (table 8.3.5.1).

Table 8.3.5.1: Training group putt classifications from initial testing for 8m putts

Player	Cluster group description
1	A mix of techniques 1 and 2
2	A mix of techniques 1 and 2
3	All technique 1
4	All technique 1
5	All technique 1
6	A mix of techniques 1 and 2
7	All technique 1

After re-calculation of the clusters based on retesting data, but using the same seeding data as that used in the original k-cluster calculation, the players were again classified into clusters. The data in table 8.3.5.2, indicates that those players (1, 2 and 6) who were originally classified as producing a mix of techniques have produced a more consistent performance on each putt on re-testing. Ultimately, four players produced techniques associated with comparatively smaller movements of the putter head and minimal movements of the COPx, whereas two players produced techniques indicating larger movements of the putter head and COPx, and one player produced a mix of techniques on re-testing after initially being associated with cluster 1.

Table 8.3.5.2: Training group putt classifications after training for 8m putts.

Player	**Cluster group description**
1	All technique 2
2	All technique 2
3	All technique 1
4	Mix of techniques 1 and 2
5	All technique 1
6	All technique 1
7	All technique 1

On absolute putting performance on the 8m putting task, player 4, who changed from a consistent technique on each performance to a mix of techniques on re-testing produced the worst result with an increase of 43.6cm on re-testing. This player was, on average, leaving the ball more than twice as far away from the hole on re-testing.

Conversely, player 2 and player 7 decreased their mean absolute putting result. Player 2 achieving this change through a consistent use of technique 2 (longer, slower, more COPx movement), after initially exhibiting a mix of techniques, whilst player 7 maintained his cluster 1 membership throughout testing.

Table 8.3.5.3: 8m putts absolute putt result means (±SD) for pre- and post-training.

Subject	Pre-training	Post-training	Mean change
1	54.6±53.3	84.2±49.7	+29.6
2	96.0±82.0	62.0±35.3	-34.0
3	81.0±69.5	93.4±58.8	+12.4
4	34.6±46.9	78.2±23.8	+43.6
5	56.8±18.4	65.4±42.0	+8.6
6	28.2±35.9	46.8±21.4	+18.6
7	61.6±35.0	34.0±37.0	-27.6
Total	59.0±52.9	66.3±41.5	+7.3

Creating two groups from within this re-testing sample was achieved by placing all those players who changed classification across tasks into one group (n=4) and all those players who maintained classification in another group (n=3). Putt result data indicates that both these groups of players performed poorly on the putting tasks on re-testing (Table 8.3.5.4). No significant differences were recorded between groups on any of the parameters associated with the two testing sessions. The trend for the exact data result is for a mean value indicating the ball was left short with negative values recorded (table 8.3.5.4). The group of players who changed classifications produced no significant changes in putting performance across the putting tasks, whilst the players who maintained their classification produced a significantly poorer performance on the exact putt result in re-testing (p=0.003) and no significant changes in absolute putt result.

Table 8.3.5.4: Comparison of 8m putt result data (exact and absolute) means (±SD) across testing sessions for players who changed and classifications on re-testing against players who maintained classification on re-testing.

	Changed (n=20)	Stayed (n=15)	p	d
Initial exact (cm)	16.6±78.7	57.9±55.5	0.09	0.54
Re-testing exact (cm)	-12.4±69.8	-24.0±79.5	0.65	0.16
Initial absolute (cm)	53.4±59.1	66.5±44.1	0.48	0.25
Re-testing absolute (cm)	62.8±29.6	64.3±50.2	0.91	0.04

8.4 Overall effect of biofeedback training

The biofeedback training program was aimed at minimizing movement of the COP. Initially, this training was provided in normal stance but then was focused on reducing movement during the putting stroke. Players were also provided with instruction as to how to reduce COP movement during the putting stroke, and this was produced by using a rotational movement of the club-arms-shoulder segment about the spine (Figure 8.4.1). However, at no time in the training program did players strike a golf ball. The training program was completed inside the clubhouse with images from the pliance® mat system projected onto the wall in front of the player in real-time. Players were either standing on the mat watching the image projected onto the wall or standing on the mat watching the image whilst making a putting action with or without their putter.

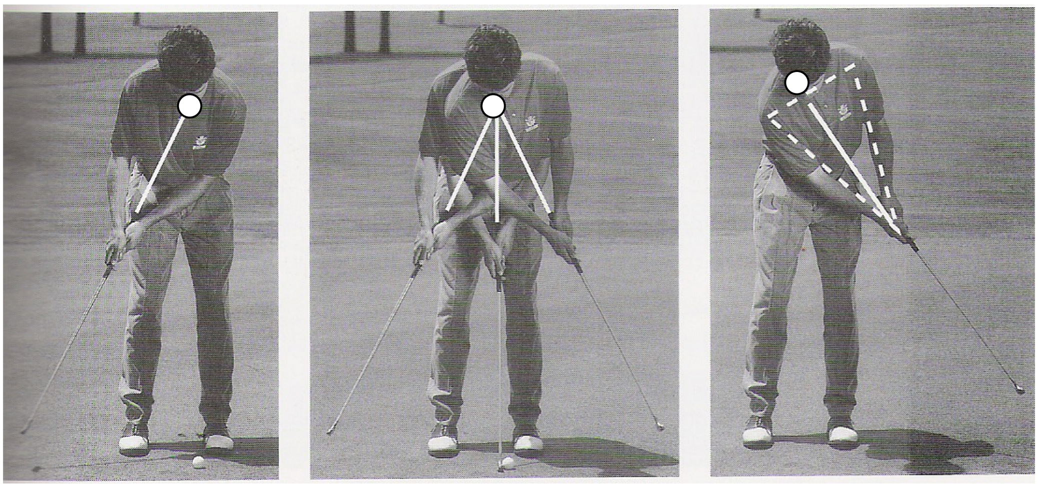


Figure 8.4.1: Modified diagram from Pelz indicating the axis of rotation of the club-arm-shoulder segment (Pelz, 2000; p. 71).

The data presented for the two putting tasks suggests that this type of biofeedback training had a minimal effect on putting performance and actually produced significant increases in COPx range in the backswing. That is, rather than COPx movement being reduced after training, mean values suggested that there were changes (some significant) across phases and putting tasks in an unexpected direction. Whilst it is acknowledged that these mean values can be influenced by outlying values, the trend across the data was for larger mean values to be recorded on re-testing. Standard deviation values fluctuated across the parameters but showed an overall trend verified by a number of significant results that indicated decreased variability on parameters, especially in relation to COPx velocity at ball contact for both tasks.

After re-testing and re-classification, four of the seven players exhibited technique 1 for all re-testing putts on both tasks, whilst two players displayed technique 1 for the 4m putts and technique 2 for the 8m putts and the other player displayed a mix of techniques on the 8m putting task (table 8.4.2). This could be considered a positive affect of the training program as it was anticipated that the velocity of COPx at ball contact could be reduced. This parameter was the most influential in cluster formation of 4m putts and a highly influential parameter in cluster formation of 8m putts. The ability to influence this parameter and to reduce it is a sign that the training program had some affect. However, if players were already classified as technique 1 the training program is largely irrelevant. Tailoring the training program to the perceived deficiencies in technique will have greater relevance in future research.

Table 8.4.1: Training group putt classifications after biofeedback training for both putting tasks.

Player	4m putt classification	8m putt classification
1	All technique 1	All technique 2
2	All technique 1	All technique 2
3	All technique 1	All technique 1
4	All technique 1	Mix of techniques 1 and 2
5	All technique 1	All technique 1
6	All technique 1	All technique 1
7	All technique 1	All technique 1

Closer analysis also suggests that the training program was more likely to produce a more consistent technique with each player. In the 4m putting task, four players had initially tested and been classified as a mix of techniques. On re-testing each of their putts were classified into the same technique. In the 8m putting task, three players were classified as a mix of techniques initially, but had each of their re-testing putts classified into the same technique. The only exception to this trend was for player 4 in the 8m putting task to be initially classified as all technique 1 but in re-testing to be a mix of both cluster techniques. Even then, only this player’s first putt at the 8m task was classified into technique 2.

Of note, player 7 was classified as technique 1 for every one of the 20 putts he struck during this study. He was the only player to maintain his technique throughout both initial and re-testing sessions and was the only player to produce a reduced absolute mean performance on re-testing for both putting tasks. It is possible that having a technique that clearly fits into the classification of minimal movements of the COPx made the biofeedback training easier for this player and his putting performance was therefore less affected than the other players in the sample. This may highlight the affect – in all other players - of trying to minimize parameters that had previously been optimized.

9 Discussion

In some sports, performance is measured not by how, but by how many. Objective scoring systems assign values to scoring shots irrespective of style or technique. The aim of the author was to determine whether one, or more than one, distinct techniques existed in golf putting. This task was aided by novel methodological features. A methodology was developed that allowed the simultaneous collection of both putter head kinematic data and COP data in the field. Players were classified according to parameters related to their technique, not based on their putting accuracy or their handicap. This investigation of putting took place in the field and required players to hit putts to a hole on a practice putting green. Perhaps surprisingly, this last feature is innovative in this research area.

Cluster analysis data indicate that there were two distinct putting techniques present within the sample of 38 players for each of two putting tasks. Two putting techniques were distinguished for each of the 4m and 8m putting tasks. The two techniques found for the 4m putting task were not the same as the two techniques for the 8m putting task. Cluster analysis provided classifications at the 4m putting task that were based entirely on parameters related to movement of the centre of pressure in the same plane as the intended line of the putt to the hole (COPx). For the 8m putting task, parameters related to movement of COPx, COPy and putter head kinematics contributed to the classification of the two putting techniques. There were some similarities across the 4m and 8m techniques, with eight parameters being influential in the classification of techniques for both the 4m and 8m putting tasks. All of these eight parameters were related to movement of COPx.

9.1 Two putting techniques

9.1.1 – 4m putting task.

The two techniques identified in the 4m putting task were defined as:

1. Less movement (relative to cluster 2) of COPx in the backswing and downswing phases with velocity of COPx at ball contact closer to zero (on average). Low COPx velocity.
2. Larger movement (relative to cluster 1) of COPx in the backswing and downswing phases with velocity of COPx at ball contact non-zero. High COPx velocity.

These two techniques were influenced by the velocity of COPx at ball contact and parameters related to displacement of the COPx during the various phases of the putting stroke. As described above, low COPx velocity group were associated with smaller movements of the COPx and a lower COPx velocity at ball contact. These classifications represent the first time that putting techniques have been identified in the research literature – as opposed to groupings based on handicap or putt accuracy.

