Biomechanics of the golf swing and putting stroke

By

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Abstract

Context: This thesis focused on two main areas of golf performance. Firstly, centre of pressure excursions influence on full golf swing performance, as despite golf coaching literature placing importance on weight transfer, literature into this mechanism is limited. Secondly, the area of the golf putt was examined; few studies have investigated the biomechanics into the putting stroke despite it being identified as the most important performance factor within golf. Areas of investigation were, centre of pressure excursions during the putting stroke, the impact point on golf ball and movement variability on performance outcomes being the ball roll kinematics. **Aims:** To examine biomechanical factors that influence golf performance. Centre of pressure excursion during the full golf swing and putting stroke were examined. Additionally, body segment kinematics and variability of rotations were correlated with putting performance outcomes. The impact point on the golf ball was considered as a mechanism that can cause variability of the kinematic ball roll. **Subjects:** All subjects used in this thesis were actively playing golf. Subjects were categorised using the golf handicap system. For studies assessing reliability, validity or isolating putter stroke kinematics a mechanical putting robot was used. **Methods:** Correlational research whereby no variables were manipulated was predominantly adopted throughout this thesis to establish relationships between biomechanical parameters and golf performance. Biomechanical parameters were assessed using the appropriate data collection and analysis techniques; this included the variability associated with segment rotations. **Results:** Significant differences were observed for the centre of pressure excursions along the mediolateral axis between three different golf clubs (full swing). For the putting stroke low handicap golfers demonstrated lower centre of pressure excursions along the anteroposterior axis in comparison to high handicap golfers, additionally, a large amount of inter-subject variability was observed for centre of pressure excursions. In regards to the impact point on the golf ball, significant associations were identified between impact variables and the performance measures horizontal launch angle and whether the ball was pushed or pulled, these results were not replicated with human participants. It was identified that the relationship between the centre of mass displacement and centre of pressure excursions is a complex one and that movement variability had a detrimental effect on the horizontal launch angle and therefore performance. **Conclusions:** The results from the full swing analysis of this thesis suggest that stance width may influence the amount of centre of pressure excursions that occur. For the golf putting stroke, golfers and coaches should reduce the amount of variability associated with the technique to improve performance. Regarding future scientific research, a combination of individual analysis accompanying group-based analysis should be utilised due to the large inter-subject differences observed.

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Abbreviations

AMTI	Advanced Mechanical Technology Inc.
AP	Anteroposterior
CHV	Club Head Velocity
CL	Confidence Limit
COM	Centre of Mass
CP	Centre of Pressure
GRF	Ground Reaction Force
HH	High Handicap
ICC	Intraclass Correlation Coefficient
LH	Low Handicap
MH	Mid Handicap
ML	Mediolateral
PGA	Professional Golfers Association
PM	Pneumatic bladder pressure tester
PMD	Plantar Measurement Device
PTD	Pneumatic force testing device
PW	Pitching Wedge
SD	Standard Deviation
SE	Standard Error
SEM	Standard Error of Measurement
Δ	Change

Chapter One

Introduction

1.0 Introduction

This thesis began with two predominant areas of focus firstly centre of pressure (CP) excursions during the full golf swing and CP excursions during the putting stroke. In regards to the full golf stroke only two particular authors have recently focused on the area of CP excursions during the full golf swing (Ball & Best, 2007a; Ball & Best, 2007b; Ball & Best, 2011; Ball & Best, 2012). Ball and Best (2007b) identified two key styles of golf swing the front foot style, which can be summarised as CP excursions moving in the same direction of the golf club during the golf swing. The second type of swing Ball & Best (2007b) identified was the reverse style, whereby, the CP excursions move in the opposite direction of the golf club. Prior to this Okuda, Armstrong, Tsunezumi and Yoshiike (2002) suggested more proficient players demonstrate increased CP excursions towards the lead foot in a shorter time during the downswing in comparison to less proficient golfers. This was supported with the amount of CP excursions being positively correlated with club head velocity (Ball & Best, 2007b; Ball & Best, 2011). Despite this other research in the area of CP excursions during the full golf swing is relatively dated (Koenig, Tamres and Mann, 1993; Wallace, Graham and Bleakley, 1990) and more research is needed in the area. As recently, literature has focused on the regulation of reaction forces, and 3D kinematics rather than the CP excursion (Chu, Sell & Lephart, 2010; McNitt-Gray, Munaretto, Zaferiou, Requejo & Flashner, 2013; Nesbit & Serrano, 2005; Okuda, Gribble & Armstrong, 2010; Zheng, Barrentine, Fleisig & Andrews, 2008). Therefore, more research is needed to reaffirm theories raised from the Ball & Best studies and Okuda et al. (2002). Study One addresses this and provides data to the literature pool regarding CP excursions during the full golf swing.

The putting stroke could be considered the most important type of golf shot of the several types, accounting for an average of 43% of swings made (Pelz, 2000). Despite recognition that at a professional level, that players have the ability to distinguish themselves by performing better with the putter than the rest of the field (Dorsel & Rotunda, 2001). Putting remains the area least taught and researched (Hurrion & Hurrion, 2008). MacKenzie and Sprignings (2005) discuss key abilities needed to hit a successful putt, firstly, to correctly read the green, and secondly, the execution of a putting stroke where the putter face is perpendicular to the target line. As Hurrion and Hurrion (2008) state a stable posture is needed for a consistent pivot point. The combination of these findings suggests a more stable posture should allow for a more consistent putter face angle at impact, increasing the number of successful putts. However, currently there is limited published work on CP excursions during the golf putting stroke. Research has generally combined directions of CP excursions (Hurrion & Hurrion, 2008), only analysed CP excursions along one axis (McLaughlin, Best and Carlson, 2008), or finally by grouping golfers by styles of technique (McLaughlin & Best, 2013), but not identifying whether CP excursions are influential in more proficient golfers having a higher success rate in making putts. No literature has included what body movements (distance and velocity) cause increased CP excursions observed in less proficient golfers in comparison to more proficient golfers (Hurrion & Hurrion, 2008; McLaughlin et al. (2008), or between putting styles (McLaughlin et al. 2013). This indicates a gap and lack of clarity within the literature that Study Two and Study Seven aim to clarify.

In addition to the limited research on CP excursions during the putting stroke there is also limited resources on ball roll kinematics during the initial phase of a golf putt. Hurrion and Hurrion (2002) has compared different brands of golf putter, one being a grooved faced putter and the other being a traditional faced putter. Hurrion and Hurrion (2002) used European Tour professionals as the subject cohort and found the grooved faced putter to produce preferable ball roll characteristics (initial ball roll (°) and the amount of skid (cm) of the golf ball) in comparison to the traditional faced putter. In contrast to this with a mechanical putting arm, no significant differences were observed for initial ball roll or the amount of skid observed during the initial stages of the golf putt where observed using a mechanical putting robot (Brouillette, 2010; Brouillette & Valade, 2008). This shows the disparity that exists within the limited amount of literature and Study Three and Seven address these problems.

The final area that is discussed within this thesis, also relates to the kinematic ball roll variables and the effect that golf ball dimples have on those variables. Limited research exists regarding the effect that dimples and different sizes of dimples have on the kinematic ball roll variables. The only research that has been presented on the topic is limited as it does not present any raw results and only considers the horizontal launch angle (initial direction) of the golf ball (Pelz, 2000). Pelz (2000) concluded that dimple error (directional variability away from the target line accountable to dimples on the golf ball) only affects putts of a short length (< 4 feet). A number of studies have examined factors of the golf putt that affect the horizontal launch angle, yet none considered the possible effect the impact point on the golf ball and the effect dimples have (Hurrion & MacKay, 2012), Karlsen, Smith & Nilsson, 2008; Pelz 2000). All of Hurrion and MacKay (2012), Karlsen et al. (2008) and Pelz (2000) state the putter face angle at impact is the most important feature of a putting stroke in regards to direction variability. Despite this, if a golfer can control for the potential effects of the different impact points on a golf ball has on the kinematic ball roll variables. Whether this effect is large or small, could potentially lead to more successful putts, due to the minimal margin of error in the golf putt. Studies Four, Five and Six assess the impact point on the golf ball and its effect on the ball roll kinematics.

1.1 Aims

The original aims of this thesis were as follows:

- To examine CP excursion during the full golf swing.
- To examine CP excursion and weight distribution during the golf putting stroke.

Additionally, the following aims were formulated throughout the thesis:

- To assess the reliability and validity of the Quintic Ball Roll software with a mechanical putting robot.
- To assess the effect of golf ball dimples on the ball roll kinematics during a golf putt, with a mechanical putting robot and human participants.
- To assess the relationship between the centre of mass and centre of pressure excursions during the putter stroke.
- To assess to what degree putter face and body segment variability affects putting performance.

Chapter Two

Literature Review

2.1 Introduction

This review contains four main sections of literature firstly, examining factors of performance and centre of pressure excursion for the full stroke. Secondly, golf putting literature is reviewed, including the importance of putting to the overall score, centre of pressure excursions and putting kinematics. The final sections of this literature review assess the reliability of force platforms and statistical methods used to assess reliability. Typical search terms used included, *golf swing kinematics, golf swing biomechanics, putting biomechanics, putting kinematics, centre of pressure excursion in golf* and *performance analysis measures in golf*.

2.2 Performance indicators for the long game of golf

2.2.1 Flexibility and power in golf

Golf is a very demanding physical game, not only in the complexity and precision of the golf swing, but also in the need of creating explosive power through a wide range of motion (Wells, Elmi & Thomas, 2009). Physical fitness is regarded as a key component in almost every sport, however golf traditionally has been a sport where players have focused on the tactical, technical and mental aspects of the game rather than that of muscular strength and power (Gordon et al. 2009). This however in recent years is changing with the increase in physical conditioning in many of the top golf professionals and increased emphasis at the collegiate level in the USA (Fletcher & Hartwell, 2004; Gordon et al. 2009). Previously it has been identified that golfers are often apprehensive about strength and conditioning programmes due to a fear of a loss of mobility (Read & Lloyd, 2014). It is up to the golf coach to explain the potential benefits. As Nesbit and Serrano (2005) summarise, the fundamental purpose of the golf swing is to generate kinetic energy and transfer it to the golf ball during impact. The backswing involves a 'wind up' from which torques are applied to the club and there is a potential to do work. During the downswing, the forces and torques generated function to control the trajectory of the golf club and increase the velocity of the golf club (Nesbit & Serrano, 2005). The speed of this work done is a direct measure of power (whereas strength is defined as the maximal force a muscle can generate at a specified velocity (Baechle & Earle, 2008)); as the faster the velocity of the club head the more kinetic energy that can be transferred to the golf ball (Fletcher & Hartwell, 2004; Nesbit & Serrano, 2005). Within golf the application of power or the time rate of doing work (Baechle & Earle, 2008) may not be as simple as maximising power for maximal club head velocity and therefore distance, something Nesbit and Serrano (2005) did not consider.

The sport of golf requires a high level of joint flexibility (the ability of a joint to move through a full range of motion (Baechle & Earle, 2008)) that allows the human body to generate powerful biomechanical positions, maximising the leverage of the human body (Wiren, 1991). In addition to this Myers, Lephart, Tsai, Sell, Smoliga and Jolly, (2008) suggest one of the most important factors in golf performance is effective pelvic-torso separation; this is to increase club head velocity (CHV), this is the velocity of the club head at impact with the ball. Burden, Grimshaw and Wallace, (1998) found effective separation of the upper extremity and lower extremity in low handicap (LH) golfers. Fletcher and Hartwell, (2004) discuss the importance of the stretch-shortening movement in the torso. Movements that involve a stretch-shortening cycle (SSC) utilise stretching active muscles (eccentric loading) to load the muscle in order to increase power output in the final phase of movement (Komi, 2000). The increased force production is a result of the utilisation of elastic energy within the muscle and tendon during the concentric phase (Finni, Ikegawa, Lepola, & Komi, 2003; Komi, 2000). The modern golf swing can be described as a powerful SSC movement; to improve performance utilisation of the SSC needs to be efficient with eventual peak velocity at impact (Hume, Keogh and Reid, 2005).

Pelvic-torso separation is often referred to as the 'X-factor' this can specifically be defined as the difference in axial rotation between the upper torso and pelvis at the top of the backswing (Hume, Keogh & Reid, 2005). From a biomechanical perspective pelvic-torso separation is an important contributor to driving distance (Myers et al. 2008), research has shown ambiguous results. McTeigue, Lamb, Mottram and Pirozzolo (1994) and Cheetham et al. (2000) did not find significant association between pelvic-upper torso separation at the top of the backswing and striking distance or skill level. However, McTeigue et al. (1994) did notice a trend in that subjects that ranked in the top 50 for driving distance on the PGA tour demonstrated a larger X-factor than the rest of the tour players. Both McTeigue et al. (1994) and Cheetham et al. (2000) placed medial positioned sensors close to the spine.

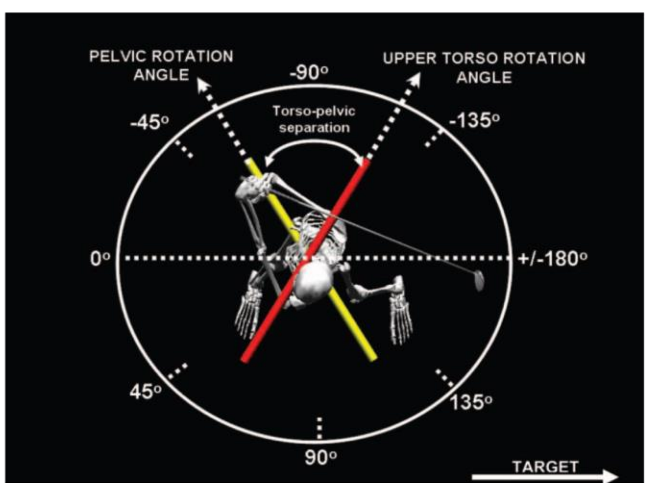

Figure 2.1 Diagram demonstrating the theory of the X-factor stretch (Myers et al. 2008, pp. 184).

In contrast Zheng, Barrentine, Fleisig and Andrews, (2008) and Myers et al. (2008) who placed sensors at the tip of the acromion, did find a significant association between the X-factor and striking distance and skill level with professional groups demonstrating larger X-factors. Zheng et al. (2008) observed a trend in trunk rotation between the different handicap levels, professionals had a mean angular displacement at the top of backswing of 60±7, LH was 55±10, MH was 54±8 and HH was 49±12. Myers et al. (2008) also observed this trend, for the low ball velocity group, a rotation of -94°±13.5 was observed, for medium ball velocity -97°±20.2 and for high ball velocity -104°±10.3. Although this wasn't found to be significantly different subsequent ball velocity was (Myers et al. 2008). Zheng et al. (2008) concluded that high handicap (HH) golfers appeared to be less flexible in the shoulder horizontal abduction and trunk rotation, while being more aggressive in using the trunk and shoulder rotation in the acceleration phase (from the club being in a parallel position with the floor to impact with the golf ball). This may contribute to the differences in performance. Burden, Grimshaw and Wallace, (1998) recommend that shoulder rotation should exceed hip rotation by at least 90°. Burden et al. (1998) also indicated that the sequential pattern of trunk rotation adheres to the summation of speed principle, which potentially could lead to a greater torque being applied to the club during the subsequent motion of the double pendulum.

A source of confusion when comparing the X-factor studies is the different definitions of rotation (Hellström, 2009). The intention of the X-factor concept is to illustrate the rotation between the upper torso and pelvis segment angle, which currently can only be investigated in relatively basic two dimensions (Hellström, 2009). The golf swing however is performed in three dimensions with rotating, tilting and bending of the spine (Hellström, 2009). Hellström, (2009) goes on to explain rotations in the two different planes are compared when measuring the rotation of the pelvis in comparison to the upper torso, where tilting and bending of both joints can affect results. Even with these limitations the maximal increase of pelvic-upper torso separation is still deemed important whether measured by lateral or medial sensors (Cheetham et al. 2000; Myers et al. 2008). This is because the increased muscle stretch during the change of direction in the swing has been suggested as to creating stretch reflexes and more elastic energy, which increases rotational velocities which in turn increases ball velocity (Myers et al. 2008). However, it is not known if the turn at the top of the backswing definitely elicits a stretch reflex, and the elastic energy is actually a function of the muscle force acting in the muscles and tendons (Okuda et al. 2002). As parts of the lower body are eccentrically activated before the direction change in the swing occurs (Bechler, Jobe, Pink, Perry, Ruwe, 1995; Okuda et al. 2002).

Many golfers believe that resistance training (which will improve the SSC) will negatively affect their flexibility and technique (Fletcher and Hartwell, 2004). Keogh et al. (2009) report that muscular hypertrophy development may not need to be emphasised as it potentially could reduce golf performance by limiting range of motion and moment of inertia. However Fletcher and Hartwell, (2004) reported no detrimental effect in flexibility with increases in golf performance, though the information on flexibility was given verbally by the subjects and not measured which is a clear limitation. In an older non golfing population Hetu, Christie and Faigenbaum, (1997) found resistance training combined with flexibility work increased range of motion.

Maintenance of flexibility while increasing strength is very important, as low handicap golfers demonstrate greater strength and flexibility (Sell et al. (2007). Golfers with a handicap of < 0 demonstrated significantly greater hip strength, torso strength, shoulder strength, shoulder flexibility, hip flexibility, torso flexibility and right leg balance in comparison to players with a handicap of 10-20 (Sell et al. 2007). This is important, as an effective golf swing requires the golfer to maintain a stable base (lower extremities and pelvis) while rotating the mass of the torso and upper extremities (Sell et al. 2007). The higher the velocity of the rotation the more core strength required, as demonstrated by the group with a HC < 0 (Sell et al. 2007). Average peak torque was however normalized to the subject’s bodyweight before comparing strength between the groups (Sell et al. 2007). This normalisation may not be valid in golf, as there are no playing categories based on body mass (Hellström, 2009).

The effect of strength training depends on the player’s skill level, training history and weight-lifting methods (Doan, Newton, Kwon & Kraemer, 2006). Less powerful players may increase CHV regardless how a weight programme is performed, whereas a golfer who has a high CHV may develop a slower CHV after a period of slow velocity strength training (Schmidtbleicher & Buehrle, 1987). The change in an objects momentum depends on the magnitude of the force and time that the force is applied (Doan et al. 2006). Schmidtbleicher & Buehrle, (1987) explain that the golfers initial rate of force development (RFD) and maximum RFD are more important in increasing the objects velocity than the maximal strength factor, when the object is less that 25% of 1 repetition maximum and the time to affect it is short (< 250 ms). Therefore the effect of weight training on the RFD depends on the subject’s fitness status and how the weight training is performed (Cronin, McNair & Marshall, 2001; Wilson, Newton, Murphy & Humphries, 1993).

Lephart, Smoliga, Myers, Sell and Tsai, (2007) also endorse an exercise programme for golf. Significant improvements were found in torso rotational strength and hip abduction strength, no significant improvements were found in shoulder rotational strength however, the Lephart et al.

(2007) strength exercise focused on scapular stabilisation rather than rotational movements. Pink, Jobe, Yocum and Mottram, (1996) discuss the benefits of a cardiovascular (CV) training programme; concluding training in this area can be greatly beneficial with golfers suffering less fatigue during a round. Lindsay, Horton and Vandervoort, (2000) also endorse the benefits of CV training especially in an older golfing population.

2.2.2 Club head velocity for golf shots

Club head velocity can be used as measure of long game golf performance as the force at impact is directly proportional to the hit distance (Fradkin, Sherman and Finch, 2004). This has long been thought crucial for golf success (Cochran & Stobbs, 1968). There are three main factors that affect CHV, muscular force applied through the limb segments (strength), the distance over which the force acts (flexibility), and the segmental sequence the force acts (to maximise velocity at impact) (Milburn, 1980).

Fradkin et al. (2004) observed a correlation between golfers handicaps and club head speed with low handicap golfers demonstrating higher club head speeds at impact than those with higher handicaps (r = 0.95). Nesbit and Serrano (2005) looked at the timing of peak work, and found that lower handicap golfers peak work is closer to ball impact than golfers with a higher handicap, these differences did translate in differences in club head speed, however not as high as Nesbit and Serrano (2005) originally thought. The player with a HC of 0 demonstrated a CHV of 52.0 ms^{-1} and the player with a HC of 13 had a CHV of 46.3 ms^{-1}. Larger cohorts of golfers would be needed to confirm this data as Nesbit and Serrano (2005) only tested 4 subjects. Zheng et al. (2008) demonstrated that players with a lower handicap demonstrate greater grip velocity (grip velocity refers to the junction between the hands and club shaft) just before impact, and the club head does not pass their hands until after impact from a frontal plane view (Cochran & Stobbs, 1968). Significant differences were found ($p<0.01$) in the late acceleration phase between timings of professional golfers (0.045s) and a HH group (0.058s) (Zheng et al. 2008). Some reports also state that maximum CHV occurs just before impact rather than impact itself (Miura, 2001) this research is quite dated however, and more recent literature would be needed to confirm this as well as why this may occur, either being a technical strategy or due to deceleration occurring at impact.

Fradkin et al. (2004) found that a warm up performed regularly can also have a benefit on club head speed, after two weeks of a warm up protocol club head speed had increased by 3 – 6 ms^{-1}, this change equates to a decreased handicap of four shots. After seven weeks of the protocol, club head speed had increased by 7 – 10 ms^{-1}, equating to a reduction in handicap of approximately seven shots. The testing was completed in an indoor facility and therefore driving distance could not be measured (Fradkin et al. 2004). Gergley (2009) also supports the use of a gradual active dynamic warm up with golf clubs without the use of static stretches, after static stretches, significant decreases were found in CHV (-4.19%), shot distance (-5.62%), accuracy (-31.04%) and consistent ball contact (-16.34%). A potential limitation of the findings from Gergley (2009) is the low number of subjects (n=15), however all subjects had a handicap of 5 or less. These findings support Fradkin et al. (2004) that a regular warm up can benefit CHV.

Keogh et al. (2009) observed LH golfers ability to generate significantly greater CHV (12%) as well as demonstrating greater accuracy. Keogh et al. (2009) tested flexibility and muscular strength of two groups LH and HH; it was observed that the LH group had significant greater strength in a golf swing-specific cable wood-chop, which could account for the greater CHV. Along with positive correlations found between CHV to the bench press and hack squat strength, no significant correlations were found between CHV and ROM variables (Keogh et al. 2009).

After an eight-week strength and conditioning programme, participants improved flexibility and the magnitude of upper-torso axial rotation, which resulted in increased CHV, ball velocity and driving distance (Lephart et al., 2007). Doan et al. (2006) reported that the relationship between strength of the chest musculature was not significantly correlated with CHV in collegiate golfers, this however was solely assessed using the bench press which doesn't mimic any phase of the golf swing, therefore is not golf swing specific. Gordon et al. (2009) did find a significant relationship between CHV and chest strength (r=0.69) and total body rotational power (r = 0.54). Lephart et al. (2007) does suggest research into golfers following conditioning programmes so an effective maintenance programme can be developed to enhance performance in this cohort. Fletcher and Hartwell, (2004) demonstrated significant improvements in performance after an eight-week plyometric programme, where driving distance increased by 4.3% and CHV increased by 1.5%.

An important factor of the golf swing is the hands, wrist and arms, as the ability of the wrist and arms to do work (force multiplied by distance) on the golf shaft can determine CHV and clubface angle (Hellström, 2009). According to results derived from computer models, the arms, wrists and hands constitute the next most important area in producing work on the club, after hip and torso (Nesbit & Serrano, 2005). Golfers have the ability to apply forces in opposite directions on the shaft with the left and right hand; the effect of actively applying this force couple during the swing is subject to some debate (Hellström, 2009). A predictive study suggests that the increase in CHV by the force couple occurring at the wrist is limited and require very accurate timing (Jorgensen, 1999). A limitation of the model used in this study, is that it was based on two stiff levers 'shaft' and ‘left arm’ and muscle dynamics were not considered (Hellström, 2009). Sprigings and Neal (2000) developed a model that included three levers adding a ‘left shoulder’ lever, along with including the force-velocity relationship of muscles. Sprigings and Neal (2000) concluded that by applying wrist torque increased CHV by 9%. A limitation of the findings from both Jorgensen, (1999) and Sprigings and Neal (2000), were that these predictions were based on two-dimensional models using a planar golf swing. During a real life golf swing, for a right handed golfer, the left shoulder, wrist and club head do not move in a consistent plane, and therefore a three-dimensional model may be more valuable (Hellström, 2009).

2.2.3 Total work and club head velocity

Nesbit and Serrano (2005) used an ADAMS (Mechanical Dynamics, Inc.) software package to generate a three-dimensional full body computer model. Energy analysis was performed on 85 players’ swings; from this the wrists were found to behave like a free hinge during the acceleration phase to impact, but not earlier in the downswing (Nesbit & Serrano, (2005). Nesbit and Serrano (2005) although analyse work and power expenditure in golfers, this demonstrated significant correlations between total work and CHV. Total work was calculated as each player’s ability to apply forces and torques in the direction of motion during the downswing (Nesbit & Serrano, 2005). A potential limitation of Nesbit and Serrano, (2005) was the small subject cohort, which was only 4 people each in a separate ability group for comparison, it was found that the best player worked at a slower rate and then faster through impact than the other three less skilled players. However, further research would need to be conducted to see if the identified trend is reliable and valid in a larger cohort of participants. The best player also achieved the highest total work, and was able to peak closest to impact (Nesbit & Serrano, 2005). Nesbit (2005) also found that better golfers generate power from their arms more so than their wrists, with a ratio of 1.4:1 (total work) for the best player. Nesbit (2005) accounted this to the wrists inability to keep up with the shaft’s angular acceleration, but the arms could pull inwards and decrease the distance from the grip to the upper torso, thus increasing acceleration (Miura, 2001; Nesbit, 2005).

A key principle in golf is the summation of angular velocity, has been discussed for many years, first being discussed by Cochran and Stobbs (1968). An increase in velocity was observed by Zheng et al. (2008), with elite golfers reaching peak angular velocity in the downswing in a bottom-up sequence (i.e. from the segments closest to the ground up through the body, all transferring to the clubhead). An increase in angular velocity was also demonstrated during the bottom-up sequence (Nesbit & Serrano, 2005; Zheng et al., 2008). The bottom-up sequence was also observed in electromyography (EMG) studies (Bechler et al., 1995; Okuda et al., 2002). Nesbit and Serrano (2005) highlight the importance of the rate of increase or decrease in segmental velocity as an important factor in determining maximal CHV at impact. The leg muscles were found not to contribute much work on the club (4%); instead the legs played a supporting role to the body and aided the very important hip motion (Nesbit & Serrano, 2005). The trunk and hips generate the most work on the club, 70% of the total body work (Nesbit & Serrano, 2005). Watkins, Uppal, Perry, Pink and Dinsay, (1996) support the bottom-up theory, after finding that activation levels of the gluteus maximus muscle in the downswing, especially on the trailing side, indicates the role of hip stabilisers and the initiation of the power to start the drive of the golf club into the acceleration phase. This may inform conditioning programmes whereby it is suggested that anti-rotation (of the trunk predominantly) and leg exercises (such as the squat) are beneficial for power generation, injury prevention and spinal control (Read & Lloyd, 2014).

To summarise, increased flexibility will allow the golfer the ability to generate more power, as increasing the range of motion allows for a greater amount of torque to be generated and applied to the golf ball (Nesbit & Serrano, 2005). This increased torque additionally gives the golfer the ability to generate increased CHV displacing the golf ball further (Nesbitt & Serrano, 2005). However, it is worth noting that the increased CHV must not influence the club face angle at impact reducing accuracy. This is reflected in the literature along with distance of the golf shot being measured and accuracy of the golf shot also being measured (Fletcher & Hartwell, 2004; Hetu et al., 1998; Keogh et al., 2009). Previously the club face angle has been identified as an important factor for initial ball velocity and direction (Miura, 2002). Therefore any increases in CHV through increased flexibility and increased power will only be beneficial, if they are controlled and do not increase the variability of club face angle and ultimately decrease accuracy. The control of power and CHV through the total work done is supported with only moderate significant correlations being observed in field-based fitness tests and CHV (Read, Lloyd, De Ste Croix & Oliver, 2013).

2.2.4 Centre of pressure excursion and ground reaction forces for the golf shot

A key element to golf performance is effective weight transfer; literature stresses the importance of weight transfer during the swing (Leadbetter, 1995; Norman, 1995) however research has been conflicting (Ball & Best, 2007b). Leadbetter, (1995) described a typical sequence of weight transfer as evenly balanced between the feet at address, moving towards the back foot during the backswing. Just before the start of downswing, weight begins to move towards the front foot, rapidly in the early downswing phase continuing through to the front foot at ball contact and follow-through (Leadbetter, 1995). Previous studies looking at weight transfer have obvious limitations, Wallace, Graham and Bleakley, (1990) had a small sample size (*n*=2). Koenig, Tamres and Mann

(1993) had a more suitable sample size (*n*=14) but didn't undertake statistical analysis on all of the data collected.

Wallace et al. (1990) conducted a case study of two golfers of varying ability, a low handicap golfer (HC = 6) and high handicap golfer (HC = 24). It was identified that both standards of golfer demonstrated similar ground pressure patterns, however, differences did exist between the two golfers, in weight distribution between the two feet (Wallace et al., 1990). On further analysis Wallace et al. (1990) attributed this to a preference in technique between the two players. As previously stated, Koenig et al. (1993) used a more suitable sample size. It was observed that less skilled golfers demonstrated reduced mediolateral and anterioposterior CP excursions than higher skilled golfers. Koenig et al. (1993) hypothesised that the reason for this was less skilled golfers adjust there technique not to shift their weight between their feet to increase stability throughout the golf swing. In addition to this the better players (more skilled) demonstrated centre of pressure migration patterns that were more circular, utilising mediolateral and anterioposterior movements (Koenig et al. 1993).

As discussed by Ball and Best, (2007a) a possible limitation of these previous studies is the absence of accounting for different swing styles in the golfers examined. Different swing styles need to be identified and then treated as different and distinct groups (Ball & Best, 2007a; Ball & Best, 2007b). As identified in Ball and Best, (2007a), the two main swing styles are 'front foot' and 'reverse'. The front foot group exhibited weight transfer recommended in coaching literature (Leadbetter, 1995). In contrast the reverse style, golfers moved their weight forward from the top of backswing to early downswing, then produced a 'reverse' movement, so that weight was positioned near mid-stance at ball contact, weight transfer continues towards the back foot (Ball & Best, 2007a). Neither style is considered a technical error, as no significant difference was found in mean performance indicated by handicap and CHV (Ball & Best, 2007a).

Larger absolute range of centre of pressure (CP) and greater maximum CP velocity were associated with larger CHV at ball contact for the front foot group (Ball & Best, 2007b; Ball & Best, 2012) which provides support for the findings Koenig et al. (1993) and Wallace et al. (1990) who both suggested that these factors are important for an effective golf swing. Centre of pressure in metres and maximum CP velocity (ms^{-1}) were strongly correlated (r = 0.54) (Ball & Best, 2007b). Ball and Best, (2007b) suggest it is possible that the mechanism behind this correlation might also be related. The mechanism may be part of the kinetic chain or proximal-to-distal sequencing often found in other striking sports such as tennis (Elliott, Marsh & Blanksby, 1986). With greater velocity of weight transfer developing greater system momentum, which then can be transferred to the club head and ball (Ball & Best, 2007b).

It is suggested a larger weight transfer range may facilitate this by allowing greater relative distance over which velocity and momentum can be generated (Ball & Best, 2007b). To date research into this mechanism has not received a lot of attention within the literature and more kinematic data is needed in this area (Ball & Best, 2007b). Increased stance width was also correlated with CHV (*r* = 0.47) (Ball & Best, 2007b), which is in conflict with Leadbetter, (1995) who suggested an increase in stance width does not lead to increased distance. However this is a coaching manual and no data collection was involved. Ball and Best, (2007b) concluded that CP range in metres was more important than increasing the range of CP% between the feet. Stemm, Jacobson and Royer, (2006) tested golfers of a different skill range, in balance, sway and weight shift and no significant differences were found between the different skill levels in all variables tested. However it is questionable how appropriate these results are, as no test was tailored to golf.

The front foot group in Ball and Best (2007a) demonstrated a balanced position at takeaway in the Y-axis CP along the mediolateral (ML) axis = 57% (expressed as a percentage relative to the feet), at top of backswing CP along the ML axis = 21%, at ball contact CP along the ML axis = 81%. In contrast to this the reverse style group moved their weight forward during the backswing CP along the ML axis = 26%, during early downswing CP along the ML axis = 61%, and unlike the front foot group, mid-stance was reached at ball impact CP along the ML axis = 53%, weight continued to the back foot during follow-through CP along the ML axis = 40% (Ball & Best, 2007a). In comparison to previous studies, Ball & Best, (2007a) shows very similar results. Robinson (1994) looked at vertical force distribution (Fz), at takeaway professionals demonstrated an Fz% = 58% and amateurs demonstrated Fz% = 49%. Within Ball and Best, (2007a) the front foot group demonstrated a CP along the ML axis = 57%. Koenig et al. (1993) also produced results consistent with this trend Fz% = 55%. Okuda et al. (2002) suggested that lower handicap players transfer more weight from the right to left side (for a right handed golfer) in a shorter time during the downswing. Worsfold, Smith and Dyson, (2008) however found the opposite where LH golfers demonstrated significantly slower weight transfer, in comparison to mid and HH golfers. Worsfold et al. (2008) suggested the slower rate of weight transfer allows for greater control during the swing. Ball and Best, (2007a) suggest more analysis in CP in terms of the X-axis is required.

In addition to identifying the different styles of swing, Ball and Best (2011) analysed centre of pressure patterns when using different clubs. Differences between a driver, 3-iron and 7-iron were analysed. Ball and Best (2011) identified that 96% of golfers used the same swing style (front foot or reverse) for all three clubs. It was observed that between subjects' very different absolute CP excursions occurred along the ML axis, however, these different absolute patterns still demonstrated the same CP excursion patterns (Ball & Best, 2011). These absolute differences observed in Ball and Best (2011) may have encouraged the authors to assess the importance of centre of pressure patterns on an individual basis (Ball & Best, 2012). The results of this study still support analysis of centre of pressure excursion using group-based analysis but also for performance based analysis individual analysis should be included. This potentially has a large effect on practical implications whereby coaches need to do individual based analysis before applying and adjusting techniques identified within the literature.

Ground reaction force (GRF) patterns have been researched in the golf swing and have identified that the largest vertical GRF typically occurs during the acceleration phase (between the parallel position of the club shaft to impact) (Chu, Sell & Lephart, 2010; McNitt-Gray et al. 2013). Both studies presented their results differently so comparisons are difficult to make, Chu et al. (2010) expressed GRF as a percentage of body weight, whereas McNitt-Gray et al. (2013) expressed GRF in its raw form. At impact between the club head and ball Chu et al. (2010) observed a GRF in the lead foot of 74.7 ± 29.7% and in the rear foot 35.5 ± 21.0%. McNitt-Gray et al. (2013) observed a vertical GRF of approximately 900 N in the lead foot and 450 N in the rear foot. McNitt et al. (2013) identified a similar trend to Chu et al. (2010) in the fact more GRF was observed for the front foot in comparison to the rear foot at impact during the golf swing. Chu et al. (2010) state that this shift of vertical GRF is as a result of CP excursion shifting to the front foot (for golfers that demonstrate a front foot style) as recognised by (Ball & Best, 2007b; Ball & Best, 2011; Ball & Best, 2012). McNitt-Gray et al. (2013) concluded that golfers that monitor that the force magnitude (of particularly horizontal GRF), have advantages during the golf swing in terms of muscle activation and coordination. In addition to this Okuda et al. (2010) state (although not significantly different) proficient golfers exhibited a larger trail foot vertical GRF at ball impact and the follow through phase, the authors attributed this to differences in the kinematics of the pelvis at impact.

Despite the majority of golf literature utilising two force platforms to measure GRF and CP excursions, such as Ball and Best (2011), Ball and Best (2012) and McNitt-Gray et al. (2013) previous literature has used one force platform within the methods. The use of one force platform such as Koenig et al. (1993) methodology used will still provide useful information, especially in higher handicap cohorts, which are under researched in comparison to low handicap golfers which additionally formulate a large portion of the golfing population. The use of one force platform is still used in other sports and movements such as cricket (Worthington, King & Ranson, 2013), the counter movement jump (Floria & Harrison, 2013), Olympic lifts (Comfort, Allen & Graham-Smith, 2011) and the baseball pitch (Werner et al., 2005). Whilst with one force platform being used analysis will not be able to be completed on individual feet, the whole body CP excursion can be recorded with accuracy and precision.

2.3 Performance indicators for the golf putt

2.3.1 Importance of golf putting in regard to total score

Putting is often described as a game within a game (Hurrion & Hurrion, 2008), or even a 'black art' (Pelz, 2000). Cochran and Stobbs, (1968) sum the skill of putting up, '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 with any other player, no matter what his handicap, is not capable of doing also' (pp.186). McLaughlin et al. (2008) reaffirm this theory, as when it comes to putting the task is the same for all golfers, roll the ball across the surface of a putting green into a hole four and a quarter inches in diameter. Carnahan, (2002) identified that handicap was a statistically significant explanatory variable of putting performance with lower handicaps demonstrating increased performance, however only accounted for approximately one-quarter of the variation in putting performance.

The putting stroke is one of several different types of golf swings, however accounts for nearly half the swings made, 43% therefore this could be considered the most important element of the game (Pelz, 2000). However as Hurrion and Hurrion, (2008) state, the putting stroke still remains the area of the game least taught. Coaching magazines, manuals and textbooks still suggest 'feel' with the combination of 'good technique' as the biggest key to success on the golf green; kinematic parameters contributing to a good technique could be the ability to create a stable posture and pivot point to return the putter head as consistently as possible (Hurrion & Hurrion, 2008). This in turn lead to a very individual style of putting, as golf professionals often state it is best to stand comfortably at address and therefore it is finding the balance of being comfortable while having complete stability for an optimum putting stroke (Hurrion & Hurrion, 2008). Choi, Kim, Yi, Lim and Tack (2007) found that elite golfers (handicap < 2) had a clear rotational centre that converged to one point; the amateur group (handicap > 25) the rotational centre did not converge into one point. This supports the point made by Hurrion and Hurrion, (2008) that a stable posture and consistent pivot point is required.

The ability to putt is clearly an important factor contributing to a low total score (Hellström, 2009). The best players on the PGA tour have the ability to differentiate themselves by putting better than the rest of the field (Dorsel & Rotunda, 2001). This was reflected in putting average being the top contributor to money won with a significant relationship identified (r^2 = .10). (Dorsel & Rotunda, 2001). In addition to money won putting average was also correlated with Top 10 finishes (r^2 = .17). Finley and Halsey (2004) found putts per round to have higher r^2 values correlations compared to scoring average r^2 = .92. Wiseman and Chatterjee (2006) state that greens hit in regulation (GIR) is the most important factor in explaining the variance in scoring average, however this was closely followed by putting average.

Putting average had a strong correlation with average score (r = 0.68), as did GIR (r = 0.78) in professional players over a fourteen-year period between 1990 and 2004 (Wiseman & Chatterjee, 2006). Putting average had a peak correlation of r = .70 in 1994, and GIR had a peak correlation of r = .82 in 1992 with average score. Finley and Halsey (2004) however found scrambling (r^2 = .92) to correlate stronger to scoring average both actual and adjusted (adjusted scores account for average score for all players) than putts per round (r = 0.34 and r = 0.36). Scrambling does however involve a putt, so this could suggest that players who make these important putts prove more successful. In contrast to this Dorsel and Rotunda, (2001) found GIR to be a less important category in regards to Top 10 tournament finishes for the elite players included in the multiple regression analysis (r^2 = .01). Tour statistics have shown that putts per GIR have become lower between 1968 and 1993 (Thomas, 1994) as well as between 1990 and 2004 (Wiseman & Chatterjee, 2006). These improvements could be down to improvements in green quality (Thomas, 1994) and therefore an increased ability in the reading of the green (Karlsen, Smith & Nilsson, 2008). Putts per GIR, is a very important measure as it has shown stronger correlation to scoring average (adjusted) than that of putts per round (Quinn, 2006).

2.3.2 Putting stroke kinematics

Brooks (2002) described three types of putting strokes commonly recommended by golf instructors, in reference to the target line and are; the straight back to straight through; inside to inside; and inside to straight through. After examining the strokes using mathematical models Brooks (2002) did not arrive at a conclusion to which stroke is best, however, a putting stroke where during the backswing the putter head moves inside the aim line, and where the putter face is square to the putter path, which means the putter face is open to the aim line at the end of the backswing was endorsed. Pelz (2000) advocates a different type of putting stroke, where the path is linear and the putter face is square to the path throughout the stroke. Pelz (2000) recommends this type of stroke with the putter face square, as there may be timing limitations, resulting in the inability to square the club face exactly at impact. The main argument against what was proposed by Pelz (2000) is that the straight stroke is more biomechanically complex than it first seems, as it relies on a fully horizontal axis of rotation for the putter, and/or muscle activity that will compensate for the deviation from the horizontal axis (Karlsen et al. 2008).

Neal and Wilson (1985) modeled the golf putt as a double-pendulum system composed of two arms and the putter. It was described that the shoulder is meant to roll in an up-and-down fashion, and the two hands hold the putter, moving back and forth in a symmetrical pattern (Neal & Wilson, 1985). Delay, Nougier, Orliaguet and Coello, (1997) however observed novices to show the typical pendulum motion, whilst expert players did not. Expert players demonstrated an asymmetrical pattern where a longer follow-through was observed (Delay et al. 1997; Sim & Kim, 2010).

Sim and Kim (2010) analysed the differences between experts and novices accuracy in golf putting in regards to impulse variability. An impulse variability model was developed by Schmidt, Zelaznik, Hawkins, Frank and Quinn (1979), to send a ball close to the target, the magnitude of the impulse applied to the ball by the putter needs to be precise. In putting, the moment of impact is extremely brief, therefore the velocity of the putter at impact becomes extremely important in achieving accuracy (Sim & Kim, 2010). Research has demonstrated that movement at impact is not decided upon the moment of impact, but that movement is attuned and planned from initiation of the movement (Bootsma & van Wieringen, 1988; Coello, Delay, Nougier & Orliaguet, 2000) and through the period of swinging up to impact referred to as downswing (Müller & Abernethy, 2006). Delay et al. (1997) suggests that movement control may not be complete at impact.

Sim and Kim (2010) results showed expert players to have a lower level of velocity in comparison to the novice group, the experts also achieved increased accuracy; Delay et al. (1997) reported the same results. The question raised from both of these sets of results is how the expert group reached the target with a lower velocity. Delay et al. (1997) suggested that energy produced by novices might not entirely be transferred to the ball, with more energy loss at the moment of impact. Sim and Kim (2010) support this claim as it was observed that expert players maximum velocity occurred after impact, which means the ball gained stronger impulse when it left the putter face rather than at the moment of impact. A second explanation was provided by Delay et al. (1997), which concerned the ball roll. During experimentation it was observed that the novice players ball often bounced during rolling, whereas the experts ball glided smoothly. Sim & Kim (2010) further this theory of different types of ball roll; they suggest expert players achieve greater energy efficiency by striking the ball with the putter during the rising phase of the stroke while increasing velocity so that it rolls rather than slides towards the target. This would explain how the expert players reached the target with reduced impact velocity as a ball will lose less kinetic energy when it rolls in comparison to when it slides (Sim & Kim, 2010).

MacKenzie and Sprigings, (2005) state that a number of elements are needed to hit a successful putt. The first being that the golfer must correctly read the green, to determine the correct target line and establish the optimal speed to impact on the golf ball to project it towards the target (hole). During the execution of the putting stroke the putter should only demonstrate horizontal velocity in the direction of the decided target line, reducing elements of velocity in other directions, which would be undesirable. This will ensure the plane of the putter face with be perpendicular to the original putting line (MacKenzie & Sprignings, 2005). A technique that can be used to read the green is the plumb-bob method; this is where the golfer stands behind the ball straddling an imaginary line that bisects the hole (MacKenzie & Sprignings, 2005). The golfer then suspends the putter at an arm's length in front of the face allowing gravity to pull the shaft into a true vertical alignment (Foston, 1992). Although it has been proven a success in certain professionals Mackenzie and Sprigings (2005) deem it to be an unreliable method at determining the intended target line due to the high sensitivity of the plumb-bob method to confounding factors.

Karlsen et al. (2008) examined the golf putting stroke and determined three main determinants of direction variability. These were putter face angle that was accountable for 80% of the variability, putter path accounted for 17% variability and the horizontal impact point on the putter face accounted for 3% (Karlsen et al., 2008). Pelz (2000) only considered two factors that contribute to direction variability, firstly, putter face angle (83%) and putter path (17%). Therefore it may be the case that putter face angle may be the most important club head kinematic variable regarding golf ball direction variability as highlighted by Karlsen et al. (2008) and Pelz (2000). To date no study has examined body movements effect on putter face and performance variability.

2.3.3 Weight distribution and centre of pressure excursion during the golf putt

Hurrion and Hurrion (2008) examined weight distribution in thirty elite PGA professional golfers and thirty amateur golfers with a handicap between (+3 to 9), a twenty-five foot putt was holed until there were 6 successful attempts. The main significant kinematic difference found between the two subject groups was in set up; the professionals weight distribution was 48.34% left foot and 51.66% right foot, whereas the amateurs weight distribution was 40.57% left foot 59.60% (Hurrion & Hurrion, 2008). Hurrion and Hurrion (2008) found a significant difference also lied in the total amount of sway between the two groups, the amateur group had a total sway of 83.10mm and the professionals had a total sway of 64.34mm. McLaughlin et al. (2008) also observed significant differences in centre of pressure movement for a 4m putt, the high handicap group (18 – 27) produced significantly more CP excursion (right to left) in the downswing phase (Study Two, Figure 4.1, pp. 62) with a value of 10.7mm, in comparison the LH group (0 – 9) was 4.5mm and the Mid handicap group (MH) CP excursion was 5.5mm. Hurrion and Hurrion (2008) observed similar results, with the amateur group recording CP excursion of 12.23mm in the downswing in comparison to the professional groups 10.13mm, this however was not found to be significant. Delphinus and Sayers (2012) did not directly measure the CP however measured the movement of the centre of mass (CM), which has a direct relationship with the CP in proficient and non-proficient golfers. It was identified that proficient golfers moved predominantly in the frontal plane in comparison to the non-proficient golfers where more sagittal movements were recorded (Delphinus and Sayers, 2012). Additionally Delphinus and Sayers (2012) found non-proficient golfers demonstrated increased movement variability in comparison to the proficient golfers, which may go some way to explain the increased CP excursions observed for less proficient groups in Hurrion and Hurrion (2008) and McLaughlin et al. (2008).

McLaughlin et al. (2008) suggests that a LH group is more able to optimise the movement of CP excursions when compared to the MH and HH groups. During the downswing the HH had a max velocity of 64.5 ± 48 mms^{-1} in comparison to 29.7 ± 25 mms^{-1} for the LH group and 39.8 ± 36.3 mms^{-1}, the LH was found to be significantly less ($p < .001$) than the HH group. A trend was identified where the higher a player's handicap was the greater values in max velocity and average velocity during the downswing were observed. Delay et al. (1997) observed that when the distance of a putt was increased subjects increased the DS amplitude while maintaining the DS movement time; this is an increase in velocity in accordance with McLaughlin et al. (2008). Karlsen et al. (2008) found some indication that long DS times have a negative effect on consistency for some players; this may be due the players consciously controlling the motion. Velocity was not reported by Karlsen et al. (2008) however it seems to be of an opposite opinion to McLaughlin et al. (2008), however it may be only extremely long DS times that have a negative effect on the putting stroke. Karlsen et al. (2008) suggests that DS times between 270 and 370 msec produced the best overall performance. Delay et al. (1997) reported longer DS times for novice (584 msec) and expert golfers (719 msec) however this was due to different definitions of DS, Karlsen et al. (2008) DS phase ended at Impact, whereas Delay et al. (1997) DS phase ended at the highest position of the club after contact with the ball. However it should be noted that expert golfers demonstrated a longer DS time in accordance with McLaughlin et al. (2008)

Karlsen et al. (2008) take a different standpoint concerning the putting stroke; arguing the fact the putting stroke only has a minor contribution to the overall success of a putt. Karlsen et al. (2008)

found mean stroke direction variability for an elite player (European PGA Tour) to be 0.39°, which is good enough to hole 95% of putts from a 4-metre distance, whereas only 17% of putts from this distance are successful. Pelz, (2000) makes the assumption that 30% of putts from 4-metres are missed due to green inconsistencies, Karlsen et al. (2008) findings support this fact, along with human controlled factors green reading and aiming have a stronger contribution to the direction of a putt, than the stroke itself. Pelz, (2000) also describes numerous factors that contribute to a successful putting stroke, which green-reading and aim are included, recently reported by Karlsen et al. (2008) reported as the most important factors; and stability more recently discussed by Hurrion and Hurrion, (2008). Low handicap golfers (<14) have the ability to combine these factors together to become more proficient putters, making putts less than 2.43 metres much more often than their HH counterparts (Carnahan, 2002). It was also reported by Carnahan (2002) that the incidence of three-putts within 3.66 metres was 2.1%; for subjects with a handicap of <14 the occurrence was 1.2%, and for subjects with a handicap that was > 14 the occurrence was 3.8%. This was found to be statistically significant ($p = 0.008$).

More recently McLaughlin and Best (2013) have critiqued previous studies for grouping golfers based on putting performance or handicap. McLaughlin and Best (2013) identified two styles of putter, firstly the arm putter that demonstrates a low CP excursion velocity at impact (5.2 ± 16.9 mms^{-1}) and a body putter that demonstrates a higher ML CP excursion velocity at impact (58.4 ± 22.9 mms^{-1}). These different styles of putter were identified using cluster analysis and ML CP excursion velocity at impact was the highest ranked cluster between types of putter. A potential limitation to McLaughlin and Best (2013) is that no kinematic variables of actual body movements were recorded, and therefore different types of putters may have just been using different movement patterns. It is possible that the arm putters move in a way that reduces the CP excursion but doesn’t in fact move less that the body putters. The lack of clarity in this area still gives studies by Hurrion and Hurrion (2008) and McLaughlin et al. (2008) validity within the literature. As both studies found significant differences were observed between more proficient golfers and less proficient golfers CP excursion parameters, even if McLaughlin and Best (2013) did not find significant differences. A potential reason for these differences observed between studies could be the large inter-subject variation observed. McLaughlin and Best (2013) even stated that half of the subjects actually interchanged between the arm putting and body putting style.

2.3.4 Vision and conscious processing on putting performance

Research has been conducted in regard to the influence of the affect that vision has on golf putting. MacKay (2008) demonstrated a positive correlation ($r = .91$) between eye alignment and putter face alignment. Of the thirty putts recorded (three for each subject), 80% had a difference of 1 degree or less between the angle of eye and putter face alignment, and 50% of putts had the exact same eye and putter face alignment. Previous to this Vickers (1992) analysed gaze behaviors and found that LH golfers (0-8) had a distinct gaze strategy during flat putts, LH golfers adopted the strategy, 'two to three fixations to the hole and then to the ball or club face, with distinct saccades linking these fixations.' During the execution of the putting stroke another trend was identified, 'players maintained a steady fixation on the top or back of the ball' LH golfers were found to have a longer fixation than HH golfers. Holed putts were also found to have longer fixations than missed putts (Vickers, 1992). This last fixation before the motor response is referred to as 'quiet eye' (Vickers, 1996). It was proposed that quiet eye is a time frame where task-relevant environmental cues are processed and motor plans are coordinated for the successful completion of a task (Vickers, 1996).

Wilson and Pearcy (2009) applied the quiet eye theory to putts with break, adding difficulty to the putt, this was demonstrated as 52% of flat putts were holed, 41% on a moderate slope and only 11% on severely sloped putt. Wilson and Pearcy (2009) explained the difference in difficulty of the putting task as slope was added more parameters needed to be processed by the visuomotor system, such as line and pace. Results from Wilson and Pearcy (2009) support Vickers (1992) as successful putts again demonstrated significantly longer quiet eye periods (approximately 2,000 msec for expert putters). However no significant differences were observed in quiet eye periods between flat and either of the sloped putts, significant differences were found to exist in the number of fixations made during the preparation phase. Wilson and Pearcy (2009) account this to fixating to different target locations during the sloped condition, reflecting the players search for the correct target line.

Research has identified that in certain skill performances, little or no conscious attention is given to the mechanics of movement or during unsuccessful completion of tasks conscious attention increases (Gucciardi & Dimmock, 2008; Jackson, Martin & Eklund, 2008; Hill, Hanton, Matthews & Fleming, 2010; Toner & Moran, 2011). It was identified for golf putting that consciously making technical adjustments to the mechanics of the putting stroke did affect kinematic features however this did not have a great influence of expert golfers' putting proficiency (Toner & Moran, 2011). In contrast to this a second experiment conducted by Toner and Moran (2011) found conscious monitoring of the putting mechanics rather than adjusting the technique proved to be a detriment to putting. Toner and Moran (2011) explain this finding to the dynamical systems theory as described by Davids, Button and Bennet (2008). Conscious processing during the golf putt essentially reduced functional variability during the putting action, which reduced the golfers ability to adapt movement behavior to the task in hand (Glazier & David, 2009; Toner & Moran, 2011). More research is however needed identifying the amount of variability across a range of abilities of golfers and how variability affects putting performance much like that has been conducted for the full golf swing (Bradshaw, Maulder & Keogh, 2007; Horan, Evans & Kavanagh, 2011; Tucker, Anderson & Kenny, 2013).

2.3.5 Ball roll kinematics

As technology has evolved, so have putters being used in an attempt to make putting an easier task. In the past, putter design has mainly focused on the inertia properties of the golf club head, to maximize the performance on off centre impacts, as well as polymer inserts on the putter face (Brouillette & Valade, 2008). The most recent innovation in putter face treatment is the introduction of grooves (Hurrion & Hurrion, 2002).

The idea of the grooves is to hold the ball on the putter face for a fraction of a second longer, which in turn improves the roll characteristics of the ball, leading to a more pure strike (Swash, 2001). As Brouillette & Valade (2008) and Swash (2001) describe, imparting spin to a moving object increases its imperviousness to perturbations along its trajectory, this is known as spin stabilisation. The main role of the grooves on a putter face is to improve the initial phase of the putt, which is characterised by the ball skidding on the surface (Brouillette & Valade, 2008; Hurrion & Hurrion, 2002). During this phase, the spin stabilisation is negligible and the ball can change trajectory more easily, potentially leading to more missed putts (Brouillette & Valade, 2008). This could contribute to the low value of 17% putts holed from 4-meters, along with aim and green reading (Karlsen et al. 2008). During skidding, friction between the ball gradually gets the ball spinning forward, until the rolling is perfectly synchronised with the forward motion of the ball, the term for this is 'pure rolling' (Brouillette & Valade, 2008). Lindsay (2003) states another advantage of reducing skid on the golf ball allows the golfer to optimise distance control in long putts. As in the initial stages of ball roll the ball loses less of its energy.

The aim of grooves on the putter face is to get the ball to the stage of 'pure rolling' quicker (Brouillette & Valade, 2008; Hurrion & Hurrion, 2002; Swash, 2001). However conflicting results have been reported within the literature. Both Swash (2001) and Hurrion and Hurrion (2002) found grooved putters to improve ball roll characteristics. Hurrion and Hurrion (2002) found significant differences between a grooved putter and traditional faced putter in the initial amount of forward roll and amount of skid of the golf ball during the first 500 mm of the putt. Whereas it was found that face grooves can modulate the coefficient of restitution of the impact between the putter face ball, but this does not cause the ball to skid less or increase the topspin on the ball in

Brouillette (2010) and Brouillette and Valade (2008). Brouillette (2010) experiment was completed using a putting robot, whereby, the grooved putter did demonstrate increased forward roll and reduced distance of ball skid. However, this also reduced the final length of the golf putt, when the amplitude of the putting robot was increased to match the distance of the golf putt, the grooved putter did not out perform that of the traditional faced putter. Differences between the studies may be the fact both Brouillette (2010) and Brouillette and Valade (2008) testing protocol used a putting robot whereas Hurrion and Hurrion (2002) used human participants.

A number of mathematical models have been developed describing the motion of a putted ball over the surface of a green (Alessandri, 1995; Lorensen & Yamrom, 1992: Penner, 2002). Differences between the models are primarily between the frictional components of force being applied to the ball. Both Alessandri (1995) and Penner (2002) keep the frictional value constant over the whole length of the putt, whereas Lorensen and Yamrom (1992) used two different constant coefficients of friction, one modeling the initial sliding phase or 'skid' and the other to model the rolling phase. The clear limitation of these studies was the fact they were mathematical models of the putt and no actual data from golfers or a putting robot was collected.

Along with putter face treatment, Karlsen and Nilsson, (2007) tested putter shaft weight, but however found no significant differences in distance and directional putting accuracy. Lindsay (2003) however states that the position of the shaft can affect the topspin imparted on the ball. A putter where the shaft coupling was positioned over the centre of mass outperformed a putter where the shaft was offset from the centre of mass (Lindsay, 2003).