The clustering process employed in this study followed Grabe and Widule (1988) in that each individual’s putts were treated as separate items to be clustered. Only 14 of 34 players consistently produced technique 1 for each of their putts and three players consistently produced technique 2 for each of their putts. Remaining players had putts clustered across the two technique groupings. This suggests that 16 players demonstrated the ability to consistently reproduce movement of the COPx during the putting stroke, whilst 16 of their colleagues did not display the same level of consistency. As the cluster analysis correctly re-classified 98% of the putts using the replication method (three random samples of 2/3rd of the total number of putts) the cluster results suggest that players did change technique during the execution of their five putting trials. This changing of technique may be a conscious decision on the part of the player, or an inability to maintain the same technique across trials.

On occasions a player who missed a putt by a large distance produced a change in technique on a subsequent putt. Of the 17 putts at the 4m hole that finished further than 50cm past the hole, seven resulted in a change in technique on the subsequent putt. The question is, do players need to change techniques to create a different performance after a poor putt, and is a bad putt just a natural variability or do they need to refine their chosen technique? The other 10 putts that went more than 50cm past the hole did not produce a change in technique on subsequent putts, so the data from the present study indicates that a mix of responses is likely after a poor putt. The only other sports biomechanics study to have clustered individual trials as opposed to averaged trials also reported that individuals move between cluster groupings when clusters were defined based on technique (Grabe and Widule, 1988). For Grabe and Widule, whilst two thirds of the individual weightlifters with multiple lifts were classified into the same technique groups for all of their lifts, the remainder varied between clusters, so were not able to be classified as lifters that produced a consistent technique. As with the present study, the individual performances varied, the individual trials were clustered accordingly, but the performer did not always fit neatly into one technique cluster or grouping. Whilst data from the present study indicated golfers move both ways between groups (i.e. from 1 to 2 or from 2 to 1), Grabe and Widule did not comment on any trend for weightlifters to move in a certain "direction" when changing clusters.

There were no significant differences in the present study between those players classified into the same clusters consistently and those who changed clusters with respect to age (low COPx velocity = 51.1±16.9 years, high COPx velocity = 60.6±7.8 years, changers = 60.6±17 years, p=0.173) or handicap (handicap: low COPx velocity = 10.4±4.8, high COPx velocity = 14.3±10.1, changers = 16.7±5.8, p = 0.091) although there is a trend, worthy of future study, for low COPx velocity to be younger and have lower handicaps and high COPx velocity and "changers" group to be older with higher handicaps. This trend is for the lower handicap player to be more consistent in technique performance than the higher handicap player. The distinction between the ability to consistently use the same technique compared to the use of two different techniques is an area that requires further research. Previous research, largely based on putt result, has not provided a distinction between techniques, and therefore this area of research – refining or changing technique – has not previously been considered in putting.

Absolute putt result was not significantly different between the clusters in the present study (low COPx velocity = 36.8±28.5cm; high COPx velocity = 39.5±32.3cm; p=0.66; d=0.09), there were significant differences between the clusters based on handicap (low COPx velocity = 12.4±5.9; high COPx velocity = 16.4±6.6; p = 0.002; d = 0.63) and age (low COPx velocity = 54.5±16.4 years; high COPx velocity = 61.5±15.2 years; p = 0.041; d = 0.43). The younger, lower handicap player was significantly more likely to be a member of low COPx velocity, whilst the older, higher handicap player was significantly more likely to be a member of high COPx velocity. Although for this data it is not possible to state categorically that the younger, lower handicap players performed better on putt performance than their older, higher handicap counterparts, correlational analysis indicates that in the high COPx velocity group, as handicap increases so to does absolute putt result (r=0.465, p =0.001). A high handicap player using the high COPx velocity technique is likely to produce a worse putt result than a lower handicap player using the same technique. The ability of the high handicap player to produce good putt results is diminished if they use the high COPx velocity technique.

The data from the present study indicates higher mean values for absolute putt result (low COPx velocity = 36.8±28.5cm; high COPx velocity = 39.5±32.3cm) than that reported by McCarty (handicap ≤ 14, absolute putt result mean = 25.6±14.7cm; handicap ≥ 14, absolute putt result mean = 32.9±18.6cm; p=0.001) (2002). The difference in the putting tasks between the two studies created this difference. Although absolute putt result was measured as radial distance from the hole in both studies, in the case of McCarty the hole was a painted circle on the ground and the players were required to produce a putt that finished exactly over the top of it. As a result, McCarty's method also produced a smaller proportion of all putts that traveled past the hole (43.8% compared to 62.6% in the present study) as players were attempting to hit the ball to stop on the hole, rather than enter the hole at a variety of speeds, as was the case in the present study where an actual hole was used. McCarty initially reported 4m absolute putt results based on handicap groupings with the lower handicap group achieving a better mean result, whilst there were no significant differences between clusters in the present study, even though there was a significant difference on handicap. However, McCarty chose to subsequently classify all players based on accuracy (ranked either side of a median value of 28cm) after his low and high handicap groups were not significantly different on putt result for a 2m task.

As a means of comparison for the data in the present study to the published data of McCarty (2002) the present sample was split in half based on absolute putt result (median value = 34cm). The data for absolute putt result, age, handicap and kinematic and COP parameters is presented in Table 9.1.1.1 for the accuracy groups from both studies.

Table 9.1.1.1: Overall and mean data for 4m putting task comparing data from the present study to McCarty (2002).

4m putts	Present study			McCarty (2002)		
	Overall (n=108)	Less accurate (n=54)	Accurate (n=54)	Overall (n=21)	Less accurate (n = 10)	Accurate (n = 11)
Putt result (cm)*	37.6±26.5	59.3±25.6	15.8±11.5	29.0±5.6	33.2±3.9	24.4±2.5
Age (years)	56.5±16.3	59.7±15.5	53.3±16.7	†48.2	51.8±17.7	44.6±16.1
Handicap	13.5±6.4	14.6±6.6	12.5±6.1	11.2±8.1	14.5±7.5	7.7±7.7
Forward swing X (cm) ‡	59.6±13.6	57.2±14.6	60.0±12.5	60.7±15.6	65.5±18.9	55.6±8
Forward swing (ms)	660±148	654±166	667±128	†656	680±154	632±106
PH velocity at BC X (cm/s) ‡	155.8±10.7	156.5±12.8	155.0±8.3	141.0±8.0	143.0±8.0	141.0±7.0
PH velocity at BC Y (cm/s) ‡	4.0±6.6	4.0±5.8	4.0±7.4	†-0.6	-2.7±5.0	1.5±0.5
COPx location end BS (mm) ‡	-3.7±5.9	-3.8±6.4	-3.6±5.5	†-7.7	-10.0±11.0	-5.3±6.5
COPx location at BC (mm) ‡	1.3±6.8	1.3±7.8	1.2±5.7	†0.2	†-2	†1.6

*Significant differences ($p<0.001$) between accuracy groups for the present study and McCarty (2002); ‡Significant differences between accuracy groups in McCarty (2002) only; †Overall mean data calculated from mean data tabulated in McCarty (2002); BS = backswing, DS = downswing, FT = follow through, PH = putter head. McCarty reported forward swing only and the present study reported downswing and follow through data. These two parameters have been combined to produce forward swing values.

There were no significant differences between any of the accuracy groups from either study for age or handicap. The membership of the accuracy groups was not influenced by these two parameters indicating that, based on this classification system, handicap is not an indicator of absolute putt result, though there was a trend from the McCarty (2002) data towards the accurate group being made up of the lower handicap players ($p=0.06$). There was no such trend in the present study ($p=0.58$).

The overall putt result data indicate a slightly higher mean value for the overall and less accurate group data in the present study, a greater level of variability and a larger difference between the accurate and less accurate groups. McCarty reported the mean accuracy of each player and then reported the standard deviation of these means. This, along with the nature of the putting task, decreases the variability in the reported data. When assessed using absolute putt result to define groups, data from the present study indicates no significant differences between groups on any kinematic or COPx parameter. This is in contrast to the results of McCarty (2002) who reported significant differences between groups on a number of parameters. This difference can be explained through the difference in methodology employed by the two studies. The putting task as defined by McCarty (2002) required the players to hit a minimum of 25 putts at a painted hole on the ground. The large number of attempts followed on from 10 practice putts under the same test conditions. Players were also required to stand in exactly the same position (as defined by traced outlines of their feet). A putt result of “holed out” (absolute result = 0cm) was achieved if the ball finished on the painted hole. The results from McCarty’s study reflect this with a lower overall putt distance from the hole. Also, as the co-efficient of variation values across the overall (19%) and accuracy groups (12% and 10% respectively) are much smaller than the same values from the present study (70%, 43%, 73% respectively). The large standard deviation values of the present study are expected, as in the field the spread of putt results would be greater. Calculated data from Cochran and Stobbs (1968) indicates a co-efficient of variation of 63.2% for putts in the range of 4 to 6 yards for professional players. As with players in the present study, the professional players in Cochran and Stobbs would have expected that the ball could drop into the hole at a range of speeds, these ball speeds could be generated by a range of clubhead velocities at ball contact and players had no practice putts. As a result, the putt result and kinematic data from studies conducted in the field is highly variable in comparison to McCarty (2002).

The splitting of the data sample from the present study into accuracy groups, and the lack of significant differences between those groups, highlights the validity of cluster analysis techniques in biomechanics studies. If the data analysis methodology of McCarty (2002) had been implemented in the present study, no significant differences between groups would have been reported. Classifying players based on mean accuracy employs a method that suggests accurate results are produced by one technique, and less accurate results are produced by a different technique. Instead, it has been demonstrated that similar putt results (similar levels of accuracy) can be achieved using different putting techniques. The two clusters identified on this putting task differed on the movement of COPx during the putting stroke, but this technical difference was not associated with a significant difference in putt result. Significant differences between groups for absolute putt result were achieved by McCarty – and could be produced in the present study also - because putt result was used to determine group membership. The clustering process in the present study produced significantly different putting techniques that were not significantly different on putt outcome. Putt result was not used to differentiate between groups and was not included in the cluster analysis. This parameter (along with age and handicap) was not included in the cluster analysis so that parameters only related to technique were influential in the formation of technique clusters.