2.4 Force platform analysis

2.4.1 Parameters used to assess centre of pressure excursion

Since the early 1970s, force platforms have been used to acquire quantitative measures for analysis of postural control (Palmieri, Ingersoll, Stone & Krause, 2002). Quantitative measures are gained by the force platform by the recording of GRF projected from the body (Browne & O'Hare, 2000). From this CP can be calculated, this reflects the trajectory of centre of mass and the amount of torque applied at ground surface to control body mass (Winter, Patla & Frank, 1990). Parameters that can be used include, mean sway amplitude, maximum sway amplitude, minimum sway amplitude, peak-to-peak amplitude, sway path, sway velocity, RMS amplitude and RMS velocity, this allows the researcher to quantify alterations in balance (Palmieri et al. 2002). Within the game of golf the double-legged stance is applicable (Palmieri et al. 2002). When CP is obtained when both feet are in contact with a single force platform, it carries the term net CP

(Winter et al. 1990). Over two thirds of body weight is balanced, two thirds above the ground when an upright stance is adopted, this is what places the demands on the postural-control system (Browne & O'Hare, 2000).

The maximum peak amplitude is defined as the absolute displacement of the CP from its mean, whereas minimum amplitude is the minimum displacement of the CP from its average point (Palmieri et al. 2002). Within terms of gait, an increase in either maximum or minimum amplitude suggests a decreased ability to maintain an upright stance, and visa versa for a decrease in either variable (Palmieri et al. 2002). Palmieri et al. (2002) questions the use of these parameters, as they are one dimensional, allowing for the assessment of postural control in both anterior/posterior and medial/lateral, but may not accurately reflect balance. The lack in accuracy may lie in the fact that it is a maximum and minimum measure, which only requires one point to be examined and therefore there can be great variability between trials and subjects (Palmieri et al. 2002). Peak-to-peak amplitude represents the difference between the maximum and minimum amplitudes of CP (Geurts, Nienhuis & Mulder, 1993). Again Palmieri et al. (2002) questions the accuracy in this parameter, due to the large variability. It was concluded in Palmieri et al. (2002) that maximum and minimum amplitude values and peak-to-peak amplitude, are likely to cause misinterpretation of alterations in balance and should not be used to evaluate postural control.

Mean amplitude of CP is an average value over all data points collected in a trial and is a more representative measure of postural control (Palmieri et al. 2002). Increased values in mean CP amplitude suggest decreased postural control, whereas a decrease is thought to represent increased postural stability (Baloh, Jacobson, Beykirch & Honrubia, 1998; Le Clair & Riach, 1996). The mean amplitude of CP does however have limitations, as it is susceptible to noise, Palmieri et al. (2002) suggests using an average of multiple trials to resolve this potential problem. Palmieri et al. (2002) states the importance of when using mean amplitude is defining where the mean amplitude is calculated from, whether it be the centre of the force platform or is dependent on stance location. Mean CP has been shown to fluctuate with different degrees of stance width, stance length and foot angle (Kirby, Price & MacLeod, 1987).

A theme discussed in Palmieri et al. (2002) is total CP excursion and CP velocity. Total excursion of the CP is defined as the total distance traveled by the CP over the course of the trial duration (Palmieri et al. 2002). In terms of postural control literature suggests that increases in total CP excursion represents a decreased ability in the postural-control system to maintain balance (Holme et al. 1999; Ekdahl, Jarnlo & Andersson, 1989; Uimonen, Sorri, Laitakari & Jamsa, 1996). Palmieri et al. (2002) identified a potential limitation in the interpretation of total CP excursion, as it is possible to see a large total CP excursion during a stable stance or a small total CP excursion representing an unstable stance. A large total CP excursion may suggest that the CP needs to make sizeable excursions to maintain a stable stance (Palmieri et al. 2002). CP velocity represents the total distance traveled by the CP over time (Palmieri et al. 2002). CP velocity has been shown to be reliable between sessions when a double-legged stance is employed (Le Clair & Riach, 1996). An increase in CP velocity is thought to represent a decreased ability in postural control, whereas a decrease in CP velocity suggests a greater ability to control posture (Baloh, Jacobson, Beykirch & Honrubia, 1998; Le Clair & Riach, 1996). Again Palmieri et al. (2002) questions the use of this parameter when assessing postural control, as how the variable is represented in the literature may not be accurate. A limitation of both the total CP excursion and velocity of CP excursion, is both are two-dimensional, representing a combination of AP and ML CP excursion, and therefore Palmieri et al. (2002) claims important directional information can be easily be missed.

Root-mean-square (RMS) amplitude represents the standard deviation of the displacement of the CP (Palmieri et al. 2002). This parameter measures the average absolute displacement around the mean CP (Palmieri et al. 2002). A decrease in both RMS amplitude and RMS velocity represents an increased ability to preserve an upright stance, an increased value for either variable suggests a decreased ability in postural control (Geurts et al. 1993). Literature suggests that RMS amplitude and velocity are reliable measures to evaluate postural equilibrium (Geurts et al. 1993; Le Clair & Riach, 1996). Geurts et al. (1993) reported that RMS amplitude had a coefficient of variance of 31.75% and RMS velocity had a coefficient of variance of 26.75% show sufficient intra-subject consistency over a 5-week period. In addition to this Le Clair and Rioch, (1996) demonstrated RMS amplitude intersession reliability in the anterior/posterior direction (r= .86) and the medial/lateral direction (r= .81). Palmieri et al. (2002) states intraclass correlation coefficients need to be analysed to support this reliability.

2.4.2 Measurements of centre of pressure within golf literature

Ball and Best, (2007b) analysed centre of pressure patterns within the golf swing, using two AMTI force plates covered in artificial turf, one placed beneath each foot. Ball and Best, (2007b) normalised CP to foot position at address, which is important as discussed by Palmieri et al. (2002). This was achieved by attaching an overhead camera (50Hz) to capture foot position at address relative to the force plate coordinates (Ball & Best, 2007b). Along with this using a Peak Motus system the heel and toe of each foot were digitised four times, with the average of the four points used to indicate the position of the foot for each swing (Ball & Best, 2007a). From the digital data of the foot position, the Y-axis mid-foot position of each foot (midway between the heel and toe along the Y-axis) can be calculated and the centre of pressure along the X-axis can be expressed (Ball & Best, 2007a).

Ball & Best, (2007a) decided to analyse CP along the ML axis at swing events in preference to using centre of pressure time curves. Swing events were chosen because; players and coaches easily understand them (Ball & Best, 2007a). Secondly, there is evidence to suggest that using time-normalised data can have significant limitations because of issues of temporal dependency (Forner-Cordero, Koopman & van der Helm, 2006). The problem arises from the assumption that there is no variability in the timing of events between take-away and ball contact and that no rescaling occurs during the percentage conversion (Ball & Best, 2007a). Ball and Best, (2007b) used the parameters Maximum CP velocity (ms^{-1}), time of max velocity relative to ball contact (s), vertical force underneath each foot (Fz%), maximum CP along the ML axis and CP along the ML axis range in metres, from this weight transfer could be analysed.

Force platforms also have been used to test the amount of torque occurring and the shoe-natural grass interface (Worsfold, Smith & Dyson, 2008). Like Ball and Best, (2007a) and Ball and Best, (2007b) two force platforms with a natural turf surface placed on top were used, one placed beneath each foot (Worsfold et al. 2008). Unlike Ball and Best, (2007a) though was the use of a thin strip of clay attached to a plastic sheet, so the turf could be fixed to the force platforms. Results of this Worsfold et al. (2008) study demonstrated considerable force generation at the golf shoe-natural grass surface interface (17-19Nm). Barrentine, Fleisig and Johnson (1994) also looked at the (GRF) using two force platforms placed beneath the feet. It was observed that LH golfers achieved maximum torque with the rear foot earlier in the downswing, which can be related to the greater CHV that was observed for the LH golfer (Barrentine et al. 1994). As Hume, Keogh and Reid, (2005) discuss this GRF is important to maximize distance obtained with the driver and long irons.

2.4.3 Reliability of force platforms

As well as hard based force platforms, there are also plantar measurement devices (PMDs) which are often considered a less powerful choice in both clinical and a research context (Giacomozzi, 2010a), although the potential of PMDs is highly recognised (Giacomozzi, 2010b; Putti, Arnold, Cochrane & Abboud, 2008). Current problems include comparisons between different PMDs; current research has not presented absolute pressure values (Alvarez, De Vera, Chhina & Black, 2008; Thijs, Van Tiggelen, Roosen, Declercq & Witvrouw, 2007), absolute pressure values may help in understanding how much comparable different datasets are (Giacomozzi, 2010a).

Rather than absolute pressure values, clinicians and researchers are often more concerned with relative pressure values or relative pressure distribution changes, relative values should be approached with caution when comparisons are being made. This is due to the values being post – processing products, and can be affected by PMD sensor response (Giacomozzi, 2010a). As shown in Table 2.1 the leading PMDs all have different Pressure ranges and resolutions, so comparisons when using different PMDs can be difficult. Giacomozzi (2010a) identified the following parameters for assessment of the reliability of PMDs. Sensor response variability with respect to different pressure levels, dividing the PMD into large sub – areas. Sensor response in terms of absolute value of pressure over a small, uniformly loaded area within the loading ranges. Sensor hysteresis, measured by a loading – unloading frequency not greater than 1 Hz. Sensor response in terms of creep, so to vary the pressure response and platform response in terms of accuracy and repeatability of CP coordinates estimation.

Table 2.1. Main characteristics of five commonly used PMDs (Giacomozzi, 2010b).

	AM CUBE	MEDILOGIC	NOVEL	RSSCAN	TEKSCAN
Tested Device	AM3 platform	Medilogic platform	EMED-x	Rsscan platform	Matscan
Technology	Capacitive, air-based	Resistive	Capacitive, elastomer-based	Resistive	Resistive
Calibration	In-factory (up to 900 kPa)	In-factory	In-factory	In factory plus user calibration	In factory plus user calibration
Overall Sensor Matrix	64 x 64	32 x 64	64 x 95	64 x 64	44 x 52
Pressure range (kPa)	0-1200	0-640	0-1270	Not Available	0-850
Resolution (sens/cm^2)	1.7	1.78	4	2.67	1.4
Active sensors per area	9	9	16	9	9

Giacomozzi (2010c) technically assessed the PMDs using a custom made pneumatic bladder pressure tester (PM) and a pneumatic – force testing device (PTD). The PM was used to uniformly apply pressure over the entire PMD sensor matrix. The PTD consists of a pneumatic testing device with an on off valve, a proportional valve and pressure controls to manipulate pressure ranges from 0 – 600 kPa (Giacomozzi, De Angelis, Paolizzi, Silvestri & Macellari, 2009; Giacomozzi, 2010b). An additional tool was built in order to assess CP coordinates allowing the application of known forces through three pylons; theoretical CP coordinates could then be acquired. For CP estimation the PMDs were split into five areas, for each area, CP coordinates were averaged over a 10 second static loading period under six angular positions, from this root means square error could be calculated (Giacomozzi, 2010c).

The RS FootScan pressure range was not reported in this research as an exclusive technical note was agreed for more extensive analysis. The technical assessment of the other PMDs showed good reliability (Giacommozzi, 2010b). Centre of pressure estimation showed high precision for all PMDs, NOVEL accuracy error was always lower than its PMD spatial resolution (0.25 cm); TEKSCAN and AM CUBE error was greater than the spatial resolution (0.35 and 0.39 cm respectively); MEDILOGIC error however was always greater than spatial resolution (0.37 cm) (Giacomozzi, 2010b), therefore for CP analysis the NOVEL would provide the most accurate results. Giacomozzi (2010b) results showed that the capacitive, elastomer – based PMD by NOVEL showed high accuracy and precision in CP estimation, with low variability of all performances over the whole sensor matrix. The resistive PMD by TEKSCAN, demonstrated high accuracy and precision in CP estimation except for one tested area, this is also applicable for the capactive air – based PMD by AM CUBE. In the current study a RS FootScan was available, like the TEKSCAN the RS FootScan uses resistive technology and therefore reliability results may be similar.

2.5 Methods of reliability testing

2.5.1 Types and the use of reliability statistics

Reliability refers to the reproducibility of values during a test of repeated trials on the same individual (Hopkins, 2000). Reliability is the measure of the amount of total variance that is attributable to true differences occurring, and not those differences occurring due to measurement error (Bruton, Conway & Holgate, 2000). Reliability is critical in the field of sports medicine and research as minimal measurement error is essential during the collection of interval and ratio data (Atkinson & Nevill, 1998). Enhanced reliability implies enhanced precision of a single measurement, which will give researchers an increased ability to identify true changes in measurements (Hopkins, 2000).

Baumgarter (1989) identified two types of reliability, relative reliability and absolute reliability. Bruton et al. (2000) defines absolute reliability as, the degree to which repeated measures vary for individuals. Therefore the less the measurements vary without intervention, the higher the reliability of the testing procedure. Bruton et al. (2000) goes on to define relative reliability as, the degree to which individuals maintain their position in a sample over repeated measurements. This allows for more variance within the data set as long as positions of individuals remain the same.

Hopkins, Hawley and Burke, (1999) explain there are three important types of measure: within-subject variation, changes in the mean, and retest correlation. Within-subject variation refers to the variation in a measure when one individual is tested numerous times (Hopkins, 2000). A statistic that can be used to capture random variability of a single individuals values over repeated tests is the standard deviation (SD), within subject SD can also be referred to as the standard error of measurement (SEM) this represents typical error in a measurement (Hopkins, 2000). Typically for measurements in sports medicine, the typical error will get bigger as the value of the measure increases (Nevill & Atkinson, 1997). To overcome the potential problem of misinterpretation, Hopkins (2000) suggests using a coefficient of variation (CV), as typical error is expressed as a percentage. An alternative measure of within-subject variation is limits of agreement (LOA), which was originally devised by Bland and Altman (1986). This measure differs as it calculate ranges within which, an individual's difference scores would fall 95% of the time, thereby eliminating outlying data (Bland & Altman, 1986). Standard error of measurement, CV and LOA are all examples of measures of absolute reliability (Bruton et al. 2000).

Hopkins (2000) suggests the use of SEM over LOA for the following reasons; the values of the limits agreement depend on the sample size of the reliability study from which they are estimated. Hopkins (2000) states in statistical terms the limits are biased, however the bias will be less than < 5% when the degrees of freedom is greater than 25. This problem does not occur with the typical error, which has a value, totally independent of sample size (Hopkins, 2000; Hopkins, Marshall, Batterham & Hanin, 2009), which gives the researcher more choice when testing reliability. Additionally LOA can not be applied to situations where only one trial is necessary (Hopkins, 2000). Atkinson and Nevill (1998) however support the use of LOA where applicable, stating measures in typical error including CV and SEM represent approximately 68% of the error that is actually present in repeated measurements, this is because both methods assume heteroscedasticity.

The second type of measure as stated by Hopkins (2000) was change in the mean, which is the change in the mean value between two trials of a test. The change can consist of two components, random change and systematic change, also referred to as systematic bias (Hopkins, 2000). Random change is reduced with larger sample sizes, as the effect of random errors from each measurement is reduced when more measurements are added for calculation of the mean (Hopkins, 2000). Systematic change in the mean is a non-random change in the value between two trials that applies will apply to all study participants (Hopkins, 2000), an example of systematic change would be learning or training effect observed in all participants. Hopkins (2000) states that these systematic changes are less important for controlled studies as the magnitude of systematic change is likely to differ from subject to subject which increases the typical error. To reduce this effect subject habituation is suggested before all trials (Hopkins, 2000; Hopkins et al., 2009).

The third type of measure is retest correlation (Hopkins, 2000); this type of measure represents how closely the values of one trial track the values of another, from individual to individual. For example, if both individuals have identical values for each of the trials the coefficient has a value of 1. When random error in the measurements increases in the real measurement, the coefficient will decrease approaching zero (Hopkins, 2000). Both Hopkins et al. (1999) and Atkinson and Nevill, (1998) suggest the use of within subject error over the use of retest correlation, as its value is sensitive to the heterogeneity of the sample.

As stated by Safrit (1976) for a group of measurements, the total variance within the data is due to the true score variance and error variance. Theoretically a true score of an individual reflects the mean of an infinite number scores from a subject, whereas the error equals the difference between the true score and the observed score (Feldt & McKee, 1958). Error can arise to a number of sources, including, biological variability, instrumentation, error due to the tester and error due to the subject (Weir, 2005).

A reliability coefficient can be used to test this. The closer this ratio is to 1.0, the higher the reliability and the lower the error variance (Weir, 2005). As the true score for each subject is not known, an index of the total variance can be used based on the between subjects variability, which is defined by the following equation (Baumgartner, 1969; Feldt, 1958; Streiner & Norman, 1995).

$$\text{Reliability} = \frac{\text{Between subjects variability}}{\text{Between subjects variability + error}}$$

Weir (2005) suggests the reliability coefficient in this equation can be quantified by various intraclass coefficients (ICC), of which 10 were previously identified in McGraw and Wong, (1996). The ICC is a relative measure of reliability (Chinn & Burney, 1987), as it is derived from a ratio of variances from the output of an ANOVA and is unit less. Weir (2005) describes the ICC to be relative as the magnitude of an ICC depends on the between-subjects variability. Atkinson and Nevill (1998) state that it is clear that the concept of relative reliability is highly useful and recommend it should be used in conjunction with absolute measure when testing reliability.

There is no standard of acceptable level of reliability (Bruton et al., 2000), however Chinn (1991) recommends measures to have a minimum ICC 0.60. Rankin and Stokes (1998) claim an ICC is unsuitable to be used in isolation, in agreement with Atkinson and Nevill (1998) that ICC needs to be used with a combination of absolute measure of reliability. As if an ICC is used in isolation and the variance between subjects is sufficiently high then reliability will appear to be high as the individuals will remain in their original position in the data set (Rankin & Stokes, 1998). The ICC is unable to provide an index of the expected trial-to-trial noise in the data, whereas the SEM can provide practitioners an absolute index of reliability, as it is measuring typical error (Hopkins, 2000; Weir, 2005).

The SEM can be calculated as follows;

$$SEM = SD\sqrt{1 - ICC}$$

The SD within the equation is derived from the SD of the data from all subjects, determined from the output of the ANOVA and the ICC is the reliability coefficient (Weir, 2005). The outcome of the SEM however is dependent on the form of ICC used, which can substantively affect the size of the SEM (Weir, 2005), which is a clear limitation of calculating the SEM this way. However an alternative method can be used to calculate the SEM avoiding these uncertainties; it can be estimated using the square root of the mean square error term from the ANOVA (Eliaziw, Young, Woodbury and Fryday-Field, 1994 & Hopkins, 2000). This is advantageous as the different forms of ICC, which could be used will not influence the eventual SEM (Weir, 2005).

From the SEM the minimum differences needed to be considered real as outlined by Weir (2005), which constructs a 95% confidence interval for the score, can be calculated. The minimum difference can then be used in later analysis giving a minimum score of difference between repeated measurements needed for a difference to be considered real.

Validity of a variable used within research is dependent on its relevance and its reliability (Morrow, Jackson, Disch & Mood, 2005). O' Donohue and Fisher (2009) describes the relevance of a variable as 'the degree to which the variable represents an important concept being measured' (p. 150). O' Donohue and Fisher (2009) goes on to describe that a variable that is not measured reliably cannot be valid, whether the variable is relevant to measuring sports performance or not. Two types of validity have been classified, norm referenced validity and domain referenced validity (Morrow et al., 2005; Thomas, Nelson & Silverman, 2011).

Norm referenced validity is where a measured variable can be used to compare a subjects performance to the norm of the whole population of relevant subjects (Morrow et al., 2005; Thomas et al., 2011). Norm referenced validity can be split into four sub categories, logical validity, which refers to when the variable measured, is valid by definition (Morrow et al., 2005; Thomas et al., 2011). For example a 10 km running time or the release angle of a javelin as this will directly affect performance if not at an optimum angle (O' Donohue & Fisher, 2009). Content validity refers to the extent to which the variable or variables cover the components of the model of interest (Morrow et al., 2005; Thomas et al., 2011). For example when analysing a technique many biomechanical indicators contribute to the skill, all of the biomechanical indicators would have to be analysed together to be considered to have content validity (O' Donohue & Fisher, 2009). Criterion validity indicates when the variable is validated against a gold standard measurement, which has previously been accepted as being valid and reliable (Morrow et al., 2005; O' Donohue & Fisher, 2009; Thomas et al., 2011). Construct validity refers to measuring variables that are not directly observable (Morrow et al., 2005; Thomas et al., 2011), for example in areas of psychology such as confidence and anxiety (O' Donohue & Fisher, 2009).

It is clear that there is disagreement within the literature to what method is most appropriate in measuring reliability of sports medicine equipment and testing protocols, as currently no consensus has been agreed which tests should be employed universally. It is apparent that reliability of equipment or protocols is essential for validity. However, a theme in the literature seems to be that no one method should be used in isolation and a combination of ICC, CV, LOA, SEM and correlations should be used to test reliability. Therefore ICC should be adopted as a relative measure of reliability, and CV, LOA or SEM should be adopted as an absolute measure of reliability.

2.6 Conclusion

A crucial element of long game golf performance is the CHV, with force at impact is directionally proportional to the shot distance. It was demonstrated across a number of studies that LH golfers have increased CHV in comparison to HH golfers. It is however important that the increased CHV does not result in reduced accuracy. Two key styles of CP excursion were identified for the full golf swing, firstly, a front foot style, and secondly, a reverse foot style. Neither of these styles was found to be an advantageous to performance in comparison to the other.

Chapter Three

Centre of Pressure Excursion during the Full Golf Swing

3.1 Introduction to Chapter

This thesis was originally designed to attain masters by research, and chapters three and four reflect the original studies conducted. The thesis started with two main areas of focus, centre of pressure excursions during the full golf swing and putting stroke. This was in light of the literature review (Chapter Two), which identified limited amounts of published work in each area. Chapter Three presents the work completed analysing centre of pressure excursions for the full golf swing. It includes Study One (Section 3.2); Centre of pressure excursions during the full golf swing with a 4 iron, 8 iron and pitching wedge Pilot Study One is presented in Appendix A. To complete the protocol an extension board was built to extend the area of the force platform so a golfer could adopt an appropriate stance. The pilot study (Appendix A) assessed the day to day reliability of the effect of the extension board on the accuracy of the AMTI force platform.

3.2 Study One: Centre of pressure excursions during the full golf swing with a 4-iron, 8-iron and pitching wedge

3.2.1 Abstract

Background: A key element to effective long game performance is effective weight transfer during the golf swing, with increased club head velocity associated with increased CP excursion on the ML axis. **Aim:** To examine the effects of different golf clubs on CP excursions, ground reactions forces and club head velocity. **Method:** Three full shots were completed with each golf club (4-iron, 8-iron and pitching wedge) on an AMTI force platform sampling at 1000 Hz. A Sony Handycam synchronised with the AMTI force platform was used to segment the golf swing into four defined phases during later analysis. **Results:** Significant differences were observed in CP excursions along the ML axis during the downswing to impact phase between the 4-iron and 8-iron and between the 8-iron and pitching wedge. No significant differences were observed between the three clubs and the variation of CP excursion as represented by the 95% ellipse value. **Conclusion:** Stance width in regards to the position of the feet in relation to the shoulders may influence the amount of CP excursion along the ML axis. Although no significant differences were observed between the 95% ellipse scores of the three clubs, practically golfers should aim to reduce the variability of CP excursions along the ML axis, which may improve accuracy of the resultant golf shots.

3.2.2 Introduction

Coaching literature has identified a key element to performance is effective weight transfer during the golf swing (Leadbetter, 1995; Norman, 1995). Both state that weight transfer is important for gaining shot distance. Until recently this was not adequately supported by the scientific literature, however an association has been found to exist between a larger absolute range of CP excursion with an increase in CHV (Ball and Best, 2007b; Ball and Best, 2012).

Putting is clearly the most important aspect within golf to record the best possible score, with an average of 43% of shots in a round performed with a putter. However, it remains the area least taught and the least researched. More proficient golfers have been observed to demonstrate reduced CP excursions in comparison to less proficient golfers. However, without the pre identification of putting style has raised these observed results into doubt. Alternatively, these studies are valid if more proficient golfers do demonstrate less CP excursion than less proficient golfers raising the question as to whether the style of putter is important. The area of ball roll kinematics is under researched with a small amount of literature publishing work on the topspin and skid of the golf ball. Additionally, there is a lack of clarity as to whether grooved faced putters produce preferable ball roll characteristics.

The majority of CP excursion research for the full golf swing is produced using two force plates whereas, for golf putting generally on plantar measurement devices (such as the RS FootScan). There is disagreement within the literature as to what is the best method to assess reliability. However, there is agreement that a combination of relative and absolute measures is best appropriate.

The literature has found CHV to be an effective performance measure of long game golf play; CHV is strongly correlated with ball velocity. Fundamentally the increased ball velocity the increased distance the ball will travel (Chu et al., 2010; McNitt-Gray et al., 2013). Lower handicap golfers have been shown to demonstrate increased CHV in comparison to higher handicap golfers (Betzler et al., 2012, Bradshaw et al., 2009, Fradkin et al. 2004, Hocknell, 2002), which again supports its use as an effective performance measure with the more proficient golfer displaying the preferable characteristic. Ball and Best (2007b) account this increase in CHV to be a result of increased whole body momentum, increasing kinetic energy, which can be transferred to the club head and ball. In addition to these findings Okuda et al. (2010) found two key differences between skilled and low skilled golfers. Firstly, the skilled golfers had a faster weight transfer to the trail foot during the backswing, and secondly, earlier transfer accompanied this weight transferred to the trail foot back to the forefoot during the downswing motion. Mason, McGann and Herbert (1995) provide a theory as to why increased CP excursion is demonstrated by low handicap golfers in comparison to their high handicap counterparts, an unskilled player may possibly limit the CP excursion to maintain stability throughout the golf swing.

In addition to identifying an association between CHV and weight transfer Ball and Best (2007a) identified two weight transfer strategies ‘front foot’ and ‘reverse’ styles, it is stated that it is essential to identify the subjects weight transfer strategy before testing and analyse separately. In a more recent study (post data collection for the current study) by Ball and Best (2011), these two different swing strategies were apparent for not only the driver, but also the 3-iron and 7-iron, with 96% of the subject cohort using the same strategy for all three clubs. In another study conducted by Ball and Best (2012) golfers CP excursion was analysed for individual subjects as well as groups, due to the large degree of inter-subject variation observed. The results from this support the continued use of group based analysis for weight transfer studies, however, also state that if the rate of weight transfer from the rear to forefoot is being measured some form of individual based analysis should also be included.

The aim of this study was to examine the effects of different golf clubs (4-iron, 8-iron and pitching wedge) on CP excursion, GRF and its relationship with CHV. These three clubs were chosen and analysed as the 4-iron is commonly accepted as a long iron, 8-iron as a mid iron, and PW as a short iron. It was hypothesised that a significant positive relationship would exist between CP excursions and CHV for the 4-iron, 8-iron and PW. Additionally, a significant difference would exist in left, right, anterior and posterior CP excursion between the 4-iron, 8-iron and PW.

3.2.3 Methods

Subjects

Following institutional ethical approval, a total of 8 active golfers (age, 24.4 ± 7.3 years; mass, 74.25 ± 19.7 kg; height, 178.5 ± 8.4 cm; handicap, 18.8 ± 7.3) participated in the study. Subjects wore their own personal golfing attire and golf shoes. Signed informed consent was gained prior to testing. Subjects were required to be actively playing golf, at least once weekly and were free of musculoskeletal injury for a minimum of 6 months.

Experimental Set Up

A Sony HDR-XR155E Handycam, operating at 50 Hz was positioned in front of the subject (4 metres away from the adjacent edge of the AMTI force platform); this allowed the trial to be segmented into the four stages of the golf swing to allow for further swing analysis. The following equipment was used, Mizuno MX-17 4-iron, 8-iron and pitching wedge (PW) all fitted with regular steel shafts. A golf safety net was placed 2 metres away from the leading edge of the AMTI force platform to catch the golf airflow balls. Shots were completed using regular airflow balls placed on an artificial turf mat (20 x 30 cm). Subjects stood on a 0.4 metre AMTI force platform operating at

1000Hz with an extension board placed and secured to the platform. The Sony HDR Handycam and the AMTI force plate were time synchronised via an LED light activated when the trial started.

Protocol

A five-minute golf specific dynamic warm up, which focused on the back and upper extremity, was performed (Appendix B). Microsoft Excel was used to generate a randomised shot order for each subject. Three full shots were then completed with each golf club, on the AMTI force platform. A full shot was instructed as a shot where the club would be selected on the golf course whereby maximal effort was not needed to reach the intended target. Shots that were topped or the golfer decided was not a good shot was excluded from analysis. Between trials a one-minute rest period was implemented to allow for all equipment to be reset and the trial saved.

Data Processing

Centre of pressure excursions (mm) were calculated as the range of movement of the CP in four directions (anterior, posterior, left and right) which was then totaled for all given movement along an axis (anterioposterior (AP) and mediolateral (ML) axis). The magnitude and peak ML (Fx) GRF were computed and then correlated with left and right CP excursions, to determine the interaction between the two variables. In addition Peak Fz ground reaction forces were identified.

The golf swing was split into the four following phases for analysis:

1. Start to the top of backswing; the start of the golf swing is the first horizontal movement of the golf club and the phase ends at the top of the backswing before the first movement towards the golf ball.
2. Top of backswing to downswing; the first movement of the phase is the club head towards the ball and the phase ends when the club shaft is parallel with the floor.
3. Downswing to impact; from the parallel position of the club shaft to the first impact with the golf ball.
4. Impact to follow-through; from impact between the club head and ball through to the whole follow-through the phase ends when the club is held once the swing has finished.

Two Excel spreadsheets were developed to calculate the 95% ellipse area (95% confidence level that all CP excursion fell into) to identify any variance of the spread of data between the three clubs. This was required, as each trial would have a different length of time, so 15 seconds of raw data was recorded and then reduced to the length of the trial.

Data Analysis

Data were exported to statistical software package SPSS v19 (SPSS, Inc., Chicago, IL, USA) for analysis. Data were first tested for normality using a Shapiro-WIlk test ($p < 0.05$). All data was found to be normally distributed, following this a one-way between samples ANOVA was used to test for differences of CP excursions while using the 4-iron, 8-iron and PW in the following directions, anterior, posterior, left, right and total CP excursions along the ML and AP axis. A LSD post hoc test was used to determine between which group's differences lie. Pearson's correlation coefficient (Pearson's – *r*) was used to measure the strength of the relationship between horizontal ground reaction force and the direction of CP excursions. The boundaries set for the correlation statistics were suggested by Salkind (2011); $r = 0.8 – 1.0$, very strong, $r = 0.6 – 0.8$, strong, $r = 0.4 – 0.6$, moderate, $r = 0.2 – 0.4$, weak, $r = 0.0 – 0.2$, no relationship. The level of significance was set at $p < 0.05$.

3.2.4 Results

Phase 1: Start to Top of Backswing

Table 3.1 displays means for CP excursions in the lateral, medial, anterior and posterior directions. No significant differences were observed between the 4-iron, 8-iron and pitching wedge for lateral (F (2, 21) = 0.20, p = 0.82), medial F (2, 21) = 0.22, p = 0.80), anterior (F (2, 21) = 0.13, p = 0.88) and posterior excursions F (2, 21) = 0.27, p = 0.77) for the start to top of backswing phase. No significant differences were found between total CP excursions on the ML (F (2, 21) = 0.03, p = 0.97) (Figure 3.2) and AP axis (F (2, 21) = 0.20, p = 0.82) (Figure 3.3). As shown in the Pedotti diagrams in Figures 3.4, 3.5 and 3.6, a significantly high positive correlation was identified (Table 3.2) between lateral CP excursions and medial GRF (p = < 0.01).

Phase 2: Top of Backswing to Downswing

Means for CP excursions in the lateral, medial, anterior and posterior directions are presented in Table 3.1. No significant differences were observed during the top of backswing to downswing phase between the three clubs for lateral (F (2, 21) = 0.29, p = 0.75), medial (F (2, 21) = 1.06, p = 0.37), anterior (F (2, 21) = 0.39, p = 0.69) and posterior (F (2, 21) = 0.48, p = 0.63) excursions. No significant difference was observed for total CP excursions on the ML (F (2, 21) = 0.50, p = 0.62) (Figure 3.2) and AP axis (F (2, 21) = 1.24, p = 0.31) (Figure 3.3) between the three clubs. As shown in the Pedotti diagrams in Figures 3.4, 3.5 and 3.6 a significant high positive correlation (Table 3.2) was identified between lateral CP excursions and medial GRF (p = 0.01).

Phase 3: Downswing to Impact

Table 3.1 displays means for CP excursions in the lateral, medial, anterior and posterior directions. No significant differences were observed for the downswing to impact phase between the three clubs for lateral (F (2, 21) = 1.75, p = 0.20), medial (F (2, 21) = 0.93, p = 0.41), anterior (F (2, 21) = 0.03, p = 0.97) and posterior excursions (F (2, 21) = 1.58, p = 0.23). Significantly greater total CP excursions were observed along the ML axis (F (2, 21) = 3.73, p = 0.04) for the 8 iron in comparison to the 4 iron (p = 0.04) and the PW (p = 0.02) shown in Figure 3.2. No significant differences were observed along the AP axis between the three clubs (F (2, 21) = 1.17, p = 0.33) (Figure 3.3). As shown in the Pedotti diagrams in Figures 3.4, 3.5 and 3.6 a significantly high positive correlation (Table 3.2) was identified between medial CP excursions and lateral GRF ($p < 0.01$).

Table 3.1. Centre of pressure excursions for the Start to Top of Backswing phase, Top of Backswing to Downswing phase, Downswing to Impact phase and Impact to Follow-through phase (mean ± S.E).

		Lateral (towards target) (mm)	Medial (away from target) (mm)	Anterior (mm)	Posterior (mm)
Start - TBS	4-iron	7.75 ± 1.59	16.18 ± 2.59	6.36 ± 0.8	5.05 ± 0.76
	8-iron	8.80 ± 2.12	15.69 ± 1.47	7.02 ± 0.66	5.79 ± 0.57
	PW	7.20 ± 1.68	17.79 ± 2.77	6.61 ± 1.16	5.87 ± 1.17
TBS – DS	4-iron	9.71 ± 3.08	1.54 ± 0.44	2.92 ± 0.66	1.56 ± 0.33
	8-iron	12.26 ± 3.11	3.59 ±1.61	3.21 ± 0.35	2.09 ± 0.32
	PW	13.11 ± 3.68	1.92 ± 0.78	3.54 ± 0.43	1.91 ± 0.49
DS - Impact	4-iron	6.11 ± 1.39	0.26 ± 0.10	1.19 ± 0.45	0.90 ± 0.27
	8-iron	8.74 ± 1.83	2.20 ± 2.03	1.23 ± 0.45	1.52 ± 0.46
	PW	5.31 ± 0.53	0.22 ± 0.17	1.34 ± 0.36	0.74 ± 0.21
Impact - FT	4-iron	31.57 ± 15.62	28.67 ± 15.32	11.46 ± 5.49	12.09 ± 5.27
	8-iron	13.56 ± 1.49	9.00 ± 1.35	7.21 ± 2.10	6.64 ± 0.90
	PW	13.33 ± 1.48	7.81 ± 1.13	6.58 ± 0.78	10.17 ± 1.64

Table 3.2. Pearson's *r* correlation for the Start to Top of backswing phase, Top of Backswing to Downswing phase, Downswing to Impact phase and Impact to Follow-through phase.

		Mean GRF	Lateral GRF	Medial GRF
Start - TBS	Lateral CPE	.384	-.377	.614*
	Medial CPE	.201	.117	-.176
TBS – DS	Lateral CPE	.241	-.244	.517*
	Medial CPE	.383	.283	.265
DS - Impact	Lateral CPE	-.013	-.170	.112
	Medial CPE	.380	.520*	.175
Impact - FT	Lateral CPE	-.383	-.474*	.536*
	Medial CPE	.378	.440*	-.430*

*Highlighted cell denotes significant correlation ($p < 0.05$).

Phase 4: Impact to Follow-through

Means for CP excursions in the lateral, medial, anterior and posterior directions are displayed in Table 3.1. No significant differences were observed for the Impact to Follow-through stage between the three clubs for lateral (F (2, 21) = 1.32, p = 0.29), medial (F (2, 21) = 1.73, p = 0.20), anterior (F (2, 21) = 0.68, p = 0.52) and posterior (F (2, 21) = 0.74, p = 0.49) excursions. No significant differences for total CP excursions were found along the ML axis (F (2, 21) = 1.52, p = 0.24) (Figure 3.2) or AP axis (F (2, 21) = 0.61, p = 0.55) (Figure 3.3).

The Pedotti diagrams Figures 3.4, 3.5 and 3.6 show that lateral CP excursions was found to have a significant positive correlation with medial GRF ($p < 0.01$) and a moderate negative correlation with lateral GRF ($p = 0.02$). Table 3.2 shows that medial CP excursions were identified to have a significant moderate correlation with lateral GRF ($p = 0.03$) and a moderate negative correlation with medial GRF ($p = 0.03$). Peak Fz vertical forces were also found to occur during this phase for the three clubs (4 iron = 826.74 N, 8 iron = 987.54 N, PW = 1025.70).

95% Ellipse Scores

No significant differences were identified between groups (F (2, 21) = 0.76, p = 0.48) for the 95% ellipse observed between the 4 iron and 8 iron (p = 0.29), 4 iron and PW (p = 0.30) and the 8 iron and PW (p = 0.99).

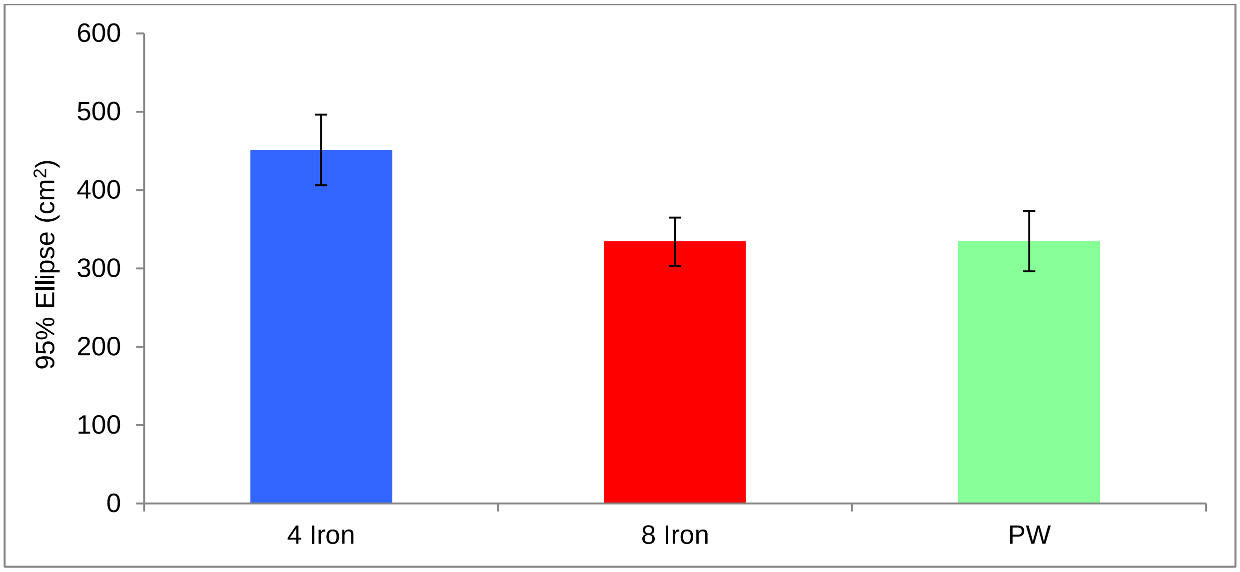

Figure 3.1. 95% Ellipse scores demonstrating the variation for the three clubs used ($cm^2 \pm$ SE).

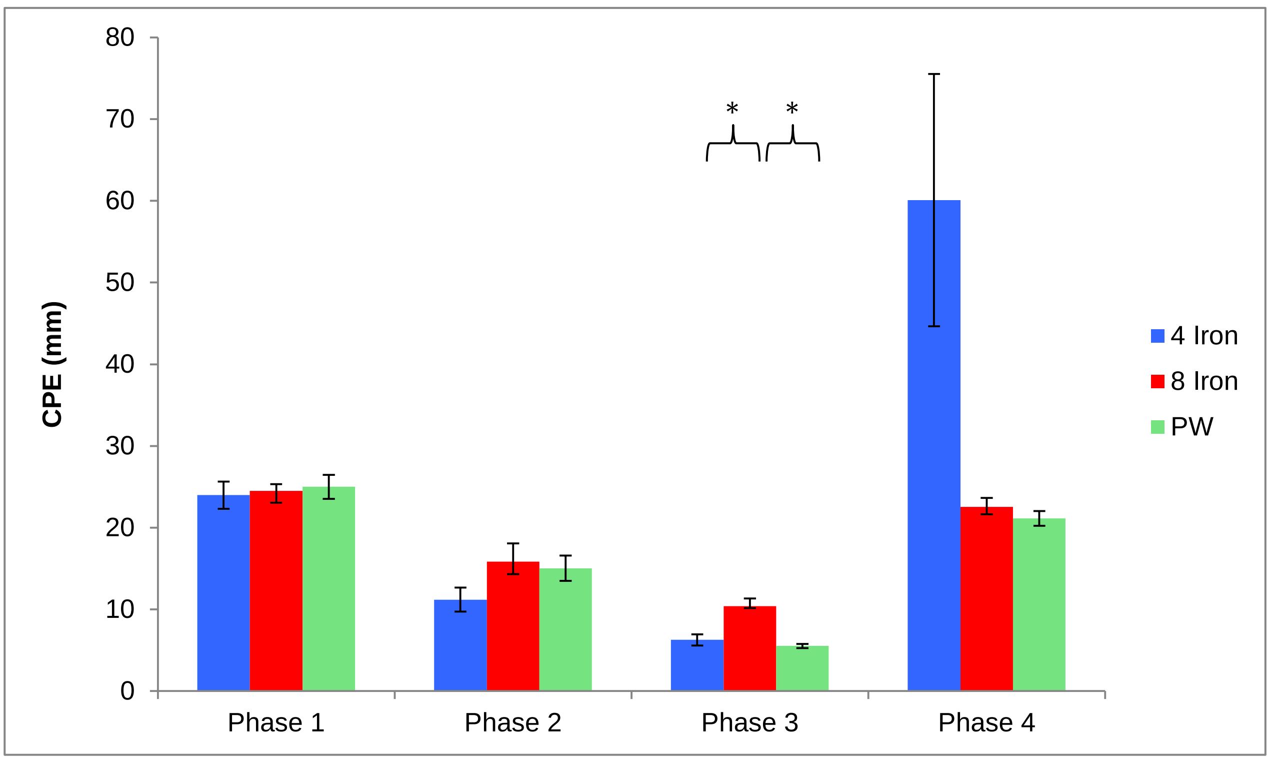

Figure 3.2. Total centre of pressure excursions along the mediolateral axis (mm $\pm$ S.E) for all four phases of the golf swing (*Significant difference, $p < 0.05$).

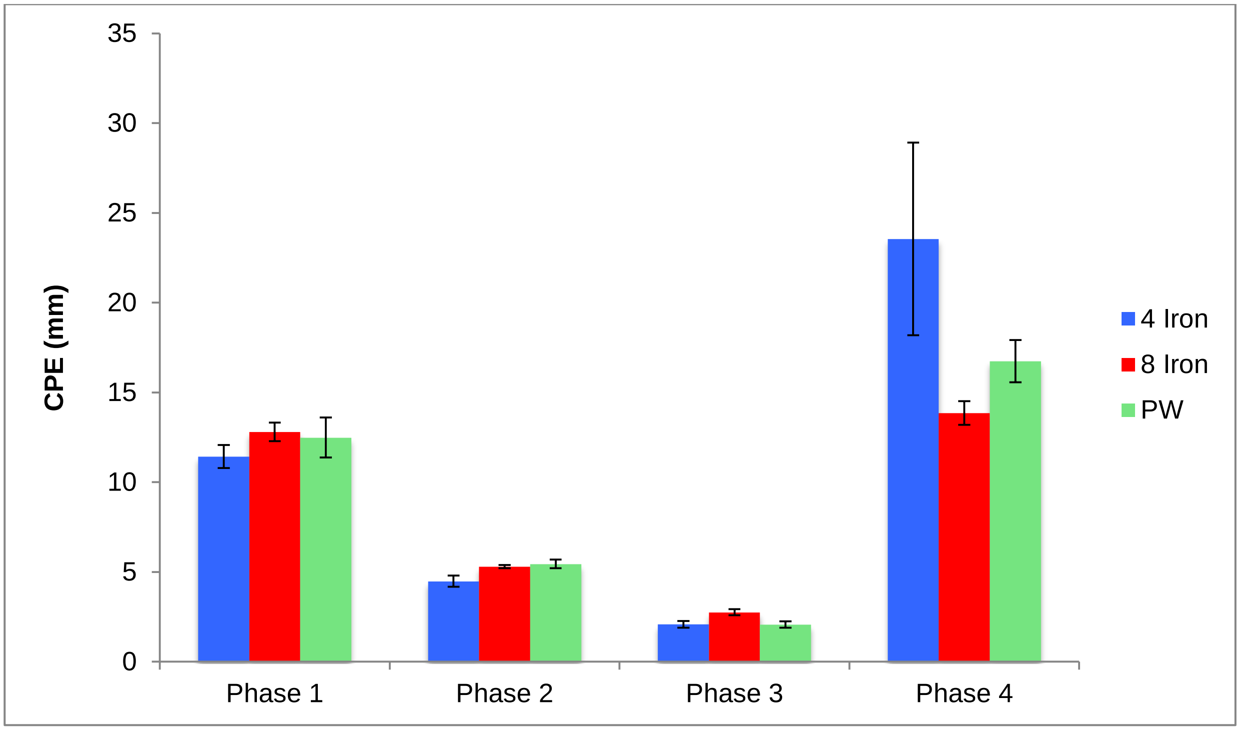

Figure 3.3. Total centre of pressure excursions along the anteroposterior axis (mm ± S.E) for all four phases of the golf swing.

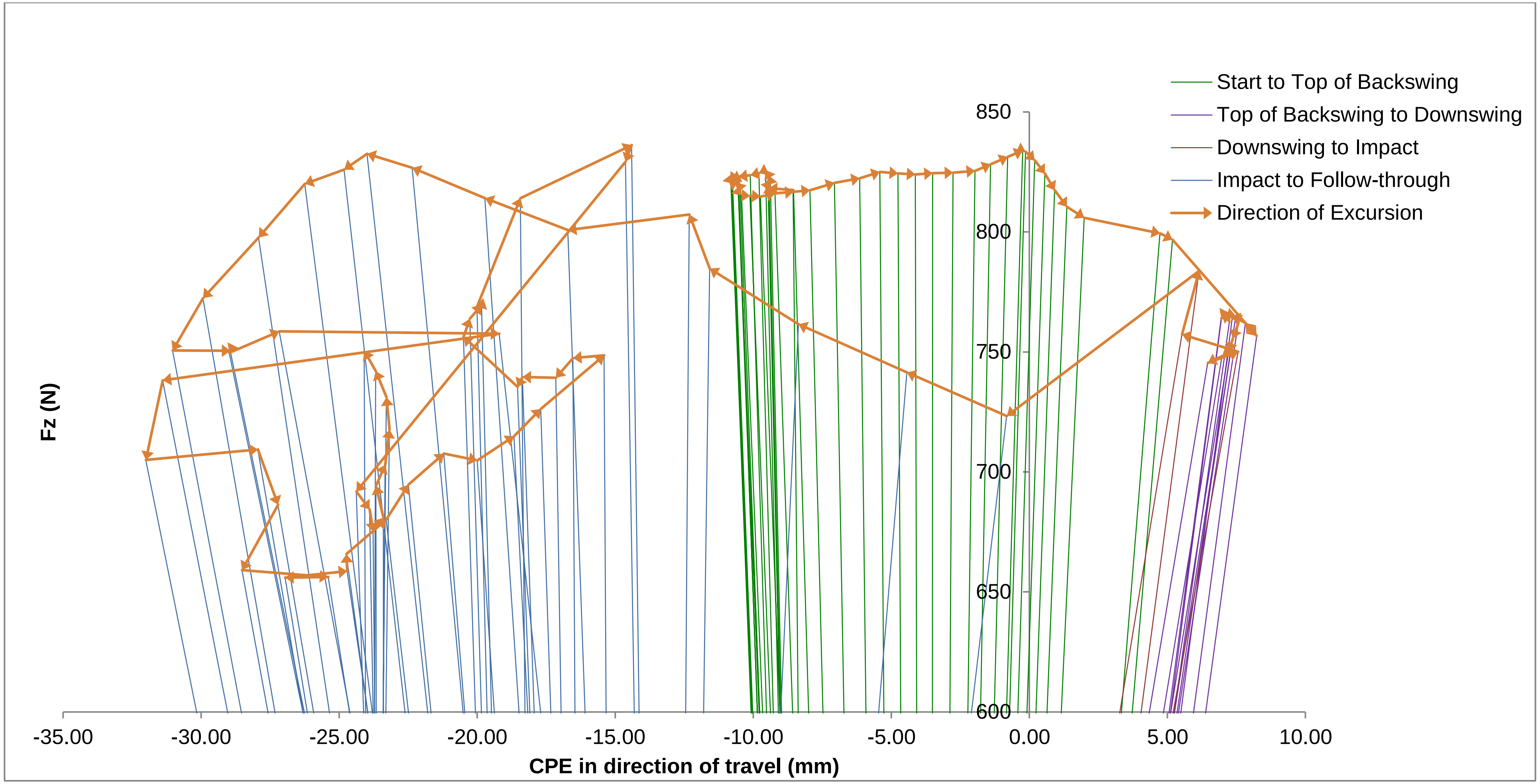

Figure 3.4. Centre of pressure excursions for the 4 iron along the mediolateral axis (mm), Fz, and Fx (N) forces for all four phases of the golf swing.

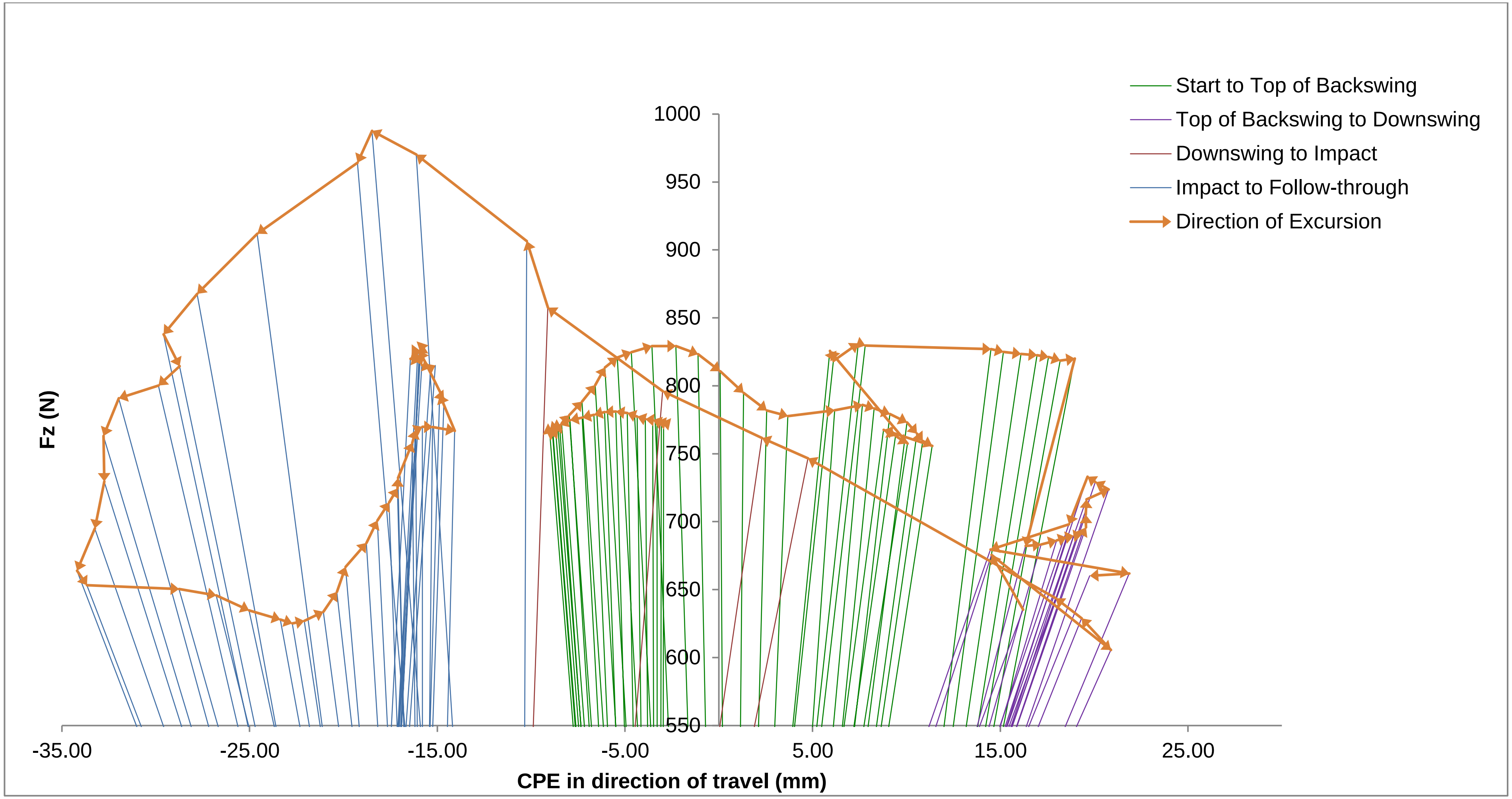

Figure 3.5. Centre of pressure excursions for the 8 iron along the mediolateral axis (mm), Fz, and Fx (N) forces for all four phases of the golf swing.

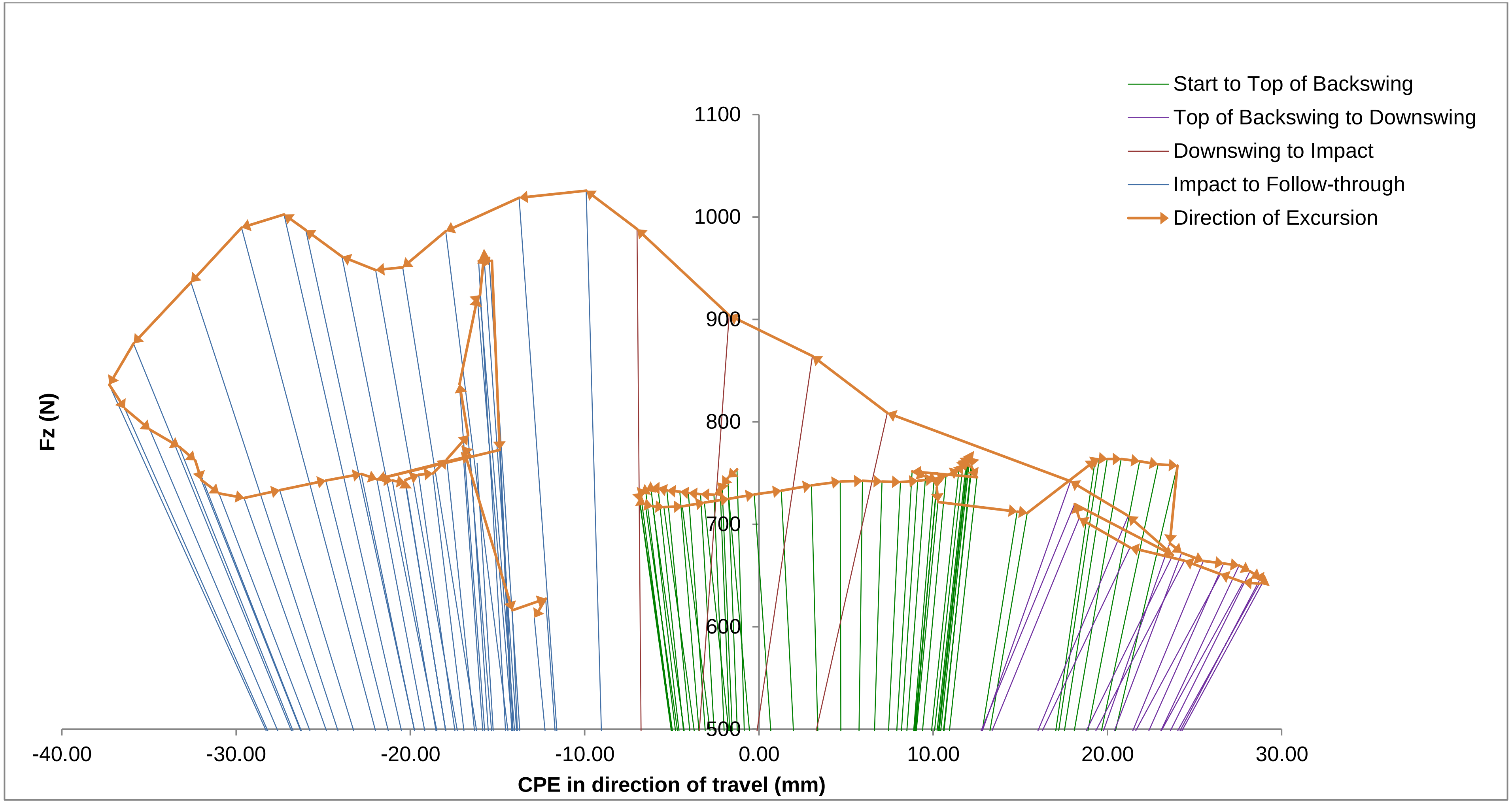

Figure 3.6. Centre of pressure excursions for the pitching wedge along the mediolateral axis (mm), Fz, and Fx (N) forces for all four phases of the golf swing.