In comparison to the present study, McCarty had used an outcome measure to differentiate groups. Players were ranked on mean absolute putt result (the range of mean values was 20.9cm to 40.1cm, overall mean = 29±5.6cm) and divided into two groups of equal size. A player with a 0.3cm greater mean value (28.3cm compared to 28.0cm) than the player ranked immediately above was classified into the less accurate group, whilst the counterpart was placed into the accurate group. It is likely that using the accuracy classification system created both Type I and Type II errors in McCarty's study. The author classified players on absolute mean putt result, assuming that the putt outcome was indicative of technique. Not only has the present study shown this to be questionable, but McCarty has also used a single continuous variable to produce two nominal groups. Whilst this may be a standard practice, the putting task required of the players contributes to the likelihood of these errors as it compresses the results into a much smaller range, and makes the separation of players more difficult as there is no clear delineation between an "accurate" and "less accurate" result. The likelihood of both Type I and Type II errors is therefore high. Type I errors are present as the classification system and subsequent statistical analysis wrongly concludes that there are statistically significant kinematic differences between players who are more accurate and players who are less accurate putters. This reinforces the perception that there is one technique for accurate putts and one technique for less accurate putts. The issue for McCarty is that the hypothesis is incorrect. Alternatively, McCarty is not able to distinguish between techniques because there is no way of determining technique differences using the accuracy classification method. If it is possible to achieve the same putt result with different techniques, as demonstrated in the present study, then Type II errors will be present in any paper that distinguishes between groups based on putt result alone as the accuracy classification will cloud the possibility of different techniques existing in the data.

In the 4m putting task in the present study, putter head kinematic data were not influential in the formation of the two clusters. This data has been previously reported for a 4m putting task by Delay et al. (1997), but like McCarty (2002), the data presented is slightly different to that produced in the present study, as in that study the author classified putts as successful when they finished within a diameter of the hole that equated to 5% of the putt distance. Players putted at a painted circle that was 5cm in diameter and needed to leave the ball within 20cm of this hole at the 4m putting task. Only successful putts were analysed and reported. Players continued to putt until they had completed 10 successful trials.

Skilled players had a handicap less than five, whilst a control group of novice players had no golf experience.

When the putt result data from the present study was re-analysed using Delay et al's definition of a successful putt, the sample of 108 putts was classified as producing 29.6% successful putts and 70.1% unsuccessful putts. Across the cluster groups, there was no difference in success rate (cluster 1; 29.9% successful, 70.1% unsuccessful: cluster 2, 29% successful, 71% unsuccessful). Using this indicator of success as a guide, it would take each of the players in the present study around 33 putts to achieve 10 successful results.

In order to compare the data from the present study to Delay et al., the data were split into groups according to handicap. As there is a clear distinction between the low (0-9) handicap and high (18-27) handicap groups in the present study, it was felt that these classifications were similar to, but not exactly the same, as the classifications used by Delay et al. (1997). The data in table 9.1.1.2 presents the data from the two groups used in Delay et al. (data is 10 subjects x 10 successful putts) compared to the present study (each putt as an individual trial).

Table 9.1.1.2: Comparison of key kinematic parameters on 4m putting tasks between Delay et al. (1997) and the present study using the high and low handicap groupings (mean±SD).

Parameter	Delay et al. Novices (n=10)	Delay et al. expert (n=10)	High handicap (n=25)	Low handicap (n=30)
BS time (ms)†	532±40	650±20	570±124	522±127
DS time (ms) ‡	273±23	289±10	272±40	247±33
FT time (ms)*	311	430	422±143	393±121
Forward swing (ms)†	584±48	719±32	694±151	641±143
BS disp (cm) ‡	30.6±2.7	28.8±0.9	23.7±4.5	21.4±3.9
DS disp (cm) ‡	32.5±3.9	27.5±1.1	25.3±4.4	22.3±4.0
FT disp (cm)†	39.2±5.1	64.2±6.4	34.9±8.5	34.7±11.8
Forward swing (cm)†	71.7±6.3	91.7±6.3	60.2±9.0	57.1±12.4
Vel at BC (cm/s)†	205±1.8	183±5	155.3±13.9	153.9±10.3

†Significant differences between groups in Delay et al. (1997). Forward swing presented by Delay et al. (1997) as combination of downswing and follow through phases. Follow through data for Delay et al. (1997) calculated from forward swing and downswing data. *There were no standard deviation data provided on follow through time from the Delay et al. paper. ‡Significant differences between high and low handicap groups ($p<0.05$).

The data from the present study reports generally lower values than the Delay et al. (1997) groups for all parameters related to putter head displacement and velocity at ball contact. These data suggest that the outdoor green used in the present study was faster than the indoor carpeted surface used by Delay et al. (1997). Delay et al. (1997) reported that there were significant differences between the novice and expert groups for a number of parameters, but across studies, there was no agreement on where the significant differences existed. On those parameters where the novice and expert were significantly different, the low and high handicap groups from the present study were not.

Significant differences in the present study between the low and high handicap groups occurred when the high handicap group recorded significantly higher mean values for downswing time (272±40ms vs. 247±33ms; $p=0.02$) and backswing (23.7±4.5cm vs. 21.4±3.9cm; $p=0.04$) and downswing displacement (25.3±4.4cm vs. 22.3±4.0cm; $p=0.01$). In the study by Delay et al. significant differences were reported when the novice players recorded significantly lower values for backswing time (532±40 vs. 650±20ms; $p<0.05$), forward swing time (584±48ms vs. 719±32ms; $p<0.05$), follow through displacement (39.2±5.1cm vs. 64.2±6.4cm; $p<0.05$) and forward swing displacement (71.7±6.3cm vs. 91.7±6.3cm; $p<0.05$). The exception to this being putter head velocity at ball contact. For this parameter the novice group recorded a significantly higher value than the expert group (205±1.8cm/s vs. 183±5cm/s; $p<0.05$). There is no agreement between the present study and the Delay et al. study on differences between these groups. It should be reiterated that the groupings used in the present study would not be reflective of a novice-expert difference.

With each putt treated individually, the variability in the kinematic data from the present study is high. By comparison, the data from Delay et al. (1997) exhibits low variability. Delay et al. reported data on 10 successful trials from each of 10 subjects at the 4m distance. Delay et al. also allowed each player five practice putts at the putting task. As with McCarty (2002) players were required to stop the ball over the target. Players "…were encouraged not only to control precisely the direction of the movement, but also to control precisely the amplitude of the movement by trying to stop the ball on the target" (page 604). Perhaps most surprising of all, the reported data for putter head velocity at ball contact for the novice group exhibits a co-efficient of variation of only 0.9% compared to the expert groups 2.7%, the high handicap groups 8.9% and the low handicap groups 6.7%. This is a clear indication that the task is constraining the variability in the data reported by Delay et al. when compared to the data from the present study.

Delay et al. (1997), like others who have published research in putting biomechanics, classified players according to handicap level (less than 5 or novice golfers in this case). As the present study has demonstrated, putts can be distinguished on technique, with some players consistently producing the same technique, but just as many players possibly choosing to vary their technique between trials. This consistency of technique is not necessarily based on handicap. The fact that Delay et al. only reported data on successful putts does not allow the putting performance of the two groups to be assessed accurately. However, the methodology employed by these authors and the terminology used in their classification (expert and novice) indicates that they expected successful putts from the two groups to be produced by different putting techniques. For a number of parameters, the reported data indicate that this assumption was incorrect at the 4m putting task. The authors also reported averaged data over 10 trials rather than treating each trial individually, and eliminated putts that did not fit a certain criteria. Subsequently, the data from Delay et al. presents an analysis of putting technique that ignores differences within and between sub groups that are formed on handicap. This would again suggest that Type I and Type II errors are likely in their study.

9.1.2 – 8m putting task

The two techniques identified in the 8m putting task were defined as:

1. Short, sharp with minimal COPx movements – a technique that involves comparatively smaller movements of the putter head and the COPx throughout the putting stroke relative to cluster 2. Velocity of the COPx at ball contact is minimal but is a heterogeneous mixture of movements away and towards the hole. Low motion.
2. Long, slow with greater movements of the COPx – a technique that incorporates larger displacements of the putter head and COPx throughout the putting stroke relative to cluster 1. Velocity of the COPx at ball contact is higher than cluster 1 but is homogeneous. High motion.

In classification of putts on the 8m putting task, both COP and putter head kinematic parameters were influential in cluster formation. This provides for a different distinction between the two techniques compared to the 4m cluster results as the putter head kinematic data means an understanding of what is happening to the club during the putting task is a part of the cluster differences. In terms of coaching outcomes from the present study, it is anticipated that the movement of the putter head will be an easier concept to interpret than movement of COPx.

At the 8m putting task, 29 players performed two or more putts that were included in the subsequent analysis. Of these 29, 15 players remained in the same cluster for all putts with 12 players in “low motion” and 3 players in “high motion”. The other 14 players changed between the clusters, with no trend in regards to direction of change. These data on consistency of technique for the 8m putting task are similar to the results achieved for the 4m putting task. On the 8m putting task, re-classification using the replication method resulted in 88% of putts being correctly classified, again indicating that the cluster analysis was robust. This tendency of players to change clusters has been discussed previously in this chapter. Where previously (4m putts), it would be difficult to determine, from a coaching point of view, how a player could change technique when the factors influencing technique were based on COPx parameters, for the 8m putting task, cluster membership is equally dependent on putter head kinematic data. The parameters relating to putter head kinematics are more likely to be manipulated by the player. Taking a longer, slower backswing on a subsequent putt would be a considered response to leaving the ball well short of the hole on the previous putt. In the 8m putting task this could lead to a re-classification of that player’s technique into a different cluster.

Players who are a part of “low motion” are slightly, but not significantly (p=0.06; d=0.35) younger (53.9±14.6 years) than those players in “high motion” (60±20.4 years). “Low motion” players have significantly lower handicaps (11.9±5.5 vs. 18.3±7.6; p = 0.00; d = 0.91) although the lowest handicap player in the study (handicap = 3) is represented in both groups. The analysis of absolute putt result (60±54cm vs. 56±43cm; p = 0.7; d = 0.07) reveals non-significant differences between the techniques. The strong tendency for the younger, lower handicap players to be members of the “low motion” technique grouping is clear, though even within this technique there were players who moved between clusters.

The data provided in Table 9.1.2.1 highlights the key putter head kinematic parameters for the two clusters, and also provides data for each of the two clusters defined for the 4m putting task. As there are no previously published data in the 8m putting task, it is not possible to compare these data. The following section provides a comparison between the two putting tasks used in the present study.

Table 9.1.2.1: Comparison of key putter head kinematic parameters on the 4m and 8m putting tasks (mean±SD).

	4m putts		8m putts	
Parameter	Low COPx velocity	High COPx velocity	Low motion	High motion
BS time (ms)	530±111	564±111	559±113	647±108*
DS time (ms)	253±44	266±37	242±40	286±26*
FT time (ms)	385±122	450±127†	378±119	480±124*
BS disp (cm)	21.7±5.3	23.2±5.1	26.8±5.9	30.5±5.0*
DS disp (cm)	23.0±5.4	24.5±5.0	28.9±7.9	32.4±4.9*
FT disp (cm)	33.6±12.1	38.9±10.6†	43.2±14.3	54.9±13.2*
PH vel at BC (cm/s)	154.5±10.1	158.9±11.7	211.3±13.0	214.2±11.5

*Parameter influential in classification of 8m putts and significant differences present between 8m clusters ($p<0.001$). †Significant differences ($p<0.05$) between 4m clusters. BS = backswing, DS = downswing, FT = follow through, PH = putter head.

It is notable that the mean values for the 8m putting task are greater than all corresponding values for the 4m task apart for putter head displacement and velocity parameters. As the putting task increases in length, the movements of the putter head travel through a greater displacement and ball velocity at contact is greater. The same trend is not observable in the temporal phase parameters. There is overlap across the putting technique and cluster means such that the follow through and downswing time means are similar for the “low COPx velocity” and “low motion”, and the mean data for the “high COPx velocity” and “high motion” techniques are also similar. On the backswing time parameter, the “high COPx velocity” group’s mean value for the 4m putting task, is of a similar magnitude to the “low motion” group’s value in the 8m putting task. In terms of temporal data, the greatest difference between putting tasks occurs in the backswing phase, whilst there is little relative change between putting tasks in the duration of the downswing and follow through.

The overall trend in displacement and velocity data has previously been reported by Delay et al. (1997) and McCarty (2002) who indicated that as the putting task length increased, so to did backswing length (and downswing length), putter head velocity at ball contact and follow through length (all p<0.001). As the putting task increases in length, so too does backswing length. For both of Delay et al. (1997) and McCarty (2002) the 4m putting task was the longest putt required of the players. However, downswing time remained similar across the putting tasks.

The test of equality was used to assess downswing time for the two putting tasks in the present study. A non-significant trend at the 5% level (p=0.08) was indicated, but at 10% tolerance a significant result was recorded (p=0.03). The exact level of difference was calculated as 8.5%, providing a p value of 0.046 for the test of equality. A tolerance of 8.5% when assessing the equality of the phase seems realistic given the method used in the identification of these phases and provides some support for the notion proposed by Delay et al. (1997) that downswing time is the same across putting tasks of different lengths. As backswing data has indicated a change in length across putting tasks, this provides clear evidence that players adjust to the distance demands of the putting task by changing backswing length but not downswing time. These data provide support for the pendulum putting theory of Pelz (2000).

The length of the backswing and its relationship to putter head velocity at ball contact is a key aspect of the pendulum putting theory. Earlier in this thesis, modeling occurred of a pendulum putting stroke. These data were able to indicate that for different downswing starting positions, the putter head velocity at ball contact will vary. A graphical representation of this data is presented in Figures 9.1.2.1. This figure indicates the relationship between backswing horizontal displacement and putter head velocity at ball contact for three different length pendulum of the same swing length.

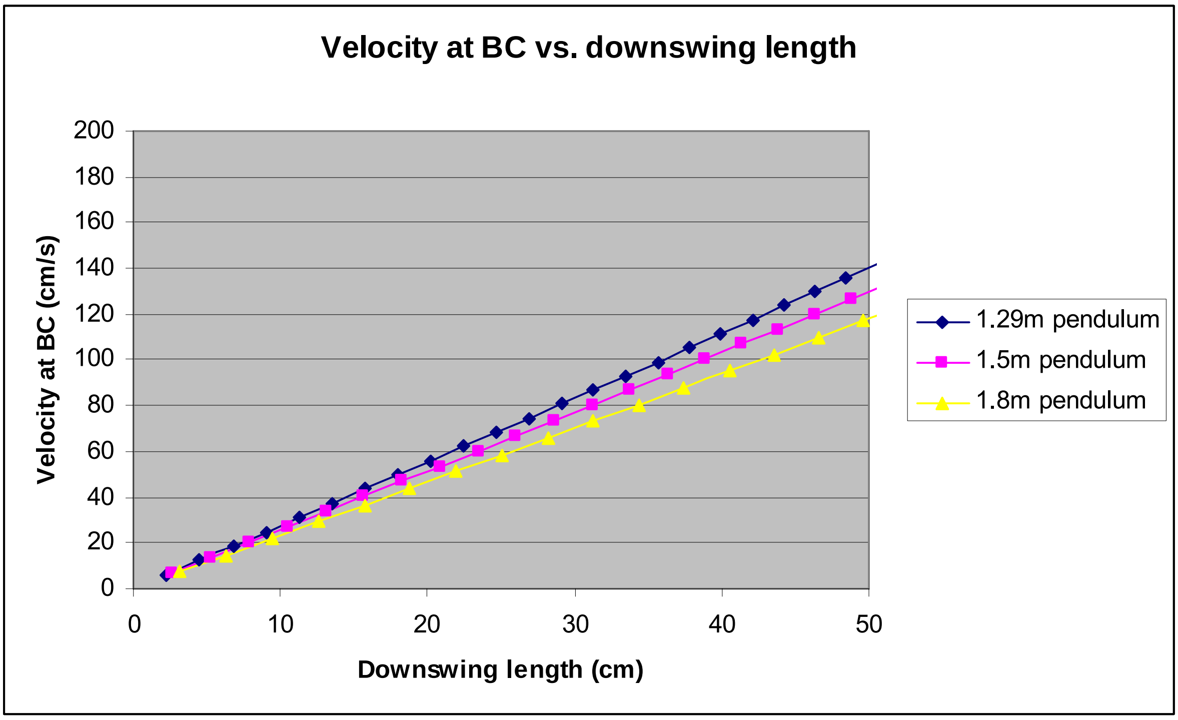


Figure 9.1.2.1: The relationship between putter head velocity at ball contact and backswing length in three different length pendulums for the same downswing length.

The data provided in table 9.1.2.1 indicated downswing lengths of around 24cm for the 4m putts, and around 30cm for the 8m putts, with overall mean putter head velocity at ball contact of around 157cm/s and 213cm/s respectively. These reported data do not equate to the data of the modeled pendulum. From figure 9.1.2.1 a downswing length of 24cm would equate to a velocity of the putter head at ball contact of between 55 and 65cm/s. A downswing length of 30cm would equate to putter head velocity at ball contact of 70 to 85cm/s depending on the length of the pendulum (the height of the person). Both of these putter head velocity values are very different to the reported values for putter head velocity at ball contact and indicate that the sample of players used in this study are not, on average, producing pendulum like putting motions. Based on the modeled pendulum data and the reported data for downswing length and putter head velocity, no player in the present comes close to representing a pendulum putting type motion.

The two techniques identified for the 8m putting task were significantly influenced by the same COPx parameters as the 4m putting task, with the exception of COPx range in the downswing (table 9.1.2.2). As the kinematic data has indicated, there is greater amplitude of putter head movement in the 8m putting task and this may be associated with increased amplitude of movement of the COPx. However, correlation analysis for each putting task by putting technique indicates no significant relationships between the putter head displacement parameters and the COPx amplitude parameters within the two techniques ($p>0.05$).

Generally, movement of the COPx in the 8m putting task was only slightly higher than the 4m putting task. Mean technique values for “high COPx velocity” and “high motion” are relatively similar across parameters. There are some differences between the “low COPx velocity” and “low motion” techniques, most notably in the maximum velocity of COPx during the downswing and the velocity of COPx at ball contact where the mean values are greater in the 8m putting task. Whilst the technique identified with large movements of the COPx in the 8m putting task is not that different to the technique identified with similar characteristics for the 4m putting task, the technique identified with relatively smaller movements of the COPx at the 8m putting task produces much higher values than the technique classified similarly in the 4m putting task.

Table 9.1.2.2: Comparison of key COP parameters on the 4m and 8m putting tasks (mean±SD).

	4m putts		8m putts	
Parameter	Low COPx velocity	High COPx velocity	Low motion (n=78)	High motion
COPx range BS	4.9±2.7	9.6±7.0†	6.7±3.9	13.2±8.2*
Position of COPx BS	-2.2±4.2	-7.4±7.7†	-3.6±5.5	-11.8±8.9*
Max. vel of COPx BS	-22.1±10.6	-42.4±1.2†	-29.6±15.1	-44.3±22.2*
COPx range DS	3.9±2.6	10.6±4.8†	8.1±6.3	11.7±6.3
Position of COPx DS	0.8±4.4	2.5±10.6	3.5±7.6	-1.3±9.6
Max vel of COPx DS	25.6±15.7	71.8±28.3†	50.5±36.8	76.4±45.9*
COPx velocity BC	5.2±16.9	58.4±22.9†	20.3±41.1	66.2±47.0*
COPx range FT	8.4±8.2	14.8±8.4†	10.6±10.7	16.5±11.6*
Max vel COPx FT	34.5±24.6	66.2±27.8†	49.1±32.4	76.0±50.0*

*Parameter influential in classification of 8m putts and significant differences present between clusters ($p<0.001$). †Significant differences ($p<0.05$) between 4m clusters. BS = backswing, DS = downswing, FT = follow through, PH = putter head.

9.1.3 Overall analysis of putting techniques

There was no trend for players to be members of cluster 1 or 2 exclusively across both the 4m and 8m putting tasks. Of the 38 players involved in this study, seven players produced technique 1 for both putting tasks on all 4m and 8m putts. The rest of the players produced a mixture of techniques. No player consistently produced the technique defined as cluster 2 across the 4m and 8m tasks. This data highlights the importance of using cluster analysis to differentiate technique both within and between players, as an individual's technique can vary between putts (i.e. each individual can have more than one technique) and classification according to handicap (*a priori*), accuracy or averaged across trials (*post hoc*), may lead to Type I errors.