3.2.5 Discussion

The aim of this study was to examine CP excursions along the ML and AP axis and identify CP excursions relationship with GRF with three different clubs (4 iron, 8 iron and PW). It was hypothesised that a significant positive relationship would exist between total CPE and GRF, this hypothesis can be partially accepted as some moderate positive correlations were observed between CPE and GRF (Table 3.2). The reason why stronger relationships may have not been observed is that the data were collected on a solitary force platform, rather than a dedicated platform beneath each foot. Secondly, it was hypothesised that significant differences between clubs would exist for CP excursions in all directions and total CP along the ML and AP axis. This hypothesis can predominantly be rejected, as no significant differences were observed for CP excursions in the anterior, posterior, medial of lateral direction and total CP excursions along the AP axis. The only significant difference identified was along the ML axis between the 8 iron and 4 iron, and the 8 iron and PW (Figure 3.2). Lastly it was hypothesised that increased variance would exist between the 4 iron, 8 iron and PW as displayed by the 95% ellipse. Although greater 95% ellipse was observed for the 4 iron this was not found to be significantly different (Figure 3.1) therefore this hypothesis can be rejected.

Significant differences in CP excursions along the ML axis were found in the downswing to impact phase between the 4 and 8-iron ($p = 0.04$) and between the 8-iron and PW ($p = 0.02$) (Figure 3.2) no other significant differences were found for any of the three golf clubs for the other phases of the golf swing. Additionally a significant positive relationship was identified between lateral CP excursions and medial GRF during the start to top of backswing phase ($r = .614$) however during this phase more medial CP excursions was observed compared to lateral CP excursions (Table 3.2), Additionally, significant positive relationships were identified between lateral CP excursions and medial GRF for the top of backswing to downswing phase ($r = .517$) and in the impact to follow-through phase ($r = .536$). No significant differences were observed in the variance observed (95% ellipse) between the 4 iron, 8 iron and PW.

No relationship was identified between lateral CP excursions and medial GRF for the downswing to impact phase, this may be due to the fact the average time of the phase was 0.08 seconds. During this phase CP excursions is occurring at its fastest rate, and due to this fact there will be reduced control of movement and therefore more potential for larger variation between subjects. Ball and Best (2011) also observed CP excursions to occur at its fastest rate during this phase (approximately 5% towards the front foot) in what would be similarly short period of time. Results from Ball and Best (2011) show that the majority of CP excursions along the ML axis to occur from the top of backswing to early downswing phase. Ground reaction forces were not reported by Ball and Best (2011).

Ball and Best (2011) compared a driver, 3-iron and 7-iron and reported golfers to adopt the same 'style' for all clubs accounting for 96% of participants, the findings of this study support this statement. The results of the current study demonstrate similar patterns of CP excursions for all three clubs tested (Figures 3.4, 3.5 & 3.6). All subjects demonstrated the CP excursion strategy resembling a front foot style, which Leadbetter (1995) described as, firstly, weight is distributed evenly between the lead and back foot at address, during the backswing weight is shifted towards the backfoot (identified as positive CP excursions in Figures 3.4, 3.5 & 3.6). Following this, before the start of the downswing, CP excursion travel will start to move towards the front foot, on Figures 3.4, 3.5 and 3.6 the Pedotti diagrams aesthetically look complicated due to different directions of excursion (bunching the visual resemblance (purple lines) of the magnitude of GRF); this is likely due to the different subjects switching their direction of CP excursion at different times. This weight transfer will start to become more rapid in the early downswing phase and continue to shift towards the front foot through impact and follow-through. This is resembled on the Pedotti diagrams where the lines showing the magnitude and direction of the GRF become more spacious (Figures 3.4, 3.5 & 3.6). Ball and Best (2011) presented results of the position of the CP between the lead and rear foot and did not present raw or total CP excursion figures and therefore direct comparisons to this study cannot be made.

It was hypothesised that more CP excursions would be observed along the ML axis for the 4-iron and the least CP excursions observed in the PW, this was due to the increased stance width. However, the results demonstrate significantly more CP excursions along the ML axis with the 8-iron (10.41 mm) during the Downswing to Impact phase in comparison to the 4-iron (6.27 mm) and PW (5.53 mm). A potential reason for these observed results could be due to the positioning of the feet in comparison to the shoulders for each of the three clubs. The 4-iron for the large majority of golf players will have the widest base of support with the lead foot placed outside of the lead shoulder, the stance for the 8-iron the lead foot will be more aligned with the lead shoulder, and the stance for the PW may be narrower still (Leadbetter, 1995). Ball and Best (2007b) found stance width to be moderately correlated with CHV ($r = 0.47$, $p = 0.005$), the current study did not measure stance width so comparisons cannot be made.

The foot position relative to the shoulders may influence which phase of the swing the majority of CP excursion occurs. Total CP excursions along the ML axis for the 4-iron was 101.54 mm, in comparison to the 8-iron (73.31 mm) and PW (66.70 mm). Along the ML axis 59.2% of CP excursions for the 4-iron occurred during the Impact to Follow-through phase, in comparison to 30.8% for the 8-iron and 31.7% for the PW. During the Downswing to Impact phase, 6.2% of CP excursions along the ML axis for the 4-iron, in comparison to 14.2% for the 8-iron and 8.3% for the PW.

Ball and Best (2007b) suggested a larger range of CP excursions were associated with a larger CHV at ball contact. Koenig, Tamres and Mann (1994) also reported LH golfers produced an increased CP excursions in comparison to HH golfers leading to an increased CHV. Ball and Best (2011) however, found no significant differences between different clubs tested (driver, 3-iron, 7-iron). This is a contentious topic within the literature, and it would have been beneficial for the current study to include accurate velocity readings. Based on angular velocity relationship with the radius from the rotational centre (Hall, 2011) it is reasonable to assume that any larger club head velocities would occur for the longer clubs (4-iron in the current study) as observed in Ball and Best (2007b) and Koenig et al. (1994). This therefore may be associated with larger variance in the CP excursions as highlighted in the 95% ellipse values (Figure 3.1), although not significant the 4-iron demonstrated a larger area. These differences in CHV may not have been statistically significant in Ball and Best (2011) due to the Bonferroni adjustments employed with a large number of variables being compared.

An increase in vertical GRF was found to occur for all three clubs during the acceleration to impact phase. This may relate to the centre of gravity of the combined golfer and club system moving down, due to the motion of the club. However, this is in contrast to Chu et al. (2010) who found a decrease during this phase from 140.3% of bodyweight to 110.2% of bodyweight at impact. The decrease in vertical GRF was found to happen later in this study during the impact to follow-through stage, 0.018 seconds after impact for the 4 iron with a decrease of 7.7% in vertical GRF forces in comparison to the peak, the 8 iron was 0.072 seconds after impact with a reduction of 2.4%, and the PW decreased 3.2% 0.054 seconds after impact. A potential reason for the smaller percentage decreases is because data from Chu et al. (2010) were taken from a larger time period during the swing, whereas in the current study the reduction was calculated from the first data point a decrease was observed (0.018 second gap). Chu et al. (2010) accredit this decrease in vertical GRF forces due to a suggested upward pull of the swing path near impact. Even though this vertical GRF occurred later during the golf swing, the current study supports this statement, as the upward pull of the golf swing continues during the follow through. The decrease in GRF at the end of the swing for all three clubs also suggests this.

McNitt-Gray et al. (2013) identified the reaction forces generated at the foot-surface interface, analysing the rear and forefoot separately. However, overall peak vertical GRF occurred at the end of top of backswing phase to downswing phase, where the majority of the vertical GRF moves from the rear foot to the front foot. Observing the Pedotti diagrams (Figures 3.4, 3.5 & 3.6) the peak vertical GRF occurs later in the golf swing during the early point of the follow-through.

Differing results between Chu et al. (2010), McNitt-Gray et al. (2013) and Ball and Best (2011) and the current study may be due to the differences in data collection, the current study had one force plate available, whereas Chu et al. (2010) used two, with one placed beneath each foot. The results from the current study provides biomechanical support along with Chu et al. (2010) for the practical application of the golf specific training programme developed by Lephart et al. (2007) as the rapid CP excursions and transfer of weight on to the leading foot requires highly activated and refined contractions of the hip adductor muscles (Bechler et al., 1995).

The 95% ellipse scores (Figure 3.1) of the three clubs demonstrate the potential practical implications of the current study. Although, found not to be statistically significant (likely due to the low subject cohort and moderate inter-subject variation) the 4-iron demonstrated larger 95% ellipse in comparison to the 8-iron and pitching wedge. According to PGA Tour statistics 2011, the GIR percentage for shots of 200+ yards for the top 10 players was 56.83%, and would be performed with longer irons such as a 4-iron. From 150-175 this percentage increases to 71.42% for the top 10 payers (PGA, 2011). This leads to the suggestion that less variability of the CP excursion (as observed for the 8-iron and pitching wedge) could lead to more accurate shots. These figures would be less for an amateur cohort and therefore should aim to produce shots with the 4-iron with the aim to reduce variability from shot to shot, which may help to increase accuracy.

3.2.6 Conclusion

Significant differences were identified for CP excursions along the ML axis in the downswing to impact phase between the 4 and 8 iron ($p = 0.04$) and between the 8 iron and PW ($p = 0.02$), no other significant differences were found for the AP about ML axis between the three golf clubs for any of the phases of the golf swing. It is difficult to draw a decisive conclusion with the results from this study, however stance width may influence the amount of CP excursins along the ML axis and during which phase the majority of CP excursions occurs. In addition to this practically golfers should aim to reduce the variability of CP excursions when using long irons, which may help, increase accuracy. The same style of swing and CP patterns (front foot style) were observed for each of the three clubs.

Chapter Four

Centre of pressure excursion during the golf putting stroke

4.1 Introduction to Chapter

This was the second part of the first phase of study (along with the long game research presented in Chapter Three). The area focused on within Chapter Four focuses on centre of pressure excursions and weight distribution during the putting stroke with low handicap, mid handicap and high handicap golfers. As identified within the literature review there is a limited amount of work published about the centre of pressure excursions during the putting stroke, especially in high handicap golfers. Chapter Four presents pilot study two (Section 4.2) assessing the reliability of the RS FootScan in comparison to an AMTI force platform, and Study Two (Section 4.3); Centre of pressure excursion during the golf putting stroke in low, mid and high handicap golfers. The Development of Research section (Section 4.4) concludes Chapter Three and Chapter Four as a whole and outlines the next study to be completed within the thesis.

4.2 Pilot Study Two: Reliability of the RS FootScan

4.2.1 Abstract

Background: The reliability of the RS FootScan needed to be assessed, hard based force platforms are considered to be more powerful and therefore the RS FootScan can be tested using and AMTI force platform. **Aim:** To assess the relative and absolute reliability of an RS FootScan. **Method:** One subject completed 15 trials mimicking a putting stroke whilst standing on an RS FootScan securely placed on top of an AMTI force platform. The AMTI force platform, RS FootScan and LED light were synchronised using an external trigger. A Sony Handycam was used to record the LED light activation and start and finish of the putting stroke. The following CP excursion parameters were assessed total ML and AP excursions, average CP excursion velocity and peak CP excursion velocity. Reliability was assessed using and ICC, SEM and change in mean. **Results:** Excellent reliability was observed for all CP excursion parameters (ICC = 0.99 – 1.00, SEM = 0.08 – 0.67, change in mean = -0.46 – 0.16). **Conclusion:** The RS FootScan demonstrated excellent reliability and previous published work having used PMDs, the RS FootScan is appropriate to use to assess CP excursion parameters.

4.2.2 Introduction

The RS FootScan (RS Scan INTERNATIONAL., Olen, Belgium) reliability needed to be assessed. It is widely regarded within the literature that hard based force platforms are more powerful for research (Giacomozzi, 2010a). To collect data for CP excursions the use of the AMTI force platform (hard based) could not be used due to not being able to place the platform securely on an artificial golf green. Therefore the use of a RS FootScan was decided as the most appropriate equipment to collect the data. The aim of this pilot study was to assess the reliability of RS FootScan measurements of total CP excursion movements and the velocity associated with the CP excursions.

4.2.3 Methods

Protocol

A RS FootScan (50 x 32 cm) was securely placed on top of an AMTI force platform (40 x 32 cm) with double sided tape between the surfaces. The RS FootScan was sampling at 100 Hz allowing for a 10 second period of recording, the AMTI force platform was sampling at 1000 Hz. One golfer with a narrow stance that fit on both the RS FootScan and AMTI force platform was selected to take part in the pilot study. The RS Scan and AMTI force platform and LED light were synchronised using an external digital trigger activating the recording of both pieces of the software at the same time. A Sony HDR-XR155E Handycam was additionally placed 90° to the path of the golf ball to record the activation of the LED light once the RS FootScan and AMTI force platform were activated. This allowed for the start (first instance of putter head movement) and end (furthest horizontal point of the putter head) of the putting stroke to be identified on both the RS FootScan and AMTI force platform. Fifteen trials were completed, whereby; the subject stepped on top both the RS FootScan and AMTI force platform, mimicked the movement of a golf putt. Between each trial the subject stepped off the RS FootScan and AMTI force platform, allowing for the trial to be saved and both the software on the RS FootScan and AMTI force platform to be reset.

Data Analysis

Four variables were selected to analyse the reliability, total ML CP excursion (mm), total AP CP excursions (mm), average velocity of the CP excursion (ms^{-1}) and peak velocity of the CP excursion (ms^{-1}). To directly compare the from the RS FootScan and AMTI force platform, for the average and peak velocity every tenth data point was used for the AMTI force platform to reduce the sampling rate from 1000 Hz to 100 Hz.

Data were exported to statistical software package Microsoft Excel 2011. The reliability between the RS FootScan and AMTI force platform for CP measurements and Fz forces was assessed using the following reliability measures:

- The SEM calculated using the formula $SEM = SD\sqrt{1-ICC}$.
- The change in mean between the RS FootScan and AMTI force platform.
- A two – way mixed ICC, calculated using the formula $\frac{1-SD\text{^}2}{SD\text{^}2}$.

The intraclass coefficient statistic boundaries were; r = 0.8 – 1.0, very strong, r = 0.6 – 0.8, strong, r = 0.4 – 0.6, moderate, r = 0.2 – 0.4, weak, r = 0.0 – 0.2, no relationship (Salkind, 2011).

4.2.4 Results

Reliability statistics between the RS FootScan and AMTI force platform are presented in Table 4.1. Very strong absolute was demonstrated across all four variables assessed (ICC = 0.99 – 1.00). In addition to this very strong absolute reliability was demonstrated across the four variables demonstrated by low SEM values and low change in mean values between the RS FootScan and AMTI force platform. Greater total ML CP excursions change in mean (-0.46) were observed in comparison to total AP CP excursions (-0.12).

Table 4.1. Mean ± SD and reliability statistics between the RS FootScan and AMTI force platform.

	Mediolateral CP excursions (mm)		Anterioposterior CP excursions (mm)		Average Velocity of CP excursions (ms^{-1})		Peak Velocity of CP excursions (ms^{-1})	
	FS	FP	FS	FP	FS	FP	FS	FP
Mean ± SD	24.83 ± 7.52	24.37 ± 7.65	22.13 ± 5.31	22.01 ± 4.89	-3.43 ± 3.40	-3.42 ± 3.40	36.32 ± 10.97	36.48 ± 10.75
ICC	0.99		0.99		1.00		1.00	
SEM	0.67		0.50		0.08		0.51	
Δ Mean	-0.46		-0.12		-0.01		0.16	

4.2.5 Discussion

In comparison to the AMTI force platform (which was found to be reliable in Pilot Study One) the RS FootScan demonstrated excellent reliability. Consistently very strong ICCs were demonstrated for total ML CP excursions (0.99), total AP excursions (0.99), average CP velocity (1.00) and peak CP velocity (1.00) (Table 4.1). These excellent ICCs were demonstrated as the data collected minimal differences were observed between the RS FootScan and AMTI force platform (as demonstrated by the change in mean) and larger differences between the trials themselves. As McDowell (2006) stated, the ICC ranks the data while measuring the similarity between the scores. The only possible anomaly observed was a larger change in mean observed for total ML CP excursions (-0.46 mm) in comparison to the total AP CP excursions (-0.12 mm). This possibly could be due to the RS FootScan being slightly wider (50 cm) in comparison to the AMTI force platform (40 cm) despite the subject having a narrow stance for certain trials the outside of the foot may have slightly overhung the AMTI force platform, and this may have made the change in mean slightly greater for the total ML CP excursions in comparison to the total AP CP excursions. Despite this the total ML CP excursions still demonstrated excellent reliability.

4.2.6 Conclusion

Excellent reliability was observed for all reliability measures (ICC, SEM, change in mean) between the RS FootScan and AMTI force platform. In addition to this previous studies have published work using PMDs such as the RS FootScan (Hurrion & Hurrion, 2008; McLaughlin et al. (2008). With both of these facts considered, the RS FootScan can be considered reliable to assess CP excursion parameters including the magnitude of CP excursions (mm) and the velocity associated with CP excursions (ms^{-1}).

4.3 Study Two: Centre of pressure excursion during the golf putting stroke in low, mid and high handicap golfers.

4.3.1 Abstract

Background: Golf handicap is significantly correlated to putting performance with low handicap golfers (LH) demonstrating increased putting accuracy compared to high handicap golfers (HH). Smaller CP excursions (during putting has been demonstrated by LH golfers, suggesting balance is important during successful putts. **Aim:** To examine CP excursions in low, mid and high handicap golfers along the mediolateral axis (ML) and anterioposterior axis (AP). **Method:** Nineteen subjects participated in the study; subjects were split into LH, mid handicap and HH groups. Subjects completed five successful 2.5m putts, standing on an RS FootScan. **Results:** The LH group demonstrated significantly smaller CP excursions in comparison to the HH group along the AP axis, for all three phases of the putt. No significant differences were found between the groups along the ML axis. **Conclusion:** The reduction of CP excursions along the AP axis suggests increased balance in that direction, which may contribute to increased accuracy. Coaches should place emphasis on reducing CP excursions along the AP axis, consequently increasing balance during the putting stroke.

4.3.2 Introduction

The putting stroke is one of several different types of golf shot including driving, iron shots, pitch shots and chips around the green. Pelz (2000) states that putting accounts for 43% of shots made, highlighting the importance of this aspect of the game.

A number of studies have examined the correlation between putting and overall performance (Dorsel & Rotunda, 2001; Quinn, 2006; Wiseman & Chatterjee, 2006). Wiseman and Chatterjee (2006) reported a strong correlation (r = 0.68) between putting performance and scoring average in professional players competing on the PGA tour over a fourteen-year period from 1990 to 2004. Quinn (2006) found putts per green in regulation showed a stronger correlation to scoring average than total putts per round (r = 0.31 vs r = 0.63) based on the top 196 players on the PGA Tour 2004. However, as Hurrion and Hurrion (2008) state, the putting stroke still remains the area of the game least taught.

MacKenzie and Sprigings (2005) state that a number of elements are needed to hit a successful putt, firstly the golfer must correctly read the green to determine the optimal speed, and decide on the correct target line based on the optimal speed with which to project the ball. During execution of the putting stroke, at impact, the putter head should only have horizontal velocity in the direction of the target line; the plane of the putter face then will be perpendicular to that line (MacKenzie & Sprignings, 2005). Putting in golf is therefore an impact movement where force is applied via a putter to a stationary ball. If the force applied to the stationary ball is of the correct magnitude and in the appropriate direction, then the ball will hit or remain close to the target (Schmidt, Zelaznik, Hawkins, Frank and Quinn, 1979; Sim & Kim, 2010). In putting, the time of impact is extremely short, therefore the velocity of the putter at impact is extremely important in achieving accuracy in regards to distance and not direction (Sim & Kim, 2010).

Previous research has shown expert players to demonstrate a slower putter head velocity at impact compared to novice golfers (Delay, Nougier, Orliaguet and Coello, 1997; Sim & Kim, 2010). It is suggested that expert players hit the ball in a fashion where more kinetic energy is transferred from putter to the ball at impact whereas more energy is lost at impact in novice players (Delay et al., 1997), this is likely due to expert players reducing the number of miss-hits. A potential contributing factor of this is discussed by Delphinus and Sayers (2012), whereby in more proficient golfers the centre of mass predominantly moves through the frontal plane along the mediolateral (ML) axis flattening the swing arc increasing the effective impact area and accuracy.

Along with impact velocity, studies have shown CP excursions to influence putting accuracy (Hurrion and Hurrion, 2008; McLaughlinet al., 2008). The centre of pressure (CP) refers to the point where the total of the pressure fields acts, if concentrated in one point (Ruhe, Fejer & Walker, 2011). Hurrion and Hurrion (2008) examined total CP excursions with no regards to whether this was along the ML or anteroposterior (AP) axis in 30 professional European Tour golfers and 30 low handicap golfers (+3 to 9 handicap) using a RS FootScan® pressure mat sampling at 125 Hz. Professionals demonstrated significantly less total CP excursions of 64.34 ± 6 mm compared to 83.10 ± 6 mm for amateurs for a flat 7.62 m putt with a stimpmeter rating of 12. The professional group demonstrated significantly less CP excursions during the start to top of backswing phase (12.24 ± 2 mm) compared to the amateur group (17.61 ± 3 mm). This was also apparent in the impact to follow-through phase with the professional demonstrating a CP excursions of 41.97 ± 5 mm compared to the amateur group with 53.26 ± 5 mm. No significant differences were observed in CP excursions between the two groups for the top of backswing to impact phase. Additionally, Hurrion and Hurrion (2008) found the professional group to have a weight distribution of 50% left and 50% right split during set up in contrast to the amateur group who demonstrated a 40% left and 60% right split.

McLaughlin, Best and Carlson (2008) found a similar trend regarding CP excursions using a pliance® pressure mat sampling at 38.5 Hz. A total of 38 golfers completed a 4 m putt, split into three groups (low, n = 10, handicap 0 – 9; middle, n = 14, handicap 10 – 18; high n = 13, handicap 18 – 27). Results showed that low handicap (LH) golfers demonstrated significantly less CP excursions along the ML axis during the start to top of backswing phase (4.6 ± 2.9 mm) in comparison to a high handicap (HH) group (7.7 ± 6.2 mm). Similarly the HH group demonstrated significantly greater CP excursions (10.7 ± 9.0 mm) along the ML axis during the top of backswing to impact phase in comparison to the LH group (4.5 ± 4.2 mm). No significant differences were found between the groups for the impact to follow-through phase. McLaughlin et al. (2008) suggest that low handicap golfers are more able to control CP excursions in the ML axis when putting compared to the mid handicap group (MH) and HH group.

These findings from Hurrion and Hurrion (2008) and McLaughlin et al., (2008) suggest that golfers with lower handicaps demonstrate reduced CP excursions throughout the putting stroke which suggests increased CP excursions is associated with less accurate putting. Additionally reduced CP excursions may result in a more consistent impact point between the putter and ball. The consistent impact point between the putter face and ball may result in less energy loss at impact for LH golfers, allowing more proficient golfers to have a lower putter head velocity at impact, as found by Delay et al. (1997) and Sim & Kim (2010). However at present no studies have reported CP excursions along the AP axis, or have isolated CP excursions for the left and right foot. Also, previous studies have not reported CP excursions on putts of a short to medium length.

Therefore, the aim of this study was to examine CP excursions along the ML axis and AP axis in low, mid and high handicap golfers during a 2.5 metre flat putt and whether this affects weight distribution during 4 swing events (start, top of backswing, impact and follow through) during the putting stroke. Weight distribution is defined as the proportion of total body weight that is supported by each foot and specific areas of each foot. , whereby which segment of each foot the subject is supporting their mass through. It was hypothesised that golfers with a lower handicap would demonstrate smaller CP excursions along the ML and AP axis than golfers that have a higher handicap. The reduction of CP excursions would suggest reduced movement of the golfers centre of gravity, showing that they are therefore more static during putting. This will increase balance during the golf putt, which is defined as the ability of an individual to control equilibrium.

4.3.3 Methods

Participants

Following institutional ethical approval, a total of 19 active golfers participated in the study [LH (n = 7), age 33.9 ± 15.2, height 1.77 ± 0.04 m, mass 84.6 ± 19.0 kg, handicap 5.4 ± 2.9; MH (n = 5), age 30.0 ± 15.0, height 1.77 ± 0.1 m, mass 79.1 ± 18.1 kg, handicap 16.6 ± 0.6; HH (n = 7), age 20.1 ± 1.8, height 1.81 ± 0.07 m, mass 70.9 ± 6.9 kg, handicap 25.9 ± 2.5]. All golfers were right handed and played golf a minimum of once a week. Subjects wore their own personal golfing attire and golf shoes. Signed informed consent was gained prior to testing.

Experimental set – up

A Huxley Golf (Huxley Golf, Hampshire, UK) artificial putting green was used (3.66 x 4.27 m) with a stimpmeter rating of 11. A level 2.5 m putt was set up with a regulation hole (diameter 108 mm). Each participant was asked to use their own personal putter due to the large variance of putters available on the current market, and all participants used Srixon Z-STAR golf balls (Srixon Sports Europe Ltd., Hampshire, UK). A 50 x 32cm RS Scan FootScan pressure plate with a total 4096 sensors, sampling at 100 Hz was used to record CP excursions movements during the putting stroke. The sampling rate of 100 Hz was selected due to a limitation in the RS Scan software allowing for a 10 second recording period, which enabled the participant ample time to complete the putt. A Sony HDR-XR155E Handycam sampling at 50 Hz was positioned 90° to the path of the golf ball and was level with the artificial putting surface. This gave a clear view of the setup, top of backswing, impact and follow-through (Figure 1), which was used in further analysis to break the putting stroke into phases. The RS Scan FootScan pressure plate and video camera were time synchronised using a LED light via an external synchronisation trigger.

Procedure

The subjects were allowed as much time as they required to familiarise themselves with the putting task. Before the first putting trial the subject was asked to line up the putt. The pressure plate was then placed parallel to the putting line to ensure the feet were aligned to allow for further analysis. Subjects then took up their putting stance on the pressure plate and were required to complete five successful putts. All unsuccessful putts were excluded from the analysis as certain subjects had a 100% success rate. However the number of unsuccessful putts was recorded to determine each groups putting success rate. Subjects were encouraged to make the putting trial as similar to their putting routine during a real round of golf.

Data Processing

After processing the digital film to a file type recognised by video analysis software MaxTRAQ Educational 2.12d (Innovation Systems Inc.) putting stroke files were then into three phases (Figure 4.1).

The CP excursions were calculated as the range of movement of the CP in all directions (anterior, posterior, left and right) which was then totaled for all given movement about a plane of motion (AP and ML axis). The CP excursions pattern was calculated by determining the distance of the CP along the AP axis and ML axis against the average of origin for each phase (average CP across the phase), giving X, and Y coordinate which then were plotted to establish each handicap groups pattern. Zero CP refers to the data point before the initiation of Phase 1.

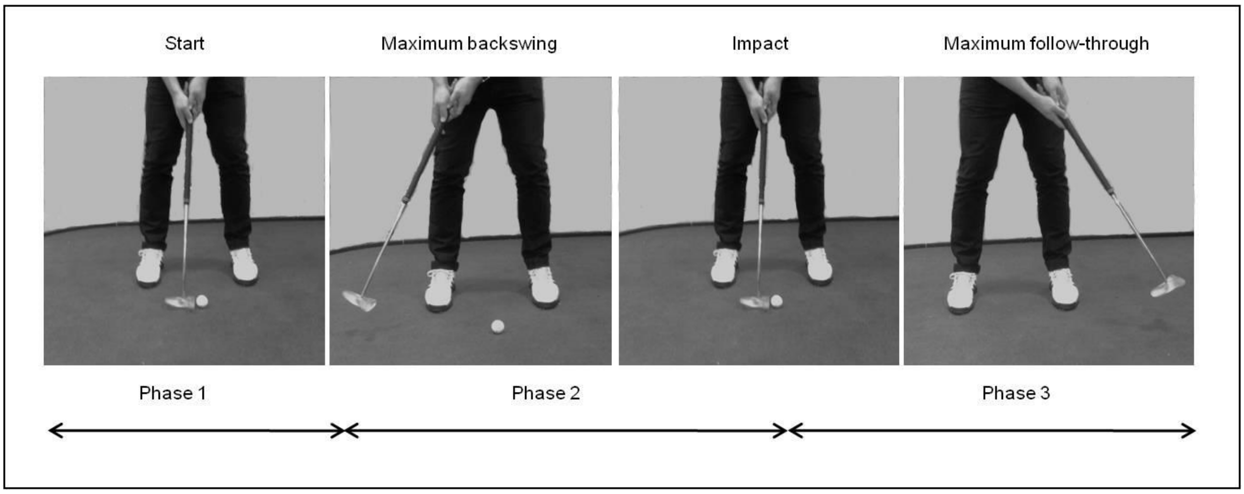

Figure 4.1. The three phases of the golf putt.

Weight distribution was calculated by splitting the foot into forefoot (50%) and heel (50%) (Figure 4.2) of total foot length, the contact pressure was then converted into percentages for each section (left forefoot, left heel, right forefoot and right heel).

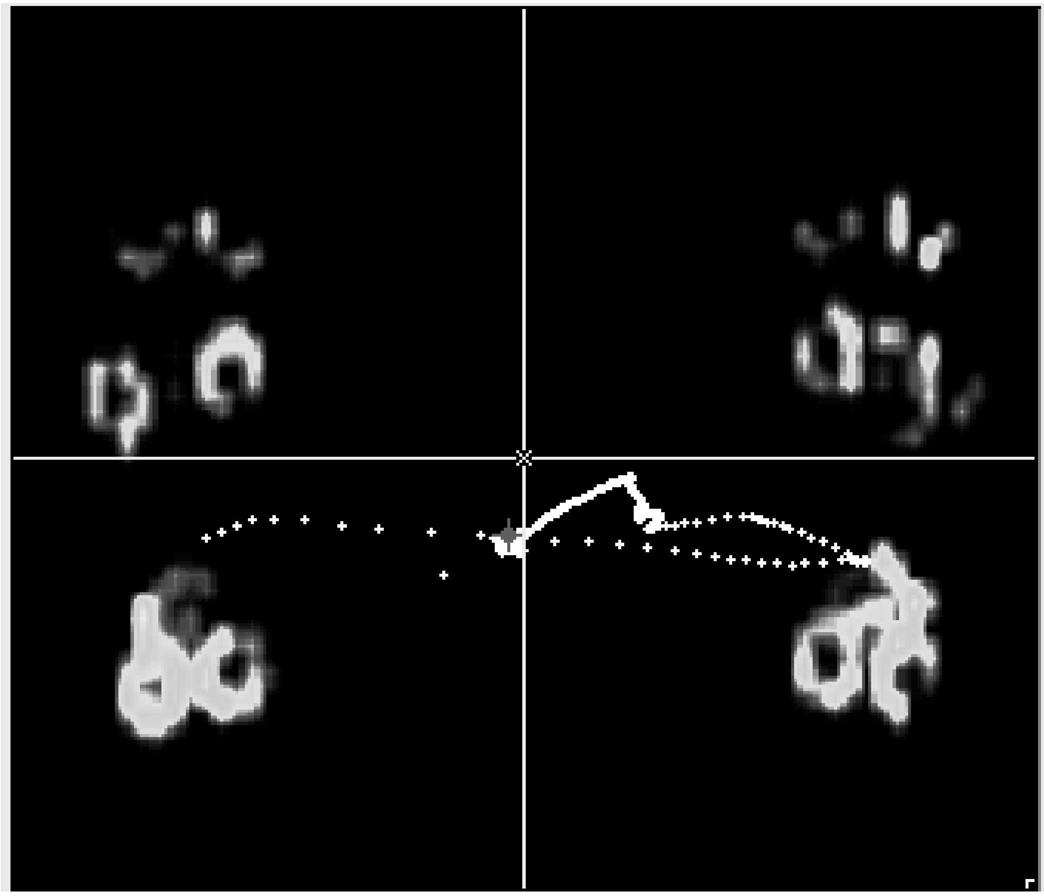

Figure 4.2. RS FootScan® screen shot depicting the typical segmentation of the putting stance.

Data Analysis

Using statistical software package SPSS 19.0 (SPSS, Inc., Chicago, IL, USA) data was first tested for normality (Shapiro-Wilk $p < 0.05$). All data was found to be normally distributed. Following this a one-way between samples ANOVA was used to test for differences between the three subject groups (LH, MH and HH) of CP excursions ML and AP in the three phases of the putt. A LSD post hoc test was used to determine between which groups the differences lie. Level of significance was set at $p < 0.05$

4.3.4 Results

Putting Proficiency

Significantly higher putting success rates were found for the LH group (81.4%) in comparison to the MH (67.6%, $p = 0.013$) and HH groups (53.8%, $p < 0.001$), additionally the MH group was found to be significantly more proficient than the HH group also ($p = 0.001$) (Figure 4.3).

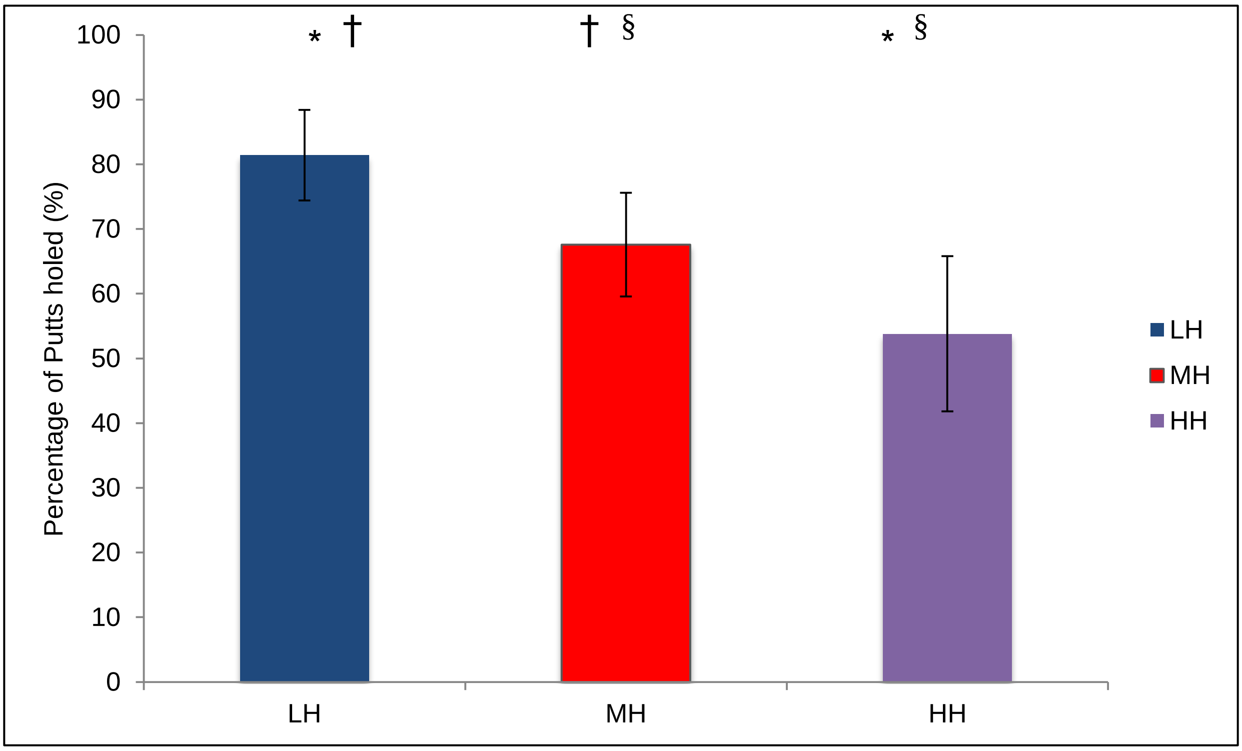

Figure 4.3. Putting success rate for the LH, MH and HH groups. *Significant difference between LH and HH group ($p < 0.05$), †Significant difference between the LH and MH group ($p < 0.05$) §Significant difference between the MH and HH group ($p < 0.05$).

Weight Distribution

No significant differences were observed between the three groups for weight distribution at all swing events. The averages (%) for all the groups combined at the four swing events were [Start; Left = 52.36 ± 7.35, Right = 47.64 ± 7.35, Anterior = 57.75 ± 20.28, Posterior = 42.52 ± 20.02; Top of back swing; Left = 53.61 ± 7.10, Right = 46.39 ± 7.10, Anterior = 57.43 ± 20.06, Posterior = 42.52 ± 20.02; Impact; Left = 54.23 ± 6.87, Right = 45.77 ± 6.87, Anterior = 55.89 ±

19.18, Posterior = 44.11 ± 19.18; Follow through; Left = 53.35 ± 7.70, Right = 46.65 ± 7.70, Anterior = 54.80 ± 18.43, Posterior = 45.20 ± 18.43]. This may be due to the large ranges observed within the subject group. Additionally at set up weight supported on the forefoot had a range of 19 – 93% and interestingly the two extremes were observed in the LH group. Throughout the putting stroke there was a slight favourability to support weight on the left foot and forefoot. The only exclusion to this trend was the HH group during set up by supporting 50.62% of total body weight on the right foot.

Centre of Pressure Excursion

Group means for whole body, left and right CP excursions during all three phases of the golf putt are displayed in Table 4.2.

Phase 1: Start to top of backswing

Low handicap golfers demonstrated significantly less total CP excursions along the AP axis in comparison to the HH group ($p = 0.027$), with the HH group demonstrating 4.07 mm greater CP excursions (Table 1). For the left foot the LH group demonstrated significantly less CP excursions along the AP axis than the HH group ($p = 0.002$) and MH ($p = 0.041$) group. For the right foot the LH group demonstrated significantly less CP excursions along the AP axis when compared to the MH group ($p = 0.037$).

Phase 2: Top of backswing to impact

Significantly less total CP excursions was demonstrated by the LH group along the AP axis in comparison to the HH group ($p = 0.022$), the HH group demonstrated 7.19 mm greater CP excursions (Table 1). No significant differences were found for total CP excursions along the ML axis. For the left foot the LH group demonstrated significantly less CP excursions along the AP ($p = 0.008$) and ML axis ($p = 0.036$) in comparison to the HH group. For the right foot, the LH group demonstrated significantly less CP excursions along the AP axis when time normalised in comparison to the HH group ($p = 0.007$).

Phase 3: Impact to follow through

Low handicap golfers demonstrated significantly less total CP excursions along the AP axis in comparison to the HH group ($p = 0.011$), the HH group demonstrated 8.61 mm greater CP excursions (Table 1). No significant differences were found for total CP excursions along the ML axis. For the left foot the LH group demonstrated significantly less CP excursions along the AP axis than the HH group ($p = 0.002$). The LH group also demonstrated significantly less CP excursions along the ML axis in comparison the HH group ($p = 0.022$). For the right foot significantly less CP excursions was demonstrated by the LH group for CP excursions along the AP axis ($p = 0.007$).

Table 4.2. Total, left and right foot centre of pressure excursions (mean ± S.E) for Phase 1) Start to top of backswing, Phase 2) Top of backswing to Impact, Phase 3) Impact to Follow through.

		Total Body CP excursions		Left Foot CP excursions		Right Foot CP excursions	
	Group	Anterioposterior (mm)	Mediolateral (mm)	Anterioposterior (mm)	Mediolateral (mm)	Anterioposterior (mm)	Mediolateral (mm)
Phase 1	LH	4.90 ± 0.44*	14.146 ± 2.37	7.53 ± 0.61*†	2.80 ± 0.33*†	8.23 ± 1.03†	3.65 ± 0.64
	MH	8.57 ± 1.03	18.65 ± 3.75	13.82 ± 2.31†	5.13 ± 0.76†	12.83 ± 2.22†	4.12 ± 0.63
	HH	8.97 ± 1.32*	15.63 ± 2.97	17.31 ± 2.44*	4.69 ± 0.55	11.01 ± 1.06	4.07 ± 0.80
Phase 2	LH	2.76 ± 0.87*	8.14 ± 2.24	4.35 ± 0.36*	1.69 ± 0.27*	5.01 ± 0.53	2.00 ± 0.37
	MH	6.00 ± 1.40	8.81 ± 1.33	7.70 ± 1.31	2.66 ± 0.41	8.75 ± 2.27	2.40 ± 0.55
	HH	9.95 ± 3.11*	15.23 ± 6.99	11.50 ± 2.54*	3.15 ± 0.62*	8.62 ± 1.28	2.27 ± 0.42
Phase 3	LH	4.51 ± 0.42*	10.88 ± 1.01	6.33 ± 0.32*	2.25 ± 0.18*†	7.04 ± 0.91*	2.78 ± 0.22
	MH	7.13 ± 0.69	13.41 ± 3.04	11.11 ± 0.88	4.24 ± 0.31†	12.77 ± 1.41	3.49 ± 0.28
	HH	13.12 ± 3.40*	17.85 ± 7.19	15.23 ± 2.66*	4.08 ± 0.51*	13.77 ± 2.00*	3.26 ± 0.49

*Significant difference between LH and HH group ($p < 0.05$), †Significant difference between the LH and MH group ($p < 0.05$).

Relative centre of pressure excursion patterns

Figure 4.4 displays relative CP excursion patterns for the three phases of the putt. Visually, it is apparent the HH group has more movement along the AP axis for all three phases of the golf putt; the LH group appears to control movement along the AP axis limiting excursions along the ML axis. The CP excursion pattern was independent of putter head movement in phase 2 of the putt, all three groups demonstrated a pattern in a right direction (towards the rear foot), in phase 1 and 3 the CP excursion pattern moves in the same direction as the putter. The HH group however show CP excursions back towards the rear foot in a right direction at the end of phase 3 while the putter would be moving in the opposite direction.

4.3.5 Discussion

The aims of the study were to examine CP excursions along the ML axis and AP axis in low, mid and high handicap golfers during a 2.5 metre level putt. Significantly higher putting success rates were found for the LH group in comparison to the MH and HH groups, the MH group was also found to be significantly more proficient than the HH group also, suggesting that the subjects' handicap reflected their ability. The results showed that the LH group demonstrated significantly less CP excursions along the AP axis in comparison with the HH group for all three phases of the golf putt. No significant differences were found along the AP axis between the MH group with either the HH group or LH group, and therefore other factors must contribute to what makes the LH group more proficient at putting as a whole. McLaughlin et al. (2008) did not publish data on CP excursions along the AP axis and Hurrion and Hurrion (2008) combined ML and AP CP excursions, therefore it is difficult to make exact comparisons to their datasets.

Increased CP excursions observed in HH golfers could be attributed to mechanisms discussed by Pelz (2000) regarding how the golf player generates power to project the ball towards the target. There are three recognised sources of power for a golf putt; a) the fingers, hands and wrists, b) forearm rotation (for players who use an arced stroke), and c) whole body rotation and movement. Body rotation in the current study was considered to be rotation of the torso around the spine (longitudinal axis). Pelz (2000) states of the three sources used to generate power, whole body rotation and movement is the least desirable, as the large muscles of the back, legs and chest are strong and difficult to control for the fine movement of putting, particularly when compared to the relatively small amounts of power needed for putting. If there is an increase in body movement it is likely that CP excursions will also increase. Delphinus and Sayers (2012) observed proficient golfers centre of mass (COM) moved predominantly in the frontal plane (ML axis) whereas non-proficient golfers moved within the sagittal plane (AP axis) whilst also demonstrating greater movement variability. This suggests controlled repeatable movement in the ML direction will increase the proficiency of putting.

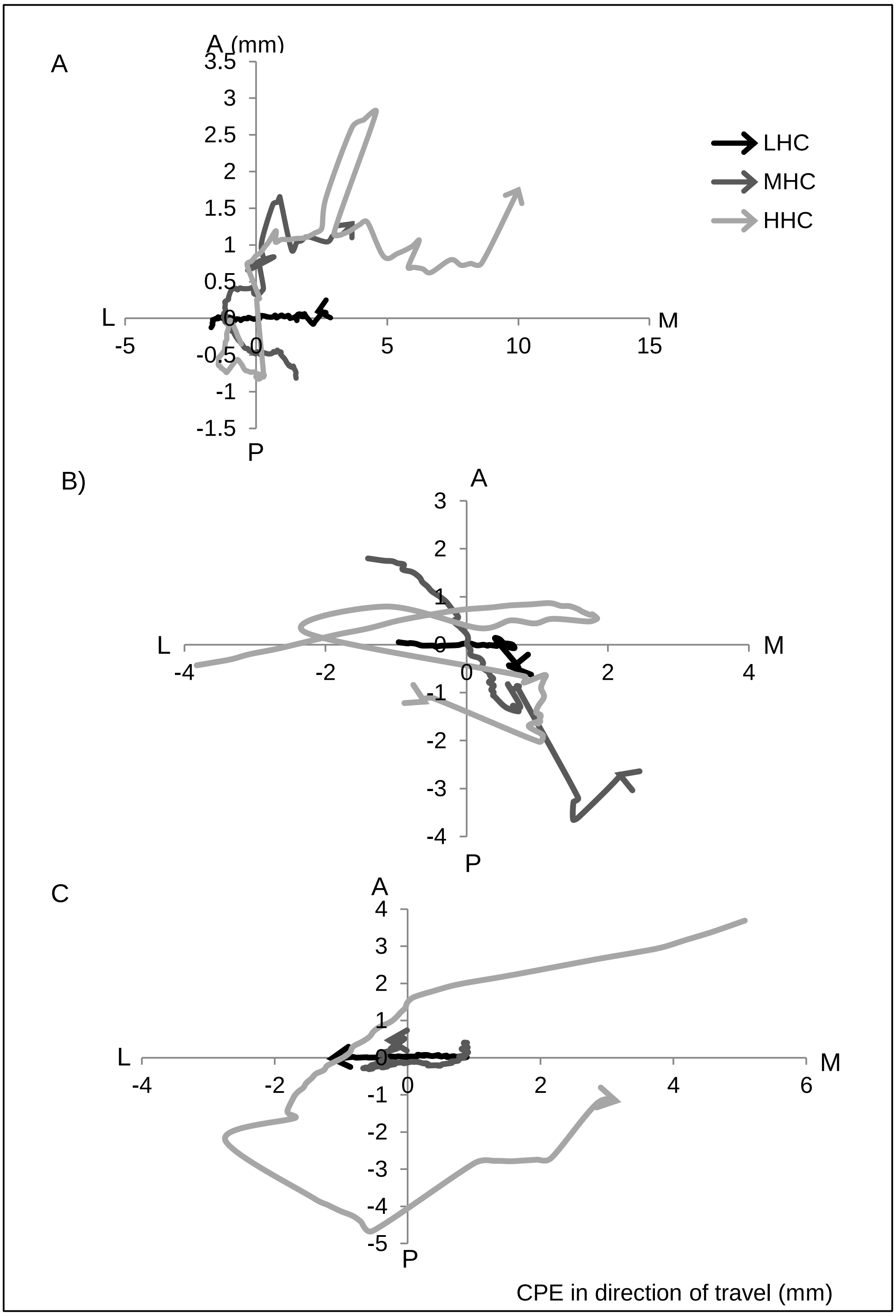

Figure 4.4 Relative CP excursion patterns for A) Start to Top of Backswing phase, B) Top of Backswing to Impact phase, C) Impact to Follow through phase (A = anterior, M = medial, P = posterior, L = lateral).

The CP will move in a similar direction to the COM as measured by Delphinus and Sayers (2012), however, the CP excursion is also dependent on the projection of the muscle forces required to produce the movement (Palmieri, et al., 2002), in this case the putting stroke. This may explain the results found in the current study, as increased CP excursion were found to occur along the AP axis for the HH group in comparison to the LH group, therefore the HH groups COM will have moved along the sagittal plane due to increased body movement. Increased variability of CP E excursions along the AP axis for the HH group was also observed.

In certain cases, increased body movement may in fact reduce CP excursion. In order to keep the centre of mass stationary, the golfer must move the body in directions opposite to that of the putter and arms. However, this is not applicable when referring to the AP axis as the putter and arms are predominantly translating along the ML axis. This suggests less proficient golfers have a reduced ability in controlling CP excursions in the AP direction, which will have a negative effect on performance. Another explanation for this may be the HH group's lack of understanding of how to execute putting stroke. High handicap golfers may not consider movement along the AP axis undesirable and therefore may not try to control the movement.

The results of the current study are not in accordance with those of McLaughlin et al. (2008), who found significant differences to exist in CP excursions along the ML axis, whereas in the current study no significant differences were found for CP excursions along the ML axis between any of the three groups in all three phases of the putt. Differences in results between McLaughlin et al. (2008) and the present study may be due to the different lengths of putt tested, (the current study used 2.5 m and McLaughlin et al. (2008) used 4 m). Hurrion and Hurrion (2008) also observed significantly less total CP excursions in European Tour professional golfers in comparison to LH golfers. Hurrion and Hurrion (2008) suggest that the smaller the CP excursions the greater the balance of the golfer during the golf putt. Hurrion and Hurrion (2008) and McLaughlin et al. (2008) found golfers with lower handicaps had significantly smaller CP excursions or along the ML axis respectively, which contrasts with the findings of the current study that found significantly smaller CP excursions along the AP axis.

The findings of this study suggest that less variability associated with CP excursions along the AP axis contributes to being a more proficient putter. This may be due to having increased balance while still being able to effectively execute a putting stroke as suggested by Hurrion and Hurrion (2008). In the current study total CP excursions (ML and AP combined) was smaller than those observed by Hurrion and Hurrion (2008). Especially in Phase 3 where Hurrion and Hurrion (2008) observed combined CP excursions of 53.26 mm for an amateur group and 41.97 mm for a professional group compared to 15.36 mm for the LH group, 20.54 mm for the MH group and 30.97 mm for the HH group in the current study. Hurrion and Hurrion (2008) accredit this movement in the follow-through phase as a reaction to the impact as the player's head moves backwards away from the target line, causing a sharp lift in the putter head during the follow-through. The reduction in CP excursions may be due to the different lengths of putts used in each study, Hurrion and Hurrion (2008) used a 7.6 m putt, and the current study used a putt of 2.5 m.

The LH group demonstrated reduced CP excursions in the left foot for all three phases of the putt along the AP axis in comparison to the HH group. This was in contrast to the right foot where the LH only demonstrated significantly less CP excursions along the AP axis in phase 3 of the golf putt. This implies that the LH group is more able to control CP excursions by eliminating excessive movement along the AP axis in the lead foot in comparison to the HH group. Increased CP excursions in the lead foot may lead to an increased number of ‘miss hits’ as it may alter the plane and potentially the face angle which Karlsen et al. (2008) state accounts for 97% of stroke direction consistency.

McLaughlin et al. (2008) reported CP excursions to be independent to movement of the putter head, in the current study, this independent movement was found to exist for Phase 2 of the putting stroke (Figure 4). Greater right CP excursions was observed in comparison to left CP excursions, resulting in a trend towards the back foot whereas the putter is moving towards the front foot. As described by Pelz (2000), many elements contribute to a successful putt, which allows for a wide range of techniques from player to player, therefore studies with a larger cohort would be needed to confirm whether CP excursions is independent to see whether CP excursions is independent of putter movement as currently there is conflict within the literature.

It is worthy to note that CP excursions along both the ML and AP axis did not influence weight distribution as no significant differences were found between the three groups for any of the four swing events. At set up Hurrion and Hurrion (2008) found significant differences between a professional group (left = 48.34%, right = 51.66%) in comparison to a LH group (left = 40.37%, right = 59.60%) this differs from the current study, as there was a trend to place more weight on the left foot. However, similar to Hurrion and Hurrion (2008) all groups favoured placing more weight on the forefoot, this is likely due to the ball being placed in front of the feet and thereby the golfer leans forward to execute the stroke, extreme values favouring the forefoot may however reduce the ability to control balance. So as Hurrion and Hurrion (2008) suggested, most golfers would assume a comfortable stance and in certain cases this will reduce balance throughout the stroke, and the present study supports this statement.

A potential limitation of the current study is that performing golf shots in laboratory conditions is very different to an actual putt during a golf round and therefore may affect results. However, the subjects were allowed time to habituate themselves to the surroundings to minimise the effect as much as possible. Although the camera frame rate in the current study was adequate in identifying the putting phases no current research in the field of CP excursions during the putting stroke has been recorded using high-speed (200 Hz) video cameras identifying what body movements are causing CP excursions. Future research should investigate the relationship between CP excursions and post impact ball kinematics using high-speed camera technology. This will further knowledge in the field of golf putting kinematics and has the potential to explain why LH golfers have a lower putter head velocity.

4.3.6 Conclusion

Low handicap golfers demonstrate smaller CP excursions along the AP axis in comparison to the HH group in all three phases of the golf putt; this was also apparent for the left (lead) foot. No significant difference was found for CP excursions along the ML axis for all three phases of the golf putt or in weight distribution throughout the putting stroke. Results suggest that a reduced CP excursion along the AP axis increases balance and subsequently improves the putting stroke. The practical implication of the study is that golfers should focus on reducing CP excursions along the AP axis to improve putting performance. Additionally the findings of the study supports the use of training aids to encourage a 50/50% weight distribution between the heel and forefoot to limit CP excursions along the AP axis during the putting stroke. Coaches should identify the golfers body parts used to generate power, to eliminate unnecessary movement of the torso within the sagittal plane allowing for more control of the equilibrium and subsequently balance.

4.4 Development of Research

This chapter demonstrated conclusive findings that HH golfers display increased CP excursions along the AP axis, for all three phases of the golf putt. Chapter Three demonstrated less conclusive findings for the golf swing where significant differences were observed between the three different golf clubs but not as was originally hypothesised. As more conclusive findings were found for the CP excursions during the putting stroke, this naturally raised more unanswered questions about the kinematics of putting stroke that could be addressed during this thesis. Firstly, as to whether increased CP excursions have a detriment to ball roll kinematics (which has limited research itself) and secondly what body movement (including distance and velocity of the body) is causing these greater CP excursions observed in HH golfers. These additional questions that arose, and the acquisition of new software package Quintic Ball Roll v2.4 drove the aim of the thesis entirely towards researching the putting stroke. The next study will assess the reliability of the Quintic Ball Roll software, which has no scientific literature published, either on the reliability or results between different proficiencies of golfers ball roll kinematics.

Chapter Five

The reliability of the Quintic Ball Roll software

5.1 Introduction to Chapter

As identified in Study Two significant differences between LH and HH golfers existed in CP excursions along the AP axis, however, there is little understanding as to whether this has a detrimental effect on the kinematics of the ball roll. Which potentially could lead to an increased number of missed putts. This chapter includes reliability testing using the Quintic mechanical putting arm, presented in Study Three: The reliability of the Quintic Ball Roll software (Section 5.2). This is followed by validity of Quintic Ball Roll software measures and software to be used in subsequent chapters of the thesis (Section 5.3). The Development of Research (Section 5.4) concludes this chapter summarising the findings and outlining the direction of the next chapter in the thesis.

5.2 Study Three: The reliability of the Quintic Ball Roll software

5.2.1 Abstract

Background: The reliability of the Quintic Ball Roll system needs to be assessed as no scientific literature using the system to date has been published. **Aim:** To assess the relative and absolute reliability of the kinematic variables recorded by the Quintic Ball Roll System. **Method:** 50 pairs of trials for four different ball conditions (aligned 0°, aligned 10° right and left and aligned randomly) of a simulated 3.2 metre golf putt were completed using a mechanical putting robot. Statistical comparisons were made between test – retest scores to assess day to day reliability in addition to this a repeated measures ANOVA was completed comparing the four different ball conditions. **Results:** Very strong absolute reliability was observed for all kinematic variables. However, weak relative reliability was found due to the nature of the study design. Significant differences were observed between all four different ball conditions, however there was no pattern to this identified. **Conclusion:** Although more day to day variation was observed than first expected the Quintic Ball Roll system can be considered reliable due to the strong absolute reliability observed. The significant differences between the four different ball conditions highlights the need to correctly calibrate the equipment and line the ball up for each trial in the same position.

5.2.2 Introduction

Literature that investigate the ball roll kinematics has to date been extremely limited with main focus being placed on the forward roll or topspin placed on the golf ball (Brouillette and Valade (2008), Brouillette (2010); Hurrion & Hurrion, 2002 and Pelz (2000). In addition to this some literature has researched the gear effect in ball collisions, concluding that the spin rate increases with the angle of incidence (Cross and Nathan, 2007). To date no scientific literature has been published using the new piece of software Quintic Ball Roll, which measures the kinematic ball variables during the first 30 cm of the balls travel. Therefore it was deemed appropriate to conduct extensive reliability testing on the software before any other data collection was completed.

The aim of this study is to assess the relative and absolute reliability of the Quintic Ball Roll software of the following kinematic variables: velocity, side spin, initial ball roll, forward roll, true roll, vertical and horizontal launch angle and whether the ball was pushed or pulled. This will allow an opinion to be formulated as to whether the software is suitable to continue conducting scientific testing with.

5.2.3 Methods

Experimental set – up

All testing was completed in the Quintic Golf Laboratory on an artificial putting surface registering 12 on the stimpmeter. The Quintic Mechanical putting arm was mounted on a 360 kg bearing (Figure 5.1a) was set up to simulate a level 3.2 metre putt, with a straight-straight-straight swing path to ensure a square club face for every trial at impact. Two putters were used for the protocol, a GEL® (GEL GOLF., Wan Chai, Hong Kong) Vicis putter with a 69º lie and 2.5º loft and Odyssey (Callaway Golf Europe Ltd., Surrey, UK) White Hot #3 with a 69º lie and 2.5º loft. These putters were selected as they both had the same lie and loft and different putter face characteristics, the GEL® putter had a grooved insert and the Odyssey putter had a traditional non-grooved insert. The golf balls used were Srixon Z-STAR golf balls and were aligned using two Superline 2D line lasers fixed to a 360˚ graduated base. One line laser was placed directly behind the ball and the other was placed 90˚ to the path of the golf ball. This split the golf ball into four equal sections ensuring the same position of the ball for each trial. A Quintic high speed camera sampling at 220 fps was positioned perpendicular to the putting line. The Quintic Ball Roll v2.4 Launch monitor software was used to analyse the kinematic variables post trial.