The cluster analysis process has been used to define two putting techniques for both the 4m and 8m putting tasks. The process of defining the final two groups was tested using the replication method, and results indicate that putts were correctly re-classified in 98% of cases in the 4m putting task, and 88% of cases in the 8m putting task. These data indicate that some player's do change technique during trials in a putting task. All of the players in this study were experienced players. They were volunteers who were about to play a regular round of golf. There were no novice golfers in the sample. It is reasonable that players of some experience would be able to make adjustment to their putting technique in response to their performance on the previous putt or putts.

These data also highlight that averaging individual trials can create Type I errors in technique analysis. Averaged data (i.e. the average of each player's trials entered into the cluster analysis) will classify players into clusters. Ball & Best (2007) used the average of 10 trials and cluster analysis methodology to determine two distinct golf swing techniques based on movement of the COP. Players, rather than trials, were classified into one of two techniques. Analysis of individual trials in the present study has indicated that there are variations between trials within individuals. The average performance may never be produced and may well be misleading. Averaging of trials does not allow for the possibility of variations of technique by individual players between trials, and would smooth out fluctuations in performance. In effect, by using averaged data, the possibility of making Type I errors is increased as there is an assumption that players will constantly produce the same technique, and differences between trials would not be determined.

Although using an averaged performance is common in biomechanics research, it does not offer as much insight into technique as cluster analysis using individual trials. From a coaching perspective, it is impossible to review the "averaged" performance. A coach would be more interested in why a certain trial or performance is different from others. Both the player and coach seek an understanding of why performance changes between trials. Understanding differences between trials, and adjusting (or not adjusting) technique is a key factor in producing optimal performance. If research has determined that techniques exist, then it is possible that players – of any sport – can produce different techniques between trials. It is recommended that future studies assess individual trials as has been completed here and in Grabe and Widule (1988). The results of this study indicate that different putting techniques exist. The techniques are based on movement of the COPx in the case of the 4m putting task, and on COPx, COPy and putter head kinematic parameters for the 8m putting task. The techniques are not differentiated based on putt accuracy, though there is a trend in the data which indicates the younger, lower handicap player will favor technique 1 (low COPx velocity and low motion) for both tasks. These data also indicate that in future studies, players should not be classified according to accuracy or handicap, but that their putting trials should be classified according to technique. Each putt should be treated separately in order to demonstrate the possibility that a player can produce different putting techniques within the same, and across, putting tasks.

9.2 Validation of the pliance® mat and the test of equality

Measurement of COP data in the field was possible through the adaptation of a rubber mat containing a 16 x 16 matrix of capacitance sensors. Though not specifically designed for use with standing subjects, this technology was shown to be as accurate as an AMTI strain gauge force platform system in assessment of standing COP. Data from the pilot study indicated that using the test of significant equality (Londeree et al., 1990) the COP peak-to-peak amplitude of the pliance® mat was equal to that of an AMTI strain gauge platform ($p=0.023$ for both parameters) for this application. Data presented on COP movements during the putting stroke in the field, and compared to McCarty (2002) who used an AMTI strain gauge force platform sampling at 240Hz in an indoor setting, indicates that the outputs (and the performance of the players on movement of the COPx) were similar across systems and samples.

The statistical test of equality used to assess the equality of the outputs of the pliance® mat system and the AMTI force plate system is novel in biomechanics research. The non-central F test – test of equality – was introduced by Londoree et al. in 1990. It is not a new technique, it has just not been used often in published work. It was most appropriate for use in this study where two systems were being assessed for equality, but it also has application to studies where repeated measures are recorded and the research question may be related to how similar the data collected is over two or more testing sessions. There are examples in the literature where the use of the test of equality would have been more appropriate than the statistical method employed. Recent work by Lacoste et al. (2006) is an example of this as is any study that states results of two groups or sets of data are similar, equal or the same.

Where the present study used a specific statistical test of equality to assess whether the output from the mat system and AMTI platform were significantly equal, Lacoste et al. assessed the similarity between two systems outputs through the use of tests of difference. The aim of Lacoste et al. was similar to the pilot study performed in the present study. In short, the authors aimed to determine the COP range output validity of a pressure mapping system against the same output from an AMTI strain gauge force platform in seated posture (specifically in wheelchairs). In the case of Lacoste et al. the authors concluded that the pressure mapping system could detect the COP displacement as effectively as the force platform system as there were no significant differences present in the output ($p>0.05$). Of course, not being statistically significantly different does not mean that they are statistically significantly the same.

The data used in the present study to determine significant equality consisted of the output of 19 trials where subjects stood on the mat system which was placed on top of an AMTI force platform. The test of equality revealed significant equality was present based on the analysis of peak-to-peak amplitude data for COPx,y. Another commonly used method for determining statistical similarity is the intra-class correlation coefficient (ICC). This is a statistical technique that indicates the level of relationship between sets of data. When this technique of analysis was applied to the data from the present study, the ICC values for COPx,y relating the two systems were highly significant (0.945 and 0.906 respectively, $p<0.001$).
In order to understand the effectiveness of the test of equality, the data presented in Table 9.2.1 highlights the relevant statistical outputs that occur if the AMTI COPx,y output has simulated systematic error added. The peak-to-peak amplitude data for each trial was multiplied by a range of factors up to 200% of the original value. The statistical outputs for the test of equality (d, ϕ, p_e), the

output of a one way ANOVA (F,p_a), and the outputs of the most commonly used relationship parameter when validity is assessed (ICC) are detailed when the original mat system output is assessed against the manipulated AMTI data at each level.

Table 9.2.1a: Output of various analyses of data relating the medio-lateral peak-to-peak amplitude output from the pliance® mat system and AMTI data at various multiplication factors of the AMTI data.

Medio-lateral (n=19)	Pliance®	AMTI	AMTI x 105%	AMTI x 110%	AMTI x 150%	AMTI x 200%
Mean (cm)	1.027	1.02	1.071	1.123	1.53	2.041
SD (cm)	0.610	0.62	0.651	0.682	0.929	1.239
D		0.2603	0.2601	0.2593	0.2416	0.2167
ϕ		0.1841	0.1840	0.1833	0.1708	0.1532
p_e		0.023	0.154	0.317	0.923	0.995
F		0.001	0.046	0.204	3.89	10.225
p_a		0.971	0.832	0.654	0.056	0.003
ICC		0.945*	0.943*	0.936*	0.792*	0.521‡

SD = standard deviation, d=computed effect size, ϕ = non-central parameter, p_e = significance of non-central F test, F = F score from one way ANOVA (1,36), p_a = significance of one-way ANOVA ICC = Intra-class correlation co-efficient.*ICC significant at $p \leq 0.001$; ‡p=0.06

Table 9.2.1b: Output of various analyses of data relating the antero-posterior peak-to-peak amplitude output from the pliance® mat system and AMTI data at various multiplication factors of the AMTI data.

Antero-posterior (n=19)	Pliance®	AMTI	AMTI x 105%	AMTI x 110%	AMTI x 150%	AMTI x 200%
Mean (cm)	1.281	1.27	1.333	1.397	1.905	2.54
SD (cm)	0.921	0.978	1.027	1.076	1.468	1.957
D		0.2097	0.2092	0.2084	0.1964	0.1797
ϕ		0.1483	0.1479	0.1474	0.1389	0.1271
p_e		0.023	0.12	0.257	0.849	0.978
F		0.001	0.027	0.127	2.46	6.435
p_a		0.971	0.870	0.724	0.125	0.016
ICC		0.906*	0.903*	0.898*	0.784*	0.579‡

SD = standard deviation, d=computed effect size, ϕ = non-central parameter, p_e = significance of non-central F test, F = F score from one way ANOVA (1,36), p_a = significance of one-way ANOVA, ICC = Intra-class correlation co-efficient.*ICC significant at $p \leq 0.001$; ‡p=0.034

The test of significant equality is sensitive to changes in the AMTI data as both COPx ($p=0.154$) and COPy ($p=0.12$) are no longer significantly equal after systematically increasing the AMTI output by 5%. By comparison, the ICC value remains highly significant ($p<0.001$). This trend in the data is evident even when the AMTI data has been increased by 150%. The one way ANOVA score indicates that the data is close to, but not quite significantly different ($p=0.056$ and 0.125 respectively for COPx,y), the test of significant equality is indicating the data is nowhere near being significantly equal, but the ICC values suggest significant relationships still exist within the data for both COPx and y ($p \leq 0.001$). When the AMTI data is doubled, and the data is significantly different ($p<0.05$), ICC for the COPy data indicates a significant relationship still exists (ICC=0.579, $p=0.034$).

On the data presented in tables 9.2.1a and b it would be possible to have a difference between the AMTI and pliance® output of 50% yet claim that the outputs were similar if a test of difference or the ICC parameters were used or a test of significant difference was not significant ($p>0.05$). Clearly, this would be an incorrect decision and a Type II error. Lacoste et al. used a test of significant difference to validate the COP output of a pressure mapping system against the output of the AMTI system. The analysis presented here suggests that Lacoste et al. was likely to have made an incorrect conclusion (Type II error). Another commonly used technique for validation of output is the intra-class correlation co-efficient. If the present authors had used this test, it would have been possible to again claim that the systems were equivalent even when the data of the AMTI system was increased by 50% (COPx output ICC = 0.79, p≤0.001; COPy ICC = 0.784, p≤0.001). A test of equality on the same data clearly indicates that the data are not significantly equal (p=0.923 and 0.894 respectively). This indicates that the chances of making a Type II error are large using the ICC to assess two methods, especially when the hypothesis being tested is one of equality. Hypothesised equality is not what the ICC tests for.

So far in 2007, the Journal of Biomechanics has published three papers that have attempted to validate new techniques of investigation against established methods by using the intra class correlation co-efficient (ICC). These papers are summarised in Table 9.2.2. Only one paper reported the difference values between the methods, and no paper reported overall mean data values. All papers reported a range of ICC values and generally concluded that their new methods were valid when compared to the established method.

Table 9.2.2: Summary of three papers published in the Journal of Biomechanics in 2007 using ICC to assess the equivalence of output from two or more systems.

Authors	Assessment	Methods	ICC	Difference	Conclusion
Eng et al.	Muscle volume	MRI vs. actual measures	0.68-0.97	8%-22%	Excellent to fair
Zinder et al.	Ankle stiffness	Modeling vs. actual data	0.93-0.96		Valid & reliable
Mall et al.	Foot indices	Photo vs. caliper vs. radiograph	0.6-0.97, 0.6-0.97		Equivalent results

The conclusions drawn from these three papers were consistent with the authors advocating the use of their newly established methodology, though Eng et al.

(2007) did advocate caution in the interpretation of their results (whilst Mall et al. advocated that either of the caliper or photobox methods were equivalent to the radiograph despite ICC values around 0.6 on some variables). The results from Eng et al. reflect most accurately the deficiency in the ICC method to determine equality in system output. The most accurate results recorded equated to a difference between the methodologies of 7.7%. These data related to an ICC value of 0.97. Using the test of equality and a practical difference of 5%, these results would not be considered to be significantly equal. However, if the authors (in this case Eng et al.) had determined an acceptable level of difference of 10%, then these data may have become significantly equal depending on the magnitude of the standard deviation data. Using the ICC method of analysis not only provides an inaccurate representation of the actual relationship between two systems in this instance, but the failure of the authors to report the relative difference data, makes it impossible to assess to what relative level the data is accurate. As has been shown here, the ICC is prone to producing Type II errors in these circumstances. All authors are encouraged to assess, via the calculation of the practical difference, the acceptable level of error in their data. It is recommended that research designed to assess the equality of two or more methods use the test of significant equality and report the relative error percentage in order to provide a more accurate and correct representation of their new method.

9.3 Cluster analysis process in determination of techniques

The use of clustering methods to discern between techniques was employed in this study. The clustering process is unlike most statistical procedures in that there is no objective procedure in place that informs the researcher of the correct number of clusters or the final outcome of the process. A vast combination of steps and rules are available to help the researcher make a final decision. The use of these steps and rules is open to interpretation but should ultimately result in the formation of clusters that produce distinct technique groupings when used in sports biomechanics research. Ultimately, that was the goal of the present project and the previously presented data has highlighted the relevance of the clustering methods in identifying two distinct techniques at each of the putting tasks.

In the present study a combination of clustering methods was used. According to Hair et al. (1995) this allows the benefits of each method to be utilized. Initially the hierarchical method was employed to establish initial clusters and to determine outliers within the sample. The cluster centres formed by the hierarchical method were then used to generate seed data for use with the nonhierarchical or k-clustering method. The hierarchical data method informed the k-cluster method. The subsequent k-clustering process was used to create final clusters based on this seed data. In both methods a range of cluster solutions were created as there were no prior indications (from past research or intuitive knowledge) of the number of possible putting techniques.

For the 4m putting data, the hierarchical method indicated that there were clearly discernible clusters at a two cluster level as indicated by the agglomerative schedule. The hierarchical method stopping rule data indicated the possibility of a two cluster or four cluster solution and the stopping rule data in the k-cluster process suggested two or four clusters were present in the data. The k-cluster process, using the seed data from the hierarchical process returned two clusters of unequal size. Subsequent replication analysis (Hodge and Petlichkoff, 2000) indicated that the clusters were robust as 98% of putts were re-classified correctly. The above steps were completed in the present study as the cluster analysis process has no definitive decision making endpoint. A most conservative process was therefore followed to ensure that the ultimate techniques identified had statistical and practical relevance.

Comparison of the final two cluster solutions from each method reveals that 16 putts classified in cluster 1 using the hierarchical method were reclassified into cluster 2 in the k-cluster method. These 16 putts were distinct in that when part of the “low COPx velocity” cluster in the hierarchical method, they represented the 16 putts with the largest COPx velocity at ball contact values (mean = 43.0±8.1cm/s). Based on the analysis of the subsequent k-cluster groups that delineated between a technique where COPx velocity at ball contact was close to zero and a technique where COPx velocity at ball contact was much greater, this reclassification of 16 putts is logical and supports the use of the combination of the two clustering methods to determine final cluster techniques.

The data in table 9.3.1 indicate how cluster membership changed in the last stages of both processes. At each of the last four stages of the hierarchical method, the 16 putts referred to above were part of cluster 1. In the k-clustering method however, they were spread across 3 clusters at the 4 cluster stage (1=13, 2=2, 4=1), and across two clusters at the 3 cluster stage (1=11, 3=5), but were all part of cluster 1 (low COPx velocity) in the final two cluster solution. Within these classifications the putts were separated based on COPx velocity at ball contact values. These data emphasise the influence of the COPx velocity at ball contact and the sensitivity of the process employed in this analysis process.

Table 9.3.1: Cluster membership at the 2, 3 and 4 cluster levels for both hierarchical and k-cluster methods for 4m putting data.

	Clusters	1	2	3	4
4 cluster solution	Hierarchical	81	6	12	9
	K-cluster	59	8	31	10
3 cluster solution	Hierarchical	81	15	12	
	K-cluster	57	20	31	
2 cluster solution	Hierarchical	93	15		
	K-cluster	77	31		

However, data based on this same parameter also highlights a limitation in the cluster analysis process. Within the data recorded on COPx velocity at ball contact, 28 putts were recorded with a value indicating the COPx was moving away from the hole at ball contact (a negative value) – the remaining 80 putts were recorded with a positive value. These 28 putts were part of cluster 1 throughout the final three stages of the hierarchical process, and were spread across different clusters in the earlier stages. These 28 putts were never a single cluster by themselves at any stage of the process. From a practical view, when the COPx is moving in the opposite direction to that expected a different technique could be indicated but was not detected during this process.

These putts that had a negative COPx velocity at ball contact (mean = -12.8±12.0cm/s) were ultimately combined with putts that had a similar absolute COPx velocity value but were positive (mean = 15.7±8.8). This combined data produced an overall mean value for cluster 1 for COPx velocity at ball contact of 5.2±16.9cm/s – a mean value close to zero, but a spread of data either side of zero. Effectively, in the k-cluster method final cluster membership is based on the ranking of COPx velocity at ball contact data. The largest positive values (n=31) formed cluster 2, whilst a combination of the lowest positive values and all negative values formed cluster 1 for the 4m putting technique. This is a similar final result to that achieved in the hierarchical method and highlights that the clustering methodologies are strongly influenced by the cluster means (or centroids) of the most influential parameters during the clustering process. Based on the data presented here, this does not always result in the identification of different techniques especially if the centroid is equal to or close to zero. Whilst mathematically, data either side of zero can be grouped to maintain a close to or equal to zero group mean value, data spread either side of zero may refer to a practical difference in technique that cluster analysis, in this instance, was unable to detect.

An important part of the decision making process in the present study was to use stopping rules to help determine the optimum solution. There was some agreement between the stopping rules on the optimum solution for the 4m or 8m putting task. Ultimately, the decision was made to focus on a two cluster solution for both of these tasks. The two cluster solution was strongly supported by the agglomeration schedules (hierarchical process) and the C Index and VRC stopping rules for both the 4m (table 9.3.1) and 8m (table 9.3.2) putting task data sets.

Table 9.3.2: Stopping rule data on 4m putting task data set.

	4m hierarchical				4m k cluster			
Cluster	Point r	C Index	VRC	R Ratio	Point r	C Index	VRC	R Ratio
2	0.59	1.03	20.51	7.47	0.55	1.22	26.24	9.93
3	0.48	1.05	14.53	4.98	0.42	1.44	19.08	4.86
4	0.48	1.03	11.68	7.47	0.44	1.28	14.76	5.86

Table 9.3.3: Stopping rule data on 8m putting task data set.

	8m hierarchical				8m k cluster			
Cluster	Point r	C Index	VRC	R Ratio	Point r	C Index	VRC	R Ratio
2	0.40	1.02	10.97	9.49	0.36	1.50	15.19	9.01
3	0.34	1.95	10.41	8.82	0.39	1.84	12.53	8.80
4	0.35	1.48	10.20	6.68	0.40	2.29	11.77	9.42

When comparing the 4m and 8m putting data, the stopping rule values – with the exception of the R Ratio - suggest that there was less distinction of clusters in the 8m putting task than in the 4m putting task as the values were further away from optimal values. Three of these rules – R Ratio being the exception – were reviewed by Milligan and Cooper (1985) as being within the best 10 stopping rules for data where there were predetermined clusters in the dataset. It should be noted that even with predetermined clusters in the data that no stopping rule returned a 100% success rate in cluster identification (Milligan and Cooper, 1985). Not surprisingly then, there is some ambiguity in the results presented here and this required the researcher to make a final decision on the optimal cluster solution based on consideration of a range of factors of which the stopping rules were a part. Using a number of stopping rules aided the decision on the optimal number of clusters, and when combined with the other decision making processes helped to determine distinct technique groupings for the 4m and 8m putting tasks.

Of the 30 stopping rules reviewed by Milligan and Cooper (1985), it was reported that 10 were capable of providing relatively accurate cluster solutions. The three rules used in the present study were part of these best 10. The R Ratio was included in the present study as it was developed after the Milligan and Cooper review paper, and had previously been used in biomechanics research (Chen and Shiavi, 1990). The calculation of the most appropriate stopping rules for the type of data used in the present study would be a useful follow up project.

Follow up validation using the replication method suggested by Hodge and Petlichkoff (2000) indicated that the two cluster solutions were stable for both the

4m and 8m putting tasks as reclassification into the same clusters was high. Assessment of re-classification was based on the comparative cluster for the same trial based on the final two cluster solution. Overall, three replications of the sample produced stable results (98% in the 4m task, 88% in the 8m task). This indicated that the analysis used in the present study was robust and that the classification of putts into technique groupings was accurate. The techniques identified by the cluster analysis process are real and are being used by regular golfers. This is the first time in the golf literature that such techniques have been identified that are not based simply on anecdotal evidence or the opinion of experts.

Previous use of cluster analysis in sports biomechanics has been notable for the lack of objective stopping rules (Wilson & Howard, 1983; Forwood et al., 1985; Grabe & Widule, 1988). Most recently though, Ball and Best (2007) reported using the point biserial correlation and C Index in their analysis of weight transfer patterns in the golf swing which represented a breakthrough in the use of this data analysis process in sports biomechanics research.

Ultimately, two distinct clusters were defined for both the 4m and 8m putting tasks in the present study. The interpretation of the clusters highlighted the differences between the two clusters, and how the cluster data defined certain techniques. Based on the assumption that the final cluster solution should be relevant to the task being assessed, in both the 4m and 8m putting task there is a clear and logical delineation between the two putting techniques. Based on these data then, cluster analysis techniques should be used more often in the biomechanics literature where technique analysis is performed. The use of such methods will ensure that differences between and within players are based on assessment of technique rather than the grouping of like (perceived) skill levels (for example, handicap or years of experience) or like performances (for example, accuracy or distance). The likelihood of producing Type I and II errors is high if cluster analysis processes are not utilized. Assessment of possible errors should be a key criteria in the selection of the most appropriate method of statistical analysis.