Procedure

Each stage of testing took place over a two-day period, during stage 1 the ball was aligned to the centre of the hole. The ball was positioned and aligned using the Superline 2D lasers marked at 0˚ for each of the 50 trials. The counterbalanced putting arm block was set to produce a putt of 3.2 metres. The putting arm was tied to a weighted pole and released using a bull clip to reduce friction and human interference to a minimum. The 50 trials were then repeated with the Superline 2D lasers marked at 0˚ for Day 2. Day 3, 50 trials were repeated with the Superline 2D laser position directly behind the ball marked at 10˚ left of the original position. Day 4, the 50 trials were repeated, with the Superline laser marked at 10˚ left of the original position. Day 5, and Day 6 a total of 50 trials for each day were completed with the Superline 2D laser marked at 10˚ right of the original position (Figure 5.1b). This was repeated without the use of the Superline laser for a random ball position.

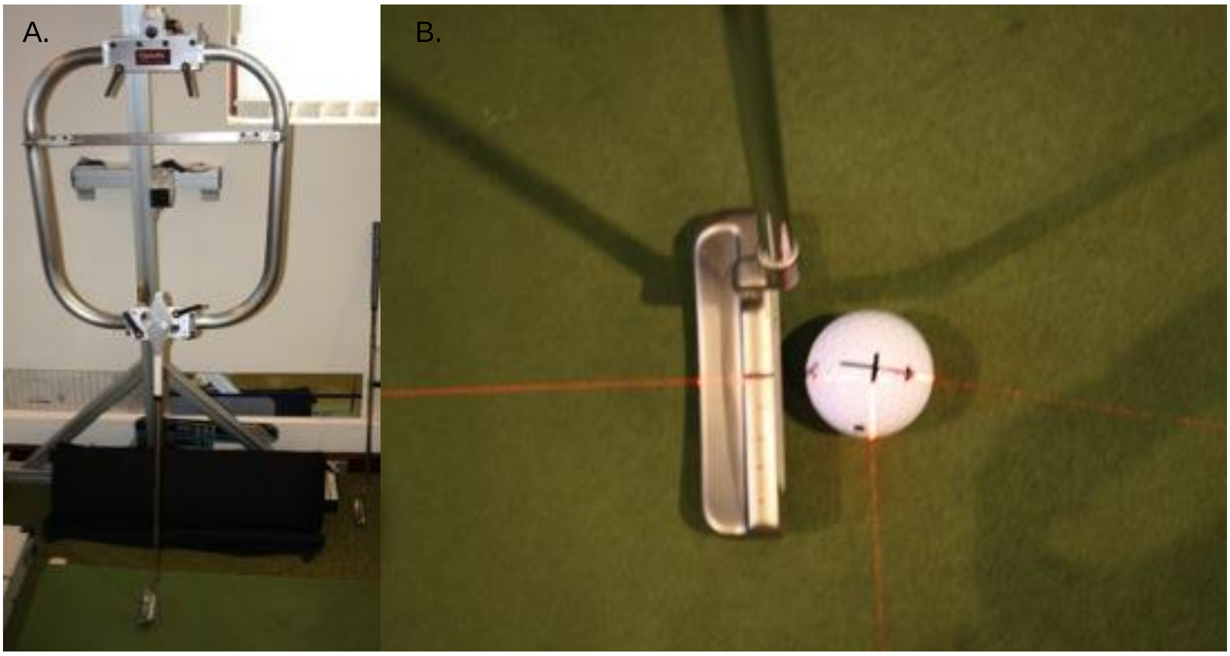

Figure 5.1. The Quintic custom built mechanical putting arm mounted on a 360 kg bearing (A) and (B) a vertical view of the ball aligned in the 10˚ right condition.

Data Processing

Means and standard deviations were calculated for velocity (ms^{-1}), side spin (rpm), initial ball roll (rpm), start of forward rotation (cm), true roll (cm), vertical launch angle (˚) using the Excel spreadsheets generated by the Quintic Ball Roll software for the four different ball conditions (ball aligned 0˚, ball aligned 10˚ left, ball aligned 10˚ right and the ball placed randomly). Data for the horizontal launch angle (˚) and whether the ball was pushed or pulled (cm) failed after two days of testing, however, reliability statistics were tested on day to day data collected on a separate occasion, comparisons between different ball placements were however not made.

The kinematic variables measured can be defined as follows:

Velocity – the average velocity the ball achieved during the first 30 cm.

Side spin (Cut or Hook) – the amount of side spin (rpm) placed on the ball during impact.

Initial ball roll – whether the golf ball has positive rotation (topspin) or negative rotation (backspin) at the point of impact.

Forward Roll – the distance at which the ball is rolling in a positive direction

True Roll – the point where the ball is rolling with no skid, whereby the ball displaces itself once over it's circumference.

Vertical launch angle – the launch angle at the point of impact on the vertical axis.

Horizontal launch angle – the launch angle at the point of impact on the horizontal axis.

Push/Pull – a calculation of the final resting point of the golf ball based on the kinematic variables recorded (3.05 metres reported).

Data Analysis

Data was exported to statistical analysis software packages Microsoft Excel 2011 and SPSS v19. Relative and absolute reliability was assessed using a range of methods previously approved within the literature (Atkinson & Nevill, 1998; Hopkins, 2000). The measures of reliability used for analysis were the SEM calculated using the following formula: $SEM = SD\sqrt{1 - ICC}$. This directly assesses the absolute reliability of the data. To test the relative reliability of the data a two – way mixed ICC was used calculated using the following formula: $\frac{1-SD^2}{SD^2}$. The boundaries set for the coefficient statistics as suggested by Salkind (2011) were as follows; *r* = 0.8 – 1.0, very strong, *r* = 0.6 – 0.8, strong, *r* = 0.4 – 0.6, moderate, *r* = 0.2 – 0.4, weak, *r* = 0.0 – 0.2, no relationship. The descriptive reliability measures used to analyse the data was the mean ± SD, the change in mean and 95% confidence limits (CL). The change in mean and 95% CL will stipulate the absolute variation between the data sets.

After tests for normality using the Kolmogorov – Smirnov. Significant differences were tested using a paired samples *t*-test between the test and retest scores. A repeated measures multivariate ANOVA was used to test differences between the different ball conditions (ball aligned 0˚, ball aligned 10˚ left, ball aligned 10˚ right and the ball placed randomly). The level of significance was set at *p* = 0.05. All of these statistical procedures as a collective will provide a strong impression as to whether the Quintic Ball Roll system is reliable and reproducible.

5.2.4 Results

Velocity

Table 5.1 and Table 5.2 displays means and reliability statistics for the Odyssey and GEL® putter with the ball in the 0° aligned condition. Significant differences were identified between the test – retest velocity values for the Odyssey putter (p = 0.001). However, no significant differences were identified for the GEL® putter (p = 0.493). The SEM was very low for both the Odyssey putter (0.04 ms^{-1}) and GEL® putter (0.05 ms^{-1}). Despite strong absolute reliability being demonstrated weak ICCs were observed for both putters (0.04 to 0.37). The change in mean was very low for the GEL® putter (0.01 ms^{-1}) and Odyssey putter (-0.02 ms^{-1}), this was also reflected in tight spread of 95% confidence limits.

Means and reliability statistics are presented for the ball aligned 10° left condition for the Odyssey and GEL® putter in Table 5.3 and Table 5.4. Significant differences between the test – retest scores for the Odyssey putter (p = 0.445), however, significant differences were identified for the GEL® putter (p = 0.001). The SEM was very low for both the Odyssey (0.03 ms^{-1}) and GEL® putter (0.04 ms^{-1}), this strong absolute reliability was supported by low change in means values and strong 95% confidence limits. Weak relative reliability was observed with ICC scores of 0.03 and 0.08 for the Odyssey and GEL® putter respectively.

Table 5.5 and 5.6 presents means and reliability statistics for the ball aligned 10° right condition for the Odyssey and GEL® putters. No significant differences were observed between the test – retest scores for both the Odyssey ($p = 0.445$) and GEL® putter ($p = 0.177$). Very strong SEMs were observed (Odyssey putter = 0.03 ms^{-1}, GEL® putter = 0.04 ms^{-1}) this was combined with strong change in mean scores at 0.00 ms^{-1} for the Odyssey putter and -0.01 ms^{-1} for the GEL® putter. Weak relative reliability was again observed (Odyssey putter = 0.13, GEL® putter = 0.17).

Means and reliability statistics for the ball aligned randomly is presented for the Odyssey putter in Table 5.7 and for the GEL® putter in Table 5.8. No significant differences were found between the test – retest values for the Odyssey putter ($p = 0.104$) and GEL® putter ($p = 0.226$). Very strong absolute reliability was observed for both the Odyssey and GEL® putter reflected with low SEM scores (0.04 and 0.05 ms^{-1} respectively). This was coupled with minimal change in mean scores and tight 95% confidence limits (0.04 ms^{-1} difference between lower and upper confidence limits for the GEL® putter).

A repeated measures ANOVA ($F_{(3,147)} = 4.27$, $p = 0.006$) indicated significant differences were apparent between Odyssey 0° aligned and Odyssey aligned 10° left ($p = 0.022$) and Odyssey aligned 10° right ($p = 0.001$). No other significant differences between the data sets for velocity were observed. For the GEL® putter a repeated measures ANOVA ($F_{(3, 297)} = 13.96$, $p = 0.001$) showed significant differences were indicated between the GEL® 0° aligned condition and aligned 10° left ($p = 0.001$), aligned 10° right ($p = 0.001$) and random conditions ($p = 0.001$). No other significant differences were observed.

Table 5.1. Reliability Measures for the Quintic Ball Roll System with the ball aligned at 0° using the Odyssey putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired *t*-test *p*-value
Velocity (ms^{-1})	2.11 ± 0.05	2.09 ± 0.03	-0.02	-0.03 to 0.05	0.04	0.37	0.001
Spin (Cut (+), Hook (-), rpm)	-2.83 ± 12.64	-9.58 ± 11.13	-6.75	-7.70 to 11.49	9.22	0.41	0.017
Initial Ball Roll (rpm)	-15.51 ± 12.50	-15.92 ± 11.93	-0.31	-10.42 to 16	12.49	0.05	0.116
Forward Rotation (cm)	1.33 ± 1.04	1.18 ± 1.00	-0.16	-0.85 to 1.27	1.02	0.10	0.352
True Roll (cm)	23.80 ± 4.80	22.24 ± 5.96	-1.56	4.35 to 6.49	5.21	0.08	0.021
Vertical Launch Angle (°)	2.56 ± 0.45	2.44 ± 0.39	-0.12	-0.35 to 0.53	0.42	0.00	0.169

(Significance denoted by highlighted cell).

Table 5.2. Reliability Measures for the Quintic Ball Roll System with the ball aligned at 0° using the GEL® putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired *t*-test *p*-value
Velocity (ms^{-1})	2.06 ± 0.04	2.07 ± 0.04	0.01	-0.04 to 0.06	0.05	0.04	0.493
Spin (Cut (+), Hook (-), rpm)	1.01 ± 13.29	0.63 ± 12.47	-0.38	-5.91 to 5.15	13.76	0.14	0.313
Initial Ball Roll (rpm)	7.25 ± 12.92	8.54 ± 14.70	1.29	-4.18 to 6.75	13.61	0.03	0.819
Forward Rotation (cm)	0.37 ± 0.46	0.49 ± 0.50	0.12	-0.06 to 0.31	0.47	0.06	0.674
True Roll (cm)	23.96 ± 1.82	23.74 ± 1.71	-0.22	-1.50 to 2.23	1.79	0.03	0.838
Vertical Launch Angle (°)	1.48 ± 0.48	1.48 ± 0.47	0.00	-0.18 to 0.18	0.44	0.13	0.384

Table 5.3. Reliability Measures for the Quintic Ball Roll System with the ball aligned at 10° left using the Odyssey putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired t-test p-value
Velocity (ms^{-1})	2.14 ± 0.04	2.15 ± 0.03	-0.01	-0.03 to 0.04	0.03	0.03	0.445
Spin (Cut (+), Hook (-), rpm)	-6.49 ± 12.81	-9.92 ± 10.01	-3.21	-8.56 to 1.7	12.16	0.09	0.190
Initial Ball Roll (rpm)	20.68 ± 11.51	17.98 ± 16.17	-2.70	-4.50 to 2.61	13.20	0.12	0.312
Forward Rotation (cm)	1.25 ± 1.0	1.29 ± 1.0	0.04	0.35 to 0.42	0.96	0.05	0.848
True Roll (cm)	25.82 ± 2.27	24.82 ± 2.73	-1.00	-1.98 to -0.02	2.43	0.07	0.045
Vertical Launch Angle (°)	2.11 ± 0.31	2.20 ± 0.40	0.09	-0.04 to 0.23	0.33	0.14	0.159

(Significance denoted by highlighted cell).

Table 5.4 Reliability Measures for the Quintic Ball Roll System with the ball aligned at 10° left using the GEL® putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired t-test p-value
Velocity (ms^{-1})	2.08 ± 0.04	2.11 ± 0.04	0.03	-0.04 to 0.05	0.04	0.08	0.001
Spin (Cut (+), Hook (-), rpm)	1.28 ± 13.34	4.89 ± 12.40	3.61	-2.12 to 9.34	14.26	0.23	0.217
Initial Ball Roll (rpm)	2.56 ± 17.52	7.81 ± 18.42	5.25	-2.30 to 12.80	18.78	0.09	0.169
Forward Rotation (cm)	0.41 ± 0.51	0.41 ± 0.59	-0.01	-0.24 to 0.23	0.58	0.12	0.944
True Roll (cm)	22.74 ± 2.69	23.54 ± 2.48	0.80	-0.31 to 1.91	2.75	0.13	0.152
Vertical Launch Angle (°)	1.97 ± 0.45	1.53 ± 0.41	-0.44	-0.60 to -0.27	0.41	0.09	0.001

(Significance denoted by highlighted cell).

Table 5.5. Reliability Measures for the Quintic Ball Roll System with the ball aligned at 10° right using the Odyssey putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired *t*-test *p*-value
Velocity (ms^{-1})	2.13 ± 0.03	2.13 ± 0.03	0.00	-0.01 to 0.02	0.03	0.13	0.485
Spin (Cut (+), Hook (-), rpm)	-9.18 ± 10.65	-10.18 ± 9.88	-1.00	-5.33 to 3.24	10.86	0.08	0.591
Initial Ball Roll (rpm)	-16.22 ± 9.15	-19.43 ± 9.63	-2.92	-7.38 to 0.96	10.37	0.08	0.128
Forward Rotation (cm)	1.32 ± 0.80	1.67 ± 1.07	0.34	0.01 to 0.70	0.88	0.48	0.053
True Roll (cm)	26.84 ± 2.10	27.38 ± 2.12	0.54	-0.32 to 1.40	2.21	0.10	0.215
Vertical Launch Angle (°)	2.25 ± 0.45	2.68 ± 0.44	0.42	0.23 to 0.64	0.52	0.35	0.001

(Significance denoted by highlighted cell).

Table 5.6. Reliability Measures for the Quintic Ball Roll System with the ball aligned at 10° right using the GEL® putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired *t*-test *p*-value
Velocity (ms^{-1})	2.10 ± 0.04	2.09 ± 0.05	-0.01	-0.03 to 0.01	0.04	0.17	0.177
Spin (Cut (+), Hook (-), rpm)	-3.30 ± 12.27	0.45 ± 11.64	3.75	-1.21 to 8.71	12.34	0.07	0.145
Initial Ball Roll (rpm)	6.21 ± 10.87	7.76 ± 10.81	1.55	-3.31 to 6.41	12.09	0.25	0.524
Forward Rotation (cm)	0.40 ± 0.44	0.36 ± 0.44	-0.04	-0.21 to 0.14	0.43	0.04	0.656
True Roll (cm)	20 ± 1.98	25.62 ± 2.04	0.22	-0.54 to 0.98	1.89	0.12	0.564
Vertical Launch Angle (°)	1.82 ± 0.46	1.83 ± 0.61	0.01	-0.21 to 0.23	0.54	0.01	0.914

Table 5.7. Reliability Measures for the Quintic Ball Roll System with the ball randomly aligned using the Odyssey putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired t-test p-value
Velocity (ms^{-1})	2.13 ± 0.05	2.14 ± 0.04	0.01	0.00 to 0.03	0.04	0.14	0.104
Spin (Cut (+), Hook (-), rpm)	-14.02 ± 12.33	-11.21 ± 10.53	2.81	-1.60 to 7.22	10.98	0.08	0.210
Initial Ball Roll (rpm)	-20.80 ± 10.23	-20.04 ± 11.32	0.76	-3.24 to 4.76	9.96	0.15	0.703
Forward Rotation (cm)	1.07 ± 0.96	1.55 ± 0.99	0.46	0.11 to 0.86	0.94	0.08	0.013
True Roll (cm)	25.82 ± 3.22	27.72 ± 3.55	1.90	0.62 to 3.18	3.19	0.12	0.004
Vertical Launch Angle (°)	2.30 ± 0.49	2.17 ± 0.57	-0.13	-0.33 to 0.07	0.50	0.11	0.206

(Significance denoted by highlighted cell).

Table 5.8. Reliability Measures for the Quintic Ball Roll System with the ball randomly aligned using the GEL® putter (n = 50 pairs).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired t-test p-value
Velocity (ms^{-1})	2.10 ± 0.06	2.11 ± 0.05	0.01	-0.01 to 0.03	0.05	0.13	0.226
Spin (Cut (+), Hook (-), rpm)	2.20 ± 13.84	2.69 ± 13.15	0.49	-4.08 to 5.04	11.37	0.30	0.821
Initial Ball Roll (rpm)	6.10 ± 14.73	9.92 ± 14.18	3.82	-1.83 to 9.47	14.06	0.06	0.181
Forward Rotation (cm)	0.35 ± 0.45	0.32 ± 0.46	-0.03	-0.20 to 0.14	0.42	0.16	0.704
True Roll (cm)	23.38 ± 2.12	22.98 ± 2.17	-0.40	-1.18 to 0.38	1.93	0.19	0.306
Vertical Launch Angle (°)	1.49 ± 0.51	1.45 ± 0.43	-0.04	-0.24 to 0.20	0.49	0.08	0.628

Side Spin

Table 5.1 and Table 5.2 shows means and reliability statistics for the variable side spin for the Odyssey and GEL® putters for when the ball was aligned at 0°. Significant differences were observed between the test – retest values for the Odyssey putter (p = 0.017). No significant differences were observed between the test – retest values for the GEL® putter (p = 0.897). Moderate SEMs were observed (10.41 rpm and 13.76 rpm) for the Odyssey and GEL® putters respectively. A larger change in mean was observed for the Odyssey putter (-6.75 rpm) in comparison to the GEL® putter (-0.38 rpm). Moderate to weak relative reliability was observed based on the ICC scores (Odyssey putter = 0.41, GEL® putter = 0.14).

Means and reliability statistics for the ball aligned 10° left condition are presented in Table 5.3 for the Odyssey putter and Table 5.4 for the GEL® putter. No significant differences were observed in the test – retest scores for the Odyssey (p = 0.190) or GEL® putter (p = 0.217). Moderate SEMs were again observed at 12.16 rpm and 14.26 rpm correspondingly for the Odyssey and GEL® putters. The change in mean was consistent between putters with -3.21 rpm demonstrated for the Odyssey putter and 3.61 for the GEL® putter. Weak relative reliability assessed by the ICC was observed for both putters (Odyssey putter = 0.09, GEL® putter = 0.23).

Tables 5.5 and 5.6 display means and reliability statistics for the Odyssey and GEL® putters for the ball aligned 10° right. No significant differences were observed for either the Odyssey (p = 0.591) or the GEL® putter (p = 0.145) for the test – retest values. The SEM for the Odyssey putter was 10.86 rpm, and this was coupled with a change of mean of -1.00 rpm. A larger SEM was observed for the GEL® putter at 12.34 rpm, additionally the change in mean was larger (3.75 rpm). Weak relative reliability was observed for both the Odyssey and GEL® putters with ICC scores of 0.08 and 0.07 respectively.

Means and reliability statistics for the random ball alignment condition for the Odyssey and GEL® putters are presented in Tables 5.7 and 5.8. No significant differences were observed for either the Odyssey (p = 0.210) or the GEL® putter (p = 0.821) for the test – retest values. Moderate SEM values were observed for both the Odyssey (10.98 rpm) and GEL® putter (11.37 rpm). Despite a larger SEM the GEL® putter had a smaller change in mean (0.41 rpm) in comparison to the Odyssey putter (2.81 rpm). The range of 95% confidence limits was similar between both putters (Odyssey putter = 8.82 rpm, GEL® putter = 9.12 rpm). Weak ICCs were observed for both putters demonstrating poor relative reliability.

For the Odyssey putter a repeated measures ANOVA ($F_{(3, 147)}$ = 2.326, p = 0.077) indicated significant differences. The significant difference was found to lie between the ball 0° aligned and random conditions (p = 0.014). A repeated measures ANOVA ($F_{(3. 297)}$ = 2.648, p = 0.49) indicated significant differences between GEL® putter aligned 10° left and 10° right (p = 0.013), a significant difference was also observed between the aligned 10° right and random ball condition (p = 0.029).

Initial Ball Roll

Table 5.1 and Table 5.2 present means and reliability statistics for the Odyssey and GEL® putters for the ball aligned at 0° condition. No significant differences were observed for either the Odyssey (p = 0.116) or GEL® putter (p = 0.639) for the test – retest values. Moderate SEM were observed for both the Odyssey (12.49 rpm) and GEL® putter (13.61 rpm). Along with a slightly larger SEM a larger change in mean was observed for the GEL® putter (1.29 rpm) in comparison to the Odyssey putter (-0.31 rpm). However very weak relative reliability was demonstrated for both putters (Odyssey putter = 0.05 rpm, GEL® putter = 0.03 rpm).

Means and reliability statistics for the Odyssey and GEL® putters for the ball aligned 10° left condition are presented in Table 5.3 and Table 5.4. No significant differences were found for either the Odyssey (p = 0.312) or GEL® putter (p = 0.169) for the test – retest values. A larger SEM was observed for the GEL® putter (18.78 rpm) in comparison to the Odyssey putter (13.20 rpm). The change in mean also reflected this trend (Odyssey putter = -2.70, GEL® putter = 5.25). Weak relative ICC was observed with ICC scores of 0.12 for the Odyssey putter and 0.09 for the GEL® putter.

Table 5.5 and Table 5.6 display means and reliability statistics for the Odyssey and GEL® putters with the ball aligned 10° right. No significant differences were observed for either the Odyssey (p = 0.128) or the GEL® putter (p = 0.524) for the test – retest values. Moderate SEMs were observed for the both putters 10.37 and 12.09 rpm for the Odyssey and GEL® putters respectively. Although a slightly larger SEM was observed for the GEL® putter, the change in mean observed was in fact smaller (1.55 rpm) in comparison to the Odyssey putters -2.92 rpm. Weak ICCs were demonstrated for both putters (Odyssey putter = 0.08, GEL® putter = 0.25).

Means and reliability statistics for the Odyssey and GEL® putters for the ball aligned randomly position are presented in Tables 5.7 and 5.8. No significant differences were observed for either the Odyssey (p = 0.703) or the GEL® putter (p = 0.181) for the test – retest values. A larger SEM was observed for the GEL® putter (14.06 rpm) in comparison to the Odyssey putter (9.96 rpm), this was also apparent with the change in mean between test scores with a difference of 3.82 rpm and 0.76 respectively. Additionally weak relative reliability was demonstrated showed by poor ICC scores at 0.15 for the Odyssey putter and 0.06 for the GEL® putter.

A repeated measures ANOVA ($F_{(2.638,\ 261.129)} = 0.842$, $p = 0.472$) indicated no significant differences for the GEL® putter between any of the conditions tested. A repeated measures ANOVA also indicated no significant differences between the test conditions for the Odyssey putter ($F_{(3,\ 147)} = 1.956$, $p = 0.123$).

Start of Forward Rotation

Tables 5.1 and 5.2 present means and reliability statistics for the Odyssey and GEL® putters for the ball aligned at 0° condition. No significant differences were observed for either the Odyssey (p = 0.352) or GEL® putter (p = 0.19) for the test – retest values. The SEM for the Odyssey putter was 1.02 cm with a change in mean of -0.16 cm. The GEL® putter had a smaller SEM (0.47 cm) and marginally change in mean (0.12 cm) this also included a smaller range of 95% confidence limit (0.37 cm) in comparison to 2.73 for the Odyssey putter. Weak relative reliability was demonstrated for both the Odyssey and GEL® putter with an ICC of 0.10 and 0.06 respectively.

Means and reliability statistics for the Odyssey and GEL® putters for the ball aligned at 10° left condition are presented in Table 5.3 and Table 5.4. No significant differences were observed for either the Odyssey (p = 0.848) or GEL® putter (p = 0.944) for the test – retest values. The SEM was low for both the Odyssey putter (0.96 cm) and GEL® putter (0.58 cm). This excellent absolute reliability is strengthened by very small change in mean between the test – retest scores (Odyssey putter = 0.04, GEL® putter = -0.01). However, again very weak relative reliability was observed with ICC scores of 0.05 and 0.12 for the Odyssey and GEL® putters.

Table 5.5 and Table 5.6 displays means and reliability statistics for the Odyssey and GEL® putter for the ball aligned at 10° right condition. No significant differences were observed for either the Odyssey (p = 0.0530 or GEL® putter (p = 0.656) for the test – retest values. Both the Odyssey and GEL® putter had strong SEMs with 0.88 cm and 0.43 respectively, along with the larger SEM the Odyssey putter also had a larger change in mean of 0.34 in comparison to the GEL® putters -0.04. A moderate ICC was observed for the Odyssey putter (0.48) and a weak ICC for the GEL® putter (0.04).

Means and reliability statistics are presented in Tables 5.7 and 5.8 for the Odyssey and GEL® putter for the ball positioned randomly condition. Significant differences were observed between the test – retest scores for the Odyssey putter (p = 0.013). No significant differences were found between the test – retest scores for the GEL® putter (p = 0.704). Along with this significant difference the Odyssey putter demonstrated weaker relative reliability in comparison to the GEL® putter. This is reflected in a higher SEM (0.94 v 0.42) and increased change in the mean (0.46 v -0.03). Weak relative reliability was demonstrated for both putters (Odyssey putter = 0.08, GEL® putter = 0.16).

A repeated measures ANOVA ($F_{(3, 147)} = 1.152$, $p = 0.330$) indicated no significant differences occurred between the different conditions tested. A separate repeated measures ANOVA ($F_{(2.792, 276.366)} = 0.737$, $p = 0.522$) also indicated no significant differences for the GEL® putter.

True Roll

Tables 5.1 and 5.2 display means and reliability statistics for the true roll variable for the Odyssey and GEL® putters for the ball aligned at 0°. Significant differences were observed in the test – retest values for the Odyssey putter (p = 0.021), however no significant differences were found for the GEL® putter (p = 0.542). A larger SEM was observed for the Odyssey putter (5.21 cm) in comparison to the GEL® putter where a small SEM of 1.79 cm was observed. This was coupled with a larger change in mean observed for the Odyssey putter (-1.56 cm, GEL® putter = -0.22). Very weak relative reliability was observed for both putters (Odyssey putter = 0.08, GEL® putter = 0.03).

Means and reliability data for the variable true roll for the Odyssey and GEL® putters while the ball was aligned at 10° left are presented in Table 5.3 and Table 5.4. Significant differences were observed in the test – retest values for the Odyssey putter (p = 0.045), no significant differences were however observed for the GEL® putter (p = 0.152). Despite significant differences being observed for the Odyssey putter the SEM observed was smaller (2.43 cm) in comparison to the GEL® putter (2.75 cm). Consistent change in means were observed for both groups at -1.00 cm and 0.80 cm for the Odyssey and GEL® putter respectively. Weak ICCs were observed for both putters (Odyssey putter = 0.07, GEL® putter = 0.13).

Tables 5.5 and 5.6 display means and reliability statistics for the ball aligned 10° right for the Odyssey and GEL® putters. No significant differences were observed for either the Odyssey (p = 0.215) or the GEL® putter (p = 0.564). Excellent absolute reliability was demonstrated for both putters, the Odyssey putter had an SEM of 2.21 cm and the GEL® putter had an SEM of 1.89. The similarity between the two putters was also reflected in the similar spread of 95% confidence limits (Odyssey putter = 1.72 cm, GEL® putter = 1.52 cm). Weak ICCs were observed for both the Odyssey (0.10) and GEL® putter (0.12).

Means and reliability statistics for the random ball placement for the Odyssey and GEL® putters are presented in Table 5.7 and Table 5.8. There were significant differences found for the test

– retest values for the Odyssey putter ($p = 0.004$), no significant differences were observed for the GEL® putter ($p = 0.306$). A larger SEM was also observed for the Odyssey putter (3.19 cm) in comparison to the GEL® putter (1.93 cm). This was also the case for the change in mean between the test – retest values (Odyssey putter = 1.90, GEL® putter = -0.40). Weak relative reliability was demonstrated, the Odyssey had an ICC of 0.12 and the GEL® putter had an ICC of 0.19.

A repeated measures ANOVA ($F_{(2.533,\ 124.124)} = 5.363$, $p = 0.003$) indicated significant differences between the four conditions tested. The significant differences were found to lie between, ball 0° aligned condition and ball aligned 10° left ($p = 0.005$); ball aligned 10° left and 10° right ($p = 0.038$) and the random ball condition and ball aligned 10° left ($p = 0.002$) for the Odyssey putter. A separate repeated measures ANOVA ($F_{(2.676,\ 264.88)} = 28.643$, $p = 0.001$) for the GEL® putter indicated significant differences. Significant differences were found to lie between ball 0° aligned condition and ball aligned 10° left ($p = 0.028$), aligned 10° right ($p = 0.001$) and the random ball condition ($p = 0.025$). Significant differences were also found between the ball aligned 10° left and right ($p = 0.001$) and the ball aligned 10° right and random ball condition ($p = 0.001$).

Vertical Launch Angle

Table 5.1 and Table 5.2 present means and reliability statistics for the vertical launch angle variable with the ball aligned at 0° condition using the Odyssey and GEL® putter. No significant differences were observed for the Odyssey ($p = 0.169$) or GEL® putter ($p = 0.998$) for the test – retest values. The SEM was consistent between both the Odyssey (0.42°) and GEL® putter (0.44°), this was also apparent in the change in mean with a difference of -0.12° and 0.00° respectively. Very weak relative reliability was demonstrated for both putters (Odyssey putter = 0.00, GEL® putter = 0.13).

Means and reliability statistics are presented in Tables 5.3 and 5.4 for the ball aligned 10° left condition for the Odyssey putter and GEL® putter. No significant difference was identified for the Odyssey putter ($p = 0.159$), however, significant differences were observed for the GEL® putter ($p = 0.001$). A larger SEM was observed for the GEL® putter (0.41°) in comparison to the Odyssey putter (0.33°). This was also apparent for the change in mean (-0.44° and 0.09°) respectively. In addition to this weak ICCs were observed for both the Odyssey (0.14) and GEL® putter (0.09).

Table 5.5 and Table 5.6 display means and reliability statistics for the Odyssey and GEL® putters for the ball aligned 10° right condition. Significant differences were observed for the test – retest values for the Odyssey putter ($p = 0.001$) however no significant differences were observed for the GEL® putter ($p = 0.914$). Very similar SEMs were observed for both the Odyssey putter (0.52°) and GEL® putter (0.54°), however, a larger change in mean was observed for the Odyssey putter (0.42°) in comparison to the GEL® putter (0.01°). Weak to very weak relative reliability was observed, the Odyssey putter had an ICC of 0.35, whereas the GEL® putter had an ICC of 0.01.

Means and reliability statistics for the random ball alignment for the Odyssey and GEL® putters are presented in Tables 5.7 and 5.8. No significant differences were observed for either the Odyssey ($p = 0.206$) or GEL® putter ($p = 0.628$). Very similar SEMs were demonstrated for the Odyssey (0.50°) and GEL® putter (0.49°). In addition to this similar change in means were also observed at -0.13° and -0.04° for the Odyssey and GEL® putter respectively. Weak relative reliability was demonstrated for both putters (Odyssey putter = 0.11, GEL® putter = 0.08).

A repeated measures ANOVA ($F_{93,\ 147)} = 6.290$, $p < 0.001$) indicated significant differences between the different test conditions using the Odyssey putter. These significant differences were found to lie between ball 0° aligned condition and ball aligned 10° right ($p = 0.015$). Significant differences were also found to lie between the ball aligned 10° right and the ball aligned 10° left ($p = 0.008$), additionally significant differences were observed between the ball aligned 10° right and the random ball condition ($p = 0.001$). Another repeated measures ANOVA ($F_{(3,\ 297)} = 13.312$, $p < 0.001$) indicated differences between the different test conditions using the GEL® putter. These significant differences were found to lie between the ball 0° aligned condition and ball aligned 10° right ($p < 0.001$) and 10° left ($p < 0.001$). Furthermore, significant differences were found to lie between the random ball condition and ball aligned 10° right ($p < 0.001$) as well as 10° left ($p < 0.001$).

Horizontal Launch Angle

Means and reliability statistics for the horizontal launch angle are presented in Table 5.9 with four different putter ball combinations (Odyssey-Srixon, Odyssey-Titleist, GEL®-Srixon and GEL®-Titleist). No significant differences were identified for any of the putter-ball combination (Odyssey-Srixon, $p = 0.540$; Odyssey-Titleist, $p = 0.109$; GEL®-Srixon, $p = 0.827$; GEL®-Titleist, $p = 0.666$). The range of SEMs were consistent across all four putter-ball combinations (0.18° to 0.46°). Very small change in means were observed for the Odyssey-Srixon (-0.04°), GEL®-Srixon (0.02°) and GEL®-Titleist (-0.06°). The only exception to this was the Odyssey-Titleist combination where a change of mean of -0.24°. Weak ICCs were observed for the Odyssey-Srixon (0.02), GEL®-Srixon (0.14) and GEL®-Titleist (0.12). A moderate ICC was observed for the Odyssey-Titleist (0.43).

Push or Pull

Table 5.10 displays means and reliability statistics for the push or pull data for four putter-ball combinations (Odyssey-Srixon, Odyssey-Titleist, GEL®-Srixon and GEL®-Titleist). No significant differences were observed for any of the putter-ball combinations (Odyssey-Srixon, $p = 0.233$; Odyssey-Titleist, $p = 0.082$; GEL®-Srixon, $p = 0.835$ and GEL®-Titleist, $p = 0.781$). The SEMs were consistent between the different golf balls (Odyssey-Srixon = 0.63 cm, GEL®-Srixon = 1.13 cm, Odyssey-Titleist = 1.70 cm and GEL®-Titleist = 1.96 cm). More variation in the change in mean was observed between the four putter-ball combinations (-0.70 to 1.45 cm). Weak ICCs were observed for the Odyssey-Srixon (0.02), GEL®-Srixon (0.22) and GEL®-Titleist (0.12). A good ICC was observed for the Odyssey-Titleist putter-ball combination (0.70).

Table 5.9. Reliability Measures for the variable horizontal launch angle (°) with four different putter-ball combinations (n = 20 pairs, for each putter-ball combination).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired *t*-test *p*-value
Odyssey-Srixon	0.36 ± 0.18	0.33 ± 0.17	-0.04	-0.15 to 0.08	0.18	0.02	0.540
Odyssey-Titleist	0.26 ± 0.34	0.02 ± 0.43	-0.24	-0.54 to 0.06	0.46	0.43	0.109
GEL®-Srixon	0.30 ± 0.25	0.32 ± 0.34	0.02	-0.17 to 0.20	0.28	0.14	0.827
GEL®-Titleist	0.50 ± 0.50	0.44 ± 0.37	-0.06	-0.37 to 0.24	0.46	0.12	0.666

Table 5.10. Reliability Measures for the variable whether the ball was pushed or pulled (cm) with four different putter-ball combinations (n = 20 pairs, for each putter-ball combination).

	Test (mean ± SD)	Retest (mean ± SD)	Δ Mean	95% CL	SEM	ICC	Paired *t*-test *p*-value
Odyssey-Srixon	1.53 to 0.78	0.83 to 0.44	-0.70	-1.11 to -0.29	0.63	0.02	0.233
Odyssey-Titleist	0.94 ± 1.56	2.39 ± 3.96	1.45	0.32 to 2.57	1.70	0.70	0.082
GEL®-Srixon	1.28 ± 1.07	1.35 ± 1.45	0.08	-0.68 to 0.83	1.13	0.22	0.835
GEL®-Titleist	2.13 ± 2.12	1.86 ± 1.56	-0.27	-1.57 to 1.03	1.96	0.12	0.781

5.2.5 Discussion

The aim of this study was to examine the absolute and relative reliability of the Quintic Ball Roll software. This was through assessing the day to day reliability and through manipulating the placement of the ball (0° ball alignment, 10° left ball alignment, 10° right ball alignment and random ball alignment). For an overview of all significant differences between the different ball alignment test conditions (Appendix C). Significant differences were observed between the test – retest values for the following variables velocity (Odyssey – ball aligned at 0° (Table 5.1), GEL® - ball aligned at 10° left (Table 5.4)), side spin (Odyssey – ball aligned at 0° (Table 5.1)), true roll (Odyssey – ball aligned at 0° (Table 5.1), Odyssey – ball aligned at 10° left (Table 5.3), Odyssey – random ball placement (Table 5.7)) and vertical launch angle (GEL® - ball aligned 10° left (Table 5.4), Odyssey – ball aligned 10° right (Table 5.5)). No significant differences were observed for initial ball roll, start of forward rotation, horizontal launch angle (Table 5.9) and whether the ball was pushed or pulled (Table 5.10) for either the Odyssey or GEL® putter.

More day to day variability was observed than was originally predicted, however, this may not solely be due to inaccuracy with the Quintic Ball Roll software. Figures 5.2 – 5.5 show visual differences of two different trials for each putter. The test conditions remained identical as each trial was taken from the 0° ball aligned condition. Therefore the differences observed in Figures 5.2 – 5.5 show that at least a portion of this variability observed might actually be occurring. Frame thirty-six of Figures 5.2 – 5.5 depict the ball at thirty cm and particularly emphasises the actual differences occurring. Moreover, the fact there was no trend where significant differences lied for either of the putters for any of the test conditions suggests that actual variability rather than measurement error existed. This along with the large variance observed for kinematic ball roll variables (Tables 5.2 – 5.10) with little to variance in the putting stroke of the mechanical putting arm, provides rationale that a previously unexplored mechanism may be causing this variance.

A variable that is very difficult to control is the putter face – ball interaction. This is due to minimal differences in contact between the putter face and ball influenced the roll of the ball. All golf balls have a dimple pattern, which will vary from brand to brand, but also from ball to ball due to the printing process (where the ball needs to be placed at a certain orientation for the camera to recognise the three dot pattern) therefore the putter may hit a different part of the dimple pattern causing different ball characteristics and thereby increasing day to day variability. Previously golf balls with different diameters and dimple size have shown to influence drag differently (Libii, 2007). There is very limited literature in regards to the influence of dimples on the roll of the golf putt, only Pelz (2000) has acknowledged that dimples cause some variability during the impact between the putter and golf ball. This is what

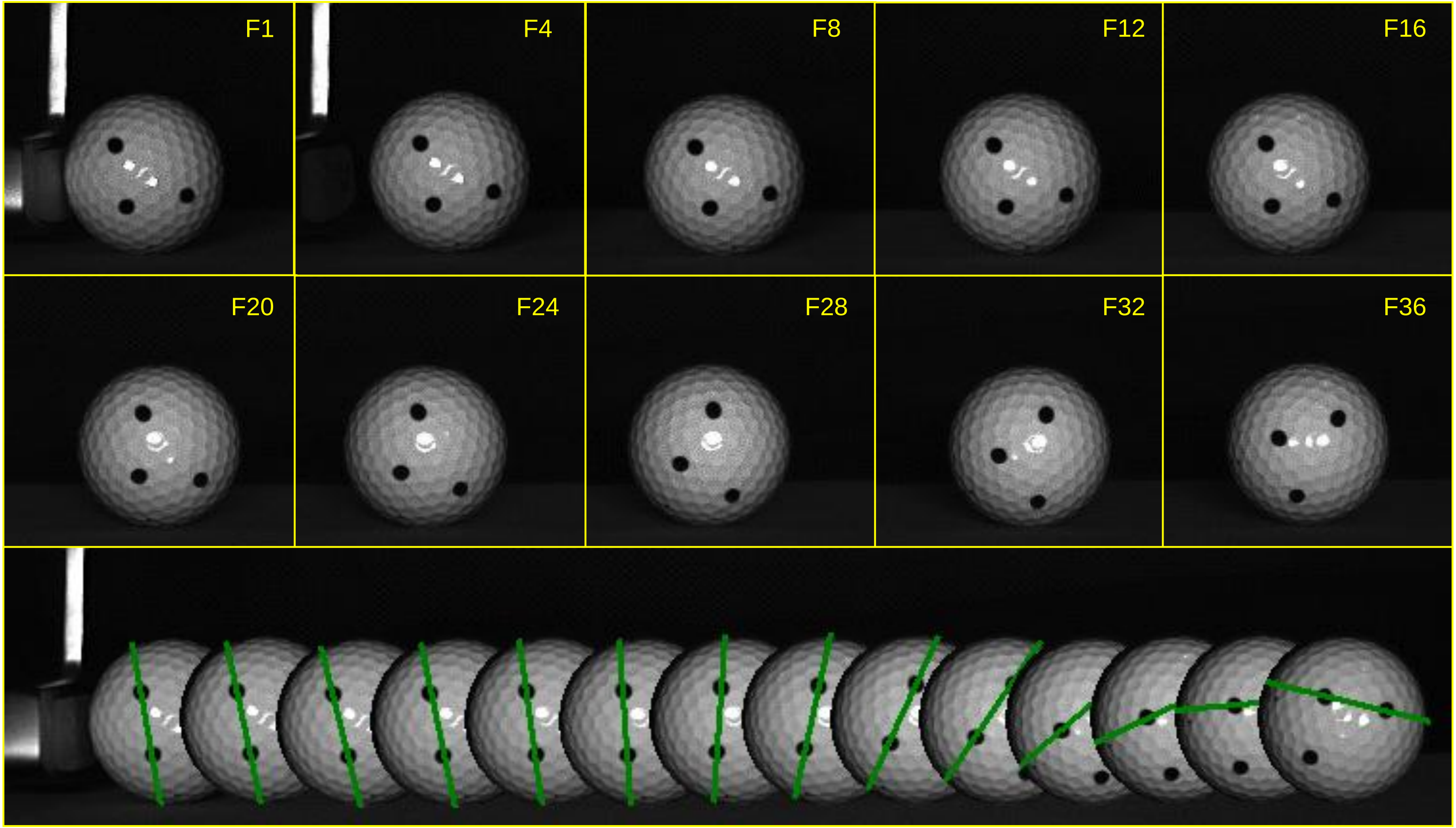

Figure 5.2. Pictures of subsequent frames and ball composite using the Odyssey putter demonstrating the variability in ball roll.

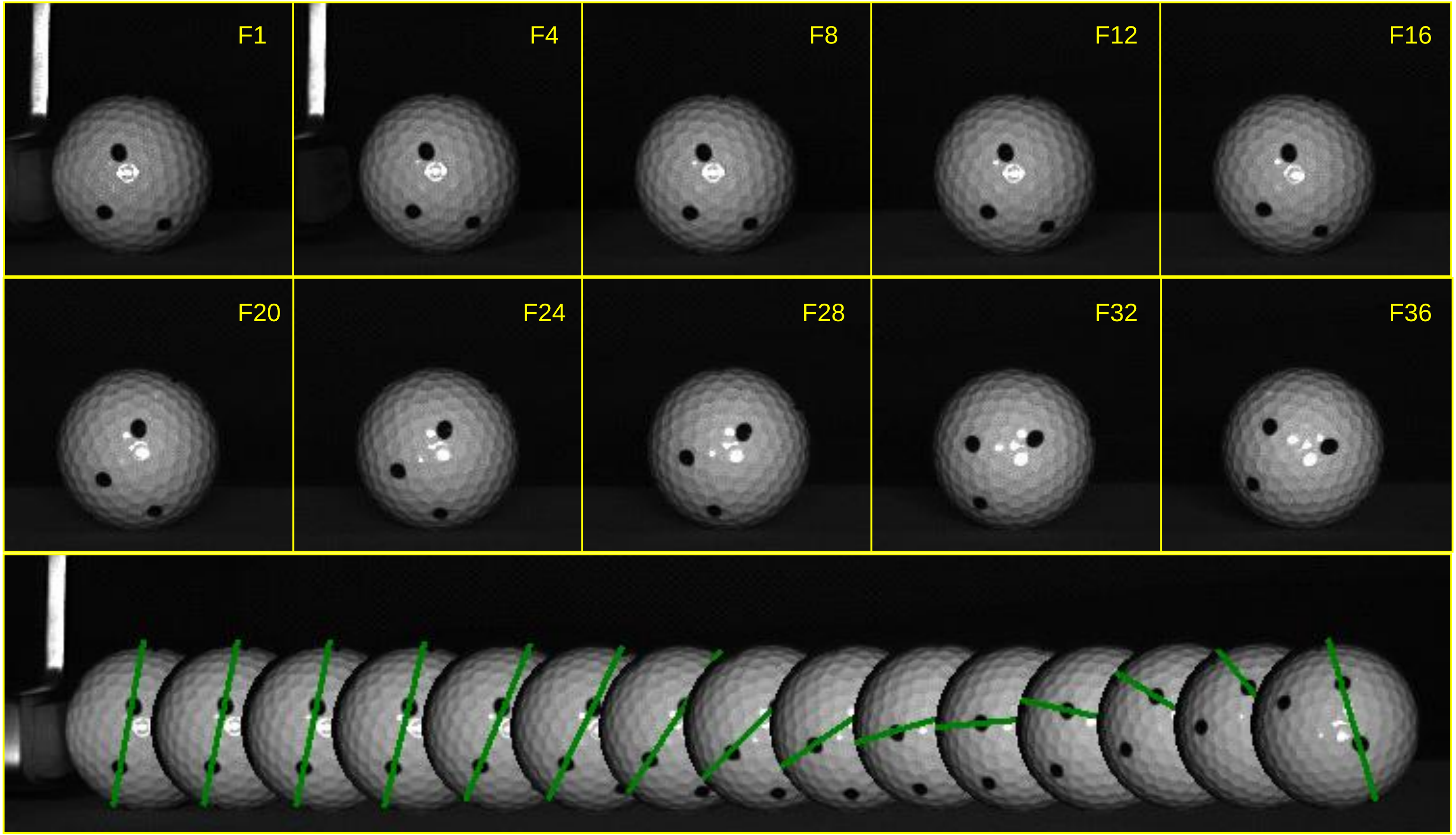

Figure 5.3. Pictures of subsequent frames and ball composite using the Odyssey putter demonstrating the variability in ball roll.

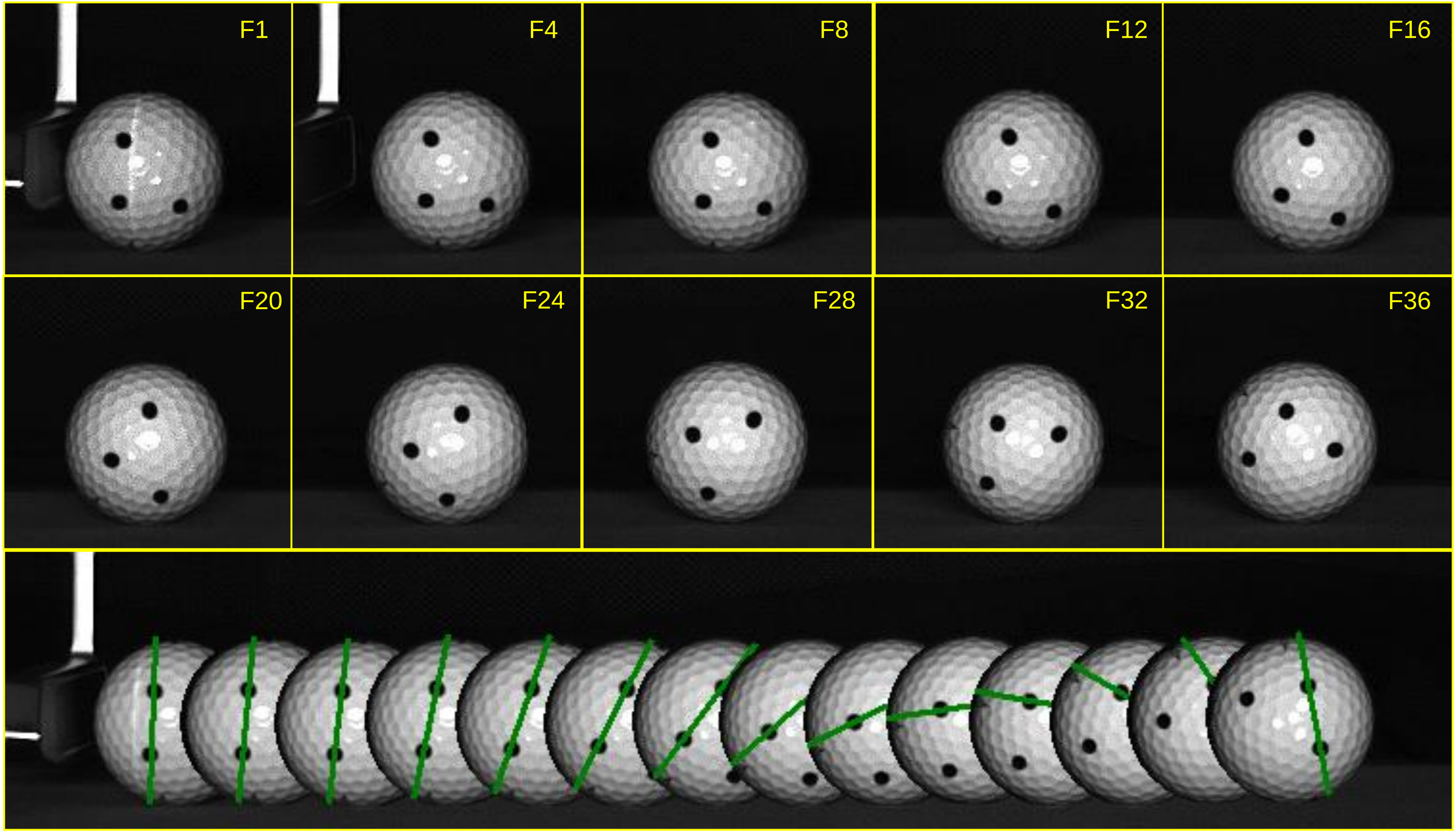

Figure 5.4. Pictures of subsequent frames and ball composite using the GEL® putter demonstrating the variability in ball roll.

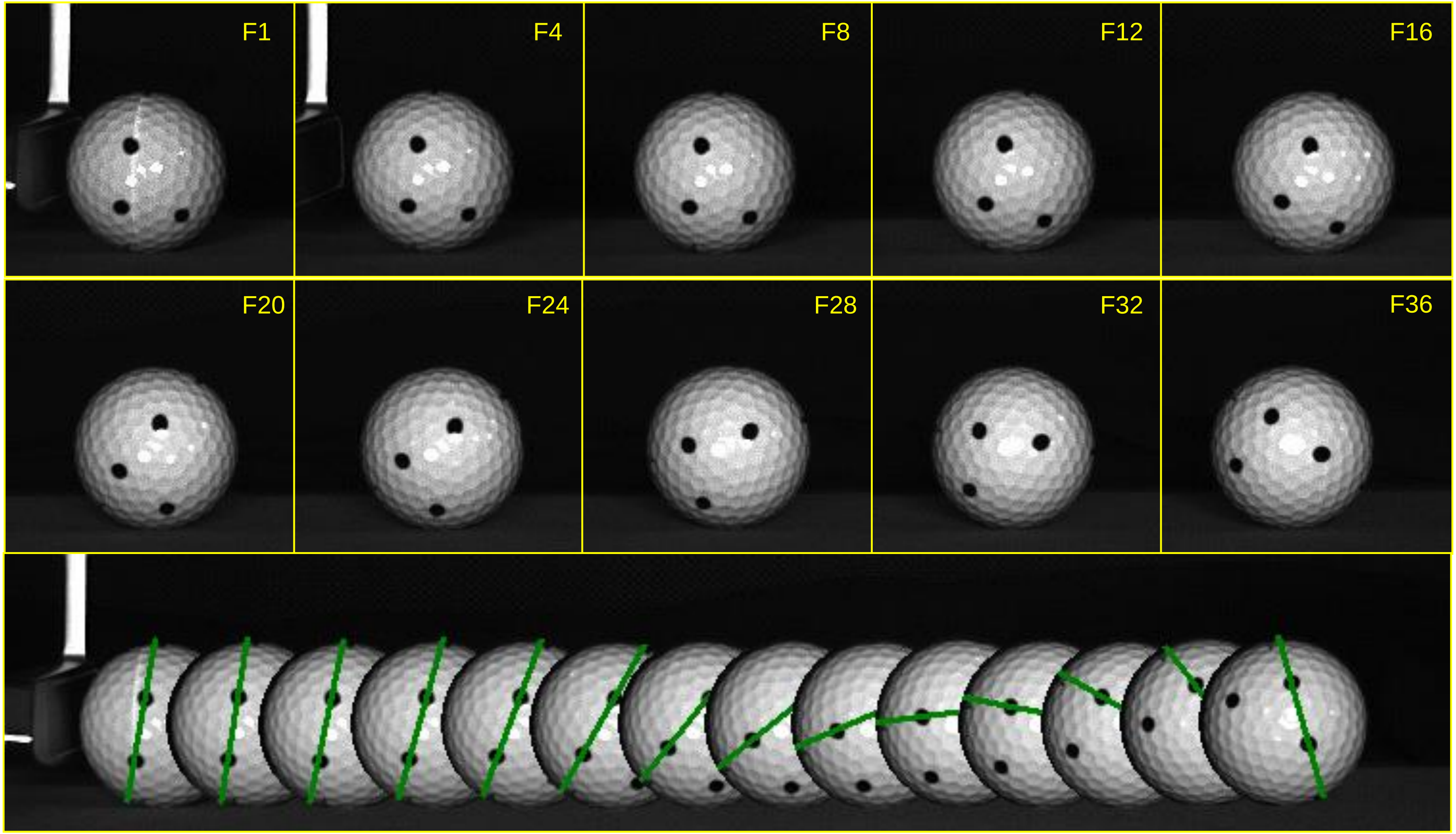

Figure 5.5. Pictures of subsequent frames and ball composite using the GEL® putter demonstrating the variability in ball roll.

could have potentially caused some of the statistically significant differences observed in the test – retest values. Additionally Cross (2006) has observed golf balls being dropped on a marble surface to deflect at different angles in comparison to a billiard ball; it is proposed the dimples cause this.

Between the different test conditions a number of significant differences were identified. For velocity significant differences were observed between the ball correctly aligned (0°) and whether the ball was aligned 10° left or right for the Odyssey putter and all other ball conditions for the GEL® putter (Appendix C). For the side spin variable again significant differences were observed, for the Odyssey putter this was between the ball correctly aligned and the random position and for the GEL® putter it was between the ball aligned 10° right and 10° left, and additionally the random ball placement (Appendix C). For true roll, significant differences were observed between the ball aligned 10° left and all other ball conditions for the Odyssey putter (Appendix C). For the GEL® putter it was between the ball aligned 10° right and all other ball conditions, in addition to this between the ball being aligned at 0° and 10° left and the random ball condition (Appendix C). More statistical differences are likely to have been found for the true roll variable as it is calculated using a formula with inputs for the other variables. A number of statistical differences were also observed for the vertical launch angle for the Odyssey putter significant differences were found to lie between the ball aligned 10° right and all other ball conditions (Appendix C). For the GEL® putter significant differences were found to exist between the ball randomly aligned and the ball aligned 10° right and left, in addition to this the ball correctly aligned at 0° was found to be significantly different to the ball being aligned 10° left or right (Appendix C). No significant differences were identified for the initial ball roll or forward roll variables. Based on these results it is clear care needs to be taken when placing the ball when using the Quintic Ball Roll system. Even though the protocol exaggerated manipulation of the ball placement to ensure this does not cause software error correct alignment for each trial is clearly important.

The SEM was decided as the most appropriate measure of absolute reliability for the current study, as it is expressed as the same unit, a long with this 95% confidence intervals were calculated to express the largest amount of error that could be expected. Variance in velocity may be due to the testing method, as the mechanical putting arm was drawn back to a predetermined position it was attached to a bull clip and then released. Friction caused by this action may account for some variance in the difference in ball velocity coupled with the impact point. For the ball 0° aligned condition the Odyssey putter (SEM = 0.03 ms^{-1}) demonstrated marginally better day to day reliability in comparison to the GEL® putter (SEM = 0.04 ms^{-1}) (Tables 5.1 – 5.2). However, this is very low and consistent across the other testing conditions and therefore can be considered very reliable. Very poor relative reliability was observed for velocity for all testing conditions, however, as discussed in Chapter Three: Section 3.2.5. This is likely to be due to the way that the ICC is calculated. McDowell (2006) discusses that the ICC ranks the data in combination with measuring the mean resemblance between scores. As again this reliability protocol assessed the Quintic Ball Roll software without using human subjects, and therefore the difference between scores is likely to be very small, greatly influencing the rank of the trial in the test – retest protocol. This is the rational to assess the reliability of the software predominantly assessing the other reliability measurements and not discussing the ICC of all of the variables.

Cut and hook spin demonstrated accuracy to within 13.76 rpm based on the SEM for the GEL® putter and 10.41 rpm for the Odyssey putter, for the ball 0° aligned condition (Tables 5.1 – 5.2). This was consistent for when the ball was aligned 10° right the GEL® putter had an SEM of 12.34 rpm and the Odyssey putter had an SEM of 10.34 rpm. However when the ball was aligned 10° left the day to day variance increased, the GEL® putters SEM was 14.26 rpm in comparison to 12.76 rpm for the Odyssey putter (Tables 5.3 – 5.4). The largest range of change in the means between the different test conditions was also observed for side spin, a minimum -6.75rpm for the Odyssey putter was observed for the 0° aligned condition (Table 5.1) and a maximum of 3.75 rpm was observed for the GEL® putter with the ball aligned at 10° right (Table 5.6). These results suggest than care should be taken when originally lining up the putt, with subsequent trials being lined up exactly the same. This will reduce the possibility of the dimples affecting the roll of the golf ball, and any potential increases in software error. This will help reduce any variance caused by inadequate ball placement in regards to line.

Initial ball roll had a variance of 12.40 rpm for the Odyssey putter and 13.61 rpm for the GEL® putter during the 0° aligned condition (Tables 5.1 – 5.2). This was consistent across the other ball placement conditions except for the GEL® putter when aligned 10° left (Table) where it increased to 18.78. Therefore the Odyssey putter demonstrated better day to day reliability however the GEL® putter demonstrated preferable ball roll characteristics. Previously putters with grooves have found to increase initial ball roll (Hurrion & Hurrion, 2002). If there were to be an increase in variation between the different ball conditions it would have been expected to occur during random ball placement as variation would likely have increased on the balls placement on the anterior – posterior axis and therefore the contact would have been at a different point on the pendulum. However, for the Odyssey putter the SEM was 9.96 rpm, and for the GEL® putter 14.06 rpm (Tables 5.7 – 5.8), therefore in comparison to the ball correctly aligned the Odyssey putter had a decrease of 2.44 rpm whereas the GEL® putter increased 0.45 rpm (Tables 5.1 – 5.2).

Forward roll demonstrated accuracy to within 1.02 cm while using the Odyssey putter and 0.47 cm with the GEL® putter with the ball aligned at 0° condition (Tables 5.1 – 5.2). This was found to be relatively consistent across the different ball conditions with the SEM observed with the Odyssey putter being approximately double that of the GEL® putter. No significant differences were observed for forward roll between the different test conditions. Hurrion and Hurrion (2002) also found forward roll to occur earlier with putters that have a grooved faced design. Brouillette (2010) also found topspin or forward roll to occur earlier with a grooved putter, however Brouillette (2010) doesn't consider the ball to roll earlier due to the reduction in velocity, the current study also found a reduction in velocity. Brouillette (2010) states inserts modulate the coefficient of restitution at impact but not in a way that produces preferable forward roll. A potential limitation of the Brouillette (2010) study is that grooved inserts were attached to the same putter with black electrical vinyl tape, which may limit how applicable the results are to the current golf market.

True roll is calculated using the other variables that the Quintic Ball Roll software measures, this distance signifies when the ball is displacing itself once over its circumference. When the ball was aligned at 0° the Odyssey putter demonstrated worse day to day reliability (SEM = 5.21 cm) in comparison to the GEL® putter (SEM = 1.79 cm) (Tables 5.1 – 5.2). This was also the case with all the other test conditions (10° left, 10° right and random) (Tables 5.3 – 5.8). Although the Odyssey putters SEM was not as elevated in these conditions as the 0° condition. The largest change in mean was also observed for the Odyssey putter with the ball randomly aligned (1.90 cm). The smaller true roll observed for the GEL® putter may contradict findings by Brouillette (2010) that although putters with a grooved face demonstrate preferable ball roll characteristics at the start of the putt, this may not result in a better overall putt or resultant putt. In addition to this, the increased friction (causing spin stabilisation) during the first 30 cm of a putt may hold the ball on the correct line resulting in a higher success rate of putts.

During the ball 0° aligned condition the Odyssey putter had an SEM of 0.42° in comparison to the GEL® putter that had an SEM of 0.44°, for vertical launch angle (Tables 5.1 – 5.2). Therefore both putters demonstrated good day to day reliability. If day to day variability were to increase, it would have been most likely to increase during the random placement ball condition, as the ball placement on the anterior – posterior axis wouldn't have been consistent and therefore impact would have been at a slightly different point during the pendulum. Standard error of measurement values showed an 11% increase for the GEL® putter and a 19% increase for the Odyssey putter, this was reflected in increased values of 0.05° and 0.08° respectively (Tables 5.7 – 5.8). The largest change in mean observed however, was for the GEL® putter while aligned 10° left, this did not seem to elevate the SEM. In accordance to the

Quintic Ball Roll Manual v2.4 the GEL® putter demonstrated preferable ball roll characteristics as for every ball condition the Odyssey had a launch angle of 2° or greater whereas the GEL® putter had an average launch angle of 1.63°.

On the week of testing the horizontal launch angle and push pull feature was not functioning correctly, so the data analysed in this study was collected at a later date with four different putter ball combinations. For the horizontal launch angle no significant differences were observed for any of the four putter-ball combinations test – retest scores (Table 5.9). It was observed that the SEM was different for both golf ball's with slightly elevated values observed for the Odyssey-Titleist (0.46°) and GEL®-Titleist group (0.46°) in comparison to the Odyssey-Srixon (0.18°) and GEL®-Srixon (0.28°) groups. This was despite the fact a considerable difference was observed for the change in mean for the Odyssey-Titleist group (-0.24°) in comparison to the other groups (-0.06° to 0.02°). However with similarities between the four putter-ball combinations, this variable can be considered to be reliable.

Like the horizontal launch angle no significant differences were observed for whether the ball was pushed or pulled data for any of the four putter ball combinations (Table 5.10). This is to be expected due to the close relationship shared between the two variables. The SEM also demonstrates strong reliability with a range of 0.63 to 1.96 cm being demonstrated. The change in means observed however were more variable with a minimum change in mean of -0.70 demonstrated for the Odyssey-Srixon group and a maximum of 1.45 cm demonstrated for the Odyssey-Titleist group. An example of the ICC not being the applicable reliability measure in this instance is demonstrated by the Odyssey-Titleist group, where the largest change in mean was observed an ICC of 0.70 was recorded in comparison to a range of 0.02 to 0.22 for the other three putter-ball combinations.

In regards to the horizontal launch angle and whether the ball was pushed or pulled it has previously been reported that putter face angle accounts for 83% of the initial direction of a putt (Pelz, 2000) with 17% accounted for by stroke path (Karlsen et al. 2008; Pelz, 2000). Both of these were fixed in the current study, with the putter being securely placed in the mechanical putting arm, therefore the current study suggests the impact point with the ball can significantly change the characteristics of the ball roll, which potentially could result in a missed putt. MacKenzie and Evans (2010) state for a 4 metre putt if the ball is started above 0.6° off the target line, the resultant putt will miss if hit with optimal speed, however this doesn't take into account the impact point of the ball. As cut and hook spin, initial ball roll and vertical launch angle could also affect the direction of the putt, and will vary from putt to putt along with the horizontal launch angle.

5.2.6 Conclusion

In conclusion, all measurement variables showed day to day variability however, this may not be solely due to measurement error. The putter face – ball interaction may have an affect on the ball roll characteristics, no published research has extensively looked at this interaction however to confirm this notion. For the best possible accuracy it is essential that the Quintic Ball Roll system is calibrated correctly, with the putt being correctly lined up and the camera being placed perpendicular to this line. Line lasers should be used as a visual aid for ball position with the correct line in subsequent putts, as well as marking the ground with permanent marker. This will ensure correct ball placement for each trial, minimising the software error that exists. Along with further investigation into the possibility that the putter-ball interaction during contact is causing variation, the Quintic Ball Roll software can be considered reliable and appropriate for further use due to the very good absolute reliability demonstrated.

5.3 Validity of the Quintic Ball Roll Software

5.3.1 Abstract

Background: No scientific literature has been published using the Quintic Ball Roll software assessing the kinematics of the golf putt; therefore it was deemed necessary to test the validity of the velocity and horizontal launch angle. **Method:** A total of 20 simulated 3.2 metre putts were completed with a mechanical putting arm. The Quintic Ball Roll software velocity and horizontal launch angle measurements were compared to measurements using the Photoshop CS5 software. Validity was assessed using the SEM, Pearson's *r,* coefficient of determination, change in mean and 95% confidence limits. **Results:** Very strong validity was demonstrated for both velocity and horizontal launch angle measurements. This included a very low change in mean (velocity = 0.02 ms^{-1}: horizontal launch angle = 0.04°) and very strong coefficient statistics (velocity, r = 0.90; horizontal launch angle, r = 0.94). **Conclusion:** The Quintic Ball Roll measurements velocity and horizontal launch angle can be considered to be valid and therefore suitable to use in future analysis.

5.3.2 Introduction

To date no scientific literature has been published using the Quintic Ball Roll software assessing the kinematics of ball roll during a golf putt. Therefore it was deemed necessary to assess the validity and accuracy of the Quintic Ball Roll software measurements of velocity and horizontal launch angle against a criterion measure. Due to the Quintic Ball Roll being a new, novel piece of software, the other variables (side spin, start of forward roll, initial ball roll and vertical launch angle were excluded from validity testing since there was no obvious criterion measure that the variables could be compared against.

The aim of this study is to assess the validity of the Quintic Ball Roll software against criterion measurements on Adobe Photoshop CS5. Secondly, to assess the accuracy of the Photoshop CS5 and Image J software measurements which are used later within this thesis. This will give the ability to gauge as to whether the software assessed is suitable to conduct further research in to; the role of the impact point on the golf ball on roll kinematics.

5.3.3 Methods

Experimental set – up

All testing was completed in the Quintic Golf Laboratory on an artificial putting surface registering 12 on the stimpmeter. The experimental set – up was as outlined in Chapter 5 (pp. 73) with the added equipment outlined below.

An additional golf ball was used along with the Srixon Z-Star, which was the Titleist Pro V1 (Acushnet Europe Ltd., Cambridgeshire, UK). An additional Quintic camera (GigE live) sampling at 200 fps was placed on a stationary Velbon CX-440 tripod 1.8 metres directly above the golf ball giving an overhead (birds eye) view of the impact.

Procedure

The first putter was held securely in the Quintic mechanical putting arm and aligned to produce a square to square swing path (Figure 5.6 A). The counter balanced putting arm block was set to produce a putt of 3.2 m. The putting arm was tied to a weighted pole and released using a clip. With two putters and two golf balls being used in the protocol, a total of four putter-ball combinations were tested (GEL® Titleist, GEL® Srixon, Odyssey Titleist and Odyssey Srixon).

A total of 20 trials were recorded (5 for each putter-ball combination in the following order, GEL® Titleist, GEL® Srixon, Odyssey Titleist and Odyssey Srixon). Testing in this order ensured that the putter face angle and putter path was the same for each ball when using each putter as the putter was not adjusted within the mount on the putting arm. Each trial was recorded using the Quintic camera offering an overhead view and the Quintic Ball Roll camera (220 fps) giving a side on view of the golf ball (Figure 5.6 B).

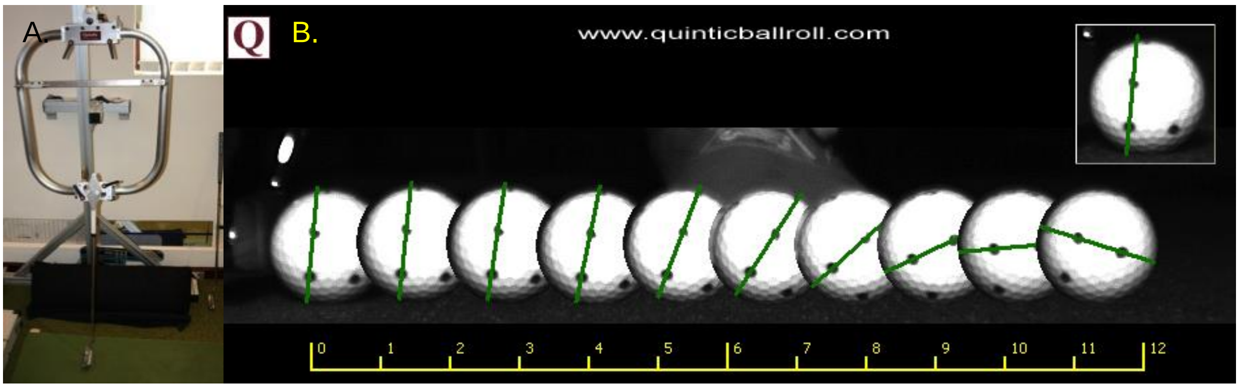

Figure 5.6. The Quintic custom built mechanical putting arm mounted on a 360 kg bearing (A) and the side view of the golf putt from the Quintic Ball Roll camera (B).

Data Processing

To ensure the Photoshop CS5 and Image J software were accurate and valid, an image of a black 10 mm^2 square on a white background was used to assess the distance measurement (on Photoshop CS5) and surface area measurement (on Image J). For accuracy the image was zoomed to 400% of its original size and scaled once using the top edge of the square (separately on both pieces of software). On Photoshop CS5 the distance tool was then selected and dragged from one corner of the square to the next, giving an accurate measurement. This was firstly done for the top edge of the square (edge 1), right edge of the square (edge 2), bottom edge of the square (edge 3) and the left edge of the square (edge 4), and repeated 10 times on separate days. On Image J software the surface area was measured by accurately clicking each corner of the square. This was conducted in a clockwise fashion with the left top hand corner being located first. Again this was completed 10 times on separate days. This will ascertain whether the measurements were accurate and valid.

To assess the validity of the Quintic Ball Roll software's velocity and horizontal launch angle measurements, still images from the vertically mounted camera were processed using Photoshop CS5. The frames processed were impact (frame 0) through to frame 6 (to manually calculate velocity), these frames were selected as they are used within the Quintic Ball Roll software to calculate the velocity. Frame 12 and frame 18 to calculate the horizontal launch angle, these were selected, as frame 18 generally was the last frame the whole ball was in the view of vision, and frame 12 allowed for an approximate midway point between frame 0 and 18.

A 2D circle structure (with a line drawn at every vertex to identify the centre) was developed to place over the golf ball, identifying the centre of the golf ball. Once the 2D circle structure had been placed on each image, where the outside of the circle was lined up with the outside of the golf ball, the images were combined on Photoshop CS5 (Figure 5.7). This was completed by reducing the transparency of both images to 50%, which offered a clear depiction of the ball in each image. Firstly, frame 0 and frame 1 were combined (Figure 5.7 A), then frame 1 and frame 2 (Figure 5.7 B), frame 2 and 3 (Figure 5.7 C), frame 3 and 4 (Figure 5.7 D) and frame 4 and 5 (Figure 5.7 E).

After the images had been combined, the images were zoomed to 400% of original size. The Photoshop CS5 ruler tool was then used to measure the distance between the centres of the 2D circles giving an accurate measurement of the distance travelled between the two frames. The distance travelled was converted into a velocity measurement (ms^{-1}) and then averaged to give the average velocity of the golf ball at impact, which could be compared to the measurements of the Quintic Ball Roll software.

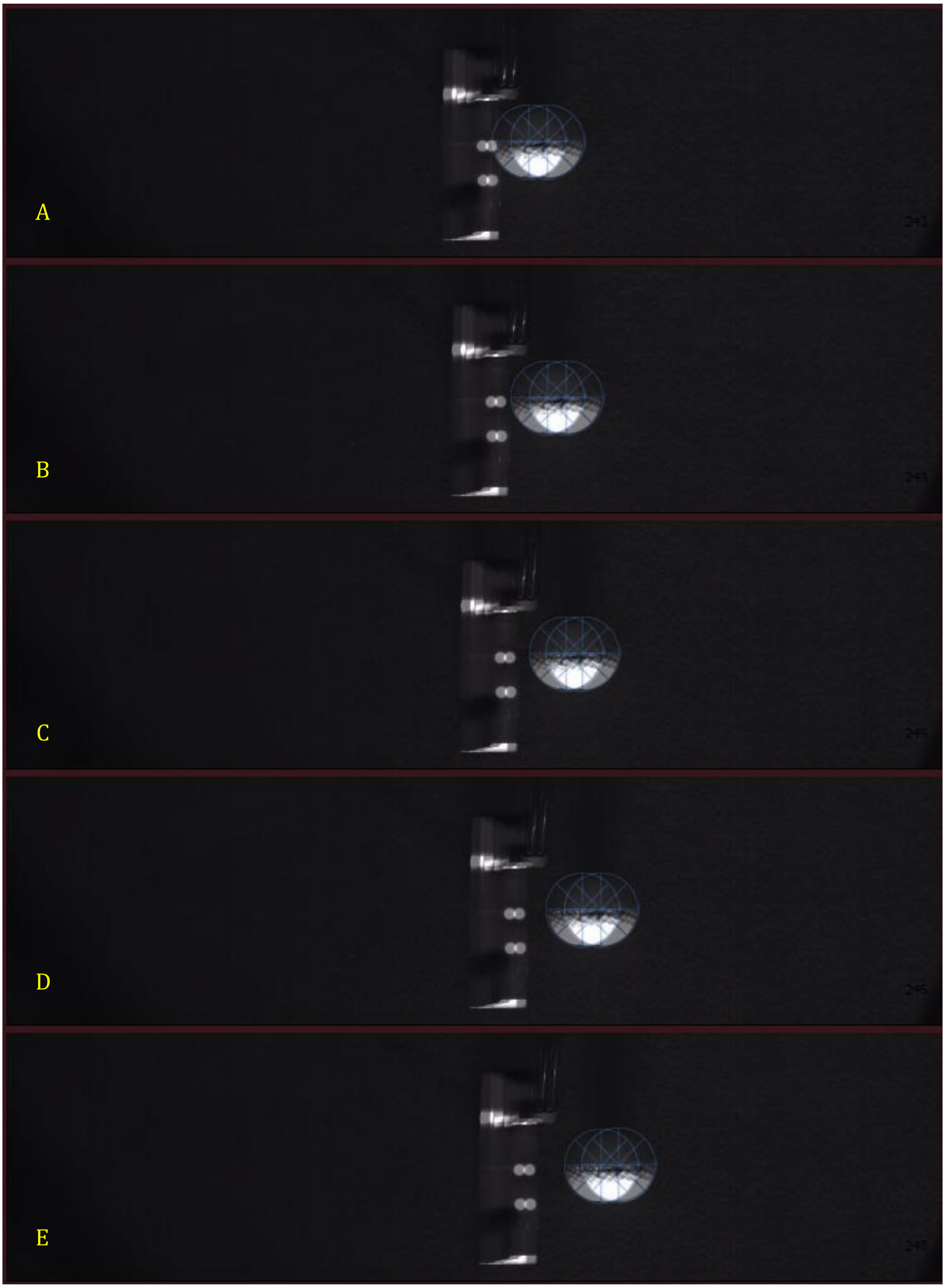

Figure 5.7. The combined images from the vertical camera used to calculate velocity measurements; A) frame 0 & frame 1, B) frame 1 & frame 2, C) frame 2 & frame 3, D) frame 3 & frame 4, E) frame 4 & 5.

To calculate the horizontal launch angle three separate frames were combined, reducing the transparency to 50% (Figure 5.8). The frames combined were frame 0 frame 12 and frame 18. After the images had been combined the image were zoomed to 400% of original size. The

Photoshop CS5 ruler tool was then moved so it intersected the centre of each 2D circle (ball). From which the angle could be measured from impact (frame 0) to frame 18 whilst intersecting the centre of the ball in frame 12 giving an indication of the horizontal launch angle.

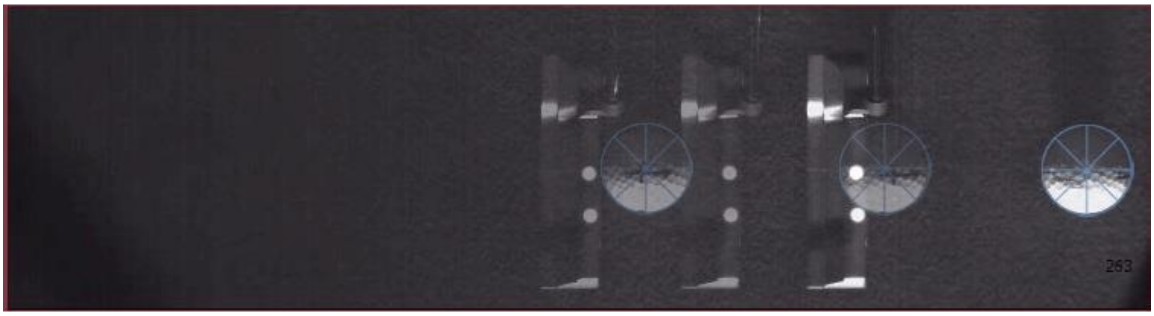

Figure 5.8. The combined images from the vertical camera used to calculate horizontal launch angle measurements, frames 0, 12 and 18 were combined.

Data Analysis

Data were exported to statistical software packages Microsoft Excel 2011 and SPSS v22 for analysis. To assess the validity of the Photoshop CS5 and Image J software a mean, standard deviation, maximum and minimum values were used to assess the accuracy of the measurements.

To assess the validity of the velocity and horizontal launch angle measurements Quintic Ball Roll software measurements were compared to Photoshop CS5 measurements (criterion measure). A combination of descriptive (mean ± SD, change in mean and 95% confidence limits (CL)) and reliability statistics were used. The change in mean and 95% CL stipulated an indication of absolute variation between the data sets. Reliability statistics were those used as of Johnstone, Ford, Hughes, Watson and Garrett (2012). The standard error of measurement (SEM), Pearson's Correlation Coefficient (r) and Coefficient of Determination (CoD) (r^2) were conducted as previously described in the literature (Hopkins, 2000). The boundaries set for the coeffictient statistics were; r = 0.8 – 1.0, very strong, r = 0.6 – 0.8, strong, r = 0.4 – 0.6, moderate, r = 0.2 – 0.4, weak, r = 0.0 – 0.2, no relationship (Salkind, 2011). The alpha level was set at $\alpha < 0.05$.

5.3.4 Results

Validity of Photoshop and Image J software

All distance (using Photoshop CS5 software) and surface area measurements (using Image J software) are displayed in Figure 5.9. The mean and standard deviation values were consistent between the edges of the square measured, edge 1 = 9.99 ± 0.02 mm, edge 2 = 10.00 ± 0.02, edge 3 = 10.00 ± 0.02 and edge 4 = 10.00 ± 0.02. No outliers were identified; the minimum measurement observed was 9.95 mm for edge 1, and the maximum measurement observed was 10.03 mm on three occasions for edge 2, 3 and 4. The surface area measurements had a mean and standard deviation of 10.00 ± 0.05 mm^2, showing slightly more variability than the distance measurements. The minimum value observed was 9.90 mm^2 and the maximum value observed was 10.06 mm^2.

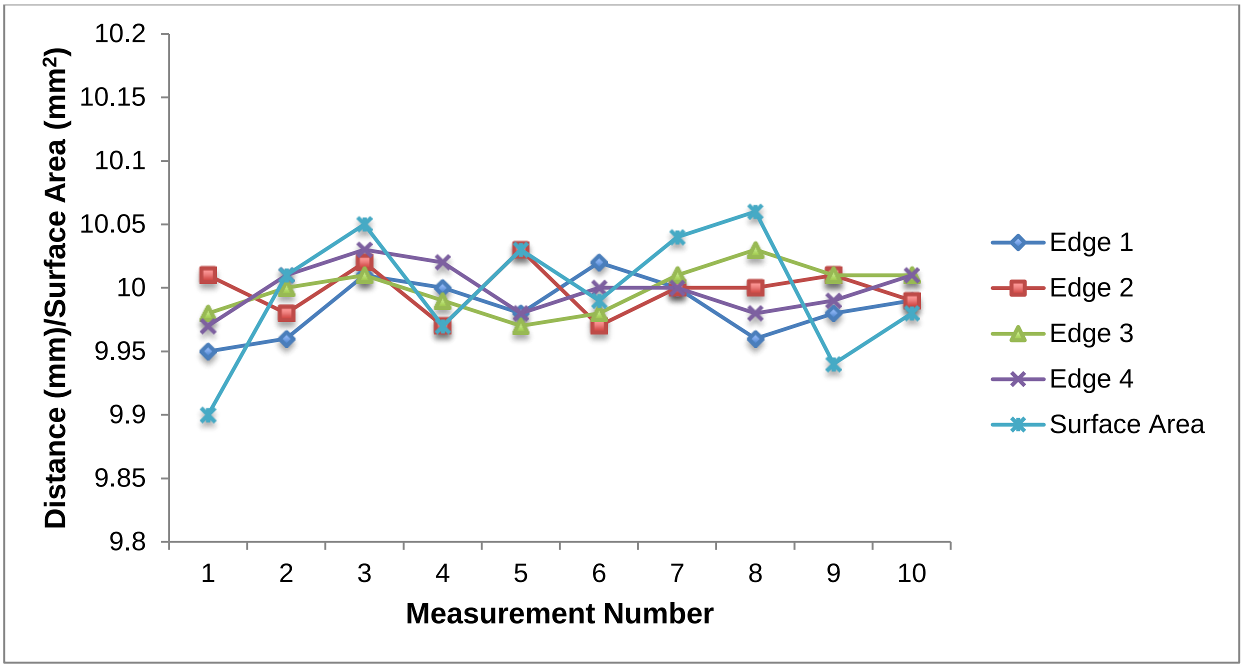

Figure 5.9. Validity measurements for distance using the Photoshop CS5 software and surface area using the Image J software.

Validity of the velocity and horizontal launch angle measurements

Table 5.11 displays validity statistics for the velocity and horizontal launch angle variables. Very strong relationships were observed for velocity (r = 0.90, $p < 0.01$) and horizontal launch angle (r = 0.94, < 0.01). This very strong validity was also reflected in tight 95% confidence intervals for the change in mean (velocity = 0.00 to 0.04 ms^{-1}; horizontal launch angle = -0.02 to 0.09°) and very low SEM values (velocity = 0.03 ms^{-1}; horizontal launch angle = 0.08°).

Table 5.11. Validity measures (95% confidence limit (95% CL), standard error of measurement (SEM), Pearson's correlation coefficient (PPC *r*) and coefficient of determination (CoD r^2)) for the Quintic Ball Roll System in comparison to Photoshop measurements (*n* = 20 trials).

	Quintic System (mean ± SD)	Photoshop System (mean ± SD)	Δ Mean	95% CL	SEM	PCC *r*	CoD r^2
Velocity (ms^{-1})	2.09 ± 0.05	2.11 ± 0.05	0.02	0.00 to 0.04	0.03	0.90	80%
Horizontal Launch Angle (°)	0.33 ± 0.25	0.36 ± 0.31	0.04	-0.02 to 0.09	0.08	0.94	88%

(Significant relationship denoted by highlighted cell, p < 0.01).

5.3.5 Discussion

The aim of this study was to firstly, examine the validity of the Quintic Ball Roll software velocity and horizontal launch angle measurements during a simulated 3.2 metre golf putt. Secondly, to assess the accuracy of the distance and surface area measurements of the Photoshop CS5 and Image J software respectively. This will ensure the software programmes are appropriate for future studies. The accuracy of the distance measurement on Photoshop CS5 was demonstrated to be very strong (Figure 5.9) in accordance with statistical boundaries (Hopkins, 2000; Johnstone et al., 2012). This was reflected in accurate mean measurements (9.99 – 10.00 mm) and very tight standard deviations (0.02 mm), additionally no outliers were observed for any of the four edges.

When all validity measures are considered (change in mean, 95% CL, SEM, Pearson's *r* and CoD) very strong validity was also observed for velocity. The change in mean between the Quintic Ball Roll and Photoshop CS5 measurements were very low (velocity = 0.02 ms^{-1}). This was coupled with a very low SEM of 0.03 ms^{-1} and a very strong significant relationship with the criterion measure (*r* = .90) (Table 5.11). This therefore demonstrates validity for the variable velocity in accordance with boundaries proposed in previous literature (Hopkins, 2000; Johnstone et al., 2012).

Additionally, the change in mean between the Quintic Ball Roll and Photoshop CS5 measurements were very low for the horizontal launch angle (0.04°), whilst the 95% CL were slightly larger in the horizontal launch angle in comparison to velocity (Table 5.11). This may be due to the fact the criterion measure only has the ability to measure angles to the accuracy of 0.1°. In addition to this the SEM was higher for horizontal launch angle in comparison to velocity. Despite this, horizontal launch angle demonstrated a very strong relationship (*r* = .94) with the criterion measure. Highlighting that a strong trend was identified between the Quintic Ball Roll software and the measurements from Photoshop CS5 (this is also reflected in the CoD measurements). The fact that a very strong relationship was observed is a positive result and demonstrates validity of the horizontal launch angle measurement (Hopkins, 2000; Johnstone et al., 2012). Additionally, the measurement of the horizontal launch angle can be considered valid, as the small amount of error highlighted by the SEM (0.08°) would still result in a successful putt (if the correct line for the putt was selected) (Hurrion & MacKay, 2012).

5.3.6 Conclusion

The Photoshop CS5 and Image J software distance and surface area measurements were shown to be highly accurate. The Quintic Ball Roll software velocity and horizontal launch angle measurements were also shown to be valid, this was reflected in very small change in means and very strong coefficient statistics reported. Therefore, it is proposed that these measures can be used for subsequent studies into whether the impact point on the golf ball influences ball roll kinematics.

5.4 Development of Research

This chapter has potentially highlighted a mechanism during the putter-ball mechanism that contributes to variation in the golf putt, whereby dimples affect the subsequent kinematics of the ball roll. This potentially will lead to significant advancements within the literature. Additionally this chapter completed extensive reliability testing for a piece of software that had no prior scientific literature published with it. The Quintic Ball Roll software demonstrated strong absolute reliability, however, this was not reflected for relative reliability due to the nature of the data collection. The validity was additionally shown to be very good for the variables velocity and horizontal launch angle in line with previous reliability literature statistics.

The next chapter in this thesis will develop a method to analyse the effects of the putter-ball interaction and distinguish whether dimples on the golf ball affect certain ball roll kinematics. Certain results within Study Three suggest that this potentially could be the case, especially those assessing the horizontal launch angle with noticeable differences in SEM between the Srixon and Titleist golf balls. Rationale for completing this study is that it has been previously identified that dimples can cause variance of kinematic ball roll variables, such as initial ball direction (Cross, 2006; Pelz, 2000). However, it has not been extensively examined with a putting robot or a cohort of golfers.

Chapter Six

The reliability and effect of the impact point on a golf ball with a putting robot

6.1 Introduction to Chapter

After identifying a larger variability in the outcome measurements of the kinematic variables of ball roll in Study Three (Chapter Five) in comparison to the variance of the putting stroke. It was hypothesised that some of this variability may be actually occurring as a result of the variability of the impact point occurring due to the minor differences in ball placement as shown in Figures 5.2 to 5.5. Along with previous literature tentatively identifying that ball dimples can affect the initial ball direction (Cross, 2006; Pelz, 2000). With the distinct lack of literature discussing in depth the kinematic variables of ball roll, it was decided this impact variability and dimple effect on kinematic variables needed to be investigated. The reliability of the new analysis technique developed is presented in Study Four: The reliability of an experimental method to analyse the impact point on a golf ball during putting (Section 6.2). Additionally, Study Five: The effect of impact point on golf ball roll during putting using a mechanical putting robot (Section 6.3) is presented in this chapter. The protocol was conducted with the hypothesis that a certain degree of the variability (accountable to the impact point on the golf ball) could not be controlled for. Both Study Four and Five will indicate as to whether the impact point and dimples does affect the kinematics of the ball roll when all other variables are held constant. The Development of Research (Section 6.4) concludes this chapter summarising the findings from both Study Four and Five with a brief discussion of the findings and outlining the future research that was conducted.

6.2 Study Four: The reliability of an experimental method to analyse the impact point on a golf ball during putting

6.2.1 Abstract

Background: To date no previous literature has discussed the role of variability of the impact point on the resulting kinematic variables of the role of the golf ball. **Aim:** To examine the reliability of an experimental method identifying the location of the impact point on a golf ball during putting. **Method:** Forty trials were completed using a mechanical putting arm set to reproduce a putt of 3.2 m, with four different putter-ball combinations. The data processing protocol was repeated for four putter-ball combinations to establish day-to-day reliability. After locating the centre of the dimple pattern (centroid) the following variables were tested; distance of the impact point from the centroid location, angle of the impact point from the centroid location, X and Y coordinates, and distance of the impact point from the centroid derived from the X, Y coordinates. **Results:** Very strong relative and absolute reliability was demonstrated across all variables (Pearson's r = 0.98 – 1.00; ICC = 0.98 – 1.00). The highest day-to-day variability observed was 7% in the variable angle of the impact point from the centroid location. **Conclusion:** The experimental method was shown to be reliable at identifying the impact point on the golf ball and therefore can be used in subsequent studies.

6.2.2 Introduction

Four clear phases have been defined that contribute to putting direction variability (Figure 6.1); these are green reading, aim, stroke and ball roll, which can be influenced by green inconsistencies (Karlsen et al., 2008). One variable that has not been analysed within the literature extensively is the impact point on the golf ball.

Literature investigating the effect of impact point on the resulting kinematics of the golf ball during putting is very limited. Cross and Nathan (2007) have researched the gear effect in ball collisions, including the golf ball. Results demonstrated the rate of spin increased when the angle of incidence (degree of deviation away from a perpendicular collision) is increased (Cross & Nathan, 2007), which could potentially be detrimental to putting performance. They concluded that the gear effect occurs as a result of static friction between the ball and object during a collision. A clear limitation of the Cross and Nathan (2007) study is that during the experimental protocol, the ball was collided off a wooden block which is not as appropriate as the use of a putter head. Alessandri (1995), Lorensen and Yamrom (1992), and Penner (2002) have all proposed mathematical models of the motion of a putted golf ball over the surface of the green. However, no studies within the literature have tested the variability of the motion of a putted ball with subjects or a putting robot to date.

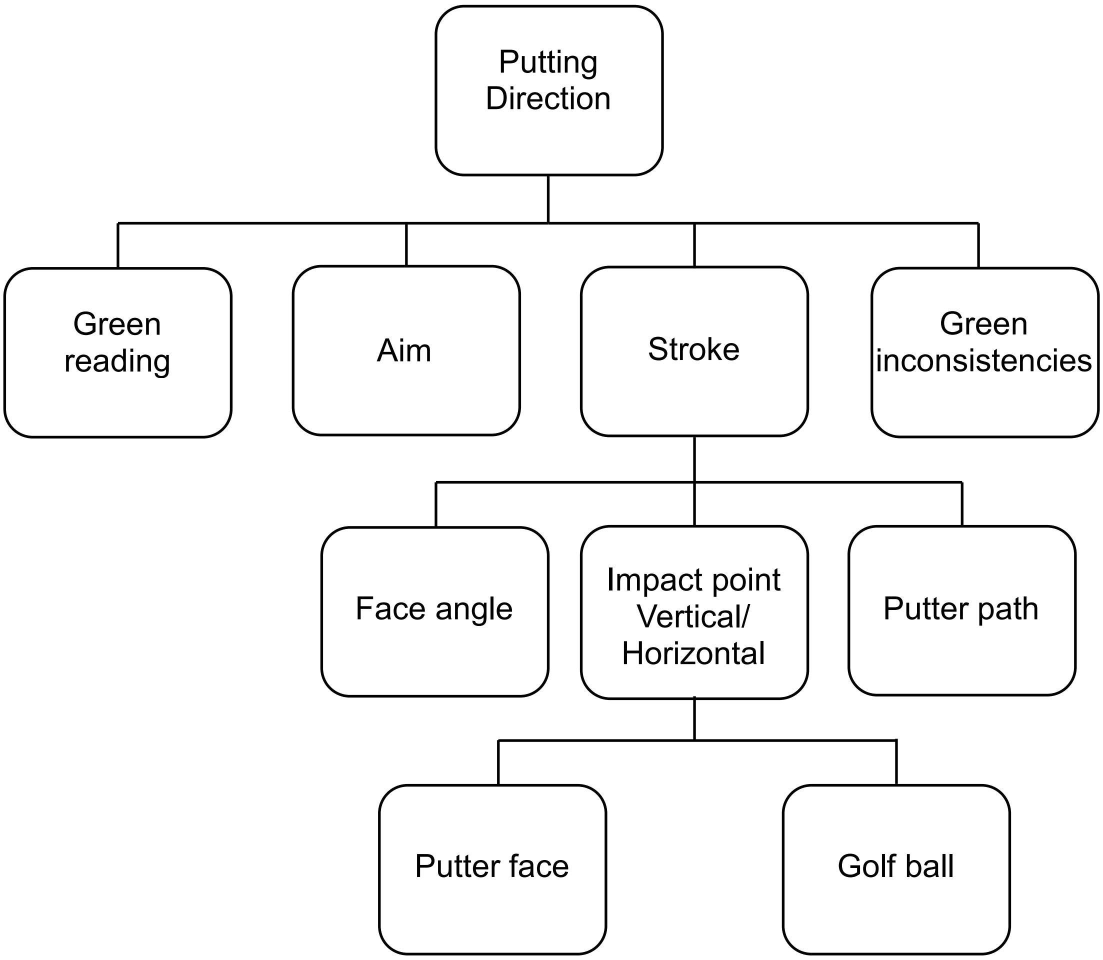

Figure 6.1. Main factors affecting golf putting direction (adapted from Karlsen et al., 2008).

More research is required to examine whether the impact point during the putter face – ball interaction influences the success of the subsequent putt. Currently no studies have investigated how variation in the impact point on the golf ball influences the resulting kinematics of the golf ball and, furthermore, how different dimple patterns on the ball can affect the resulting kinematics of the ball. No method for the analysis of the effect of the impact point has been devised or suggested within the literature. Therefore, the aim of this study was to develop a valid and reliable method of assessing the impact point on a golf ball during putting to allow for further research to determine whether the impact point has an effect on the resultant kinematics of the ball during the golf putt.

6.2.3 Methods

Experimental set - up

All testing was completed in the Quintic Golf Laboratory on an artificial putting surface registering 12 on the stimpmeter. The Quintic mechanical putting arm mounted on an 360 kg bearing (Chapter Five, Figure 5.2a) was set up to simulate a level 3.2 m putt, with a square to square swing path to ensure a square club face at impact (Figure 6.2).

Two putters with different putter face characteristics (grooved or non grooved) were selected and used for the experiment. The GEL® Vicis putter (grooved face) had a 69º lie (angle formed by the shaft and sole of the putter head when the putter is in a neutral position) and 2.5º loft (angle formed by the putter face and level surface when the putter is in a neutral position), and the Odyssey White Hot #3 (non grooved) with a 69º lie and 2.5º loft. Srixon Z-STAR golf balls and Titleist Pro V1 golf balls were aligned using two Superline 2D line lasers fixed to a 360˚ graduated base. One was placed directly behind the ball and the other was placed 90˚ to the path of the golf ball intersecting a visual putting aid printed on the ball. This split the golf ball into four equal sections ensuring the same position of the ball for each trial. A Quintic high speed camera sampling at 220 fps was positioned perpendicular to the putting line. The Quintic Ball Roll v2.4 Launch monitor software was used to analyse the recorded videos. A Quintic GigE high speed camera sampling at 220 fps was positioned vertically to the ball to calculate velocity of the putter head. A Canon EOS 1000d camera was situated on a stationary Velbon CX-440 tripod in front of the line of the golf putt 2.5 m away from impact.

Procedure

The testing was completed over a six day period. The first putter was held securely in the Quintic mechanical putting arm and aligned using a swing path laminate and laser line to ensure a square to square swing path (Figure 6.2). The counterbalanced putting arm block was set to produce a putt of 3.2 m. The putting arm was tied to a weighted pole and released using a clip to reduce friction to a minimum. Before the first trial was completed, a thin layer of pigmented emollient was applied to the face of the putter and smoothed out to confirm an even coating. This was repeated after every trial. After each trial a picture was taken showing the pigmented emollient imprint on the ball and the imprint of the dimple pattern left on the putter face.

Ten trials were completed using the first brand of golf ball and then repeated using the second brand of golf ball. This completed Day 1 testing for the first putter. This protocol was executed in the same fashion, on Day 2 and Day 3. This protocol was then completed using the same method for the second putter on days 4, 5 and 6.

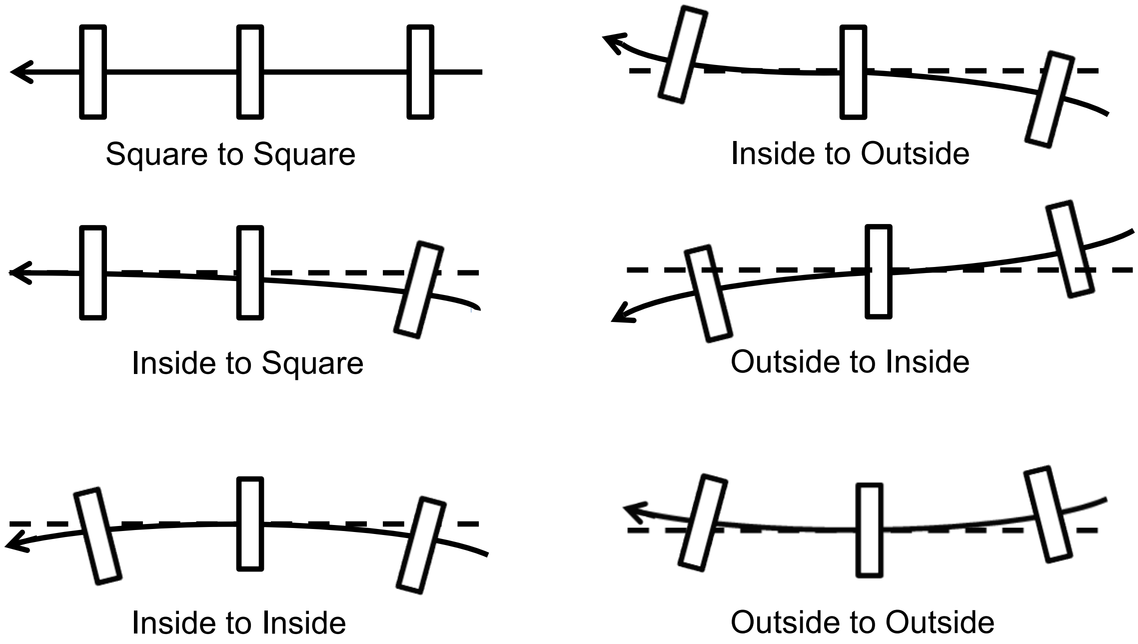

Figure 6.2. The different types of putter swing paths depicted the perspective of a right-handed golfer.

Data Processing

Day to day reliability was assessed for the following variables: distance of the impact point from the centroid, angle of the impact point from the centroid, X coordinate from the centroid, Y coordinate from the centroid and the resultant distance from the centroid (using the X, Y coordinates and the following formula: $x^2 + y^2 = z^2$). To ensure unbiased results, the day-to-day analysis was completed blind, without reference to the other days analyses.

Determining the centroid

Two 2D structures (Figure 6.3) were developed matching the Titleist and Srixon golf ball dimple patterns using Microsoft PowerPoint 2011 to locate the centroid (0, 0 coordinate of the dimple pattern). The Srixon golf ball had a single consistent size of dimple and therefore an equilateral triangle with a line drawn at every vertex fitted the dimple pattern identifying the centroid (0, 0 coordinate) of the three dimples (Figure 6.3 A). In contrast the Titleist golf ball had two sizes of dimple (Figure 6.3 B), one smaller dimple encapsulated by 5 larger dimples, so a pentagon with a line drawn at every vertex fitted the dimple pattern, identifying the centroid (0, 0 coordinate) of the six dimples.

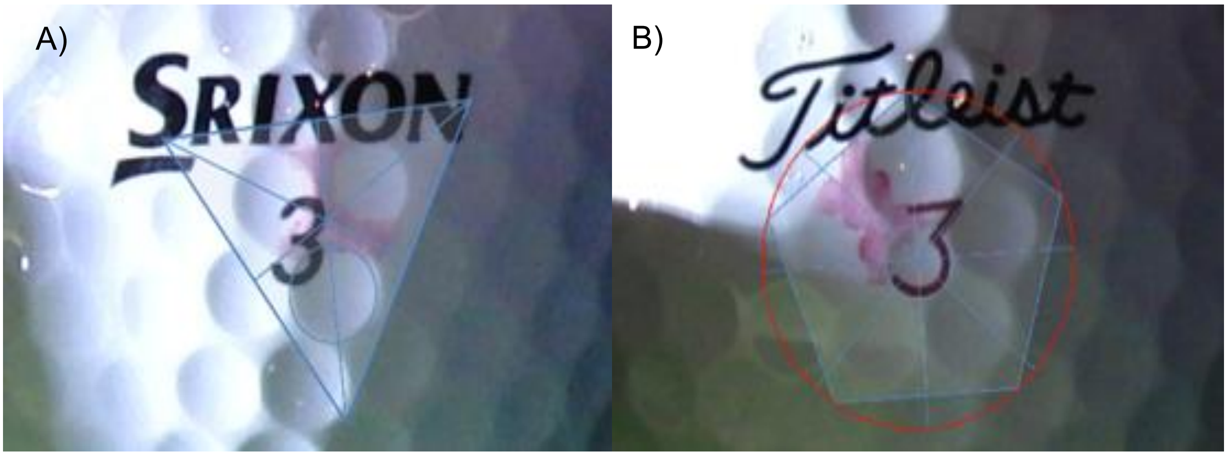

Figure 6.3. Two structures developed to identify the centroid of the A) Srixon and B) Titleist golf ball.

Scaling the picture

The photograph from each trial was exported into Adobe Photoshop CS5 (Adobe Systems Incorporated., CA, USA) and scaled using the known distance of the GEL® and Odyssey putters hosel (Figure 6.4). The hosel was selected as it was flat on each of the putters and therefore was the most appropriate part to measure accurately.

Figure 6.4. The anatomy of the traditional faced Odyssey White Hot putter (A) and the grooved faced GEL® Vicis putter (B). PH = Putter Hosel, PF = Putter face, PT = Putter toe, HP = Putter heel.

The Photoshop ruler tool was used to calculate the angle that the ball was placed at; this was to confirm that the 2D structure was placed in the correct and same position giving the same centroid (0, 0 coordinate) for each trial.

Calculating the centre of the impact area

To calculate the centre of the impact area or the impact point, a polygon was drawn at the four outermost edges of the impact area (Figure 6.5). The first edge was drawn horizontally from the two outermost edges and the angle was adjusted to the angle of the dimple pattern identified (Figure 6.5 A) when placing the 2D structure on the ball. This line was then copied and placed at the opposite outermost edge (Figure 6.5 B). These steps were repeated for the two vertical lines (Figure 6.5 C and 6.5 D). Each side was parallel to the opposite side and adjusted to fit correctly together. Generally this involved either lengthening or shortening the horizontal lines and this allowed for the polygon to be intersected from its four corners (Figure 6.5 E and 6.5 F) giving the centre point of the impact area.

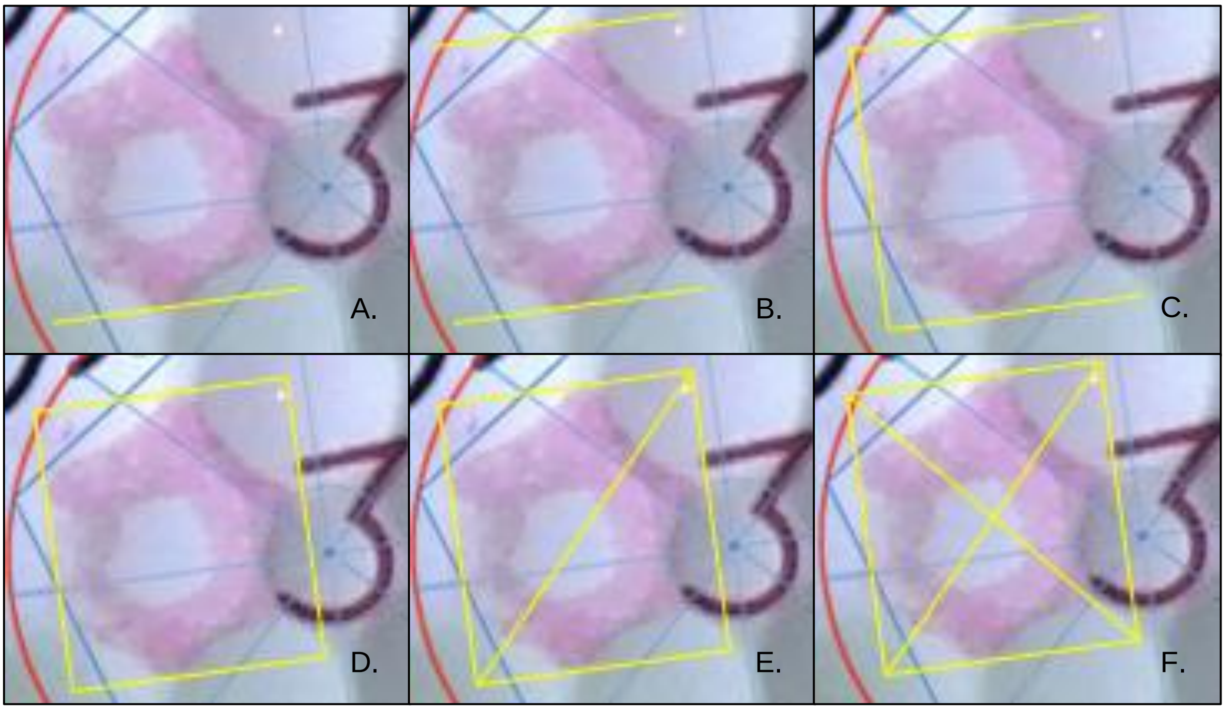

Figure 6.5. Step by step process of constructing and intersecting a polygon to identify the coordinate of the impact point.

The Photoshop ruler tool was then used to measure the distance and angle (defined in Figure 6.6) of the impact point from the centroid of the dimple pattern, producing a measurable vector. Additionally, the X and Y coordinates were measured from the centroid of the dimple pattern using vertical and horizontal guides.

Calculating the area of the impact zone

Scientific image processing software ImageJ (National Institutes of Health., Bethesda, Maryland, USA) was used to calculate the surface area of the impact area. The image was scaled using the hosel (Figure 6.4) of the GEL® and Odyssey putters. The polygon selection tool was used to draw around the impact area imprint on the golf ball (Figure 6.7) and gave an output of the surface area.

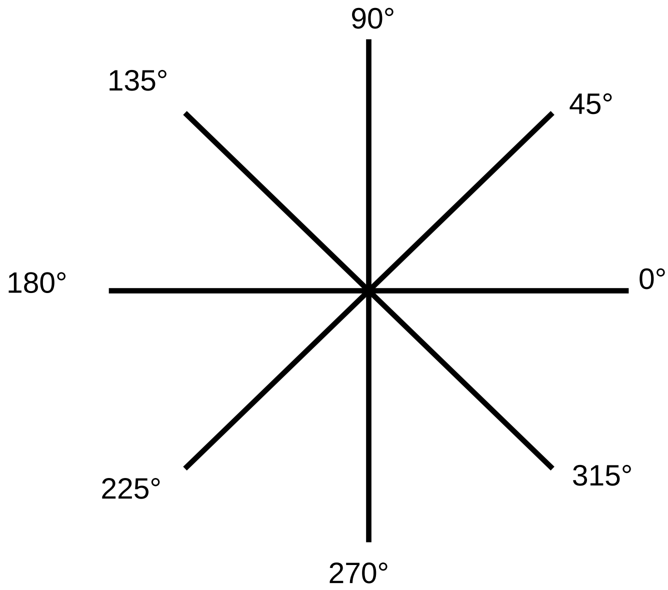

Figure 6.6. The angle of the impact point in relation to the centroid of the dimple pattern.

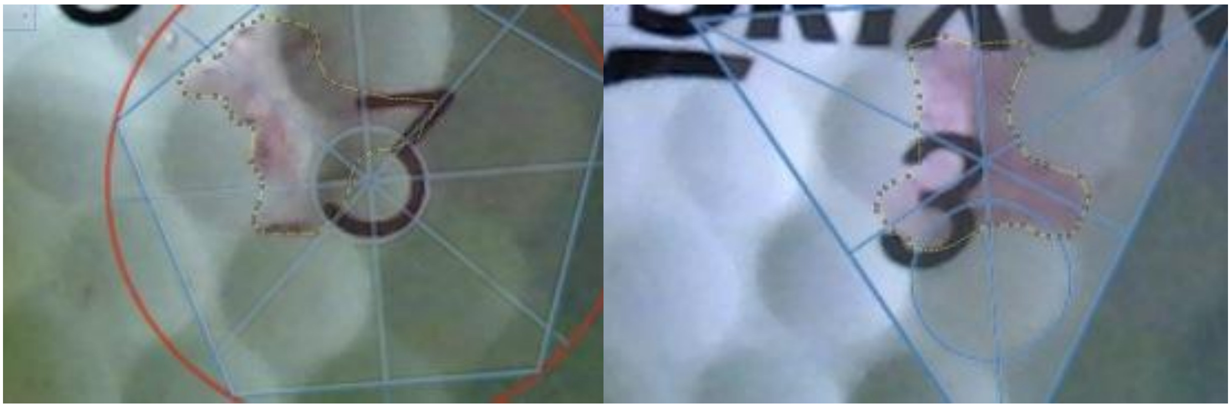

Figure 6.7. Images of the Titleist and Srixon golf balls with the polygon outline for calculation of total surface area.

Data Analysis

Data was exported to statistical software packages Microsoft Excel 2011 and SPSS v19 (SPSS Inc, Chicago, USA) for analysis. The data was found to be normally distributed using a Shapiro – Wilk test for normality. Reliability of the data was assessed using a range of statistical methods and procedures previously discussed within the literature (Atkinson & Nevill, 1998; Hopkins, 2000). A combination of descriptive (mean ± SD, change in mean and 95% confidence limits (CL)) and reliability statistics were used. The change in mean and 95% CL stipulated an indication of absolute variation between the data sets.

Reliability statistics included, the standard error of measurement (SEM) which was calculated using the following formula: $SEM = SD\sqrt{1 - ICC}$. Additionaly a two – way mixed intraclass coefficient (ICC) was used, calculated using the following formula: $\frac{1-SD^{\wedge}2}{SD^{\wedge}2}$. This was to test the relative reliability and relationships between data sets. The ICC was suitable as it is sensitive to systematic bias and can be used for multiple retests (Atkinson & Nevill, 1998; Hopkins, 2000).

Pearson's correlation coefficient (Pearson's – *r*) was used to measure the strength of the relationship between the data sets. The boundaries set for the correlation statistics were suggested by Salkind (2011); r = 0.8 – 1.0, very strong, r = 0.6 – 0.8, strong, r = 0.4 – 0.6, moderate, r = 0.2 – 0.4, weak, r = 0.0 – 0.2, no relationship. The alpha level was set at $p < 0.05$. All of these statistics analysed as a collective group will provide a clear impression of the reliability and reproducibility of the method being analysed.

6.2.4 Results

Surface Area

Surface area results are displayed in Figure 6.8 and Table 6.1. Surface area demonstrated very strong relationship across the data sets. Pearson's – *r* values were consistently high between combined data sets (Day 1 – Day 2, r = 0.98, $p < 0.01$; Day 2 – Day 3, r = 0.99, $p < 0.01$; Day 1 – Day 3 r = 0.99, $p < 0.01$). The SEM for all days was < 1 mm^2 and the ICC values demonstrated very strong reliability for the combined group and individual putter golf ball combintations. No anomalies were observed in the descriptive statistics the biggest variance in the change in the mean was -0.85 mm^2 for the Odyssey Srixon group between Day 1 and Day 2.

Distance of Impact point from the centroid location

The distance of the impact point from the centroid location demonstrated excellent reliability across the day to day trials (Figure 6.9 & Table 6.2). This was reflected in very strong relationships across the combined data sets, Pearson's – *r* values were high (Day 1 – Day 2, r = 1.00, $p < 0.01$; Day 2 – Day 3, r = 1.00, $p < 0.01$; Day 1 – Day 3, r = 1.00, $p < 0.01$). In addition the SEM was consistently small (< 0.06 mm) and the ICC values demonstrated strong reliability for all groups. Descriptive statistics reaffirmed the strong reliability of the data with the largest change in the mean observed was -0.06 mm in the GEL® Srixon group between Day 1 and Day 3.