One issue that needs to be considered for future research is whether each trial from each subject is treated individually (as was done in this project) or whether the data input for each subject is a mean performance based on a number of trials (for example, Ball & Best (2007)) in the cluster analysis process. The former approach has been used previously in the sports biomechanics literature (Wilson & Howard, 1983; Grabe & Widule, 1988) and demonstrated that individual technique can vary across trials. The present author suggests that cluster analysis should be used with individual trial data. For consideration in future work on technique analysis is the possibility that the skilled performer will be different to a less skilled performer in terms of consistency of technique. A skilled performer may be able to reproduce the same technique consistently – in the case of cluster analysis, more of their trials will be classified into the same technique grouping – whilst the less skilled performer may be less likely to have their trials grouped into the same cluster.

The clustering process used in the present study often classified one individual's trials into different clusters. Conversely, some individuals remained consistently in the same cluster for both tasks – and in the case of one subject throughout the training program also. If the data for each individual had been represented by mean values only, the delineation between the putting techniques would not have occurred. As highlighted by Grabe and Widule (1988), it is possible that an individual will perform differently on consecutive trials and will therefore warrant being classified into different clusters. The future use of cluster analysis on discrete skills should be based on the treatment of each individual trial as a set of data.

9.4 The effect of biofeedback training on putting technique

The biofeedback training program was carried out to determine whether a change could be elicited from the players in terms of putt result and technique. The cluster analysis process had demonstrated that individual's could vary between technique groups within a putting task. Of the seven players who were involved in the biofeedback training program, four had putts classified into the two technique groups after initial 4m testing, whilst the other three players had demonstrated a consistent technique on each putt and had all putts classified into the “low COPx velocity” technique. After completing the training program, all players were classified into the “low COPx velocity” technique.

This is an important finding in the context of this study. The cluster analysis process had defined two distinct techniques in the 4m putting task that were greatly influenced by parameters associated with movement of the COP. The biofeedback training had focused on this aspect of the putting technique and the results for the 4m putting task indicate that this was successful in producing a consistency of COPx movement that resulted in those four players who previously displayed a mixture of techniques having all putts classified into the “low COPx velocity” technique.

Conversely, the three players who were already consistent members of “low COPx velocity” produced no significant change in terms of putting technique, but displayed improved putting performance (38.8±19.7cm vs. 17.3±20.0cm; $p = 0.001$). Whilst those players who were classified into “low COPx velocity” after re-testing did not change in terms of putt performance (34.5±26.7cm vs. 37.2±28.7cm; $p = 0.21$). On re-testing then, the players who stayed in the same technique group (17.3±20.0cm) performed significantly better than those players who changed into more consistent performers (37.2±28.7cm; $p = 0.03$) on putt result.

The most influential parameter in classification of putts for the 4m putting task was the velocity of the COPx at ball contact. On re-testing this parameter was shown to have significantly decreased in those players who changed technique groups (28.7±14.4cm/s; 17.3±11.3cm/s; $p = 0.03$). These data, for all players in the biofeedback training program, indicate that the velocity of COPx at ball contact can be reduced but will never be equal to zero.

On reflection it was clear that the training program was suited to those players who displayed a mix of techniques on the 4m putting task. Those three players who were already displaying a consistent "low COPx velocity" technique derived no technical benefit from their involvement in this part of the study. Their technique, in terms of the goals of the training program, was already "optimized" compared to the four players who displayed a mix of techniques. However, the evidence indicates that biofeedback training can be used to modify putting technique.

The training program had a varied effect on players performance at the 8m putting task with no significant change in performance on putt result (59.0±52.9cm vs. 66.3±41.5cm; $p=0.52$). In comparison to the data produced on re-testing for the 4m putting task, the 8m putt data showed no trend towards players being more homogenous after the training program. After initial testing, four players were classified into "low motion" and the three other players displayed a mixture of the two techniques. After training, three players maintained “low motion” membership, one player changed from “low motion” to a mix of techniques, one player who had displayed a mix of techniques had changed to “low motion” and two players who had displayed a mix of techniques became members of the “high motion” group. For two of these players then, the effect of the training program was for them to produce a more consistent technique associated with large movements of the COPx and the putter head. The former at least was opposite to the intention of the training program. The intention of the biofeedback training program was to reduce the amount of COPx movement during the putting stroke.

Tailored biofeedback programs based on the outcomes of cluster analysis is advised for future studies. The goal of reducing each player’s COPx movement has been shown, on reflection, to be erroneous, as analysis has clearly indicated that it is not possible, nor optimal, to reduce COPx movement to zero. Those players who were already at an optimally low level of movement, could not change to a more optimal level. Future use of biofeedback training should be tailored based on which group each player prefers.

9.5 The pendulum putting technique

In the assessment of kinematic data from the sample used in this study, it is also possible to assess techniques for the presence of the pendulum putting motion advocated by Pelz (2000). There are three key parameters that can be examined in the assessment of this theoretical putting motion. Pelz advocates that a pendulum putting stroke has: (a) downswing and follow through phases that are close to equal, with a slightly longer follow through; (b) the length of the backswing determines the length the ball will roll; (c) the time to complete the pendulum putting swing is consistent within players irrespective of the length of putt (as a pendulum of fixed length takes the same time to complete one swing irrespective of how far it travels).

There is no evidence that the pendulum putting swing exists as part of the techniques identified in this study. Using the clusters defined in the 4m and 8m putting tasks, comparative length of downswing and follow through values were calculated. These data indicate that for neither putting task is there an indication that the length of these phases is equal (table 9.5.1). Whether assessing this data by clusters and tasks, or by handicap groups and tasks, there are significant differences between the length of the downswing and follow through phases ($p<0.01$). The data presented by Delay et al. (1997) on the length of the phases in the 4m putting task was not assessed for significant differences, but as there is a larger difference in the expert group, it is clear that these players would also have produced significant differences between the downswing and follow through phases. Pelz (2000) advocated a ratio of 6:7 for downswing length to follow through length (or 116%). The only group who produce a pendulum “type” action appear to be the novice group used in the Delay et al. study. All other group mean values indicate a follow through that is significantly longer than the downswing.

Table 9.5.1: The difference in putter head displacement between the downswing and follow through. A positive value indicates a longer follow through. (Putter head displacement in follow through as a percentage of putter head displacement in the downswing). Data calculated from values reported in Delay et al. (1997) are compared to data from the present study.

Difference (mm)	Delay et al.	Present study handicap groups			Present study clusters			
	4m		4m	8m		4m		8m
Novice	67 (121%)	High h'cap	96 (138%)	180 (155%)	Low COPx velocity	106 (146%)	Low motion	148 (152%)
Expert	367 (233%)	Low h'cap	124 (156%)	194 (169%)	High COPx velocity	143 (159%)	High motion	224 (169%)

Within the techniques, there are individual players who produce downswing and follow through lengths that have characteristics similar to those suggested by Pelz for the pendulum putting motion. At the 4m putting task, 20 putts (or 19%) have a ratio of follow through to downswing length of between 100% and 120%. Of these putts, 18 are from the low COPx velocity technique which is 23% of all putts in this technique. Whilst at the 8m putting task, 13 putts (11%) have a ratio of between 100% and 120%. Whilst there is some evidence at the individual level that pendulum putting type motions exist based on these criteria, the overall trend in the technique data suggests that the pendulum putting motion is not a defining characteristic of the techniques displayed by this sample of golfers.

The second aspect of the pendulum putting stroke to be investigated is the relationship between the length of the backswing and the distance the ball travels. It is likely that this relationship is within-individual rather than within-technique as for many players putting trials were placed into different techniques. In order to answer this question accurately using these two parameters, it would be necessary to collect a greater range of data on a larger variety of putting tasks – that is, a putting task at each 1m interval from 1m-10m for example. As the present study did not collect data of this type, this analysis is recommended for future work.

The third aspect of the pendulum putting stroke is the consistency in swing time. This is particularly relevant to the forward swing time which is a combination of the downswing and follow through times. In order to assess for the presence of a consistent swing time within players, the data for forward swing time were calculated and then paired data were analysed. Each data pair includes the forward swing times of a 4m putt and an 8m putt from the same player. Of the sample of data assessed in the cluster analysis process, this resulted in 95 pairs of data with numerous players having more than one pair.

The overall mean data for the two putting tasks indicates that the 4m putting task forward swing time (661±154ms) was not significantly different ($p = 0.22$) to the 8m putting task forward swing time (674±153ms) for these 95 paired samples when assessed using paired t-test. Analysis using correlation coefficients indicates that there is a significant relationship between the two putting tasks for forward swing time (ICC=0.87, p<0.001), but when assessed using the test of equality, the data is not significantly equal, until a practical difference of 25% is used (p = 0.04). These data suggest that the forward swing time is not the same across putting tasks for the players in the present study (figure 9.5.2). Delay et al. (1997) investigated the relationship between forward swing time for putts of 1m, 2m, 3m and 4m in length. The authors reported no significant differences between the forward swing times for the 2m, 3m and 4m putting tasks, but the data were not assessed for significant equality. The data from the test of equality in the present study, and the lack of analysis in Delay et al. further highlights the importance of the correct statistical test in assessing significant equality.

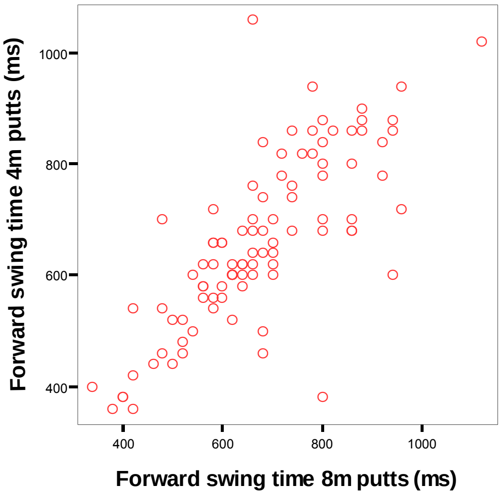


Figure 9.5.2: Scatterplot of forward swing time from each putting task for paired player data (n=95).