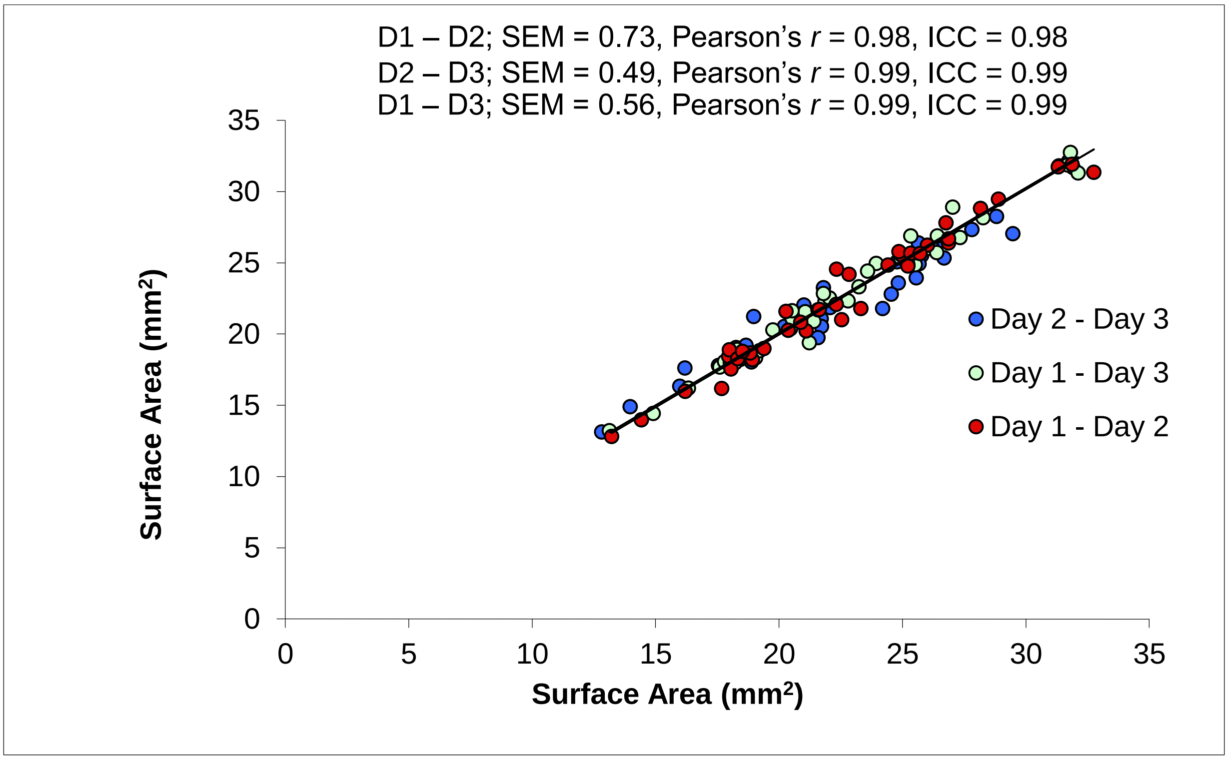

Figure 6.8. Pearson's - *r* correlations for surface area between ball – putter combinations across all testing days.

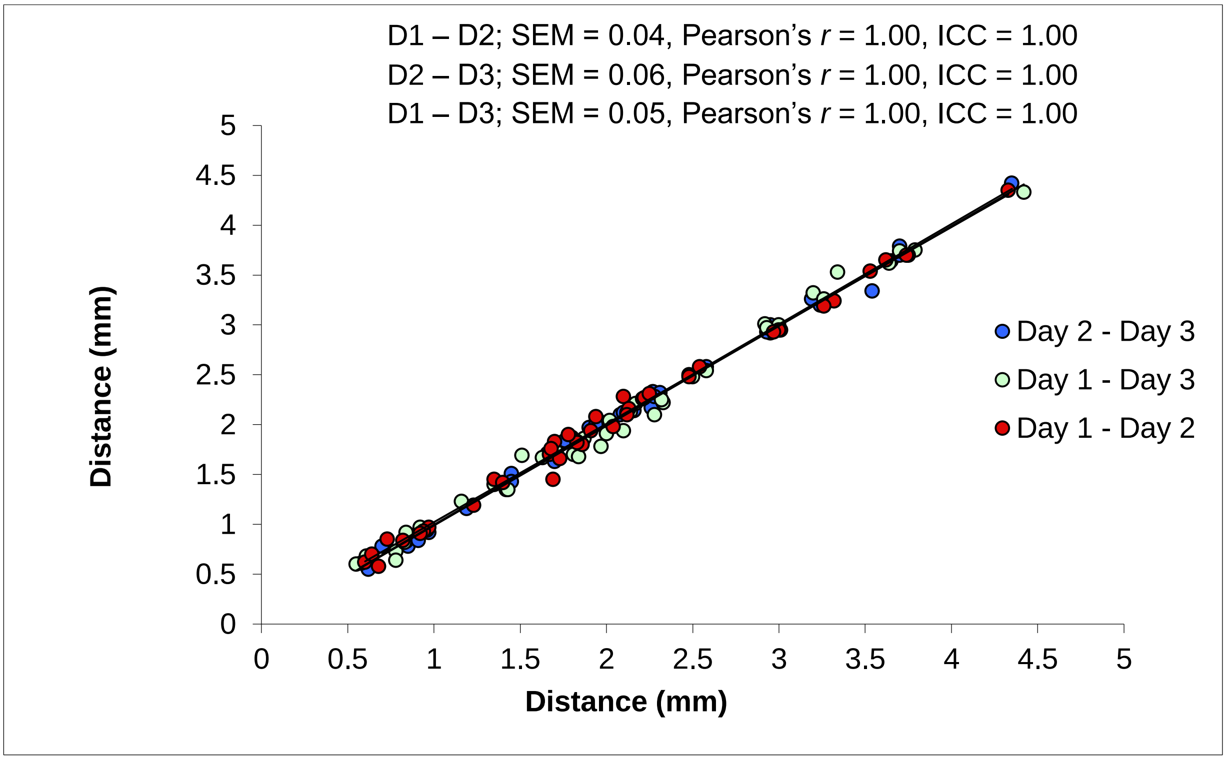

Figure 6.9. Pearson's - *r* correlation for the distance of the impact point from the centroid location across all testing days.

Table 6.1. Descriptive statistics for the surface area variable across all days testing for the combined data set and individual golf ball putter combinations.

	Day 1 (mm^2 ± SD)	Day 2 (mm^2 ± SD)	Day 3 (mm^2 ± SD)	Day 1 to 2		Day 2 to 3		Day 1 to 3	
				Δ Mean (mm^2)	95% CL (mm^2)	Δ Mean (mm^2)	95% CL (mm^2)	Δ Mean (mm^2)	95% CL (mm^2)
Combined	22.75 ± 4.76	22.60 ± 4.47	22.74 ± 4.61	-0.15	-0.48 to 0.18	0.14	-0.08 to 0.36	-0.01	-0.24 to 0.27
Odyssey Srixon	27.40 ± 2.79	26.55 ± 3.32	26.80 ± 3.16	-0.85	-1.64 to -0.05	0.25	-0.43 to 0.93	-0.59	-1.13 to 0.06
Odyssey Titleist	22.21 ± 3.26	21.79 ± 3.10	21.87 ± 3.30	-0.42	-1.08 to 0.25	0.08	-0.34 to 0.50	-0.34	-0.76 to 0.08
GEL® Srixon	21.83 ± 4.05	21.86 ± 3.71	22.08 ± 3.73	0.04	-0.54 to 0.61	0.21	-0.12 to 0.54	0.25	-0.29 to 0.79
GEL® Titleist	19.57 ± 5.19	20.19 ± 5.21	20.21 ± 5.51	0.62	0.09 to 1.14	0.02	-0.54 to 0.58	0.64	0.29 to 0.99

Table 6.2. Descriptive statistics for the distance of impact point from the centroid location across all days testing for the combined data set and individual golf ball putter combinations.

	Day 1 (mm ± SD)	Day 2 (mm ± SD)	Day 3 (mm ± SD)	Day 1 to 2		Day 2 to 3		Day 1 to 3	
				Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)
Combined	2.08 ± 0.97	2.08 ± 0.97	2.07 ± 0.98	0.00	-0.02 to 0.02	-0.01	-0.04 to 0.02	-0.01	-0.04 to 0.02
Odyssey Srixon	1.56 ± 0.73	1.57 ± 0.73	1.56 ± 0.74	0.01	-0.03 to 0.04	0.01	-0.05 to 0.04	0.00	-0.03 to 0.03
Odyssey Titleist	2.86 ± 0.80	2.86 ± 0.80	2.87 ± 0.83	0.00	-0.06 to 0.05	0.01	-0.06 to 0.08	0.01	-0.05 to 0.06
GEL® Srixon	1.37 ± 0.57	1.36 ± 0.59	1.31 ± 0.52	-0.01	-0.05 to 0.03	-0.05	-0.13 to 0.02	-0.06	-0.12 to -0.01
GEL® Titleist	2.51 ± 0.91	2.53 ± 0.90	2.54 ± 0.91	0.02	-0.02 to 0.06	0.01	-0.05 to 0.07	0.03	-0.03 to 0.09

Angle of the Impact point from the centroid location

Results for the angle of the impact point from the centroid are displayed in Figure 6.10 and Table 6.3. Very strong reliability was observed and this was reflected in very low SEM values and strong ICC scores. This reliability was consistent in the very strong Pearson's *r* correlations (Day 1 – Day 2, $r = 0.99$, $p < 0.01$; Day 2 – Day 3, $r = 1.00$, $p < 0.01$; Day 1 – Day 3, $r = 0.99$, $p < 0.01$). The descriptive statistics confirm very strong reliability with no apparent anomolies for the combined data set or individual putter ball combinations, with consistent SD observed over all testing days. It is worth noting that greater variability was observed in the Srixon ball in comparison to the Titleist ball, however this was consistent across all three days data sets.

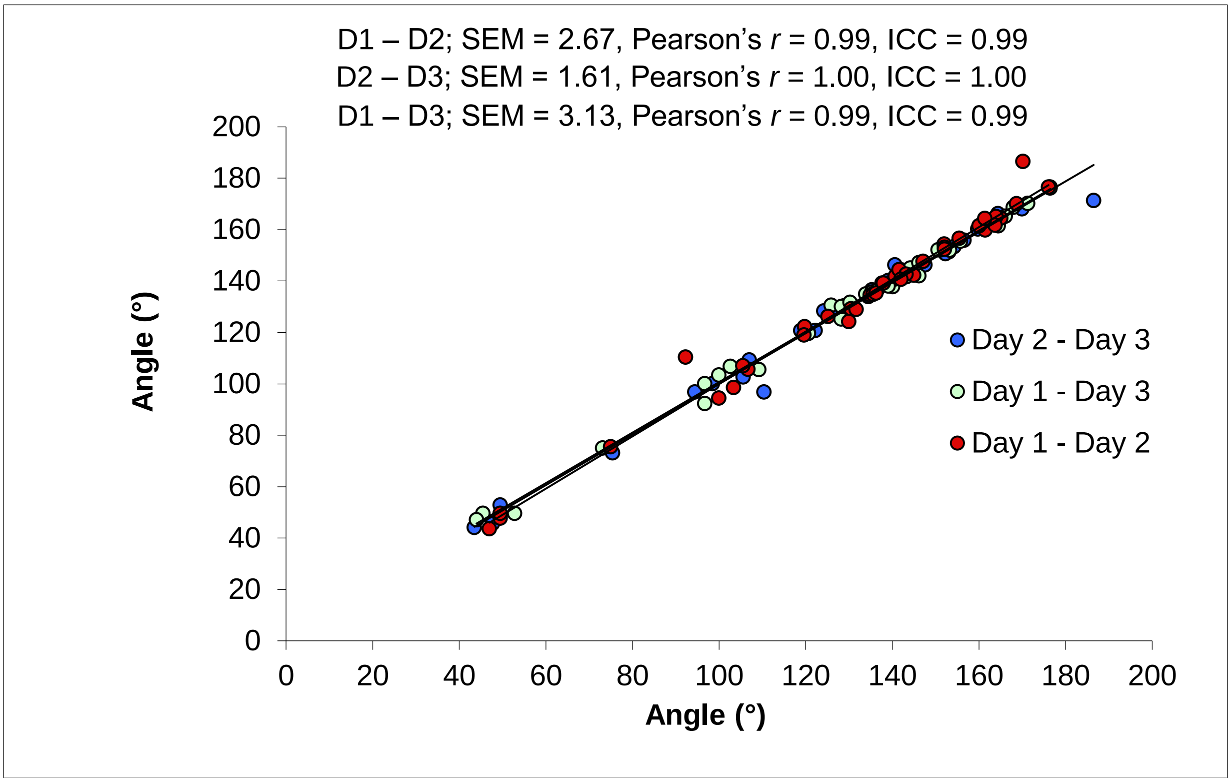

Figure 6.10. Pearson's - *r* correlation for the angle of the impact point from the centroid location for all days testing.

Table 6.3. Descriptive statistics for the angle of the impact point from the centroid across all testing days for the combined data set and individual golf ball putter combinations.

	Day 1 (° ± SD)	Day 2 (° ± SD)	Day 3 (° ± SD)	Day 1 to 2		Day 2 to 3		Day 1 to 3	
				Δ Mean (°)	95% CL (°)	Δ Mean (°)	95% CL (°)	Δ Mean (°)	95% CL (°)
Combined	132.79 ± 34.16	132.30 ± 33.83	132.35 ± 33.31	-0.49	-0.98 to 1.86	0.05	-0.68 to 0.78	-0.44	-1.86 to 0.98
Odyssey Srixon	137.43 ± 33.42	137.06 ± 33.84	137.13 ± 33.84	-0.37	-1.66 to 0.92	0.07	-1.59 to 1.73	-0.30	-1.30 to 0.70
Odyssey Titleist	150.64 ± 11.21	151.42 ± 11.16	150.69 ± 11.48	0.78	-0.62 to 2.18	-0.73	-1.86 to 0.40	0.05	-1.13 to 1.03
GEL® Srixon	108.25 ± 51.61	105.66 ± 48.64	106.44 ± 48.23	-2.59	-7.26 to 2.08	0.78	-1.30 to 2.86	-1.81	-7.85 to 4.23
GEL® Titleist	134.84 ± 9.88	135.06 ± 9.76	135.14 ± 9.44	0.22	-1.31 to 1.75	0.08	-1.48 to 1.64	0.30	-1.52 to 2.12

X and Y coordinates from the centroid location

The distance of the X and Y coordinates from the centroid position demonstrated very strong reliability across the repeated trials (Figures 6.11 & 6.12, Tables 6.4 & 6.5). Very strong relationships were observed across the trials, reflected in high Pearson's *r* correlations (X; Day 1 – Day 2, $r = 1.00$, $p < 0.01$; Day 2 – Day 3, $r = 0.99$, $p < 0.01$; Day 1 – Day 3, $r = 0.95$, $p < 0.01$; Y; Day 1 – Day 2, $r = 0.99$, $p < 0.01$; Day 2 – Day 3, $r = 0.99$, $p < 0.01$; Day 1 – Day 3, $r = 0.99$, $p < 0.01$). This was reaffirmed with the low SEM scores (< 0.08 mm) and very strong ICC values demonstrating relative as well as absolute reliability. No outliers were observed in the descriptive statistics and this again confirms the strong reliability observed across the three days testing. The SD was consistent across trials, suggesting that variability observed existed.

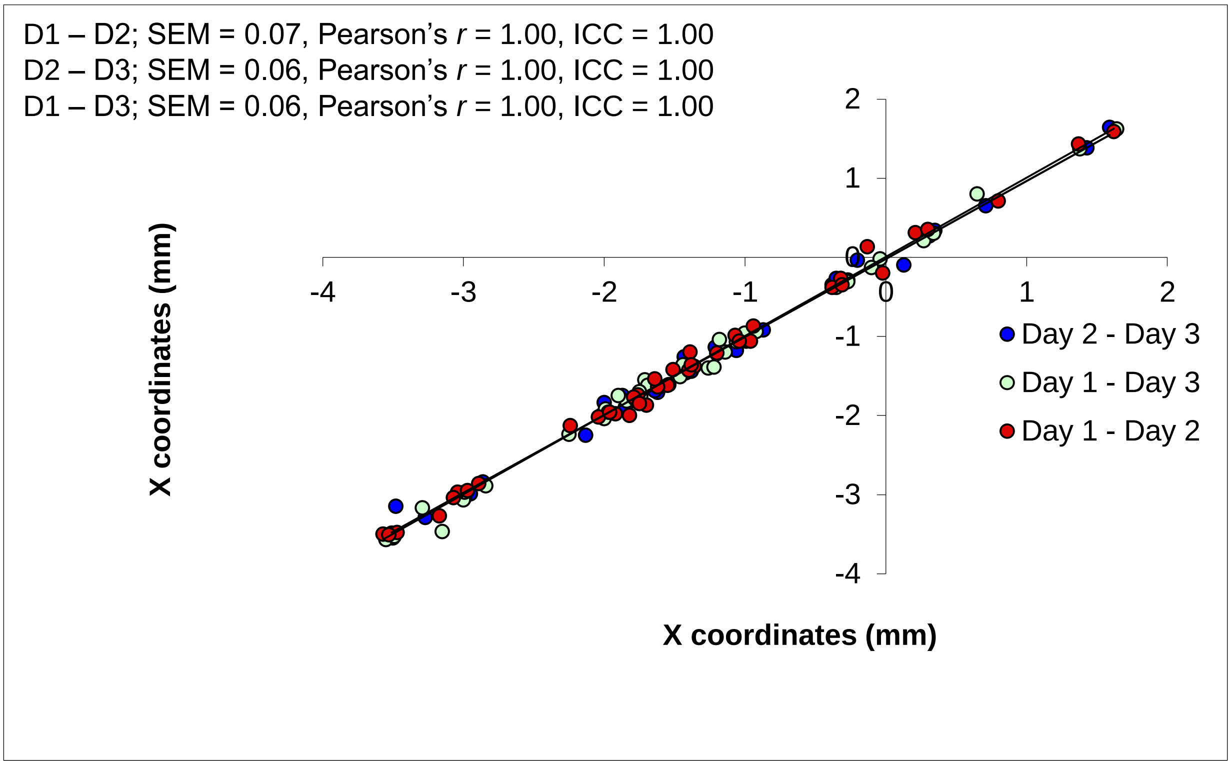

Figure 6.11. Pearson's - *r* correlation for the distance of the X coordinate from the centroid across all testing days.

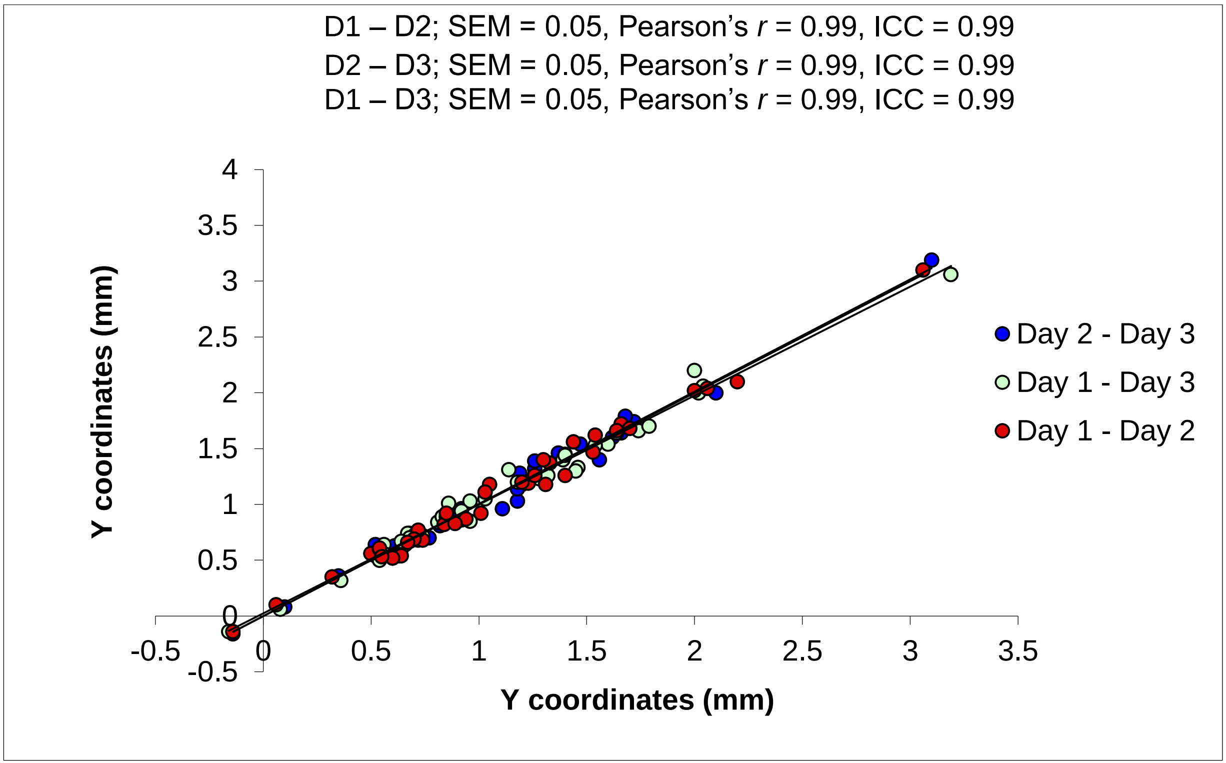

FIgure 6.12. Pearson's - *r* correlation for the distance of the Y coordinate from the centroid across all testing days.

Table 6.4. Descriptive statistics for the distance of the X coordinate from the centroid across all days for the combined data set and individual golf ball putter combinations.

	Day 1 (mm ± SD)	Day 2 (mm ± SD)	Day 3 (mm ± SD)	Day 1 to 2		Day 2 to 3		Day 1 to 3	
				Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)
Combined	-1.41 ± 1.29	-1.41 ± 1.27	-1.42 ± 1.28	0.00	-0.03 to 0.03	-0.01	-0.03 to 0.02	-0.01	-0.02 to 0.04
Odyssey Srixon	-1.18 ± 0.99	-1.18 ± 1.00	-1.19 ± 0.99	0.00	-0.03 to 0.04	-0.01	-0.06 to 0.03	-0.01	-0.05 to 0.03
Odyssey Titleist	-2.50 ± 0.92	-2.46 ± 0.89	-2.49 ± 0.95	0.04	-0.06 to 0.13	-0.03	-0.11 to 0.05	0.01	-0.06 to 0.08
GEL® Srixon	-0.21 ± 1.26	-0.25 ± 1.28	-0.20 ± 1.24	-0.04	-0.11 to 0.03	0.05	-0.02 to 0.10	0.01	-0.09 to 0.09
GEL® Titleist	-1.75 ± 0.79	-1.75 ± 0.80	-1.77 ± 0.77	0.00	-0.05 to 0.05	-0.02	-0.09 to 0.04	-0.02	-0.09 to 0.04

Table 6.5. Descriptive statistics for the distance of the Y coordinate from the centroid across all days for the combined data set and individual golf ball putter combinations.

	Day 1 (mm ± SD)	Day 2 (mm ± SD)	Day 3 (mm ± SD)	Day 1 to 2		Day 2 to 3		Day 1 to 3	
				Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)
Combined	1.08 ± 0.62	1.08 ± 0.63	1.08 ± 0.62	0.00	-0.02 to 0.03	0.00	-0.03 to 0.02	0.00	-0.02 to 0.02
Odyssey Srixon	0.66 ± 0.28	0.68 ± 0.30	0.67 ± 0.30	0.02	-0.01 to 0.06	-0.01	-0.05 to 0.03	0.01	-0.03 to 0.06
Odyssey Titleist	1.28 ± 0.36	1.26 ± 0.40	1.27 ± 0.36	-0.02	-0.09 to 0.04	0.01	-0.03 to 0.06	-0.01	-0.07 to 0.05
GEL® Srixon	0.64 ± 0.40	0.65 ± 0.41	0.63 ± 0.38	0.01	-0.01 to 0.03	-0.02	-0.07 to 0.03	-0.01	-0.05 to 0.03
GEL® Titleist	1.73 ± 0.61	1.73 ± 0.62	1.73 ± 0.59	0.00	-0.06 to 0.07	0.00	-0.08 to 0.08	0.00	-0.05 to 0.06

Distance of the impact point from the centroid derived from the X, Y coordinates

The results for the distance of the impact point derived from the X, Y coordinates are shown in Figure 6.13 and Table 6.6. Pearson's *r* correlations (Day 1 – Day 2, $r = 1.00$, $p < 0.01$; Day 2 – Day 3, $r = 1.00$, $p < 0.01$; Day 1 – Day 3, $r = 1.00$, $p < 0.01$) showed very strong relationships and therefore reliability across the three days testing. The descriptive statistics reassert the excellent reliability demonstrated across the three days and no irregularities were observed for the combined or separate club and ball data. The largest c 95% CL observed was -0.13 between Day 1 and Day 2 in the Odyssey Titleist group, a small difference when considered a percentage (4.5%) of the mean distance (2.86 mm). The SD remained consistant for all groups across all trials, suggesting the variability observed actually existed rather than being an analysis error.

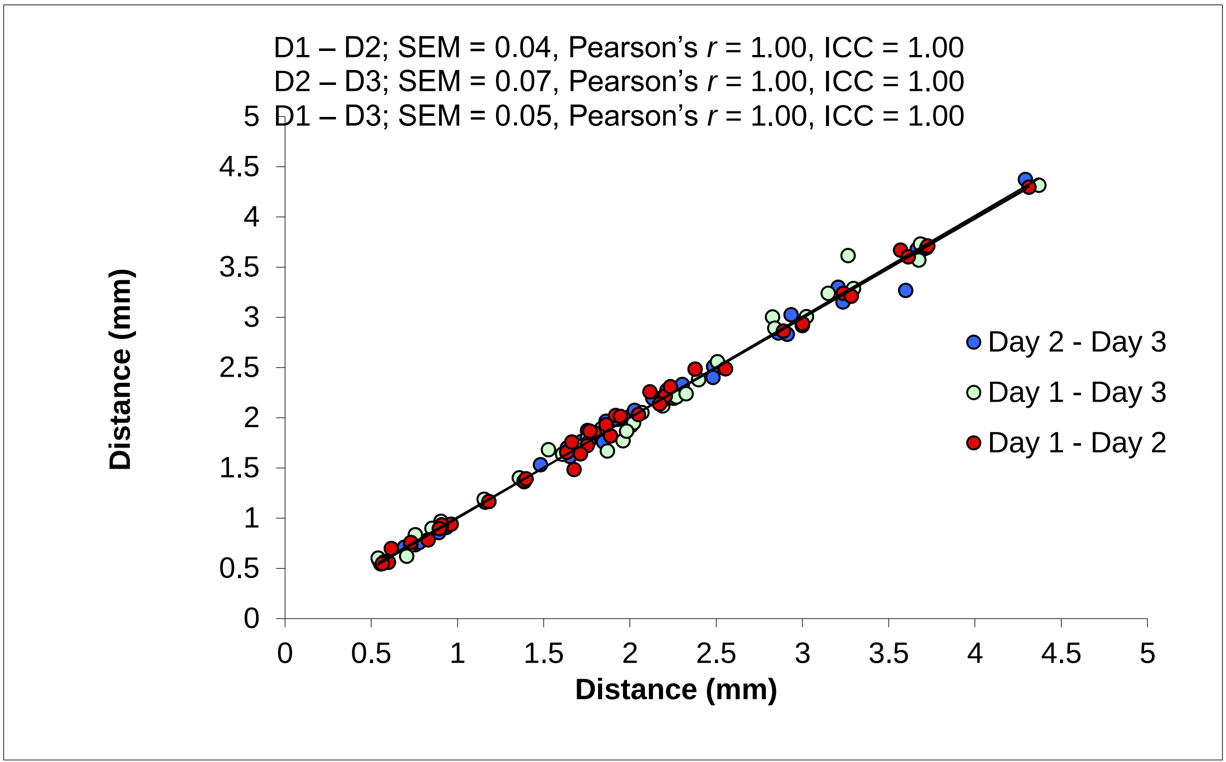

Figure 6.13. Pearson's - *r* correlation for the distance of the impact point derived from the X, Y coordinates from the centroid location across all testing days.

Table 6.6. Descriptive statistics for the distance of impact point derivied from the X, Y coordinates from the centroid location across all days testing for the combined data set and individual golf ball putter combinations.

	Day 1 (mm ± SD)	Day 2 (mm ± SD)	Day 3 (mm ± SD)	Day 1 to 2		Day 2 to 3		Day 1 to 3	
				Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)	Δ Mean (mm)	95% CL (mm)
Combined	2.05 ± 0.98	2.05 ± 0.97	2.05 ± 0.98	0.00	-0.03 to 0.02	0.00	-0.03 to 0.02	0.00	-0.02 to 0.02
Odyssey Srixon	1.53 ± 0.72	1.54 ± 0.73	1.53 ± 0.73	0.01	-0.02 to 0.04	-0.01	-0.05 to 0.04	0.00	-0.04 to 0.04
Odyssey Titleist	2.86 ± 0.81	2.82 ± 0.79	2.85 ± 0.84	-0.04	-0.13 to 0.05	0.03	-0.06 to 0.12	-0.01	-0.06 to 0.04
GEL® Srixon	1.32 ± 0.57	1.34 ± 0.59	1.30 ± 0.53	0.02	-0.02 to 0.06	-0.04	-0.10 to 0.03	-0.02	-0.05 to 0.02
GEL® Titleist	2.49 ± 0.89	2.50 ± 0.90	2.51 ± 0.87	0.01	-0.04 to 0.05	0.01	-0.05 to 0.08	0.01	-0.05 to 0.08

6.2.5 Discussion

The aim of this study was to test the reliabilty and validity of a method developed to test the effect of impact point on the golf ball. This would allow for further analysis to see the effect on resultant ball roll kinematics. Very strong reliability was demonstrated for all variables across the three days of testing. The experimental data processing method used to identify impact point and surface area of the impact zone was shown to demonstrate high absolute and relative reliability. Therefore this method can be considered suitable to evaluate the effect of the impact point on the subsequent kinematics of the golf ball.

The calculation of surface area demonstrated very strong correlations (r = 0.98 – 0.99; ICC = 0.98 – 0.99) demonstrating high relative reliability (Figure 6.8 & Table 6.1). Absolute reliability was also excellent with the largest SEM of 0.73 mm^2. Differences were observed between the different putter golf ball combinations, but the differences between change in mean were consistent between testing days, suggesting that this was not due to measurement error. The largest change in mean observed was in the Odyssey Srixon group between Day 1 (27.40 mm^2) and Day 2 (26.55 mm^2) at -0.85 mm^2. The 95% CL for this was -1.64 to 0.05 mm^2 Day 3's mean was between these two figures (26.80 mm^2). At first glance, this variance may look relatively large, however, the lower confidence limit represents only 6% variance of the combined means. This does emphasise the fact that care is needed when processing the images for surface area. Before the polygon is drawn the analyst should identify the impact zone so the polygon can be drawn as accurately as possible eliminating any potential inaccuracy. When analysed separately, all putter ball combinations showed similar day to day variance.

Results presented in Figure 6.9 and Table 6.2 show very strong relative reliability was observed for the distance of the impact point from the centroid location (r = 1.00; ICC = 1.00) for all combined trials. This very strong reliability was also shown in the distance from the impact point derived from the X, Y coordinates (r = 1.00; ICC = 1.00) for all combined trials (Figure 6.13 & Table 6.6). The SEM for both variables also demonstrated very strong absolute reliability. For the distance from the centroid a range of 0.04 – 0.05 mm was observed, when derived from the X, Y coordinates the range was 0.04 – 0.07 mm. Therefore, the distance from the centroid when measured directly, demonstrated marginally better absolute reliability, but when the differences in SEM are insignificant, both methods can be considered valid for measuring the impact point. A general trend identified that the distance derived from the X, Y coordinates were slightly shorter than that when directly measuring the impact point from the centroid, but again the differences were minimal and did not increase as the distance from the centroid increased. Therefore as long as one method is chosen and all trials are analysed using the same procedure, both methods could be used to calculate the distance of the impact point from the centroid. No anomolies were apparent when the different putter ball combinations were analysed independently of one another.

Results show in in Figure 6.10 and Table 6.3 demonstrate angle of the impact point from the centroid location also had very strong relative (*r* = 0.99 – 1.00; ICC = 0.99 – 1.00) and absolute (SEM = 1.61 – 3.13°) reliability. This is imperitive, as it is needed in combination with the distance from the centroid location to depict the exact location of the impact point, unless it is derived from the X, Y coordinates. Variability existed between the different putter golf ball variations, however, the day to day repeatibility was consistent across all three days trials. The largest change in the mean observed, was -2.59° in the GEL® Srixon group between Day 1 and Day 2, the 95% CL was -7.26° to 2.08°. Initially this looks like a larger variance than the other variables, however this still only shows 6 – 7% variability. With very strong relative and absolute reliability demonstrated, the angle of the impact point from the centroid location can be deemed reliable. Slightly higher SEM was observed in the GEL® Srixon group in comparison to the other putter ball combinations, however, even using the mechanical putting arm, more variability was observed between trials with the GEL® Srixon which will cause a larger SEM. This could potentially reveal that certain styles of putters (groove faced/ traditional faced) demonstrate more consistency when used in conjunction with certain brands of balls with differing dimple patterns.

Results for the X and Y coordinates are displayed in Figures 6.11 and 6.12, as well as Tables 6.4 and 6.5. Excellent day to day reliability was demonstrated for both coordinate values. A very small range of SEMs were observed (0.06 – 0.07 mm for the X coordinate) and (0.05 mm for the Y coordinate). This excellent reliability is supported by the minimal change in mean values also, the largest change in mean observed was between days 2 and 3 for the GEL® Srixon group with an increase of 0.05 mm observed in day 3. The largest change in mean for the Y coordinate was 0.02 mm also observed for the GEL® Srixon group. These differences are so small it may be an error in the actual measurement from the centroid location to the X, Y coordinates rather than differences in the placement of the polygon around the impact zone. Excellent relative reliability was also observed with a range of ICCs from 0.99 – 1.00 for the X and Y coordinates.

Two methods calculating the distance and direction of the impact point from the centroid were tested. The manual measurement of the distance coupled with the angle from the centroid location and measuring the X, Y coordinates and calculating the distance of the impact point from the centroid. The results for both methods were reliable, therefore both methods are appropriate for full analysis. It was the preference of the authors to use the X, Y coordinates, over the X, Y over the distance angle measurement. This was because of the equal ease of carrying out the method and additionally it is more suitable for later data analysis problems when correlating with ball roll kinematics. However, for statistical analysis the distance angle method allows for more statistical power during multiple regression analysis, due to reducing the number of independent variables by one. So there are arguments for both methods as to which is the most suitable to use.

It is difficult to draw comparisons to other methods that identify and analyse the effect of the impact point on the subsequent roll of the golf ball, as currently within the literature the variable has been overlooked. Research such as Brouillette and Valade (2008), Brouillette (2010) and Hurrion and Hurrion (2008) has been limited to analysis of the roll of the golf ball, with no discussion of the effect of the impact point. This is also apparent in studies (Alessandrini 1995; Lorensen & Yamrom, 1992 and Penner, 2002) that have used mathematical models to predict the roll of the golf ball. Karlsen et al. (2008) state that impact point accounts for 3% of direction variability, however, they only tested impact from the sweet spot in comparison to horizontal miss-hits and not the variability observed within each impact type, therefore this claim may be unabstantiated.

One limitation of this study is that there is no criterion measure that this method can be compared to, therefore the validity of this method can't be tested. Additionally, some researchers may demonstrate more subjective variability. To ensure reliability of future analysis using this method, it is suggested that a pilot analysis is undertaken before the main analysis. This is to certify that there is no indication of variablilty during the data processing. By demonstrating very strong relative and absolute reliability, it shows that in this study the researcher was consistently accurate in identifying all variables.

6.2.6 Conclusion

Very strong relative and absolute reliability was demonstrated for all variables during analysis of the experimental method to determine the impact point of the putter on the golf ball. All variables had very low SEM and demonstrated very strong correlations (Pearson's r = 0.98 – 1.00; ICC = 0.98 – 1.00). This method can be considered reliable in the assessment of the point of impact on the golf ball. Therefore, the method can be used for subsequent analysis of the effect of variation in the impact point on the golf ball does affect the subsequent ball roll kinematics. Care needs to be taken during the entire data processing method, due to the high number of stages involved in the image processing protocol. If an error is made during one stage it will ultimately effect the following stages, therefore reducing relative and absolute reliability. It is suggested that all researchers test the relative and absolute reliability to eliminate variance in subjectivity before main analysis takes place.

6.3 Study Five: The effect of impact point on golf ball roll during putting using a mechanical putting robot

6.3.1 Abstract

Background: The literature is very limited on whether the impact point on a golf ball influences the resulting ball roll kinematics. **Aim:** To investigate the effect of impact point variability on golf ball roll kinematics using a mechanical putting robot. **Method:** One hundred and sixty trials were completed using a mechanical putting arm set to reproduce a putt of 3.2 m, with four different putter-ball combinations. To identify impact point, firstly, the centre of the dimple pattern (centroid) was identified. From this the following impact variables were measured; the distance of the impact point from the centroid location, angle of the impact point from the centroid location, X and Y coordinates of the impact point on the golf ball and putter. Multiple regression analysis was conducted to identify whether these impact variables had significant associations with the following kinematic ball roll variables; velocity, side spin, initial ball roll, forward roll, true roll, vertical and horizontal launch angles and whether the golf ball was pushed (ball ended right of the target line) or pulled (ball ended left of the target line). **Results:** Significant associations were identified between the combined impact variables and horizontal launch angle and whether the ball was pushed or pulled, for three out of four putter-ball combinations. **Conclusion:** The effect of the variability of the impact point on the golf ball is minimal when putts are completed with a mechanical putting robot. The variability observed causing 'dimple error' was minimal and would not affect the success rate of golf putts within 15 feet.

6.3.2 Introduction

Previous research investigating putting in golf has shown expert golfers to demonstrate a slower putter head velocity at impact compared to novice golfers (Delay, Nougier, Orliaguet and Coello, 1997; Sim & Kim, 2010). Both Delay et al. (1997) and Sim and Kim (2010) suggest that expert players strike the ball in a fashion whereby more kinetic energy is transferred to the golf ball in comparison to their amateur counterparts, which allows for a reduced putter head velocity at impact. However, no resultant kinematic variables of the golf ball were measured, therefore it is difficult to draw clear conclusions as to why this was observed.

Pelz (2000) accounted all direction variability to two variables, face angle at impact (83%) and putter path (17%), neglecting to account for any influence of the impact interaction between the putter face and ball. Karlsen et al. (2008) discussed factors that influence the consistency of direction during golf putting. Karlsen et al. (2008) accounted 80% of direction consistency to face angle at impact (0.50° effective variability), 17% to putter path (0.18° effective variability) and 3% to horizontal impact point on the putter (0.09° effective variability). Karlsen et al.

(2008) concluded that the putting stroke has a minor influence on direction consistency. Based on this variability observed (collected from a top European Tour player), 1% of putts would miss from a distance of 10 metres, if all other variables remained constant (Karlsen et al. 2008). However, as previously documented by Pelz (2000) professional golfers miss 95% of putts from this distance. Both, Pelz (2000) and Karlsen et al. (2008) neglected to measure the impact point on the golf ball or measure kinematic variables of the roll of the golf ball, which may also effect putting direction and ultimately success rate. Pelz (2000) has acknowledged that dimples do affect the direction variability during a golf putt; however, only presents limited data on the effect by analysing the distance that putts have rolled off line. This direction variability away from the intended target line (Figure 6.14) is termed dimple error.

Therefore it is difficult to draw conclusions as to whether Karlsen et al. (2008) or Pelz (2000) were correct to not consider the influence of the impact point on the golf ball on direction consistency, as to date it has never been extensively investigated. Cross and Nathan (2007) have identified the gear effect during ball collisions identifying a significant positive correlation between the angle of incidence and resultant rate of ball spin. However more research is needed where the putting stroke mechanism is used. Identifying the potentially detrimental effect to putting performance with variance being observed in putter face angle, putter path, impact point on the putter face and impact on the golf ball all possibly influencing this gear effect, as the angle of incidence would change with all these variables.

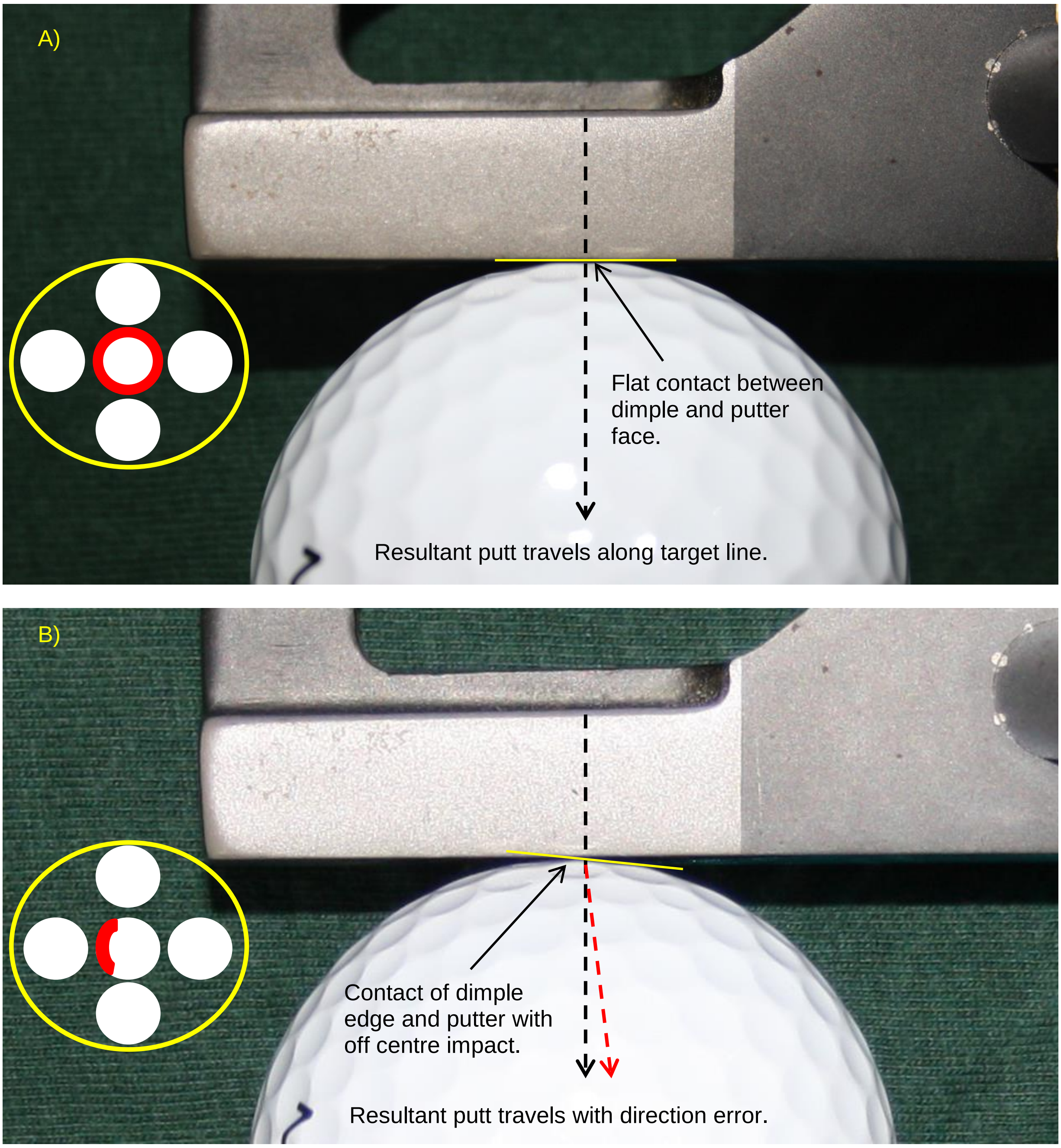

Figure 6.14. Diagram depicting the two types of contact possible during impact between the putter face and golf ball. A) A square contact with the dimple resulting in a putt that starts travelling on the intended target line, and B) Contact on a ball's dimple edge (right) causing the ball to travel in a direction different to the intended target line. The diagrams on the left resemble the posterior view of a golf ball, the white circle is a dimple and the red area highlights the point of the dimple the putter is making contact with.

A method developed in Study Four to identify and analyse the impact point on the golf ball was found to be reliable. Therefore, the aim of this study is to investigate the effects of the impact point on a golf ball and the impact point on a putter on the resulting ball roll kinematics using a mechanical putting robot. It was hypothesised that variance would exist in the distance and direction of the impact point from the centroid location (identified and defined in Study Four) and size of the impact zone which would have a direct relationship with the resultant ball roll kinematics (velocity, side spin, initial ball roll, forward roll, true roll, vertical and horizontal launch angle and whether the ball was pushed or pulled).

6.3.3 Methods

Experimental set – up

All testing was completed in the Quintic Golf Laboratory on an artificial putting surface registering 12 on the stimpmeter. The experimental set – up was exactly the same as outlined in Study Four (pp. 110).

Procedure

The procedure mirrored that outlined in Study Four with the following adjustments. The testing was completed over a two-day period. Forty trials were completed with four (2 balls x 2 putters) putter-ball combinations (GEL®-Srixon, GEL®-Titleist, Odyssey-Srixon and Odyssey-Titleist).

Data Processing

The data was processed as described in Study Four with the addition of X, Y coordinates for the impact point on the putter face as well as the golf ball. This was executed using the polygon technique as described in Study Four (Figure 6.5, pp. 114). Figure 6.15 identifies where the origin of the coordinate system (X = 0, Y = 0) was for each putter so X, Y coordinates could accurately and repeatedly be measured from. The top left of the insert was selected as the origin of the coordinate system as Adobe Photoshop CS5 selects the top left of the image as the origin. The X, Y coordinates of top left of the insert could be measured from the top left corner of the image, these coordinates then subsequently were subtracted from the X, Y coordinate measurements of the centre of the impact point. This ensured that the coordinates were calculated from the exact same point for each trial to eliminate the minimal variability of the position of the golf putter as it came to rest after each completed trial.

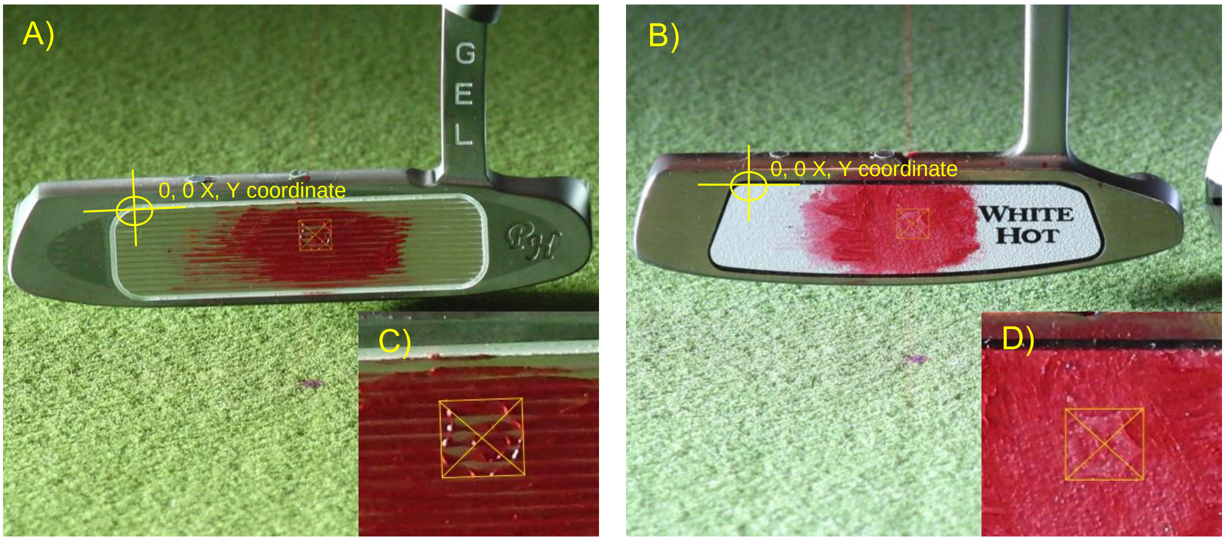

Figure 6.15. The location of the 0, 0 X and Y coordinates indicated by the intersected circle for A) GEL® Vicis putter and B) Odyssey White Hot putter. Images C) and D) show a zoomed in perspective of the polygon technique used to identify the centre of the impact point.

Comparisons could then be made between the variance of the impact point on the golf ball and putter face, ensuring any variance observed on the golf ball was not due to differences of impact point on the putter face.

Data Analysis

The impact variables measured were the length of the impact point from the centroid location, angle of the impact point from the centroid location and surface area of the impact zone, which was used for the multiple regression analysis. Additionally the X, Y coordinates from the centroid location were used to correlate with the X, Y coordinates of the golf club. Kinematic variables measured were velocity, side spin, launch angle (vertical and horizontal), initial ball roll, forward roll, true roll (where all elements of skid have been eliminated) and whether the putt was pushed (right) or pulled (left).

Data was exported to statistical software packages Microsoft Excel 2011 and SPSS v19 for analysis. Variability of the X, Y coordinates of the impact point on the putter face and golf ball were assessed using the coefficient of variation ($CV = \sigma/\mu$). This was so variance of different scales could accurately be compared.

The data were firstly analysed for normality by assessing histogram and box-plot graphs, kurtosis and skewness values. If kurtosis or skewness values were found to be > ± 1 the data set was identified as highly skewed or kurtosed, between ± 0.5 and ± 1 the data set was identified as moderately skewed or kurtosed, and between 0 and ± 0.5 the data was considered to be approximately symmetrical and therefore displaying normality. Any data sets that were found to be highly skewed or displaying high kurtosis was transformed logarithmically (log) in order to increase uniformity to a normal distribution curve (Atkinson & Nevill, 1998; Hopkins, Marshall, Batterham & Hanin, 2009) thereby reducing skewness and kurtosis. Descriptive data of the log-transformed data sets however are still presented in their absolute form. Box-plots were used to identify outliers within the data set. If an outlier was identified for one variable the entire trial was removed from analysis. Normality statistics are presented in Appendix E.

Bivariate analysis was undertaken for the independent and dependent variables to ensure multicollinearity was avoided. Correlations were identified as very high if $r \geq 0.9$ (Ntoumanis, 2001). Additionaly, collinearity diagnostics, variance inflation factor (VIF) and the tolerance statistic were used to assess multicollinearity. A VIF greater than 10, was identified as a cause of concern (Bowerman & O'Connell, 1990; Myers, 1990) and a tolerance below 0.2 indicated a potential problem (Menard, 1995). However, no problems were identified within this data set in terms of multicollinearity (normaility and multicolinearity statistics are presented in Appendix E, therefore multiple regression analysis was completed. The independent variables length from the centroid location (mm), angle from the centroid location (°) and surface area (mm^2) were the predictors used to assess whether the impact point on the golf ball effects velocity, side spin, initial ball roll, forward roll, true roll, vertical and horizontal launch angle and whether the ball was pushed or pulled. Level of significance was set at $p < 0.05$.

6.3.4 Results

Variation in X, Y coordinates of the impact point

Variability statistics are presented in Table 6.7. Variation was observed for X and Y coordinates for both the golf ball and the putter, however, variability of the impact point on the golf ball was greater than the golf putter for both X and Y coordinates. This trend was apparent across all four putter ball combinations. Peak CV for the golf ball X coordinate was 0.97 observed in the Odyssey-Srixon combination. Peak CV for the putter face X coordinate was 0.06 observed in the GEL®-Titleist combination. For the Y coordinate again the largest CV (1.08) for the golf impact was observed in the Odyssey-Srixon combination. For the Y coordinate on the putter face, the largest CV observed was 0.09 for the GEL®-Srixon combination.

Table 6.7. Mean ± SD and variability (CV) observed in the X, Y coordinates for impact point on the golf ball and putter face.

	Ball		Putter Face	
X Coordinate	Mean ± SD	CV	Mean ± SD	CV
GEL®-Titleist	1.63 ± 0.48	0.29	31.87 ± 1.78	0.06
GEL®-Srixon	0.82 ± 0.42	0.52	31.31 ± 0.69	0.02
Odyssey-Titleist	1.67 ± 0.48	0.29	32.97 ± 0.79	0.02
Odyssey-Srixon	0.50 ± 0.49	0.97	31.70 ± 0.98	0.03
Y Coordinate	Mean ± SD	CV	Mean ± SD	CV
GEL®-Titleist	2.18 ± 0.92	0.42	4.89 ± 0.33	0.07
GEL®-Srixon	0.84 ± 1.15	1.36	4.87 ± 0.43	0.09
Odyssey-Titleist	2.50 ± 0.84	0.34	7.79 ± 0.35	0.04
Odyssey-Srixon	1.06 ± 1.15	1.08	8.24 ± 0.45	0.05

Velocity

The multiple regression outputs are presented in Table 6.8. The regression model was found to be a significant predictor of velocity (as identified by the F-ratios) for two of the four putter ball combinations, GEL®-Srixon (p = 0.01) and Odyssey-Titleist (p = 0.02). Therefore, the impact variables accounted for 27% (0.01 ms^{-1}) and 25% (0.01 ms^{-1}) of the variance observed the GEL®-Srixon and Odyssey-Titleist groups respectively. Angle from the centroid location was found to be the most strongly associated with velocity for the GEL®-Srixon combination β = 0.51 and this was found to be significant (p = 0.002). No individual impact variables were found to be significantly associated for the Odyssey-Titleist combination. The regression model was found to be not significant as a predictor for the GEL®-Titleist and Odyssey-Srixon ball-putter combinations.

Side Spin

Outputs from the multiple regression analysis are presented in Table 6.9. Significant association was found between side spin with all predictors (length, angle and surface area) coupled for the Odyssey-Srixon combination (p = 0.04), the impact variables accounted for 20% (2.8 rpm) of the variation within this group. Even though significant when combined, no individual impact variables were found to be significantly associated for the Odyssey-Srixon combination. However, it was observed that the angle from the centroid had an increased association with side spin in comparison to the length and surface area. There was no significant association between the impact variables and kinematic variables for the other three putter-ball combinations.

Table 6.8. Linear regression model, between predictors and the kinematic variable velocity, R^2 and standardised β coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (ms^{-1})	2.14 ± 0.04	2.18 ± 0.03	2.13 ± 0.04	2.11 ± 0.05
R^2 ± SE	0.05 ± 0.04	0.27 ± 0.03	0.25 ± 0.04	0.01 ± 0.05
F-ratio, (*p*-value)	0.65 (0.58)	4.39 (0.01)	3.89 (0.02)	0.07 (0.98)
Length (β), (*p*-value)	0.03 (0.90)	-0.04 (0.82)	0.20 (0.31)	-0.01 (0.97)
Angle (β), (*p*-value)	-0.18 (0.44)	0.51 (<0.01)	0.46 (0.08)	0.03 (0.90)
Surface Area (β), (*p*-value)	-0.09 (0.69)	-0.16 (0.31)	-0.39 (0.07)	-0.08 (0.68)

Table 6.9. Linear regression model, between predictors and the kinematic variable side spin, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (Cut (+), Hook (-), rpm)	-12.62 ± 18.35	1.64 ± 15.25	-13.36 ± 13.76	0.86 ± 14.32
R^2 ± SE	0.20 ± 16.50	0.17 ± 14.47	0.16 ± 13.16	0.20 ± 13.31
F-ratio, (*p*-value)	2.84 (0.052)	2.43 (0.08)	2.21 (0.10)	3.04 (0.04)
Length (β), (*p*-value)	-0.31 (0.10)	-0.32 (0.07)	-0.29 (0.16)	-0.02 (0.93)
Angle (β), (*p*-value)	-0.26 (0.24)	-0.14 (0.39)	-0.07 (0.79)	-0.37 (0.052)
Surface Area (β), (*p*-value)	0.10 (0.62)	0.27 (0.11)	-0.13 (0.56)	-0.16 (0.35)

Initial Ball Roll

The multiple regression model was found to be significant predictor of initial ball roll (Table 6.10) for the GEL®-Srixon (p = 0.01) and Odyssey-Srixon (p = 0.008) groups. The impact variables accounted for 26% variability observed in the initial ball roll for the GEL®-Srixon group and 28% for the Odyssey-Srixon group. No individual impact variables were significant for the Odyssey-Srixon group. However, for the GEL®-Srixon group the angle from the centroid had a significant association with initial ball roll (p = 0.04). The regression model was not a significant predictor of initial ball roll for the GEL®-Titleist and Odyssey-Titleist groups.

Table 6.10. Linear regression model, between predictors and the kinematic variable initial ball roll, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (rpm)	7.04 ± 18.74	8.16 ± 20.04	-2.58 ± 13.00	6.59 ± 17.31
R^2 ± SE	0.06 ± 18.87	0.26 ± 17.92	0.02 ± 13.38	0.28 ± 15.30
F-ratio, (*p*-value)	0.82 (0.49)	4.25 (0.01)	0.26 (0.85)	4.62 (<0.01)
Length (β), (*p*-value)	-0.03 (0.88)	-0.17 (0.32)	-0.09 (0.67)	-0.36 (0.06)
Angle (β), (*p*-value)	-0.29 (0.23)	-0.34 (0.04)	0.03 (0.91)	-0.26 (0.15)
Surface Area (β), (*p*-value)	0.94 (0.67)	-0.21 (0.17)	0.12 (0.62)	0.05 (0.75)

Forward Roll

Outputs from the multiple regression analysis are presented in Table 6.11. The regression model was found to be a significant predictor of forward roll for the GEL®-Srixon (p = 0.03) group, for all other putter ball combinations the model was found to be not significant. For the GEL®-Srixon group 22% of total variability of forward roll can be accounted to the impact variables, this explains a variance of 0.23 rpm. The variable with the strongest association with forward roll was length from the centroid location and this was found to be significant (β = 0.35, p = 0.047).

True Roll

The regression model was found to be non significant for all putter ball combinations (Table 6.12). Variance in true roll accounted by the impact variables was customarily low across all groups (5 – 13%). However, as the model was found to not be significant there is error within the model of providing an accurate prediction of variability.

Table 6.11. Linear regression model, between predictors and the kinematic variable forward roll, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (rpm)	1.05 ± 1.39	0.85 ± 1.06	1.50 ± 1.55	1.05 ± 1.14
R^2 ± SE	0.03 ± 1.43	0.22 ± 0.98	0.09 ± 1.54	0.04 ± 1.17
F-ratio, (*p*-value)	0.38 (0.77)	3.31 (0.03)	1.21 (0.32)	0.45 (0.72)
Length (β), (*p*-value)	-0.10 (0.62)	0.35 (0.05)	0.20 (0.34)	0.03 (0.88)
Angle (β), (*p*-value)	0.24 (0.31)	0.11 (0.50)	0.12 (0.65)	0.18 (0.38)
Surface Area (β), (*p*-value)	-0.15 (0.48)	0.14 (0.38)	0.02 (0.92)	-0.05 (0.78)

Table 6.12. Linear regression model, between predictors and the kinematic variable true roll, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (cm)	65.02 ± 4.18	62.36 ± 7.99	66.17 ± 5.63	61.40 ± 6.25
R^2 ± SE	0.13 ± 4.04	0.05 ± 8.10	0.10 ± 0.03	0.07 ± 6.26
F-ratio, (*p*-value)	1.63 (0.20)	0.65 (0.59)	1.35 (0.27)	0.92 (0.44)
Length (β), (*p*-value)	-0.27 (0.17)	-0.16 (0.41)	-0.06 (0.77)	0.19 (0.37)
Angle (β), (*p*-value)	0.19 (0.40)	0.21 (0.25)	0.45 (0.11)	0.13 (0.53)
Surface Area (β), (*p*-value)	0.26 (0.21)	0.14 (0.43)	-0.40 (0.09)	-0.17 (0.35)

Vertical Launch Angle

The multiple regression outputs for the variable vertical launch angle are displayed in Table 6.13. The regression model was found to be a significant predictor of vertical launch angle for the GEL®-Srixon group (p = 0.001), the impact variables accounted for 36% (0.12°) of the variance observed. The variable angle from the centroid location was found to have the largest association with vertical launch angle, with a standardised β = 0.39 and this was confirmed to be significant p = 0.01. Length from the centroid location had a standardised β value of 0.31, however this was found not to be significant (*p* = 0.052). The model was not a significant predictor of vertical launch angle for the other three groups.

Table 6.13. Linear regression model, between predictors and the kinematic variable vertical launch angle, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (°)	1.12 ± 0.25	1.08 ± 0.32	1.43 ± 0.27	1.29 ± 0.24
R^2 ± SE	0.05 ± 0.25	0.36 ± 0.26	0.08 ± 0.27	0.03 ± 0.24
F-ratio, (*p*-value)	0.53 (0.66)	6.88 (<0.01)	1.11 (0.36)	0.33 (0.80)
Length (β), (*p*-value)	-0.01 (0.98)	0.31 (0.05)	-0.11 (0.60)	0.03 (0.88)
Angle (β), (*p*-value)	0.27 (0.25)	0.39 (0.01)	0.23 (0.41)	0.15 (0.46)
Surface Area (β), (*p*-value)	-0.18 (0.42)	0.08 (0.57)	0.12 (0.59)	-0.03 (0.87)

Horizontal Launch Angle

The multiple regression outputs for horizontal launch angle are displayed in Table 6.14. The multiple regression model was found to be a significant predictor of horizontal launch angle for the GEL®-Titleist (*p* = 0.002), GEL®-Srixon (*p* = 0.001) and Odyssey-Srixon (*p* = 0.03) groups, no significance was found for the Odyssey-Titleist group. The impact variables accounted for 34% of the variability of horizontal launch angle for the GEL®-Titleist group, 44% for the GEL®-Srixon group and 21% of the variability for the Odyssey-Srixon group. Length from the centroid location was significantly associated with the horizontal launch angle for all three groups, β = *-0.43, p* = 0.02 (GEL®-Titleist), β = *-0.60, p* = 0.001 (GEL®-Srixon) and β = *-0.41, p* = 0.04 (Odyssey-Srixon). Additionally for the GEL®-Titleist group angle from the centroid location was significantly associated with the horizontal launch angle (β = *0.76, p* = 0.001), however, this was not the case for the other putter ball combinations. Surface area was significantly associated with the horizontal launch angle (*p* = 0.003) for the GEL®-Srixon group with a standardised β value of 0.42.

Table 6.14. Linear regression model, between predictors and the kinematic variable horizontal launch angle, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (Right (+), Left (-), °)	0.47 ± 0.43	0.31 ± 0.30	0.12 ± 0.44	0.34 ± 0.18
R^2 ± SE	0.34 ± 0.37	0.44 ± 0.23	0.13 ± 0.42	0.21 ± 0.16
F-ratio, (*p*-value)	6.17 (<0.01)	9.58 (<0.01)	1.71 (0.18)	3.23 (0.03)
Length (β), (*p*-value)	-0.43 (0.02)	-0.60 (<0.01)	-0.22 (0.29)	-0.41 (0.04)
Angle (β), (*p*-value)	0.76 (<0.01)	-0.14 (0.30)	0.21 (0.45)	0.23 (0.22)
Surface Area (β), (*p*-value)	-0.07 (0.72)	0.42 (<0.01)	0.21 (0.36)	-0.23 (0.17)

Push and Pull

The multiple regression model was identified as a significant predictor of whether the ball was pushed or pulled (Table 6.15) for the GEL®-Titleist (p = 0.003), GEL®-Srixon (p = 0.001) and Odyssey-Srixon (p = 0.008). The impact variables accounted for 33%, 37% and 28% of variability of whether the ball was pushed or pulled for the GEL®-Titleist, GEL®-Srixon and Odyssey-Srixon groups respectively. In terms of the raw variance 0.24 cm, 0.18 cm and 0.08 cm can be attributed to the impact variables, this distribution of the ball is based on an 8 foot putt and all the trials for each group would still have resulted in a successful putt. For the GEL®-Srixon and Odyssey-Srixon groups, length from the centroid location had the largest association with the push and pull kinematic variable, standardised β values of -0.52 (p = 0.001) and -0.50 (p = 0.01), the GEL®-Titleist group also had a significant association between these variables (β = -0.41, p = 0.02). However, the largest significant association with whether the ball was pushed or pulled identified for the GEL®-Titleist group was angle from the centroid location with a standardised β value of 0.72 (p = 0.01). In addition to length from the centroid location being significantly associated with push and pull, surface area was also significantly associated (β = 0.44, p = 0.004) with push and pull for the GEL®-Srixon group. The model was found not to be significant for the Odyssey-Titleist group.

Table 6.15. Linear regression model, between predictors and the kinematic variable push and pull, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®-Titleist	GEL®-Srixon	Odyssey-Titleist	Odyssey-Srixon
Mean ± SD (cm)	2.00 ± 1.84	1.32 ± 1.26	0.40 ± 1.49	1.18 ± 0.72
R^2 ± SE	0.33 ± 0.63	0.37 ± 0.41	0.14 ± 0.57	0.28 ± 0.25
F-ratio, (*p*-value)	5.59 (<0.01)	6.93 (<0.01)	1.89 (0.15)	4.64 (<0.01)
Length (β), (*p*-value)	-0.41 (0.02)	-0.52 (<0.01)	-0.36 (0.09)	-0.50 (0.01)
Angle (β), (*p*-value)	0.72 (<0.01)	-0.11 (0.43)	0.35 (0.20)	0.23 (0.21)
Surface Area (β), (*p*-value)	-0.08 (0.64)	0.44 (<0.01)	0.08 (0.73)	0.22 (0.17)

6.3.5 Discussion

This is the first study to have measured and analysed the effects of the impact point on the golf ball on the subsequent ball roll kinematics. It was hypothesised that variance would exist in the distance, direction from the centroid location and surface area of the impact point which would have a direct relationship with the kinematics variables (velocity, vertical and horizontal launch angle, initial ball roll, forward roll and whether the putt was pushed or pulled). This hypothesis was expected to occur across all kinematic variables for all four putter-ball combinations. Therefore the hypothesis is partially accepted for two kinematic variables the horizontal launch angle and whether the ball was pushed or pulled (Tables 6.14 & 6.15). A significant association was identified with the impact variables for the majority of groups. The hypothesis was rejected for the remaining kinematic variables (velocity, side spin, initial ball roll, forward roll, true roll and vertical launch angle). The two kinematic variables that displayed the strongest relationship with the impact measurements were horizontal launch angle and push/pull, where associations were identified for the GEL®-Titleist, GEL®-Srixon and Odyssey-Titleist putter-ball combinations.

Even though it has not been discussed at length within the literature, the fact that golf balls are predominantly designed with ball flight in mind, maximising distance a golf ball will travel in flight may be a detriment to putting. Golf balls are designed with dimples to reduce drag and improve the aerodynamics of the golf ball (Aoki, Muto & Okanaga, 2010; Goff, 2013). This may be detrimental to putting, as essentially golf balls are not perfectly spherical and as a result the ball may potentially rebound off the putter during the impact at an unexpected angle (Cross, 2006) (Figure 6.14). With the golf putt being the most common shot in golf, and having been identified as having a significant relationship with overall scoring performance (Dorsel & Rotunda, 2001; Quinn, 2006: Wiseman & Chatterjee, 2006) this dimple error could be important to the golf putt.

The findings from this study show that variability existed for all the kinematic variables side spin, initial ball roll, forward roll, true roll, vertical launch angle, horizontal launch angle and whether the ball was pushed or pulled to varying degrees. However, the majority of putter-ball combinations significantly associated with the impact point on the golf ball were found for horizontal launch angle and whether the putt was pushed or pulled only. This could be attributed to the dimple error during impact. The centroid location identified for this study was between three dimples and therefore on the edge of a dimple for the Srixon ball, whereas for the Titleist balls centroid location was in the middle of a smaller dimple encapsulated by five larger dimples. The difference between brands is purely down to the different dimple patterns employed by each manufacturer and may have affected the significant associations observed. Length from the centroid location was found to be significantly negatively associated with the horizontal launch angle for three groups (GEL®-Titleist, GEL®-Srixon and Odyssey-Srixon). The variation in the length from the centroid may cause the ball to launch at a different horizontal angle due to the different points of the initial contact on the golf ball and dimple.

Pelz (2000) states that the larger the dimples, the more likely contact made on an edge will affect the roll of the putt in terms of the horizontal launch angle, as each dimple is covering a larger surface area. However, the smaller the dimple, the greater the number of dimples there will be covering the ball, and therefore the chance of making contact with the edge of a dimple increases in comparison to a golf ball with larger dimples. Although a golf ball with larger dimples has less chance of contact being made to a dimple edge, the horizontal deviation caused by impact may increase. Based on the results from the horizontal launch angle, this did not seem to be the case in this study. The Titleist Pro V1 dimple had a circumference of 12.38 mm and the Srixon Z-STAR dimple had a circumference of 12.94 mm. Based on Pelz (2000) predictions more variability would be expected to occur for the Srixon golf ball. However, for the horizontal launch angle, the impact variables were accountable for 0.13° variance for the GEL®-Srixon group and 0.04° variance for the Odyssey-Srixon group. This was in comparison to 0.15° variance for the GEL®-Titleist group and 0.06° variance (not found to be significant during analysis) for the Odyssey-Titleist group. Whilst, differences are marginal between each group, based on these results, it seems the different putters had more influence on the horizontal launch angle rather than the impact point on the golf ball.

The second kinematic ball roll variable that the impact variables had a significant association with was whether the ball was pushed or pulled, estimating the final position of the golf ball at 8 feet from the point of contact. Multiple regression analysis found a significant association between whether the ball was pushed or pulled and the impact variables for the GEL®-Titleist, GEL®-Srixon and Odyssey-Titleist group, with the length from the centroid location being significantly associated with push/pull for all three groups. The impact variables accounted for 0.61 cm of variation for the GEL®-Titleist group, 0.47 cm variation for the GEL®-Srixon group and 0.20 cm for the Odyssey-Srixon group. Based on the data from the Quintic Ball Roll software, all 160 trials would have been successful, even with the variation observed. Therefore, the variation accountable to the impact variables can be considered negligible for a simulated 3.2 m putt. This is in accordance with Karlsen et al. (2008) who state that variables of the putting stroke (putter face angle, putter path and horizontal impact point on the putter face) only have a minor influence on the direction consistency in golf putting in elite players. Karlsen et al. (2008) accounted 3% of direction consistency to the impact point on the putter face; it was observed that impact point variability was 2.72 ± 0.78 mm, with an effective variability on horizontal launch angle of 0.09°. This variability may not just be due to the variability on the putter face but also the impact point on the golf ball, as demonstrated by the results in this study. This is because the variability of the impact point on the putter face was standardised for this study, with 5.6% variation of the horizontal impact point and 6.7% variation of the vertical impact point. This is in comparison to 28.7% variation displayed by the subjects in Karlsen et al. (2008) protocol. Yet variability, even though small, still existed in this protocol for the horizontal launch angle and push and pull.

With the variability observed in this protocol being minimal for the horizontal launch angle and push and pull data this is unlikely to effect the putting success rate of a golfer. Karlsen et al. (2008) states that a stroke with a horizontal launch angle variability of 0.39° will miss approximately 5% of putts made from 13 feet. The data from this study falls well within this range (0.04° - 0.15°). Hurrion and MacKay (2012) further demonstrate that this minor variation will not affect success rate from 15 feet as they state that the largest horizontal launch angle needed that will ensure a successful putt is 0.60°.

Weak association was observed between all other kinematic ball roll variables and impact point variables in this study. No significant associations between the kinematic variable true roll and the impact variables (Table 6.12), therefore dimple error did not effect the distance of at which the golf ball had eliminated all elements of skid (the ball rotates 360° across its circumference). The length and angle from the centroid and surface area had one putter-ball combination significantly associated with the variables side spin (Table 6.9), forward roll (Table 6.11) and vertical launch angle (Table 6.13), consequently the impact point on the golf ball can be considered not to effect these variables. Specifically for the variable side spin, when the putter face angle and path remain constant the variability observed in impact on the ball adjusting the angle of incidence does not significantly influence the gear effect as previously highlighted by Cross and Nathan (2007). The angle of incidence was manipulated to a much higher degree in the protocol conducted by Cross and Nathan (2007) than the current study and therefore the conclusions drawn from Cross and Nathan (2007) may not be practically applicable to the golf putt.

The variable velocity (Table 6.8) had two groups whereby the impact variables were significantly associated, however, one group was GEL®-Srixon and the other Odyssey-Titleist, so little can be drawn from this data for the variable velocity. The impact variables of two putter ball groups (GEL®-Srixon and Odyssey-Srixon) were associated with the kinematic variable initial ball roll (Table 6.10). It may be the case that the different dimple patterns react differently to the variation observed in the point of impact on the golf ball, as no association was identified for the Titleist Pro V1 with either of the golf putters. The most likely individual impact variable thought to be associated with velocity was considered to be surface area, due to the compressive nature of the golf ball. However, the angle from the centroid location was the only impact variable found to be associated with velocity was angle from the centroid location for the GEL®-Srixon group. The reason this was not the case may be because of the use of the putting robot whereby the putter head velocity was controlled. More data would need to be collected to confirm whether the impact point on the golf ball is associated with the initial ball roll.

The reason for the variation in all kinematic variables and the impact variables may be due to the placement of the golf ball during the protocol. The increased variability observed in the X, Y coordinates of the impact point on the ball in comparison to the putter face demonstrates this (Table 6.7). Even though it was controlled for using two laser lines to ensure the correct placement of the golf ball, small dissimilarities may have occurred, as this was the only human element within the protocol and therefore subject to a certain degree of error. However, it is suggested that a golfer would not be able to control for this variability during an actual golf round to the same extent as was performed during this protocol. The rationale for this suggestion is, although often golfers of all abilities will use an aim guide either printed or manually drawn on the golf ball, they do not have the added guide of laser lines to place the ball in the same position every time. Additionally, golf greens will not be perfectly flat and there may be green irregularities such as pitch or stud marks, which may affect the final resting place of the ball before the execution of the putt. With this is mind it is reasonable to assume that there is likely to be greater variation in the placement of the golf ball during a golf round in comparison to this protocol.

Practical implications of this study are that golfers should not be concerned with dimple error since dimple error will be negated due to the compressive nature of the golf ball for the large majority of golf putts. The results from this study suggest that Pelz (2000) may have overestimated the compressive nature of the golf ball during a golf putt, with variability observed for a 10.5-foot putt in this protocol. Additionally, it is clear from the imprints left of the pigmented emollient that one dimple or dimple edge came into contact with the putter. Figure 6.16 shows the impact zone for four lengths of putt and it is apparent that an increased number of dimples come into contact with the putter for the 10-foot putt during Pelz (2000) experiments than the current study (Figure 6.17) even though a similar length of putt was completed. The likely reason for the differences is differences in the resilience of the surface of either the putter or golf balls used in the experiment. It is the belief of the author that some of this additional surface area between the shorter lengths of putt (3 and 10 foot) may be due to small amounts of rotation occurring during impact and not just compression of the ball.

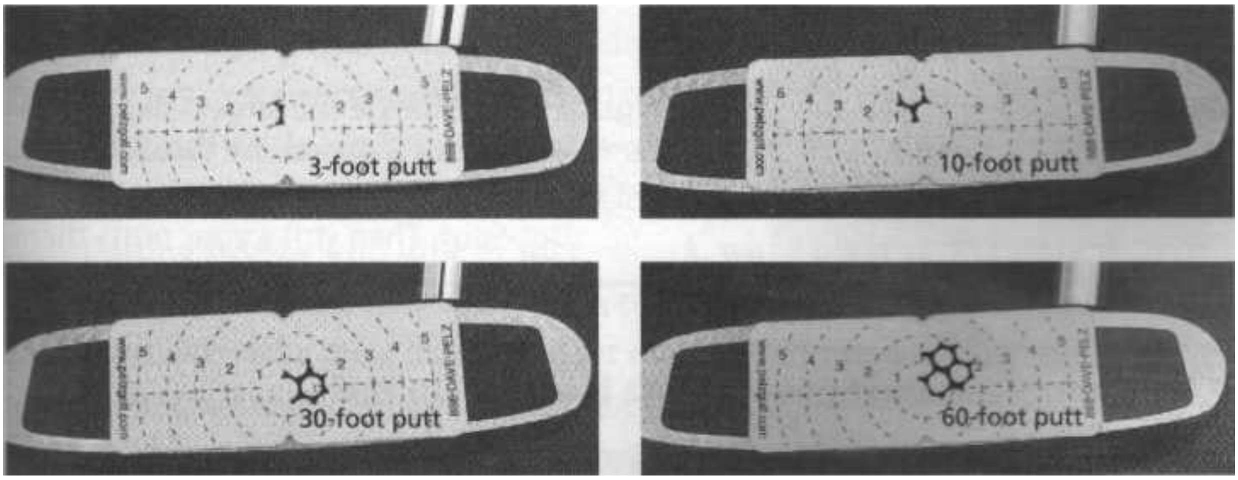

Figure 6.16. Dimple edges that come into contact with the putter at four distances (3-foot, 10-foot, 30-foot and 60-foot) taken from Pelz (2000).

Figure 6.17. Example of the size of the impact zone for the Titleist and Srixon golf ball.

The effects of the variability of the impact point on the golf ball causing dimple error are minimal, with all other parameters of technique remaining constant (putter face angle at impact, putter path and horizontal impact point on the putter face), dimple error will not effect the success rate of a putt. However, techniques demonstrated in Pelz (2000) (circling an area on a golf ball with the largest dimple free zone) may still be beneficial, since this may minimise the chance of dimple error occurring. As for all golfers putting stroke parameters (face angle and path) will never be a constant like this protocol. This is possible on the Titleist Pro V1 golf ball as the ball has an obvious seam across the golf ball, whereas, the Srixon Z-STAR has no obvious seam and therefore it may be more difficult to locate a dimple free zone (Figure 6.18).

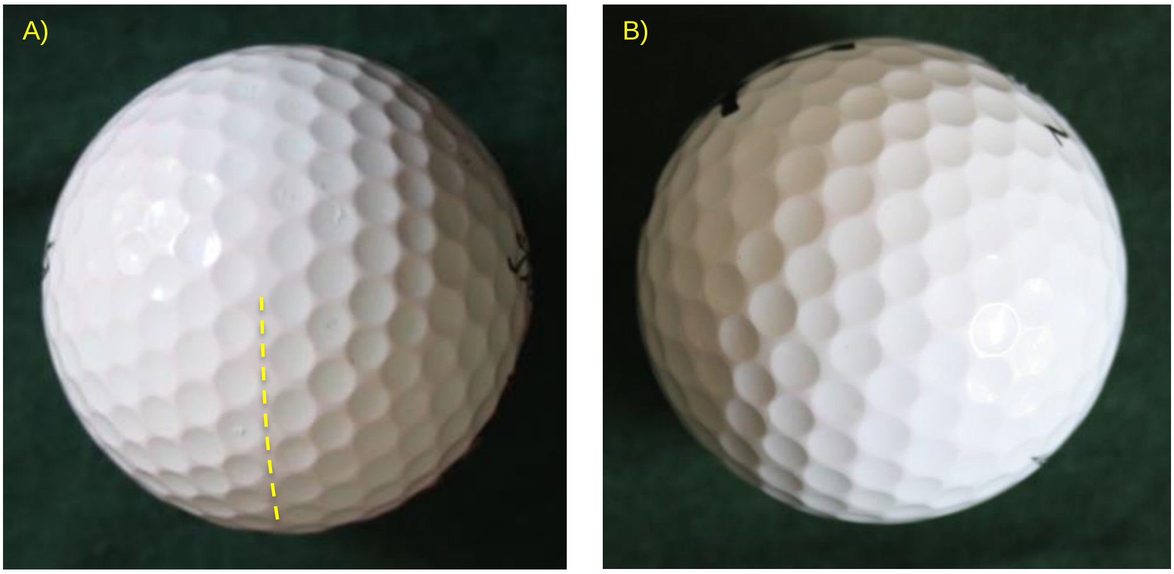

Figure 6.18. Dimple patterns for A) Titleist Pro V1 and B) Srixon Z-STAR. The dashed yellow line shows the seam of the golf ball for the Titleist Pro V1.

A limitation of this study is that the impact was not recorded at a sufficiently high camera frame rate to allow type of contact (either where the contact is identified as striking a dimple flat or striking the edge of the dimple) could be identified. This would help clarify the situation of whether there was error in the placement of the golf ball. Another limitation of the study could be the method used to identify the centre of the impact zone, where a polygon was drawn around the impact zone and intersected to identify a coordinate, which was related back to the coordinate of the centroid location. Potentially, there is a more accurate way that the centre of the impact point could be identified, as this method did not account for the centre of the dimple which would not come into contact with the putter due to the depression in the golf ball design. No other options were available to the authors' knowledge.

In future research it would be interesting to observe the isolated impact point with high-speed video recordings. Hurrion and Hurrion (2002) suggest that a frame rate of 2000 Hz would be needed to effectively record this. It would be beneficial to see whether different putting strokes

(Study Four, Figure 6.2) influenced the variance observed in the impact point on the golf ball and the subsequent kinematics of the ball roll. This potentially could identify if a golfer should strive for a particular type of putting stroke regarding reducing the effects of dimple error. Impact variability on the golf ball needs to be investigated with a human population with a varying range of handicaps as to date no published research has extensively investigated this mechanism. Finally, this research only examined two premium golf balls on the market both with a soft Urethane Elastomer cover (Srixon, 2013; Titleist, 2013). Investigations into cheaper branded golf balls needs to be conducted to see if different covers of differing hardness have different variability in the impact point on the golf ball and whether this alters ball roll kinematics.

6.3.6 Conclusion

Two kinematic variables, horizontal launch angle and whether the ball was pushed or pulled, were identified to have a significant association with the point of impact on the golf ball for the majority of putter ball combinations. The variability observed however would not alter the success rate of a putt. The small degree of variability observed in horizontal launch angle would not come into effect of missing a putt within 15 feet and due to the compressive nature of a golf ball dimple error would be negated at putts greater than this length. The practical implications of this are that the golfing populating should not be concerned with dimple error during the putting activity and should instead focus on other elements that contribute to a successful golf putt. Such as, focusing on the putter face angle, which has previously been found to significantly contribute to the direction of a golf putt.

6.4 Development of Research

This was the first chapter that has diverted from the original aims of the thesis, due to the variance observed in Study Three and the perceived lack of literature in the area. This chapter shows two methods that were attempted at analysing the impact point on the golf ball, one of which presented in Pilot Study Five being unsuccessful. This has made this thesis stronger as it allowed for a far more sophisticated method to be developed, strengthening the theme and complexity of this research. Additionally, it allowed for a more comprehensive investigation and clearer conclusion of the problem in hand.

This chapter contributes to the current literature by highlighting the degree to which the impact point on the golf ball affects ball roll kinematics. Study Four shows that the method used to accurately identify the impact point on the golf ball was reliable and repeatable. Study Five demonstrated that the impact point on the golf ball is significantly associated with the kinematic variables horizontal launch angle and whether the ball was pushed or pulled. The other kinematic variables, velocity, side spin, initial ball roll, forward roll, true roll and vertical launch angle were not significantly associated with the impact variables for the majority of putter-ball combinations. These variables should still be analysed with a human subject sample a long with the horizontal launch angle and whether the ball was pushed or pulled, as the variability of the impact point on the putter face and ball is going to increase. This may highlight more associations between the impact variables and kinematic variables, which were not identified as significantly associated while using a putting robot.

This will additionally establish as to whether this affects the success rate of a golf putt, as the variability observed in Study Five of the horizontal launch angle and whether the ball was pushed or pulled would not effect the success rate of a putt and therefore renders this mechanisms influence on direction variability of a golf putt negligible. The next chapter will assess the influence of the impact point on the golf ball with a human subject sample.

Chapter Seven

The relationship between centre of pressure excursions and centre of mass displacement and the influence of body kinematic variability and impact point of the golf ball on the kinematic ball roll variables

7.1 Introduction to Chapter

In Study Five it was observed that a significant association existed between the kinematic ball roll variables horizontal launch angle and the push/pull variable and the impact point on the golf ball. These results raised another question and therefore aim of the thesis:

- If the impact point on the golf ball was found to be significantly associated with the horizontal launch angle and whether the ball was pushed or pulled when using a fixed mechanical putting arm, does this association also exist with human participants?

The findings from answering this aim and question will determine as to whether golfers should consider and take actions in an attempt to reduce dimple error. It was observed in Study Two that LH golfers demonstrated smaller CPE along the AP axis in comparison to the HH group for all three phases of the golf putt. However, there is very little research investigating whether CP excursion patterns reflect that of the displacement of the COM. This therefore raised another new aim of the thesis:

- To assess the relationship between the centre of mass and centre of pressure excursions during the putter stroke. To identify whether CP excursions can accurately reflect the movement of the golfer.

Investigating this will provide more rationale for one of the conclusions and practical implications of Study Two, whereby coaches and players should identify the golfer's body parts used to generate power, and therefore whether it is suitable to reduce the amount of torso rotation. Movement variability is explored within this chapter and whether this is the key variable for the golf putt. This movement variability affect on performance to date is unexplored within the golf putt. Therefore the final aim of the thesis was explored:

- To assess to what degree putter face and body segment variability affects putting performance.

This chapter includes two studies, firstly, Study Six: The effect of the impact point on golf ball roll kinematics (Section 7.2), following this Study Seven: The evaluation of centre of mass' relationship with centre of pressure excursions and the effect of movement variability on putting performance (Section 7.3) is presented. With the development of research section concluding the chapter (Section 7.4).

7.2 Study Six: The effect of the impact point on golf ball roll kinematics.

7.2.1 Abstract

Background: Study Five identified a significant association between the impact variables and the variables horizontal launch angle and whether the ball was pushed or pulled when using a putting robot, this needed to be investigated with human participants. **Aim:** To investigate the effects of the impact point on the golf ball and the impact point on a putter on the resulting ball roll kinematics. **Method:** After the subjects habituated themselves to the task they completed six successful 3.2 m putt trials with two different putters (one groove faced and the other a traditional face). The impact point was identified by firstly identifying the centroid location (centre of dimple pattern). From this the following impact variables were measured; the distance and angle from the centroid location and surface area of the impact zone. Variability of the impact location on the putter face and golf ball between groups was assessed using the X and Y coordinates from the centroid location. Multiple regression analysis was used to identify if any significant associations existed between the impact variables and the following kinematic ball roll variables; velocity, side spin, initial ball roll, forward roll, vertical and horizontal launch angles and whether the golf ball was pushed (ball ended right of the target line) or pulled (ball ended left of the target line). An independent samples *t*-test (or non parametric alternative) was used to assess the variability of the impact point on the golf ball and putter face. **Results:** A significant association was identified between the impact variables and the ball velocity. No other significant associations were observed for both putters for any of the other variables. The only significant difference between the variation of the impact point between both groups was the Y coordinate on the putter face. **Conclusion:** No significant associations between the impact variables and horizontal launch angle and whether the ball was pushed or pulled may have been due to the fact the variance in the putter face angle and putter path rendered the effects of dimple error negligible. No differences for intra-subject variability of the X coordinate on the club head and ball may not have been significant due to the club head velocity being not significantly different between the two groups.

7.2.2 Introduction

Very little research to date has investigated the effect of the impact point on the golf ball and ball roll kinematics (velocity, side spin, initial ball roll, forward roll, vertical launch angle, horizontal launch angle and whether the ball was pushed or pulled). Pelz (2000) identified that dimples do affect the direction variability during the golf putt via the mechanism shown in Figure 6.14. However, the data presented is very limited and needs expanding on using human participants. Study Five of this thesis identified a significant association between the impact variables (length and angle from the centroid location and surface area of the impact zone) and the kinematic ball roll variables horizontal launch angle and whether the ball was pushed or pulled for three of the four putter-ball combinations while using a mechanical putting robot. During this protocol the face angle at impact, putter path and horizontal impact point on the putter remained constant. Karlsen et al. (2008) and Pelz (2000) have previously identified these variables to affect direction consistency and did not consider the influence of the impact point on the golf ball.

Therefore, the aim of this study was to investigate the effects of the impact point on the golf ball and the impact point on a putter on the resulting ball roll kinematics using golfers with a range of ability. Based on the results observed in Study Five it was hypothesised that significant associations would exist between the impact variables and the kinematic ball roll variables horizontal launch angle and whether the ball was pushed or pulled. It was additionally hypothesised that increased variability of the impact point on the golf ball and putter face would be observed in the < 80% success rate group.

7.2.3 Methods

Participants

Following institutional ethical approval, a total of 22 right handed golfers participated in the study (age 42 ± 12.38 years; handicap 13.6 ± 7.4 (handicap range 0-28); height 1.76 ± 0.21 metres; mass 88.6 ± 23.8 kg). All golfers played a minimum of once a week and wore their own personal golfing attire and golf shoes. Signed informed consent was gained before testing.

Experimental set - up

All testing was completed in the University of Hertfordshire human performance laboratory. A Huxley Golf artificial putting green (3.66 x 4.27 metres) was used that registered 11 on the stimpmeter. A level straight 3.2 metre putt was setup with a regulation 108 mm hole. Two putters were used for the experiment a GEL® Vicis putter (grooved faced, 69º lie and 2.5º loft) and Odyssey White Hot #3 (non grooved face, 69º lie and 2.5º loft). Putters were standardised for the protocol as differences were identified in kinematic ball roll variables between putters in Study Three and Five. A thin layer of pigmented emollient was applied to the putter face and smoothed out before each trial for subsequent impact point analysis. The golf ball used for the protocol was the Srixon Z-STAR, and each trial completed used the same ball. Each trial was completed with subjects standing with both feet on an RS Scan FootScan pressure plate with a total 4096 sensors, sampling at 120 Hz was used to record CPE movements during the putting stroke.

To record the ball roll kinematics, a Quintic high speed camera sampling at 220 Hz was positioned perpendicular to the putting line. The Quintic Ball Roll v2.4 launch monitor software was used to analyse the recorded videos of the ball roll, allowing for analysis of the kinematic ball roll variables. Kinematic variables measured were initial velocity ($m \cdot s^{-1}$, calculated across the first 6 recorded frames); side spin (the amount of side spin (rpm) placed on the ball during impact); launch angle measured in degrees (vertical (whether the ball was launched in the air) and horizontal (the degree to which the ball deviates from the original putting line), initial ball roll (whether the golf ball has positive rotation (topspin) or negative rotation (backspin) at the point of impact (rpm)), forward roll (the distance at which the ball starts positive rotation (cm)) and whether the putt was pushed (right) or pulled (left) (a calculation of the final resting point of the golf ball based on the kinematic variables recorded (cm)). A Canon EOS 1000d camera was situated on a stationary Velbon CX-440 tripod was placed away from the putting line where it did not disturb the view of the participant during the trial.

Procedure

Participants were allowed as much time as they needed to habituate themselves to the first putter that had been randomly selected. This habituation period was repeated when the putters were swapped mid protocol. Once the participant was comfortable and ready to proceed with the trial the investigator lined up the putt with the Superline 2D line lasers, before the trial was completed the laser lines were turned off so not to distract the participant. The FootScan pressure plate was zeroed before the participant stepped on before each trial. Following the participant stepping onto the FootScan pressure plate the Quintic Ball Roll v2.4 software was activated. The participant was then verbally instructed the trial was due to start once the RS Scan FootScan pressure plate was activated via the external trigger this was due to the 8-second recording time limit while recording at 120 Hz.

Once the trial had been completed and the result clear, the participant was asked to step back off the pressure plate, the trial was then saved on the Quintic Ball Roll software, RS Scan FootScan software. After each trial two pictures were taken with the Canon EOS 1000d camera with the pigmented emollient imprint on the ball and of the imprint of the dimple pattern left on the putter face. If the putt was missed, the putt result was manually measured as the radial distance from the centre of the hole, and identified as long, short, left and right or a combination of two of the directions in accordance with McLaughlin and Best (2013) and Wilson et al. (2007). This process was completed until six successful putts had been completed with each putter; however, missed putts were included within analysis.

Data Processing

The data identifying the centroid location, length and angle from the centroid location was processed in the manner described in Study Four (pp. 112 – 116). The X, Y coordinates for the impact point on the putter face where processed using the polygon technique as described in Study Four (Figure 6.5, pp. 114). Additional information about this process is described in Study Five (Figure 6.15, pp. 134).

Data Analysis

Data was exported to statistical software packages Microsoft Excel 2011 and SPSS v19 for analysis. To compare the variance between scales could be, variability of the X, Y coordinates of the impact point on the golf ball and putter face were assessed using the coefficient of variation ($CV = \sigma/\mu$).

Firstly, the data was tested for normality by assessing the data set skewness and kurtosis values, histogram and box-plot graphs. Any data sets that were found to be highly skewed or displaying high levels of kurtosis was log transformed to increase uniformity to a normal distribution curve (Atkinson & Nevill, 1998; Hopkins et al., 2009). Further information on boundaries set for skewness and kurtosis values is found in Study Five. Normality statistics are presented in full in Appendix F.

For the multiple regression analysis the independent variables used were the length of the impact point from the centroid location (mm), angle of the impact point (°) from the centroid location and surface area of the impact zone (mm^2). These were used as the predictors for the multiple regression analysis. The dependent variables were the kinematic ball roll variables (velocity, side spin, launch angle (vertical and horizontal), initial ball roll, forward roll, and whether the putt was pushed (right) or pulled (left)), these were analysed individually from one another. Level of significance was set at $p < 0.05$.

Statistical analysis completed assessing the variation of the X, Y coordinates on the golf ball and putter face was completed by grouping the participants by putting success rate (> 80% success rate and < 80% success rate). An independent samples t-test (or the non parametric alternative (Mann-Whitney U test) if the data was found to be not normally distributed) statistically compared the groups. All trials were tested together as not all participants missed a putt with either putters, however, all trials (successful putts and missed putts) are presented. The multiple regression analysis was completed with all participants' data in an attempt to identify the relationship between the impact and kinematic ball roll variables.

7.2.4 Results

X, Y coordinates of the impact point on the golf ball and putter face

Variation was observed for X and Y coordinates for both the putter face (Tables 7.3 and 7.4) and golf ball (Tables 7.1 and 7.2). Increased variation was observed for X and Y coordinates on the golf ball in comparison to the putter face. No statistical differences between intra-subject variation were identified between the > 80% success group and the < 80% success group for either the GEL® or Odyssey putter (Figure 7.1). The > 80% success group demonstrated statistically significantly greater variation for the Y coordinate on the putter face ($p = 0.02$) while using the GEL® putter, no statistical differences were observed for the Odyssey group (Figure 7.2).

Peak CV for the X coordinate for the golf ball was observed for the < 80% success group while using the GEL® putter (CV = 3.30 for all trials). An increase was observed for successful putts also with the GEL® putter (CV = 4.23). Peak CV for the Y coordinate on the golf ball was also observed for the < 80% success group with the Odyssey putter (CV = 7.42 for all trials). Again similarly to the peaks observed for the X coordinate an increase was observed when only successful putts were used to calculate the CV (9.56). Peak CV for the X coordinate on the putter face was observed for the > 80% group using the GEL® putter (CV = 0.14 for all trials), this was also observed for the Y coordinate (CV = 0.42 for all trials).

Table 7.1. Mean ± SD and variability (CV) observed for the impact point on the golf ball for the > 80% successful putts group.

	GEL®		Odyssey	
X Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	0.59 ± 0.71	1.20	0.68 ± 1.11	1.63
Successful	0.59 ± 0.67	1.13	0.70 ± 1.11	1.58
Missed	1.17 ± 1.13	0.96	-0.44 ± 0.25	0.57
Y Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	0.77 ± 1.00	1.29	0.98 ± 1.35	1.38
Successful	0.69 ± 0.95	1.36	1.02 ± 1.29	1.27
Missed	1.15 ± 2.08	1.81	-0.32 ± 2.40	7.55

Table 7.2. Mean ± SD and variability (CV) observed for the impact point on the golf ball for the < 80% successful putts group.

	GEL®		Odyssey	
X Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	0.48 ± 1.59	3.30	0.57 ± 0.98	1.72
Successful	0.40 ± 1.69	4.23	0.67 ± 1.06	1.58
Missed	0.43 ± 0.83	1.97	0.60 ± 1.16	1.91
Y Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	0.34 ± 1.02	3.00	0.14 ± 1.07	7.42
Successful	0.35 ± 0.97	2.72	0.13 ± 1.20	9.56
Missed	0.33 ± 1.31	4.03	0.18 ± 1.29	7.06

Table 7.3. Mean ± SD and variability (CV) observed for the impact point on the putter face for the > 80% successful putts group.

	GEL®		Odyssey	
X Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	28.61 ± 3.95	0.14	30.92 ± 2.44	0.08
Successful	28.85 ± 4.07	0.14	30.82 ± 2.34	0.08
Missed	25.85 ± 6.05	0.23	31.62 ± 2.51	0.08
Y Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	7.28 ± 3.04	0.42	7.41 ± 2.25	0.30
Successful	7.28 ± 3.06	0.42	7.42 ± 2.22	0.30
Missed	9.25 ± 2.89	0.31	6.01 ± 2.71	0.45

Table 7.4. Mean ± SD and variability (CV) observed for the impact point on the putter face for the < 80% successful putts group.

	GEL®		Odyssey	
X Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	30.69 ± 3.38	0.11	31.80 ± 2.95	0.09
Successful	30.03 ± 4.21	0.14	31.41 ± 2.92	0.09
Missed	31.22 ± 4.26	0.14	32.26 ± 3.74	0.12
Y Coordinate	Mean ± SD	CV	Mean ± SD	CV
All Trials	8.52 ± 2.85	0.33	8.18 ± 1.56	0.19
Successful	8.58 ± 2.47	0.29	7.97 ± 2.02	0.25
Missed	8.39 ± 2.90	0.35	8.40 ± 1.58	0.19

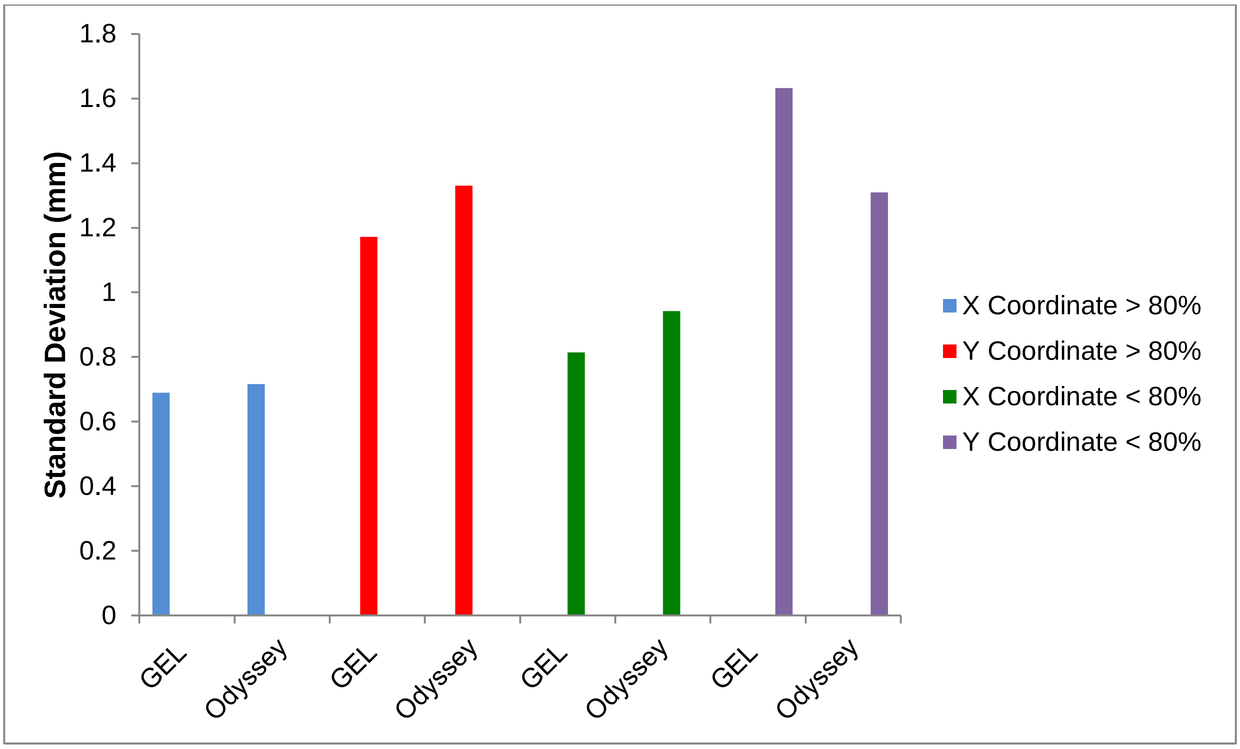

Figure 7.1. Standard deviation scores for the X, Y coordinates on the golf ball.

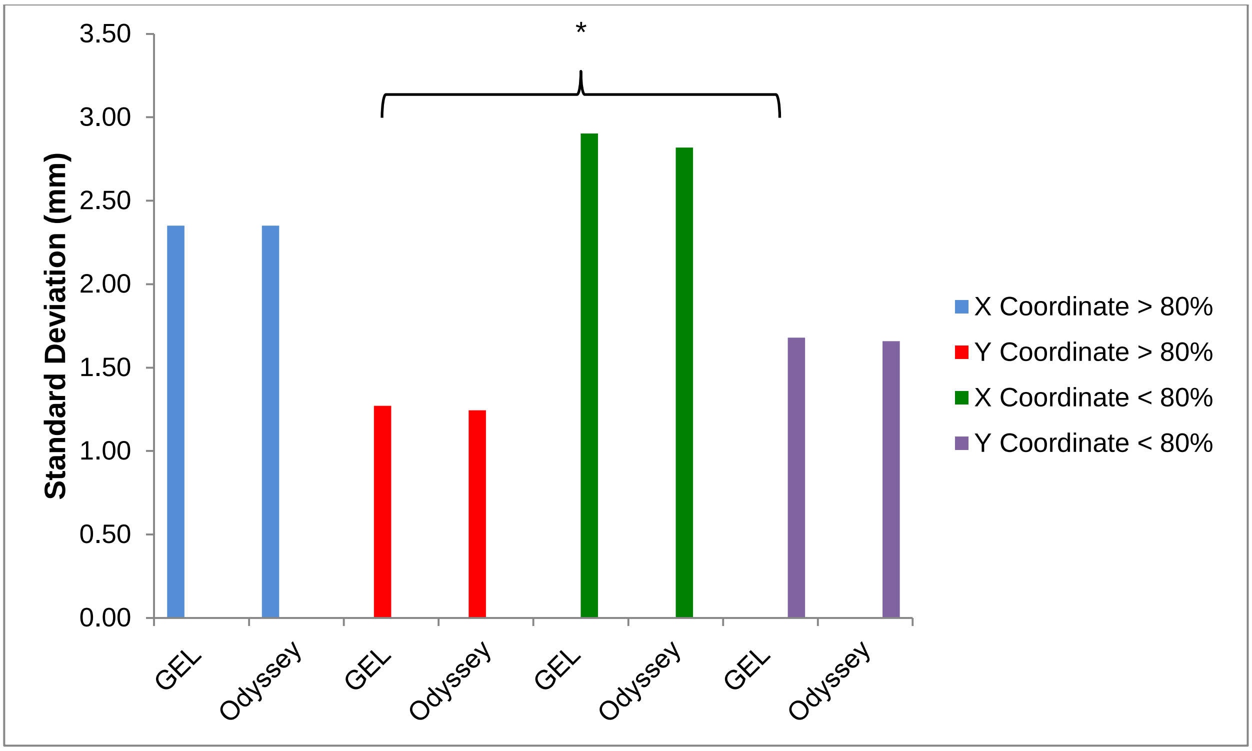

Figure 7.2. Intra-subject variability for the X, Y coordinates on the putter face (* denotes statistically significant difference, $p < 0.05$).

Velocity

The multiple regression outputs are presented in Table 7.5. The regression model was found to be a significant predictor of the variation observed for velocity accountable to the impact variables (GEL®, F = 6.59 (p < 0.001); Odyssey, F = 5.96 (p < 0.001)). Therefore, the impact variables were accountable for 12% (0.02 ms^{-1}) and 9% (0.01 ms^{-1}) of variability observed for the GEL® and Odyssey putters respectively. Surface area was the individual impact variable found to be significantly associated with velocity for the both the GEL® (β = -0.25, p = 0.006) and Odyssey (β = 0.32, p < 0.001) putters. Neither length nor angle from the centroid location was found to be significantly associated with velocity.

Table 7.5. Linear regression model, between predictors and the kinematic ball roll variable velocity, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®	Odyssey
Mean ± SD (ms^{-1})	2.05 ± 0.16	2.09 ± 0.14
R^2 ± SE	0.12 ± 1.05	0.09 ± 0.13
F-ratio, (p-value)	6.59 (< 0.01)	5.96 (< 0.01)
Length (β), (p-value)	0.14 (0.08)	-0.15 (0.06)
Angle (β), (p-value)	0.13 (0.17)	0.07 (0.37)
Surface Area (β), (p-value)	-0.25 (< 0.01)	0.32 (< 0.01)

Side Spin

The multiple regression model was found to be a significant predictor of side spin (Table 7.6) for the GEL® putter (p = 0.04) but not for the Odyssey putter (p = 0.93). The impact variables accounted for 6% of variation observed in side spin (1.54 rpm) for the GEL® putter. The individual impact variable that was significantly associated with side spin was surface area (β = 0.21, p = 0.03). Both the length and angle from the centroid location were not found to be significantly associated for the GEL® putter.

Table 7.6. Linear regression model, between predictors and the kinematic ball roll variable side spin, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®	Odyssey
Mean ± SD (Cut (+), Hook (-), rpm)	-10.90 ± 25.69	-8.00 ± 24.87
R^2 ± SE	0.06 (20.74)	0.003 ± 25.04
F-ratio, (*p*-value)	2.87 (0.04)	0.15 (0.93)
Length (β), (*p*-value)	-0.10 (0.26)	-0.05 (0.52)
Angle (β), (*p*-value)	-0.04 (0.69)	-0.002 (0.98)
Surface Area (β), (*p*-value)	0.21 (0.03)	0.007 (0.94)

Initial Ball Roll

Outputs from the multiple regression analysis are presented in Table 7.7. The regression model was found to be a significant predictor of the variability for initial ball roll for the GEL® putter (p = 0.02), however, it was not a significant predictor for the Odyssey putter (p = 0.42). Surface area was the only one of the three impact predictors that was found to be significantly associated with initial ball roll (β = -0.24, p = 0.01). The amount of variability accountable to the impact variables was 7% (1.93 rpm) of total variability observed.

Table 7.7. Linear regression model, between predictors and the kinematic variable initial ball roll, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®	Odyssey
Mean ± SD (rpm)	25.25 ± 27.61	35.48 ± 21.41
R^2 ± SE	0.07 ± 23.06	0.02 ± 21.42
F-ratio, (*p*-value)	3.56 (0.02)	0.94 (0.42)
Length (β), (*p*-value)	0.10 (0.23)	-0.78 (0.35)
Angle (β), (*p*-value)	0.03 (0.79)	-0.02 (0.82)
Surface Area (β), (*p*-value)	-0.24 (0.01)	0.13 (0.10)

Forward Roll

The regression model was found to be a significant predictor (Table 7.8) for the GEL® putter (p < 0.001), it was not found to be a significant predictor for the Odyssey putter (p = 0.29). The impact variables were accountable for 52% overall variation (1.35 cm), surface area was the only individual impact variable to be significantly associated with forward roll (β = 0.66, p < 0.001). Length and impact from the centroid location was found to not be significantly associated with forward roll.

Table 7.8. Linear regression model, between predictors and the kinematic variable forward roll, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®	Odyssey
Mean ± SD (cm)	1.12 ± 2.59	0.38 ± 1.27
R^2 ± SE	0.52 ± 8.97	0.21 ± 0.50
F-ratio, (*p*-value)	53.29 (< 0.01)	1.27 (0.29)
Length (β), (*p*-value)	-0.001 (0.99)	-0.05 (0.55)
Angle (β), (*p*-value)	-0.11 (0.12)	-0.09 (0.24)
Surface Area (β), (*p*-value)	0.66 (< 0.01)	-0.10 (0.24)

Vertical Launch Angle

The outputs from the multiple regression analysis are presented in Table 7.9. The regression model was found to be a significant predictor of vertical launch angle for the GEL® putter (p = 0.03), the impact variables accounted for 6% (0.06°) of the variance observed. The variable surface area was found to have the only significant association with vertical launch angle, the standardised β was -0.19 (p = 0.04). Neither length nor angle from the centroid location was found to be significantly associated with vertical launch angle. The regression model was found to not be a significant predictor for the Odyssey putter.

Table 7.9. Linear regression model, between predictors and the kinematic variable vertical launch angle, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®	Odyssey
Mean ± SD (°)	3.07 ± 1.08	2.80 ± 1.02
R^2 ± SE	0.06 ± 1.06	0.01 ± 1.03
F-ratio, (*p*-value)	3.13 (0.03)	0.75 (0.52)
Length (β), (*p*-value)	-0.07 (0.39)	0.001 (0.99)
Angle (β), (*p*-value)	0.05 (0.61)	0.11 (0.16)
Surface Area (β), (*p*-value)	-0.19 (0.04)	-0.34 (0.68)

Horizontal Launch Angle

The multiple regression outputs for horizontal launch angle are displayed in Table 7.10. The multiple regression model was not a significant predictor of horizontal launch angle for both the GEL® (F = 0.76, p = 0.52) and Odyssey putters (F = 0.81, p = 0.49). If the regression had been found to be a significant predictor of horizontal launch angle the variability accountable to the impact variables would be negligible at 2% (0.03°) and 1% (0.02°) for the GEL® and Odyssey putter respectively.

Table 7.10. Linear regression model, between predictors and the kinematic variable horizontal launch angle, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®	Odyssey
Mean ± SD (Right (+), Left (-), °)	-0.07 ± 1.57	-0.22 ± 1.50
R^2 ± SE	0.02 (1.58)	0.01 ± 1.50
F-ratio, (*p*-value)	0.76 (0.52)	0.81 (0.49)
Length (β), (*p*-value)	-0.04 (0.65)	-0.09 (0.28)
Angle (β), (*p*-value)	-0.12 (0.23)	0.03 (0.67)
Surface Area (β), (*p*-value)	0.02 (0.88)	-0.04 (0.66)

Push and Pull

Table 7.11 displays the multiple regression outputs for the variable push and pull. The regression model was found to not be a significant predictor for both the GEL® ($F = 0.50$, $p = 0.68$) and Odyssey ($F = 0.84$, $p = 0.48$). The total amount of variance observed between the GEL® and Odyssey putter was very similar with scores of 7.87 and 7.83 cm respectively.

Table 7.11. Linear regression model, between predictors and the kinematic variable push and pull, R^2 and standardised coefficients are reported (Significance denoted by highlighted cell).

	GEL®	Odyssey
Mean ± SD (cm)	-0.54 ± 7.87	-1.38 ± 7.83
R^2 ± SE	0.01 ± 7.91	0.01 ± 7.85
F-ratio, (*p*-value)	0.50 (0.68)	0.84 (0.48)
Length (β), (*p*-value)	-0.02 (0.86)	-0.11 (0.20)
Angle (β), (*p*-value)	-0.12 (0.25)	0.02 (0.76)
Surface Area (β), (*p*-value)	-0.03 (0.74)	-0.01 (0.86)

7.2.5 Discussion

This is the first study to use human participants to assess the effects of impact point on the golf ball on the ball roll kinematics. The aim of this study was to investigate the relationship between the impact variables (length and angle from the centroid location and surface area) and kinematic ball roll variables (velocity, side spin, initial ball roll, forward roll, vertical and horizontal launch angle and whether the ball was pushed or pulled). It was hypothesised that a significant association would exist between the impact variables and the variables horizontal launch angle and push or pull this was because significant associations were identified in Study Five. This hypothesis can be rejected as no significant associations were observed for the GEL® or Odyssey putters for the variables horizontal launch angle or push or pull (Tables 7.10 and 7.11). The only kinematic variable that displayed an association with the impact variables for both the GEL® and Odyssey putter was velocity (Table 7.5). No significant associations were identified between the length and angle from the centroid location and any of the kinematic ball roll variables, the only impact variable where any significant associations were identified was surface area of the impact zone. It was additionally hypothesised that increased variability would be observed in the X, Y coordinates on the golf ball and putter for the < 80% success rate group in comparison to the > 80% success rate group. However, this was only apparent for the Y coordinates on the putter face (Figure 7.2), no statistical differences were observed for the golf ball (Figure 7.1), therefore, and this hypothesis can only be partially accepted.

As previously reported within the literature golf balls are designed with ball flight predominantly in mind, dimples are designed to improve the aerodynamics of the golf ball by reducing drag (Libii, 2007; Goff, 2013). It additionally has been reported that this may have a detrimental effect on putting (Pelz, 2000), with the golf ball potentially rebounding off the putter face at an unexpected angle taking the ball roll off its intended path (Figure 6.14). With putting having been identified as having a significant relationship with overall scoring performance (Dorsel & Rotunda, 2001; Quinn, 2006: Wiseman & Chatterjee, 2006) it was reported previously in this thesis that dimple error may be detrimental to putting.

The findings from this study show that variability existed for all kinematic ball roll variables (velocity, side spin, initial ball roll, forward roll, vertical launch angle, horizontal launch angle and whether the ball was pushed or pulled) however, excluding velocity none of this variation can be accounted to the impact point on the golf ball. Velocity was the only kinematic variable where the multiple regression analysis identified significant associations for both the GEL® and Odyssey putters. The surface area of the impact zone was found to be significantly negatively associated with velocity (β = -0.25, p = 0.006) for the GEL® putter and significantly positively associated for the Odyssey putter (β = 0.32, p < 0.001) (Table 7.5). This seems counterintuitive, however, the opposite relationships may be due to the different putter face properties, the GEL® putter has a grooved design, whereby; the coefficient of restitution will be reduced in comparison to the Odyssey putter, as previously identified by Brouillette (2010). When it is considered the actual amount of variability is accountable to the impact variables (0.02 ms^{-1} and 0.01 ms^{-1}) it is clear that any effect is insignificant, only in a very rare case would this variation in ball velocity affect the success of a putt.

The main findings from Study Five showed significant associations between the impact variables and horizontal launch angle and whether the ball was pushed or pulled. This was the opposite when using human participants with no significant associations identified for either variable (Tables 7.10 and 7.11). Contrasts in results are likely due to the fact when using a putting robot; other variables that contribute to the direction variability of the golf ball remain constant across all trials. Pelz (2000) and more recently Karlsen et al. (2008) identified direction consistency was accountable to the following main variables of the putting stroke; putter face angle, putter path and horizontal impact point on the putter (only Karlsen et al. 2008 recognised this a factor). Both neglected to consider the impact point on the golf ball influencing the direction of the golf ball, Study Five of this thesis found the impact variables to be accountable for 0.13° and 0.04° variance for a GEL®-Srixon and Odyssey-Srixon putter-ball combinations. Whilst this variance is marginal and well within a range set by Karlsen et al. (2008) (a putt with a horizontal launch angle variability of 0.39° will miss approximately 5% of putts made from 13 feet). The rationale for this study was to determine whether this variability that a participant could not control for could take more putts over the threshold of 0.39° leading to more than 5% of putts missed. It is clear from the results of this study this was not the case.

It may be that the magnitude of the effects of the variation in putter face angle and putter path render the effects of dimple error statistically negligable. For example, if the left hand side of the dimple was struck by the putter for dimple error to potentially effect the the horizontal launch angle of a putt the putter face angle would have had to be open. However, natural variation will occur with a square, or closed clubface at impact and the exact ball placement. Whereby, in this situation the dimple error would not effect the horizontal launch angle (creating more of a pushed putt) reducing the potential success rate of the putt. For a putt of 12 feet Hurrion and Mackay (2012) state a putt with a horizontal launch angle of 0.75° will be successful, this would be produced with a putter face angle of 0.69°, if the dimple error observed in Study Five was added to this horizontal launch angle it would result in a more pushed or pulled putt, reducing the chance of success. However, as stated above the variation observed in the putter face angle and ball placement will never be exactly the same, so therefore it can be considered that dimple error is not a problem a golfer should be concerned with.