As highlighted throughout this paper, the cluster analysis process separated trials into technique groupings. The 95 pairs of 4m and 8m forward swing time data contain multiple pairs of cross-cluster data. The data contained in tables 9.5.2 and 3 indicates how the 95 pairs of data are separated based on the cluster that the trial was classified into for the 4m and 8m task respectively. The mean values indicate that across the two putting tasks, players who used technique 1 (low COPx velocity) in the 4m task and technique 1 (low motion) in the 8m putting task were relatively consistent in the production of forward swing time irrespective of putting task (r = 0.8), as were players who used technique 2 (high COPx velocity) in the 4m putting task and technique 1 (low motion) in the 8m putting task (r = 0.93). Analysis of the downswing times in isolation, revealed that all paired data were significantly correlated (table 9.5.3).

Table 9.5.2: Analysis of forward swing time pairs for the 4m and 8m putting tasks.

Pair (4m cluster v 8m cluster)	Mean (SD)	R	F (p) (ANOVA)	P (5% practical difference)	p (10% practical difference)
1 v 1 (n=56)	613±140, 628±153	0.8 (p<0.001)	0.29 (0.59)	0.29	0.2
1 v 2 (n=14)	731±170, 807±154	0.67 (p=0.004)	1.53 (0.23)	0.68	0.59
2 v 1 (n=10)	626±74, 636±74	0.93 (p<0.001)	0.09 (0.77)	0.17	0.12
2 v 2 (n=15)	803±124, 755±81	0.3 (p=0.14)	1.57 (0.22)	0.63	0.51

Table 9.5.3: Analysis of downswing time pairs for the 4m and 8m putting tasks.

Pair (4m cluster v 8m cluster)	Mean (SD)	R	F (p) (ANOVA)	p (5% practical difference)	p (10% practical difference)
1 v 1 (n=56)	248±47, 292±22	0.88 (p<0.001)	0.18 (0.67)	0.2	0.12
1 v 2 (n=14)	271±26, 283±26	0.78 (p=0.001)	1.38 (0.25)	0.55	0.4
2 v 1 (n=10)	232±25, 234±35	0.74 (p=0.015)	0.02 (0.89)	0.08	0.06
2 v 2 (n=15)	288±27, 292±22	0.63 (p=0.012)	0.19 (0.22)	0.19	0.11

These data suggest that across putting tasks and techniques players are repeatable in their production of downswing and forward swing time, but not to a level that could be classified as being significantly equal (up to a practical difference of 10%). Interestingly, the paired groupings associated with relatively faster forward swing times for both putting tasks have shown to be more consistent than the other paired groupings. This suggests that higher consistency may be easier to maintain when forward swing time is shorter and this may be indicative of a pendulum putting type motion in these particular players, but the evidence is far from conclusive. The data on downswing time indicates that irrespective of technique, players use a similar, but not significantly equal, downswing time for both putting tasks. By comparison, this data suggests that the analysis of forward swing time is susceptible to large variations because of differences in follow through time. Detecting the finish of the follow through is difficult, and players vary greatly in their “finish”, so it is likely that providing more specific instruction to the player may help solve the problem of variation in this parameter across putting trials.

While it was not a specific focus of this study, there is little evidence to suggest the pendulum putting stroke is present in this sample of players. Whilst analysis of the techniques utilized in the 4m and 8m putting tasks indicates a general lack of support, it is suggested that future work should focus on a pendulum putting motion from a totally within-individual perspective. This would be especially applicable using a larger range of putting tasks to determine whether there is a distance at which players switch putting techniques to suit the specific task.

9.6 Practical vs. statistical significance in sports biomechanics research

Statistically significant results often determine whether research is published. The literature review detailed in this paper, for example, contains references to many papers that found statistically significant results, but there are no references to research that detailed results that were not statistically significant. The level of significance determines publication in many cases, but does not necessarily indicate the importance of the research.

In sports biomechanics research, how practical is it to determine statistical significance at the $p<0.05$ level? In golf coaching, a program that can produce an improvement of one or two strokes to a player’s 18 hole score would be considered a significant practical achievement, but may not be a significant statistical achievement. Does this mean the intervention (coaching) is not worthwhile? No, it makes the statistical analysis questionable or inappropriate in its design. It also makes it likely that many researchers who find their results are non-significant (whether published or unpublished) are making type II errors simply because they are using standard statistical analysis techniques with no reference to practical significance. In these situations, researchers report that (because they did not find a statistically significant result) there was no effect of the coaching/training program.

In order to simulate this, a theoretical group of 19 golfers was created. Each player had a handicap in the range from 0-19 (one player at each handicap level). Using a par score of 72, each players normal 18 hole score was created (72-90) and then compared to simulated improvements of one stroke, two strokes and three strokes. The data were analysed using paired t-tests ($p<0.05$) and effect size. These data are reported in table 9.6.1. An improvement of one or two strokes does not produce a statistically significant result ($p>0.05$). An improvement of three strokes only just produces a significant result ($p=0.048$). Based on these theoretical results, an improvement in a sample of players of two strokes is not significant, and would result in the conclusion that the coaching program is not effective. In reality, improvements in handicap tend to be incremental and small changes are the norm. Based on this analysis, not only is it practically difficult for a single figure handicapper to achieve a one stroke improvement in handicap, it is impossible for this improvement to be considered statistically significant.

Figure 9.6.1: Simulated data for a group of golfers who gradually improve their 18 hole score.

n=19	Original	Improved by 1	Improved by 2	Improved by 3
Mean	81	80	79	78
SD	5.6	5.6	5.6	5.6
d		0.18	0.35	0.52
p		0.49	0.17	0.048

Effective coaching is often not statistically significant but is practically significant. Judging the practical effect of a change is an area that demands more research in sports biomechanics. In this area of research, statistical conventions ($p<0.05$) are likely to increase the chances of a Type II error, practical findings are not published or ignored, and important coaching information never reported. Consideration must be given to establishing more realistic means of analysis in sports biomechanics.

10 Conclusion

Researchers have previously tended to investigate putting using the assumptions that, (a) low handicap players are better putters than high handicap players, and (b) accurate putting is based on one putting technique and inaccurate putting uses a significantly different technique.

This study has demonstrated that these assumptions are incorrect. Many players do not consistently produce the same putting technique when performing repeated trials, that is, one player can use both techniques. Technique grouping is not related to putting performance.

These findings highlight the importance of treating each putting trial for each individual separately, using cluster analysis to produce technical groupings of like techniques and not separating players according to handicap or accuracy. Previous research has been prone to making Type I and Type II errors because of this. It is therefore recommended that in order to avoid these common errors, analysis of individual trials be used as the standard rather than the exception and grouping players nominally by factors such as handicap should be avoided in future research.

The two putting techniques at the 4m putting task were defined by parameters related solely to the movement of the COPx. Neither technique produced a better putting performance than the other, though the techniques were different on mean handicap and mean age. However, many players were members of both groups.

Two putting techniques at the 8m putting task were defined by parameters related to the movement of the COPx, COPy and putter head kinematics. Neither technique produced a better putting performance than the other. There was no significant difference between groups for mean age, but again the groups were different on mean handicap.

These putting techniques have not previously been identified in research into this area. This is the first time putting techniques of any sort have been statistically identified in putting research. Future work would benefit from using a greater range of putting tasks to establish whether the distinction between putting tasks established in the present study is part of a continuum of techniques, or whether there is a putting distance or some other factor that causes players to switch to a different technique.

Handicap was generally not an indicator of putting accuracy. However, when putting performance was assessed using the number of holed out putts as the determining factor there was a significant difference between handicap groups. Based on measures of accuracy, there is no significant difference between groups. Previous authors have also questioned whether handicap is a good indicator of putting performance, and the present study provides further evidence to indicate that the link is tenuous. However, as in this study, measuring how far the ball finished from the hole may not necessarily be the best indicator of putting performance. Ultimately, golfers count how many shots it takes to complete a hole. A measure that is closely aligned with this ultimate goal would be the number of putts holed. The accuracy of a missed putt may not provide an accurate guide of skill level in this task, and a better alternative should be sought in future work.

Field-based putting research is rare. The majority of the previous work in the area has been laboratory-based and often required players to undertake tasks that have questionable field validity (for example, stopping the ball on a painted hole or on a line) when compared to the putting tasks employed in the present study. The present study established that field-based putting research incorporating analysis of the COP is possible, and the protocols established here could be used as a guide for future work in the area.

The assumption made at the start of the study was that biofeedback training would be useful for all players irrespective of their identified techniques. This proved to be incorrect, in general terms, as the overall putting performance on both tasks did not significantly improve. However, the data indicates that it is possible to influence putting technique using biofeedback training. Future work using biofeedback training should be tailored to specific techniques.

This study developed a number of new methods of analysis in order to achieve the aims. A validated method for assessing COP movement was developed. The pliance® mat system was demonstrated to be significantly equal to an AMTI strain gauge force platform in COP peak-to-peak amplitude output. This has implications for all field-based testing where COP movement is the parameter of interest. This study has also shown that this same system can be adapted to serve as an effective biofeedback training device that can help players decrease the amount of movement of the COP. This finding may have implications for all research that seeks to analyse and/or decrease movement of the COP in activities where COP movement influences performance.

Further work is required to develop the body of knowledge on putting technique and putting performance. Of most interest, is the putting performance profile of players under competition conditions. Whilst analysis from this, and other studies, suggests no significant difference in putting performance based on handicap, it is possible that the difference in handicap groups is due to where first putts on the green are taken from. The information from both the professional tour and the club player on first putt length is lacking from the research data.

Is the low handicap player hitting their approach shots closer to the hole thus leaving themselves with shorter first putts than the high handicap player? As analysis of the two putting tasks in the present study has shown, the success rate of all players was greater at the 4m hole than the 8m hole. If the high handicap player is taking more of their first putts from the 8m distance compared to the low handicap player who is taking more of their first putts from the 4m distance, the number of putts per round will account for a large percentage of the difference in handicap. This may be the most important factor in improving one’s performance on the scorecard and would be a most useful follow up study to the present work.

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12 Appendices

- Appendix A - Summary page of peak-to-peak amplitude data and graphical output for each trial from pilot study comparing systems
- Appendix B - Raw and standardized input for 4m and 8m putts
- Appendix C - Euclidean distance and correlation data matrices for 4m and 8m putts
- Appendix D - VIF and collinearity results for all parameters for 4m and 8m putts
- Appendix E – 4m and 8m putt dendograms
- Appendix F – Cluster seed files for k-clustering process 4m and 8m putts
- Appendix G - ANOVA outputs indicating the influence of parameters for 4m and 8m putts