It may be the case that during impact that in addition to the ball compressing slightly during impact (Pelz, 2000) that the golf ball is subjected to very small amounts of rotation (Figure 7.3), negating the effect of dimple error. These small amounts of rotation during impact may be more prevalent while using a human cohort in comparison to a mechanical putting robot. The theory behind this relates to grip pressure. A human will have a lighter grip pressure in comparison to the putting robot, which is formed of rigid steel; this in turn may alter the impact. If Newton’s second law is considered;

‘A force applied to a body causes an acceleration of that body of a magnitude proportional to the force, in the direction of the force, and inversely proportional to the body’s mass’ (Newton, cited in Hall, 2012).

It is clear that the human participant and the putting robot impart the same amount of force on the golf ball to displace it the same distance, the impact may differ in terms of how the impulse (F.t) is applied, it is hypothesised that the putting robot applies a greater amount of force over a shorter period of time, whereas the human participant will apply less force over a longer period of time, both resulting in the same amount of overall force being applied. The light grip may allow the body to absorb a certain amount of the external force (or vibrations) transferred to the body through the shaft of the putter, which the putting robot cannot do as effectively, due to the different mechanical loading properties. It is the belief of the author that this could cause the small amounts of rotation at impact, as the time of impact will be increased.

Within the coaching literature it is often taught that a light grip is more beneficial than a tight grip (Pelz, 2000). This is suggested because if a golfer adopts a tight or strong grip, the muscles and arms become less pliant and less sensitive to delicate feelings, a light grip allows the golfer to ‘stroke’ the putt rather than ‘hit’ the putt. Scientific literature into the suggested mechanism is extremely limited. Motor control research have suggested that the central controller can learn and predict reaction loads, and then can adjust muscle activity proactively to compensate (Debicki & Gribble, 2004; Osis & Stefanyshyn, 2012; Hirashima, Kudo & Ohtsuki, 2003). Whilst none of these studies tested the golf putt, it would suggest a similar mechanism could exist for the golf putt, whereby, during impact the fine muscles in the forearm and hand control the impact. Additionally, golf manufacturers are often developing equipment in an attempt to reduce this impact vibration, by making the putting face out of high-loss materials such as urethane (Lindsay, 2003).

This small rotation potentially occuring at impact may help explain the large amount of variation observed for the variable side spin (GEL® = 25.69 rpm; Odyssey = 24.87 rpm) (Table 7.6). This rotation may also change depending on the type of surface; both Study Five and Seven were completed on fast (11+ on the stimpmeter) artificial greens, most golfers are likely to play on greens slower on the stimpmeter. This will mean the grass (or artificial grass) will be longer, whereby, the ball may ‘nestle’ down, which would create more frictional force between the ground and the ball, which may then increase the hypothesised mini rotation occurring impact. No literature to data has analysed this and focus on when the ball enters a state of pure rolling (Alessandri, 1995; Hurrion & Hurrion, 2002; Lorensen & Yamrom, 1992; Penner, 2002). Therefore further investigation would be needed. Pelz (2000) states that friction between the ball and green removes all spin in about the first 20% of the roll, therefore it may be possible that friction between the stationary ball and green contributes towards the spin initially.

Weak association was observed for all other variables, the regression analysis for side spin (Table 7.6), initial ball roll (Table 7.7), forward roll (Table 7.8) and vertical launch angle (Table 7.9) was only found to be significant for the GEL® putter and non significant for the Odyssey group. Even when it is considered that the GEL® putter was found to be significant the effects accountable to the impact variables are always very small (side spin = 6%, initial ball roll = 7%, vertical launch angle 6%). The only exception to this was the variable forward roll where the impact variables accounted for 52% of the variance observed. During statistical analysis, forward roll was identified to be not non-parametric (Appendix F), even after log transformation the variable was still found to be kurtosed and skewed. Due to the nature of the variable, often a score of 0 cm was recorded as the ball displayed positive rotation at impact, and therefore it can be questioned that the statistical analysis completed is accurate.

The < 80% success group displayed statistically greater variability in the impact point of the Y variable on the golf putter in comparison to the > 80% success group (Figure 7.2). Previously it has been identified that expert players demonstrate a slower putter head velocity at impact compared with novice golfers (Delay et al. 1997; Sim & Kim, 2010). Additionally, Betzler et al., (2012) identified that LH golfers exhibit significantly lower variability of club head speed, impact location, face angle and club path for a full golf swing in comparison to HH golfers. Therefore, it may be the case that the less proficient golfers consciously monitor the mechanics of the golf putt (Toner & Moran. 2011) that causes the more proficient group (> 80% success rate) to have a more consistent impact point for the Y coordinate and possibly the X coordinate. Both groups demonstrated less variability of the Y coordinate (> 80% success group combined mean = 1.26 mm and < 80% success group combined mean = 1.67 mm) in comparison to the X coordinate (> 80% success group combined mean = 2.35 mm and < 80% success group combined mean = 2.86 mm). The non-significant difference may be because there was a larger range of standard deviations across both groups for the X coordinate in comparison to the Y coordinate (Tables 7.1 - 7.4). Larger subject groups would be needed to identify a statistical difference between the two groups for the X coordinate with increased inter-subject variability.

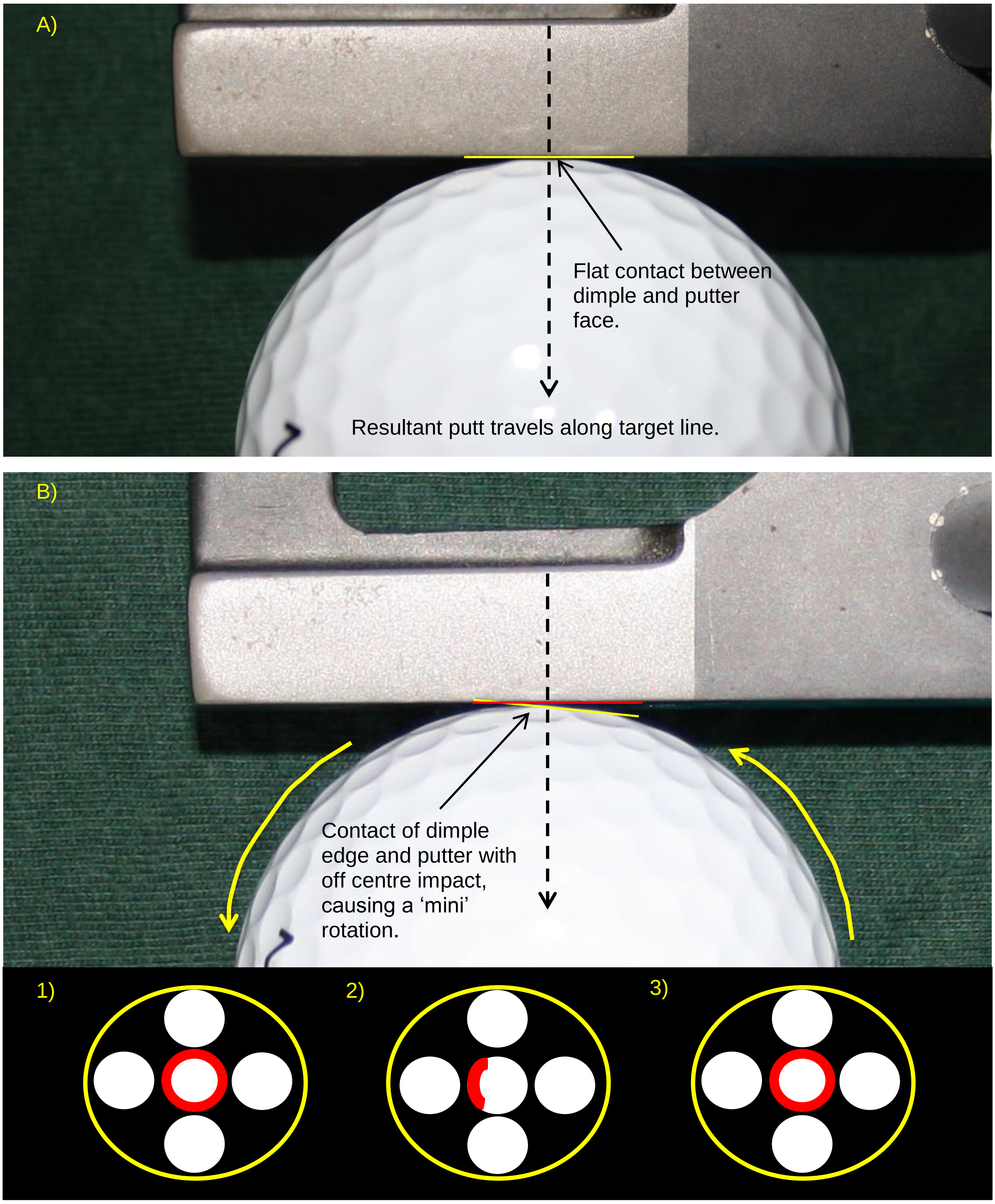

Figure 7.3. Diagram depicting two types of contact possible during the impact between a putter and a golf ball. A) A square contact with the dimple resulting in a putt that starts travelling on the intended target line, and B) Contact on a ball's dimple edge (right) (illustrated by the yellow line) causing a 'mini' rotation in an anticlockwise direction with the dimple leaving the putter face with a square contact (illustrated by the red line). The illustrations below resemble the posterior view of a golf ball, the white circle is a dimple and the red area highlights the point of a dimple that the putter is making contact with. Diagram A) contact is shown by illustration 1); Diagram B) initial contact is shown by illustration 2) the final contact when leaving the putter face is shown by illustration 3).

It was also hypothesised that increased variability would exist for the X and Y coordinates on the golf ball (Figure 7.1), again this was predicted due to the increased velocity of the putter head at impact (Delay et al. 1997; Sim & Kim, 2010). The increased variation of the putter head velocity it would be expected the variability of the putter face angle and path would increase, which may have an influence on the impact location on the golf ball. Putter face angle and path was not measured in this study and therefore it can not be identified if the < 80% success group demonstrated greater variability of these variables. However, it may that the club head velocity was not significantly different between the > 80% and < 80% success rate groups as identified in Study Six.

Future research should aim to identify whether small amounts of rotation occur at impact when an edge of a golf ball dimple is struck. This could be achieved isolating the impact with high-speed video recordings. As previously acknowledged in Study Five Hurrion and Hurrion (2002) suggest a frame rate of 2000 Hz would be needed to effectively record the impact at a sufficient detail. This could be combined with reflective markers could be placed on the putter head to calculate the putter face angle and putter path, to identify whether there is a significant difference between the different proficiencies of golfer. If the impact of the golf ball could be recorded to a level of detail sufficient to identify the time of the contact between the putter face and golf ball. Additional analysis could be conducted to analyse the effect of grip pressure during the putting stroke and whether this does in fact influence the time of the contact between the putter and golf ball. The reliability of hand sensors that measure grip pressure have previously been analysed and found to be reliable during a full golf swing (Komi, Roberts & Rothberg, 2007).

7.2.6 Conclusion

The impact point on the golf ball assessed using the length and angle from a defined centroid location have no relationship on the following kinematic ball roll variables; side spin, initial ball roll, forward roll, vertical and horizontal launch angle and whether the ball was pushed or pulled. The only variable that significant associations were identified for was velocity, however the variability accountable to the impact variables was minimal (0.02 ms^{-1} and 0.01 ms^{-1}) and therefore would have little bearing on the success rates of a putt. Previously in Study Five a significant association was identified between the impact variables and the variables horizontal launch angle and the variable push and pull, this was not observed when using human participants. It is suggested that either the fact humans will display variance in other putting variables such as putter face angle or putter path negates the effect of dimple error. Additionally, small amounts of rotation may be occurring at impact. Variance of the impact point on the golf ball was not significantly different between the two groups, on the golf club the only significant difference between groups was the variance in the Y coordinate. No significant differences in the variance of the X coordinate may be the lack of significant differences in the club head velocity at impact. The practical implications of this study is that golfers should not be concerned with the effects of dimple error and should focus on areas of the putting stroke previously identified to significantly contribute to the putting stroke.

7.3 Study Seven: The evaluation of centre of mass' relationship with centre of pressure excursions and the effect of movement variability on putting performance

7.3.1 Abstract

Background: Centre of pressure (CP) excursions has been demonstrated to influence putting performance but its relationship to centre of mass (COM) displacement has not been examined. This raises doubts as to whether conclusions regarding putting techniques is appropriate when only interpreting CP excursions. Movement variability is currently unexplored within the golf putt, this is potentially important considering the very small margins of error between a successful and missed putt. **Aim:** The aims of this study were to assess the relationship between CP excursions and COM displacement during the golf putt and to examine the effect of segment rotation variability on putting performance. **Method:** A total of 8 right-handed golfers participated in the study. All testing was completed on an artificial putting green registering 11 on the stimpmeter with participants standing on an RS FootScan sampling at 120 Hz recording CP excursions. Body kinematics were recorded using an ten camera motion analysis system (120 Hz) using a modified whole body Helen Hayes marker set (total 29 markers). To record ball kinematics a Quintic high speed camera (220 Hz) was used to record the first 30 cm of ball roll, Quintic Ball Roll software 2.4 was used to analyse this data. Movement variability was calculated for the body segments based on a scalene ellipsoid volume and correlated with performance measure variability (ball roll variables). The relationship between the CP excursions and COM displacement were also assessed. **Results:** Significant moderate to strong group correlations between CP excursions and COM displacement were observed, however, it was evident that a large inter-subject variability existed between participants. Segment rotation variability was strongly to very strongly correlated with the variability of the horizontal launch angle; this was evident for all segments apart from the golf putter Z rotations. **Conclusion:** The relationship between COM displacement and CP excursion is a complex one; the differences between the variables need to be interpreted cautiously due to the time normalisation process. It is proposed that golfers may employ strategies to minimise the CP excursion during the trial to optimise balance. The lower the movement variability of segment rotations will lead to increased performance, due to the relationships identified with the horizontal launch angle. Additionally, it is proposed that individual based analysis alongside group based analysis due to the large inter-subject variability demonstrated in movement variability, segment rotations, CP excursions and COM displacement patterns.

7.3.2 Introduction

As previously reported within this thesis, putting contributes 43% of shots to an average round of golf (Pelz, 2000). In addition to this, putting performance has been the most highly correlated performance measure to score average (r = 0.68) in professional golf (Wiseman and Chatterjee, 2006). This makes it surprising that putting is still fundamentally under researched in comparison to the other types of shot within the game.

Centre of pressure excursion has been demonstrated to influence putting accuracy (Hurrion & Hurrion, 2008; McLaughlin et al., 2008) with more proficient players demonstrating less CP excursions than less proficient players. In Hurrion and Hurrion (2008), significantly less CP excursion was observed in professional players, in comparison to LH golfers (AP and ML directions totaled) for the start to top of backswing phase (Chapter Four, Figure 4.1) (12.14 ± 2 mm v 17.61 ± 3 mm) and impact to follow–through phase (41.97 ± 5 mm v 53.26 ± 5 mm). A similar trend regarding CP excursions was found by McLaughlin et al. (2008) with LH golfers demonstrating significantly less CP excursions in comparison to HH golfers along the ML axis for the start to top of backswing phase (4.6 ± 2.9 mm v 7.7 ± 6.2 mm) and top of backswing to impact phase (4.5 ± 4.2 mm v 10.7 ± 9.0 mm). Study Three of this thesis, identified a similar trend, however, significantly less CP excursion was observed for LH golfers along the AP axis.

A recent study by McLaughlin and Best (2013) has identified two golf putting strategies regarding CP excursion: arm putting and body putting. Arm putting relates to a putting technique, whereby relatively small CPE along the ML axis was observed during the start to top of backswing phase (4.9 ± 2.7 mm) and top of backswing to impact phase (3.9 ± 2.6 mm). In addition to this, the velocity of the CP excursion along the ML axis is closer to zero (5.2 ± 16.9 $mm.s^{-1}$) for those clustered into the arm putting technique (McLaughlin & Best, 2013). Body putting relates to a putting technique, whereby larger CP excursion along the ML axis is observed during the start to the top of backswing phase (9.6 ± 7.0 mm) and top of backswing to impact phase (10.6 ± 4.8 mm). The velocity of the CP excursion at impact for the body putting technique was also higher than that observed by the arm putting technique (58.4 ± 22.9 $mm.s^{-1}$). McLaughlin and Best (2013) identified during cluster analysis, that CP velocity along the ML axis was the highest ranked distinguishing variable across all cluster solutions during cluster analysis. Their conclusions need confirming, as to date; no research has examined the relationship between body kinematics and displacement of the COM and CP excursions in putting. Whether golfers reproduce similar movement patterns (influencing the displacement of the COM) to one another, has not been examined and therefore it is difficult for golfers to be grouped by CP excursions. Another method of analysis which may be more appropriate, has previously been adopted within full golf swing literature is individual-based analysis combined with group-based analysis (Ball & Best, 2012). It is felt that group-based analysis can mask important information and as golf coaching is largely individual based, this may be more applicable to golf research, including putting (Ball & Best, 2012). With no literature to date assessing the relationship between COM displacement and CP excursion, it is difficult to gauge the effect of only interpreting CP excursion parameters on putting performance to influence future coaching practice.

Another area within golf putting that is under researched is movement variability, previously having been highlighted as an important area to research in the golf swing (Glazier, 2011; Tucker, Anderson & Kenny, 2013). It has been identified as important since golf-teaching professionals assist golfers in developing appropriate movement patterns to swing the club: this 'optimal' movement pattern may differ between different golfers (Bradshaw et al., 2009; Tucker et al., 2013). This may not be an effective approach with individual-specific constraints dictating each player producing a different movement pattern, however, this may be optimal for the individual in question (Bradshaw, Maulder & Keogh, 2007; Davids, Glazier, Aruajo & Bartlett, 2003). As outlined in the dynamical systems theory, movement patterns arise and develop from synergistic organisation of the neuromuscular system due to environmental factors, morphological factors and task constraints (Kurz & Stergiou, 2004). This implies that the existence of an invariant movement pattern is unlikely (Tucker et al., 2013). This principle of the variance of movement affecting golf performance has previously been examined in the full golf swing (Bradshaw et al., 2009; Langdown et al., 2012; Horan et al., 2011; Tucker et al., 2013). The consensus of the literature was to reduce variability at key swing events for successful performance (Bradshaw et al., 2009; Langdown et al., 2012; Horan et al., 2011). Tucker et al. (2013) however found no relationship with an outcome measure (initial velocity of the golf ball).

The effect of movement variability has yet to be applied within the golf-putting stroke, with a very small margin of error between success and failure, particularly in initial ball direction after impact. It is believed that the putter face angle accounts for 80-95% of the initial putt angle (Hurrion & Mackay, 2012; Karlsen et al., 2008; Pelz, 2000). Movement variability, therefore, may be a determining factor to the variance of the putter face angle and therefore subsequent performance.

The aims of the present study were to firstly, examine the relationship between CP excursion parameters and the displacement of the COM. Secondly, to determine whether different patterns of segment rotations exist between participants (informing whether individual based analysis is suitable for use) and finally, whether variability of body segments and putter rotations influence the variance of performance measures (ball roll kinematics).

7.3.3 Methods

Participants

Following institutional ethical approval, a total of 8 right-handed golfers participated in the study (age 34 ± 11 years; handicap 10.0 ± 5.3 (handicap range 0 – 16); height 1.80 ± 0.06 metres; mass 83.4 ± 12.2 kg). All golfers played a minimum of once a week and wore tight fitting shorts, sleeveless tops and their own golf shoes. Signed informed consent was gained before testing.

Experimental set-up

All testing was completed in the University of Hertfordshire 3D motion analysis laboratory. A Huxley Golf artificial putting green (3.66 x 4.27 metres) was used and registered 11 on the stimpmeter. A level, straight 3.2 metre putt was setup with a regulation 108 mm hole. The participants used their own personal putter for the protocol. The rationale for this was that the participant would be using a putter they are habituated to. This ensured the body movement kinematics were a true reflection of technique, whereas a standardised putter not fitted to each of the participants could negatively influence this. The golf ball for the protocol was standardised (Srixon Z-STAR) and each trial completed used the same ball.

Each trial was completed with participants standing with both feet on a RS Scan FootScan pressure plate (50 x 32 cm) with a total 4096 sensors, sampling at 120 Hz. The RS Scan FootScan was aligned to the participants' stance at address whereby the edges of the FootScan were parallel to the feet. This was to accurately record the CP excursions along the ML and AP axis during the putting stroke. Body movement kinematics were recorded using a ten camera motion analysis system (Motion Analysis Corporation., Santa Rosa, CA, USA) sampling at 120 Hz.

Retro-reflective markers were attached to participants in accordance with a modified whole body Helen Hayes marker set (total 29 markers; 20 mm) at the following anatomical locations; the top of head, front of head, rear head, acromion process (left and right), lateral epicondyle of radius (left and right), styloid process of the radius (left and right), the anterior superior iliac spine (left and right), the sacrum, the thigh (parallel to hip and knee markers (left and right)), lateral aspect of the joint centre of the knee (left and right), the shank (parallel to knee and ankle joint markers (left and right)), the lateral malleolus (left and right), the posterior aspect of the calcaneus (left and right), and the third metatarsal (left and right). Markers were placed directly on the skin using double sided sticky tape for all markers except the acromion process (pair of), anterior superior iliac spine (pair of), sacrum, calcaneus (pair of) and third metatarsal (pair of). Which were placed on skin tight clothing or shoes ensuring minimal movement of markers relative to underlying body landmarks. Additionally, a marker was placed on the left scapular for asymmetry (to determine left from right during analysis) and the medial aspects of the knee (left and right) and medial malleolus (left and right) so the joint centres of the knee and ankle could be calculated. The centre of mass was calculated through segmental analysis of a fifteen segment model (pelvis, right thigh, left thigh, right shank, left shank, right foot, left foot, trunk, head/neck, right upper arm, left upper arm, right forearm, left forearm, right hand and left hand) using anthropometric data provided (de Leva, 1996).

Two retro-reflective markers were placed on the superior aspect of the putter face to calculate putter face angle at impact and throughout the putting stroke. A retro-reflective marker was placed at the top of the shaft below the grip. Additionally, two retro-reflective markers were placed on the putting line (directly behind the centre of the hole and behind the participant). The capture volume was calibrated according to manufacturer's guidelines, resulting in an average residual for all cameras of < 0.5 mm. The motion analysis system was calibrated where the positive movement along the X-axis was defined as movement towards the target (golf hole); positive movement along the Y-axis was defined as movement anteriorly perpendicular to the target; and the Z-axis perpendicular to the X, Y plane. The 0, 0 coordinates of both the RS FootScan and motion analysis system were the same point (bottom right hand corner of the RS FootScan). This was achieved by calibrating the motion analysis system with the calibration L-frame placed over the RS FootScan once aligned to the participants' stance at address. The RS FootScan and motion analysis system were time synchronised using an analogue trigger, exporting a file on the motion analysis software of the time of recording the RS FootScan was triggered.

To record the ball roll kinematics, a Quintic high speed camera sampling at 220 Hz was positioned perpendicular to the putting line. The Quintic Ball Roll v2.4 launch monitor software was used to analyse the recorded videos of the ball roll, allowing for analysis of the kinematic ball roll variables. Kinematic variables measured were initial velocity ($m \cdot s^{-1}$, calculated across the first 6 recorded frames); side spin (the amount of side spin (rpm) placed on the ball during impact); launch angle measured in degrees (vertical (whether the ball was launched in the air) and horizontal (the degree to which the ball deviates from the original putting line), initial ball roll (whether the golf ball has positive rotation (topspin) or negative rotation (backspin) at the point of impact (rpm)), forward roll (the distance at which the ball starts positive rotation (cm)) and whether the putt was pushed (right) or pulled (left) (a calculation of the final resting point of the golf ball based on the kinematic variables recorded (cm)). For a trial to be considered valid, the initial ball velocity had to be between 2.10 – 2.28 ms^{-1}. This was to eliminate participants' preference of either putting to hole the ball successfully at a low or high velocity. Putts that were successful in being holed, but did not meet the initial ball velocity requirements were eliminated from analysis.

Procedure

Participants' height and mass was recorded upon arrival to the laboratory. Twenty-nine retro-reflective markers were attached to the participant using a modified Helen Hayes marker set previously identified. A static trial was completed with the participant stationary in a position whereby arms were placed in front of the torso, so that the markers could be identified and labeled, enabling the formation of a three dimensional model. Following this, a dynamic trial was completed, whereby; the participant moved their joints through their full range of motion.

Participants were then allowed up to ten minutes to habituate themselves to the golf putt, to ensure that the markers did not inhibit or alter their technique. Within the ten minute habituation period, the investigator instructed the participant as to the velocity required for a putt to be categorised successful. Once the participant was comfortable and ready to proceed, they lined up the golf putt and stepped onto the FootScan pressure plate. The Quintic Ball Roll v2.4 software was then activated. The 3D motion analysis system was triggered followed by the FootScan pressure plate via the external trigger, which registered on the motion analysis software. This was due to the 8-second recording time limit while recording at 120 Hz.

Once the trial had been completed and the outcome of the putt was recorded (successful or missed), the participant was asked to step back off the pressure plate. The trial was then saved on all recording systems. This process was completed until 10 successful putts had been completed.

Data Processing

Three-dimensional coordinate data was processed using Motion Analysis Corporations Cortex software with an Euler sequence of X, Y, Z. The 3D coordinate data was filtered using a fourth-order low pass Butterworth filter, consistent with previously published literature (Coleman & Rankin, 2005; Wheat et al., 2007; Horan et al., 2010). Cut off frequency was determined using residual analysis with an r^2 threshold of 0.85 (Giakis & Baltzopoulos, 1997). Cut off frequencies used for the markers are presented in Table 7.12. Due to intra and inter subject differences in the duration of trials, COM, CP excursion, segmental and putter rotations were time-normalised to 101 data points using a cubic spline algorithm. This allowed for accurate means and variation to be calculated.

Table 7.12. Cut off frequencies used for individual markers.

6 Hz cut off frequency	7 Hz cut off frequency	8 Hz cut off frequency
Right shoulder, left shoulder, right wrist, left wrist, right ankle, left ankle, right knee, left knee, calcaneus, toe, shaft of club, heel of club, toe of club.	Top of head, front of head, back of head, right elbow, left elbow.	Right ASIS, left ASIS, Sacrum.

Following this, kinematic data were processed into segments and the whole body centre of mass was calculated. Segmental rotations (°) (X, Y and Z) were formulated for the pelvis, torso, left and right upper arm and left and right lower arm. These segments were selected as they have previously been analysed (Delphinus & Sayers, 2012; McLaughlin & Best, 2013) and are thought to contribute to the impulse being imparted on the ball during the putt (Pelz, 2000). Rotational movements are documented in Table 7.13.

Table 7.13. Positive and negative rotations about the X, Y, Z axes for all segments analysed.

	X Rotations		Y Rotations		Z Rotations	
	Positive	Negative	Positive	Negative	Positive	Negative
Pelvis	Left pelvic obliquity	Right pelvic obliquity	Anterior pelvic tilt	Posterior pelvic tilt	Left rotation	Right rotation
Trunk	Left lateral flexion	Right lateral flexion	Flexion	Extension	Left rotation	Right rotation
Upper Arm	Adduction	Abduction	Flexion	Extension	Lateral rotation	Medial Rotation
Forearm	Adduction	Abduction	Flexion	Extension	Supination	Pronation

The putter face angle at impact was calculated by identifying the location of the two retro-reflective markers placed on the superior aspect of the putter head relative to the putter face orientation (angle) at address (Karlsen et al., 2008). The CP excursion was defined as the range of movement of the CP in two directions (anteroposterior and mediolateral). The CP excursions and COM patterns (X, Y coordinates) were calculated by determining the displacement along the AP and ML axis against the starting X, Y coordinate of the putting trial. Zero movement refers to the data point before the initiation of the start of the trial.

Performance variability was calculated for all body segments as outlined by Tucker et al. (2013). Rotations were normalised to the position at address one frame before the trial started to ensure that variation of rotational movement was being analysed rather than variation of the position at set-up. Following this normalisation process, the standard deviation was calculated for the 101 data points for all the trials of each participants X, Y and Z coordinates. These were then combined via multiplication to have a single number represent the 3D variability. This method of data processing previously had been adopted by Lin, Liu, Hsieh and Lee (2009) and Tucker et al. (2013), with the rationale being that one number representing variability easier for coaches to interpret and implement. The equation below was used to calculate a scalene ellipsoid for each participant representing the 3D variability of the rotations for the 101 data points. This was then average giving a mean variability volume (degrees^3):

$$VV = \frac{\sum_{n=1}^{101} \frac{4}{3}\pi\left(sd_{xi} \cdot sd_{yi} \cdot sd_{zi}\right)}{101}$$

where VV is the mean variability for each segments rotation. When interpreting the mean variability score (VV), it was important to consider the range of rotation for each of the segments. Therefore the mean variability score was standardised to the 3D rotations. The calculation used to calculate the average 3D distance over the trials (degrees) were:

$$\mathrm{PD} = (\sum_{i1}^{101} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2})$$

where PD is the performance distance. Performance variability was defined as the mean variability volume divided by the performance distance:

$$\mathrm{PV} = \frac{\mathrm{VV}}{\mathrm{PD}}$$

where PV is termed the performance variability. This provided a volume per distance measure (degrees^3/degrees). The only segment that was analysed in a different fashion was the putter segment where only Z rotations were recorded, therefore the standard deviations were totaled and normalised by the Z rotations displacement.

Data Analysis

Data were exported to statistical software package SPSS v22.0. All data were first tested for normality using Shapiro-Wilk test of normality, $p < 0.05$). The data was found to be non-parametric and therefore a two-tailed Spearman's rank correlation coefficient test were carried out. The boundaries set for the coefficient statistics were; r = 0.8 – 1.0, very strong, r = 0.6 – 0.8, strong, r = 0.4 – 0.6, moderate, r = 0.2 – 0.4, weak, r = 0.0 – 0.2, no relationship (Salkind, 2011). Significant differences were tested using a Wilcoxen signed rank test. The alpha level was set at $p < 0.05$.

Relationships were tested between the average and individual COM and CP excursion parameters (range of displacement and peak velocity for the three phases of the putt). The significant differences tested for were between averaged COM and CP excursion parameters for the three phases of the golf putt. Additionally, a Cohen's effect size (*d*) was utilised to identify whether the differences observed were true and not skewed due to a sample size. In accordance with Saunders, Pyne, Telford and Hawley (2006) effect sizes were interpreted as < 0.1 as trivial, 0.1 – 0.6 as small, 0.6 – 1.2 as moderate and > 1.2 as large.

Relationships between performance variability for the body segments (left forearm, right forearm, left upper arm, right upper arm, pelvis, trunk and COM) and the outcome variability (ball velocity, side spin, initial ball roll, forward rotation, vertical launch angle, horizontal launch angle and whether the ball was pushed or pulled (defined in Chapter Five, pp. 73) were calculated as a coefficient of variation (%) (Tucker et al., 2013). Time-normalised segment rotations (X, Y, Z) were correlated for each participant to see whether different movement strategies existed between participants. Lastly, segment rotations at time of ball contact were correlated with the ball roll performance measures to identify which body segment rotations have a relationship with the kinematic ball roll variables.

7.3.4 Results

Relationship between Centre of Mass and Centre of Pressure Excursions

Positions of the COM and CP at four points of the golf putt are presented in Figure 7.4. Significant strong and moderate correlations were observed for the ML (r = .61) and AP (r = -.54) axes, between the range of CP excursions and COM displacement (Table 7.14).

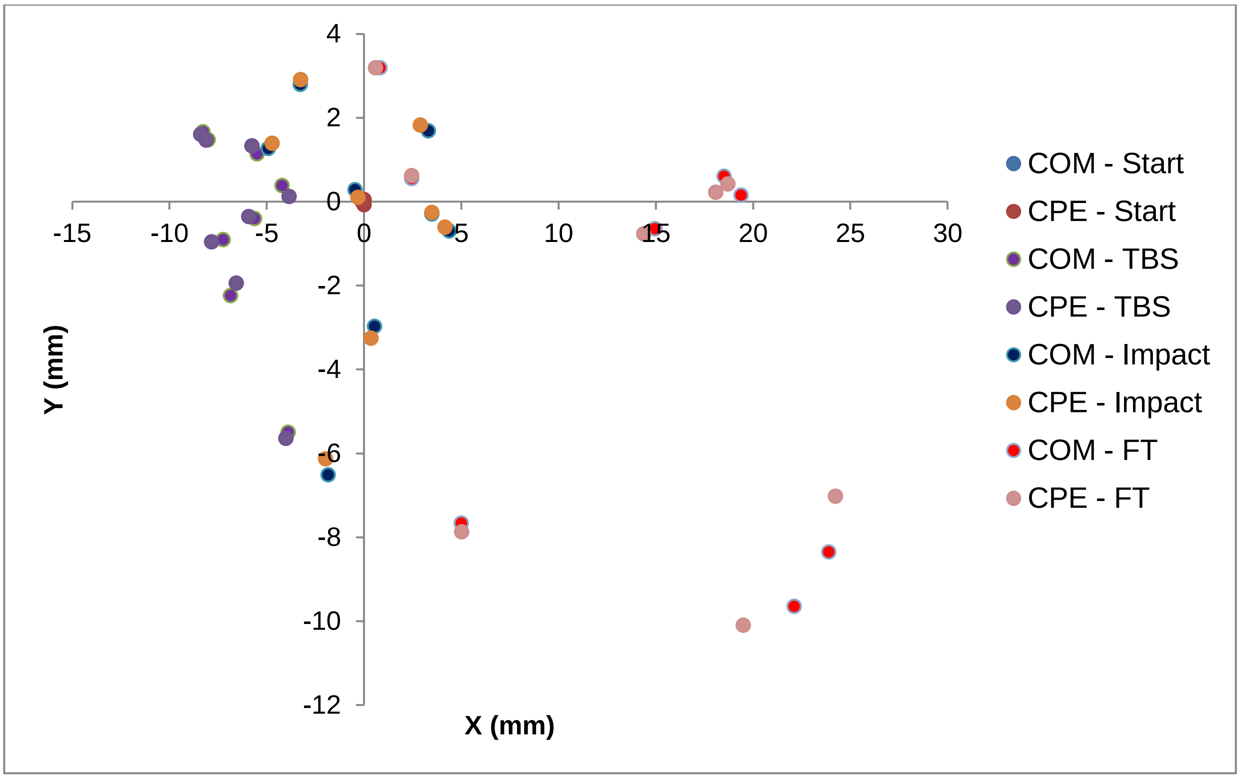

Figure 7.4. Scatterplot showing mean figures for the COM displacement and CP excursions for the the three phases in the golf putt (Figure 4.1).

Table 7.14. Correlation coefficients for the relationship between the time-normalised COM displacement and CP excursion and velocities on the mediolateral and anterioposterior axes (Significant differences denoted by a highlighted cell, $p < .05$).

Participant	Mediolateral range of displacement *r (p)*	Anteriopostierior range of displacement *r (p)*	Mediolateral peak velocity *r (p)*	Anteriopostierior peak velocity *r (p)*
Average	.61 (.001)	-.54 (.001)	.23 (.024)	-.02 (.837)
1	.24 (.014)	-.69 (.001)	-.12 (.243)	-.09 (.377)
2	-.38 (.001)	.59 (.001)	.17 (.083)	.14 (.151)
3	.72 (.001)	.75 (.001)	-.15 (.132)	.31 (.002)
4	-.43 (.001)	.08 (.076)	-.71 (.001)	-.67 (.001)
5	-.24 (.015)	-.03 (.768)	.52 (.001)	-.18 (.079)
6	.77 (.001)	.60 (.001)	.79 (.001)	.12 (.225)
7	.07 (.507)	-.72 (.001)	.13 (.190)	.22 (.024)
8	-.42 (.001)	.97 (.001)	.23 (.019)	.03 (.793)

Total range of CP excursions (not time-normalised) and COM displacement are presented in Table 7.15 for all participants. A general positive trend was identified for the variance observed in the total CP excursions and COM displacement for the mediolateral axis (r = .69, p = .058) and anterioposterior axis (r = .76, p = .028) (Figure 7.5), whereby increased variance was observed for CP excursions compared to COM displacement.

Table 7.15. Total range of CP excursions and COM displacement for the whole putting stroke (from non-time-normalised data) (mean ± SD).

	Range CP Excursion (mm)		Range COM Displacement (mm)	
Participant	Mediolateral Axis	Anterioposterior Axis	Mediolateral Axis	Anterioposterior Axis
Average	21.55 ± 8.84	11.13 ± 4.67	25.60 ± 8.42	7.34 ± 2.35
1	13.54 ± 6.20	11.87 ± 5.85	16.80 ± 3.11	7.35 ± 2.12
2	29.50 ± 12.54	8.52 ± 3.90	33.40 ± 6.32	4.80 ± 1.51
3	34.59 ± 8.58	11.93 ± 7.20	34.91 ± 9.38	9.77 ± 5.13
4	9.71 ± 3.81	6.63 ± 2.33	19.76 ± 2.52	5.20 ± 1.29
5	20.84 ± 5.51	19.12 ± 7.57	33.45 ± 4.52	11.03 ± 2.54
6	27.36 ± 13.39	10.21 ± 3.52	29.20 ± 4.11	6.06 ± 1.98
7	24.11 ± 14.66	15.98 ± 20.10	22.61 ± 8.86	5.06 ± 3.91
8	12.92 ± 4.22	5.07 ± 2.70	12.89 ± 1.65	9.05 ± 2.28

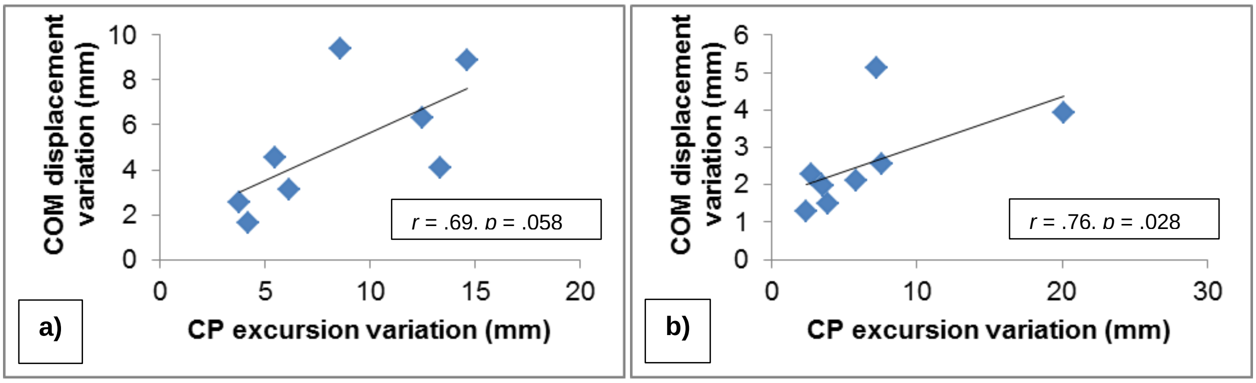

Figure 7.5. Relationship between the variaton of COM displacement and CP excursions for a) X axis and b) Y axis.

Figure 7.6 shows scatterplot COM displacement and CP excursion for four points of the golf putt for each of the eight participants. It is clear that between participants there was considerable inter-subject variation of CP excursions and COM displacement, with variability between participants apparent. Mean time normalised COM displacement and CP excursions are presented in Appendix I.

Table 7.15 presents associated *r* and *p* values of the relationship between COM and CP range of displacement and peak velocity on the ML and AP axes. Different strengths of relationship were identified in participants for range of displacement on the ML (*r* = -.43 to .77) and AP (*r* = -.72 to .97) axes. The strongest relationship for range of displacement was in participant three, who demonstrated strong relationships for both ML and AP movements between COM and CP excursions (.72 and .75 respectively). In addition to this positive relationships were identified in participant six (ML, *r* = .77; AP, *r* = .60). For all other participants either only one strong relationship (either ML or AP) or no strong relationships were identified between COM displacement and CP excursions.

Fewer relationships were identified for the peak velocity of COM displacement and CP excursion on the ML and AP axis. The strongest relationship observed was for participant six on the ML axis (*r* = .79), however, no relationship was identified on the AP axis. Weak relationships were observed for participant three for peak velocity (ML, *r* = -.15; AP, *r* = .31) in contrast to the strong relationships for displacement.

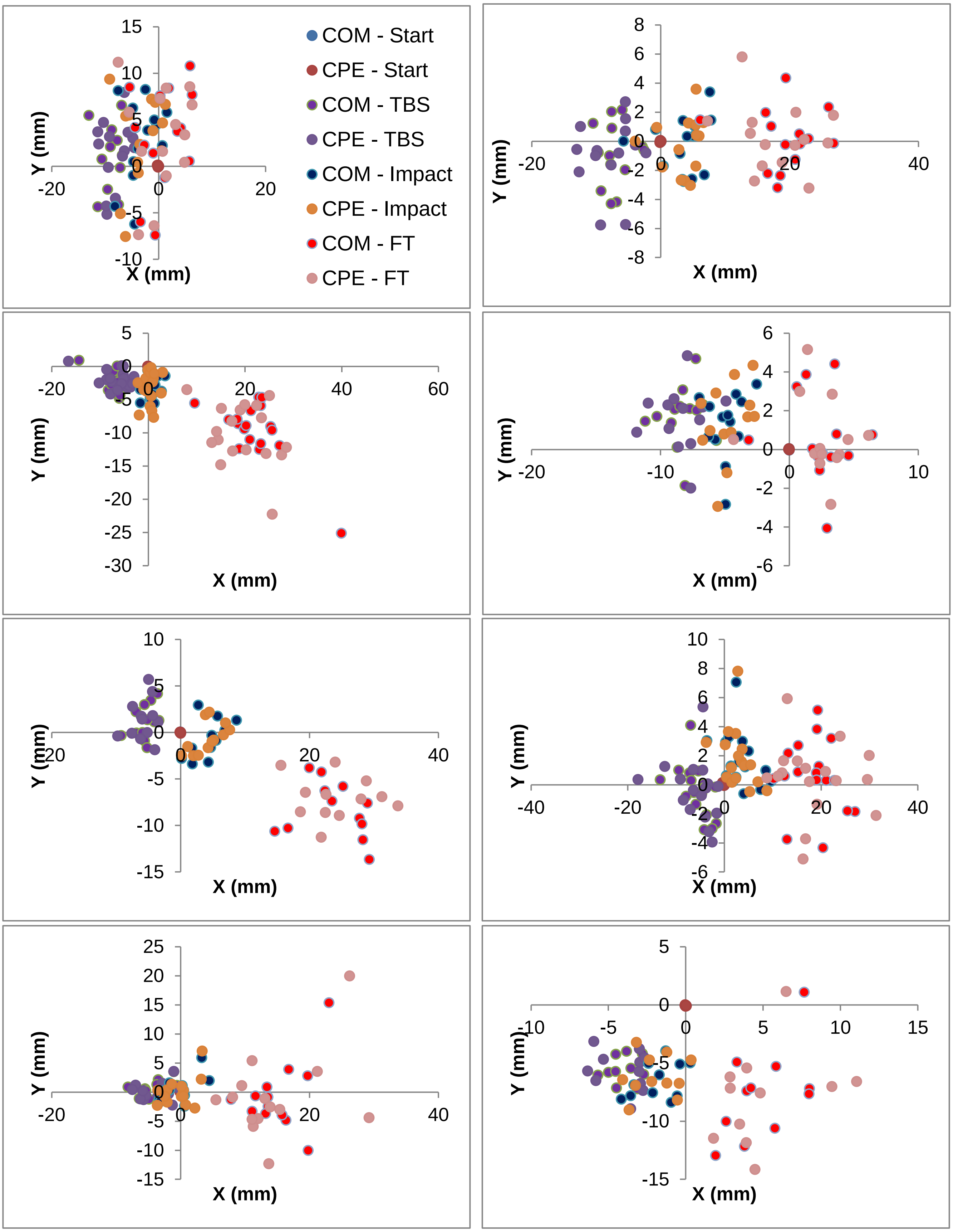

Figure 7.6. Scatterplot COM and CP excursion displacement patterns for participants one – eight (left – right, top to bottom). Axis Y denotes displacement in the anterioposterior direction and axis X denotes displacement in the mediolateral axis.

Table 7.16 displays mean data and Cohen's *d* effect sizes for the three phases of the golf put, for range of CP excursion and COM displacement and peak velocities of the excursion or displacement. For Phase One of the putting stroke all peak velocities were identified as being significantly greater for CP excursions in comparison to COM displacement (peak velocity away, p = .012; peak velocity anteriorly, p = 0.12; peak velocity posteriorly, p = 0.12). This trend was also apparent for Phase Three (peak velocity away, p = .012; peak velocity anteriorly, p = 0.12; peak velocity posteriorly, p = 0.17). Effect size statistics also support differences being observed between the variables (d = 0.67 – 2.33). With regards to the range of displacement two significant differences were observed. On the anterioposterior (Y) axis during Phase Two (p = .012) whereby increased displacement was observed for CP excursions and on the mediolateral (X) axis during Phase Three (p = .025) whereby increased COM displacement was observed. There was no significant difference (p = .902) for the total range of displacement during the three phases of the golf putt between CP excursions (32.67 mm) and COM displacement (32.91 mm).

Table 7.16. Descriptive statistics for all three phases of the golf putting stroke. (Significant difference between CP excursion and COM displacement measurements denoted by a highlighted cell, $p < .05$).

	Phase One (Start – top of backswing)			Phase Two (top of backswing – impact)			Phase Three (Impact – follow-through)		
	CP excursion (mean ± SD)	COM displacement (mean ± SD)	*d*	CP excursion (mean ± SD)	COM displacement (mean ± SD)	*d*	CP excursion (mean ± SD)	COM displacement (mean ± SD)	*d*
Range of Displacement X (mm)	8.58 ± 5.84	6.45 ± 1.64	0.50	4.75 ± 1.79	6.51 ± 3.20	0.68	8.21 ± 3.83	12.62 ± 2.71	1.26
Range of Displacement Y (mm)	4.06 ± 1.84	2.59 ± 1.36	0.91	2.64 ± 1.01	1.36 ± 0.46	1.63	4.43 ± 2.71	3.38 ± 2.27	0.40
Max velocity away (negative) or towards(positive) hole ($mm \cdot s^{-1}$)	-55.61 ± 19.07	-22.93 ± 5.39	2.33	48.41 ± 20.32	38.40 ± 13.34	0.58	57.78 ± 21.73	43.61 ± 17.98	0.67
Max velocity anteriorly ($mm \cdot s^{-1}$)	27.18 ± 13.92	6.55 ± 3.78	2.02	24.66 ± 11.16	5.83 ± 4.54	2.21	27.82 ± 11.24	6.75 ± 4.99	2.29
Max velocity posteriorly ($mm \cdot s^{-1}$)	-29.43 ± 16.67	-7.88 ± 4.46	1.77	-18.41 ± 7.02	-6.86 ± 4.47	1.96	-25.77 ± 11.79	-13.52 ± 5.22	1.27

Performance Variability Results – Segment Rotations and Ball Kinematics

Individual performance variability for the segment rotations are presented in Figure 7.7. A range of variability was observed, the largest being 2.85 degrees^3/degrees for participant three. Participant one demonstrated the largest COM variation (2.11 degrees^3/degrees), this was accompanied with larger variance in the pelvis (0.98 degrees^3/degrees) and trunk (0.97 degrees^3/degrees) segments. Very low segment variations were observed for participant eight (0.01 – 0.04) excluding the COM (0.41 degrees^3/degrees). Despite the low segment variation observed in Participant eight, they exhibited a higher putter rotation variation (0.28 degees) (Table 7.17) in comparison to the other participants. The lowest putter variation was observed in participant four (0.13 degrees). In regards to segments the least variation was observed for the right upper arm (0.01 – 0.19 degrees^3/degrees) and left upper arm (0.01 – 0.12 degrees^3/degrees). There was a weak correlation between putter variability and putting proficiency (r = .35, p = .396). Non significant correlations were also identified for all other segment variability and the variability of the COM (r = -.14, p = .734).

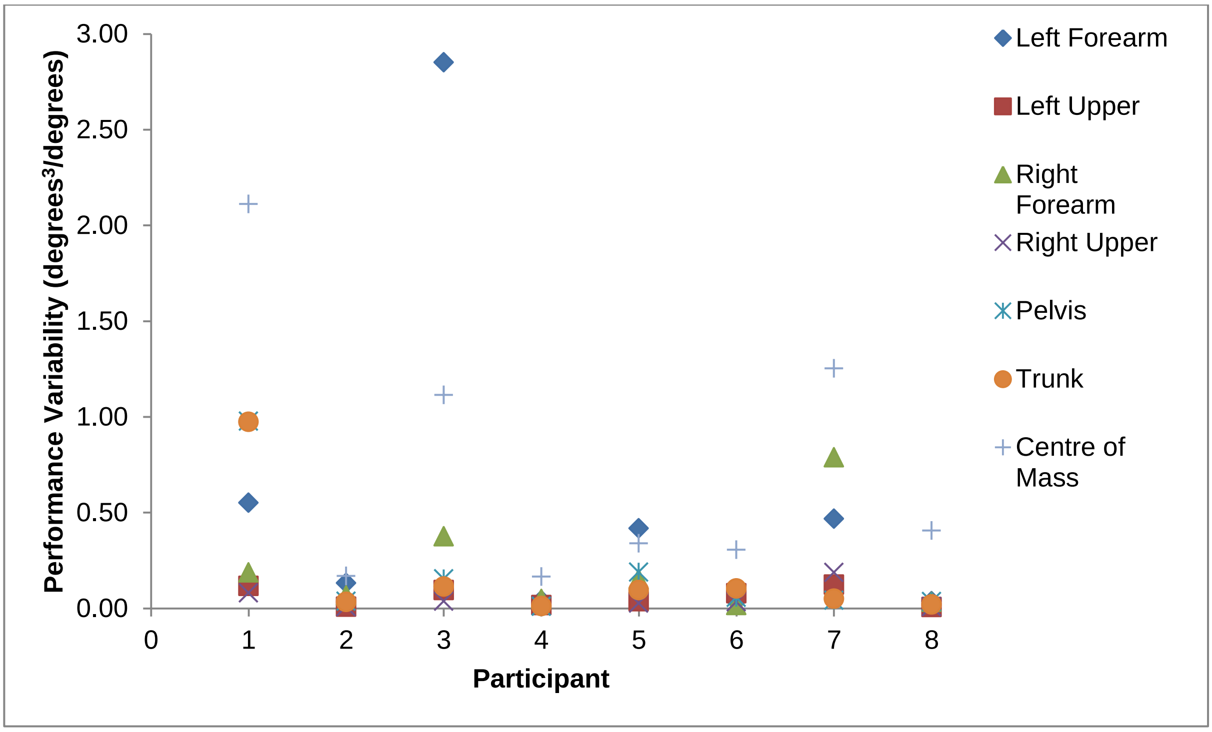

Figure 7.7. Scatterplot of performance variability scores for the segment rotations during the putting stroke.

Table 7.17. Performance variability scores for the putter Z rotations during the putting stroke.

Participant	Performance variability (degrees)	Putting Proficiency (Success Rate)
1	0.27	73%
2	0.28	75%
3	0.18	52%
4	0.13	71%
5	0.14	76%
6	0.27	59%
7	0.22	67%
8	0.28	83%

Table 7.18 presents mean performance variability scores for all segments. The largest amount of variance observed across all participants was the COM (0.73 degrees^3/degrees) and left forearm (0.57 degrees^3/degrees). Despite this these values may be skewed by participant ones COM and participant three's left forearm variation, which were elevated above all other variation scores. The lowest mean performance variability was the left (0.06 degrees^3/degrees) and right upper arm (0.05 degrees^3/degrees); this was accompanied with low amounts of variation between participants. The right forearm, pelvis and trunk segments all had similar amounts of performance variability (0.18 – 0.21 degrees^3/degrees), larger amounts of variation were observed in comparison to the upper arm segments however.

Table 7.18. Mean (±SD) performance variability scores for the segment rotations during the putting stroke.

Segment	Performance variability (degrees^3/degrees)
Left Forearm	0.57 ± 0.95
Left Upper Arm	0.06 ± 0.05
Right Forearm	0.21 ± 0.26
Right Upper Arm	0.05 ± 0.06
Pelvis	0.19 ± 0.33
Trunk	0.18 ± 0.32
Centre of Mass	0.73 ± 0.70

Ball roll kinematics are presented in Table 7.19 It is worth noting that there was large variability for side spin, initial ball roll, vertical launch angle, whether the ball was pushed or pull and horizontal launch angle between participants. The range of whether the ball was pushed or pulled was 17.84 cm between participant three and four, this was also observed for horizontal launch angle (4.22 degrees). The only variable that demonstrated consistency amongst participants was the ball velocity (2.08 – 2.30 ms^{-1}).

Table 7.20 displays correlation coefficients between performance measurement variability (kinematic ball roll) and segment rotation variability. The kinematic ball roll variable that had the most significant relationships with segment variation was the horizontal launch angle, whereby strong to very strong positive correlations were observed (r = .73 to .93). No significant relationship was identified between horizontal launch angle and the putter head angle variability (r = -.20). The closely related ball roll variable of whether the ball was pushed or pulled was only correlated with the left and right forearm variability with r values of .98 and .93 respectively. Moderate to strong correlations were identified for all other segments variability (r = .51 to .69), however these were non-significant results. Like horizontal launch angle, the correlation with the putter z rotations was weak (r = -.28). Putter Z rotations had significant negative correlations with ball velocity (r = -.75) and vertical launch angle (r = -.71). The only other significant correlations were observed between initial ball roll and the variability of the pelvis (r = -.83), initial ball roll and the variability of the trunk (r = -.74), additionally between the variability of the pelvis and forward roll (r = -.81).

Table 7.19. Ball roll kinematic variables for all participants (mean ± SD).

Participant	Velocity (ms^{-1})	Spin (Cut (+), Hook (-), rpm)	Initial Ball Roll (rpm)	Forward Rotation (cm)	Vertical Launch Angle (°)	Push/Pull (cm)	Horizontal Launch Angle (°)
Average	2.22 ± 0.09	1.05 ± 17.53	17.68 ± 39.03	2.99 ± 3.27	3.98 ± 2.99	4.30 ± 5.82	1.02 ± 1.38
1	2.28 ± 0.09	19.47 ± 17.36	65.42 ± 14.30	0.03 ± 0.10	1.96 ± 1.08	7.95 ± 7.35	1.87 ± 1.74
2	2.11 ± 0.09	-19.77 ± 10.90	10.41 ± 16.90	1.90 ± 2.33	4.26 ± 0.57	0.71 ± 2.92	0.17 ± 0.68
3	2.08 ± 0.11	33.56 ± 9.65	37.96 ± 11.95	0.07 ± 0.16	3.09 ± 0.59	-5.37 ± 3.83	-1.27 ± 0.90
4	2.20 ± 0.15	-5.26 ± 10.92	-16.66 ± 14.44	5.22 ± 2.53	7.12 ± 3.04	12.47 ± 4.28	2.95 ± 1.01
5	2.30 ± 0.13	3.60 ± 18.21	75.06 ± 16.64	0.04 ± 0.09	0.83 ± 0.51	2.44 ± 4.53	0.58 ± 1.07
6	2.22 ± 0.08	-12.85 ± 8.01	-30.53 ± 10.44	8.99 ± 1.78	5.58 ± 0.83	5.94 ± 5.17	1.41 ± 1.24
7	2.25 ± 0.16	-6.40 ± 16.87	15.56 ± 11.22	2.23 ± 2.84	3.53 ± 0.65	0.48 ± 4.53	0.11 ± 1.07
8	2.26 ± 0.07	-3.97 ± 11.02	-15.78 ± 11.24	5.44 ± 4.45	5.51 ± 0.88	9.85 ± 4.86	2.33 ± 1.15

Table 7.20. Correlation coefficients *(r (p))* between performance measures variability and segment rotation variability. (Significant differences denoted by a highlighted cell, *p* < .05).

	Left Forearm	Left Upper Arm	Right Forearm	Right Upper Arm	Pelvis	Trunk	Centre of Mass	Putter (Z rotations)
Velocity	.32 (.444)	.31 (.450)	.62 (.102)	.32 (.441)	-.24 (.560)	-.14 (.734)	-.01 (.978)	-.75 (.033)
Side Spin	.07 (.843)	-.12 (.776)	.29 (.493)	.03 (.954)	-.10 (.818)	-.19 (.649)	-.01 (.978)	.30 (.468)
Initial Ball Roll	-.42 (.307)	-.34 (.414)	-.10 (.823)	-.25 (.558)	-.83 (.011)	-.74 (.035)	.20 (.629)	.31 (.450)
Forward Roll	-.36 (.373)	-.25 (.545)	-.07 (.867)	-.18 (.662)	-.81 (.016)	-.68 (.062)	-.11 (.799)	.40 (.329)
Vertical Launch Angle	.42 (.307)	.40 (.329)	.41 (.320)	.34 (.404)	.49 (.220)	.36 (.382)	.37 (.365)	-.71 (.048)
Push/Pull	.98 (<.001)	.64 (.088)	.93 (.001)	.69 (.060)	.51 (.194)	.62 (.099)	.66 (.076)	-.28 (.506)
Horizontal Launch Angle	.93 (.001)	.84 (.009)	.78 (.023)	.88 (.004)	.74 (.037)	.89 (.003)	.73 (.040)	-.20 (.635)

Time-normalised segment rotations

Figure 7.8 displays time-normalised segment rotations and segment velocities on the X, Y and Z axis for participant three who was identified to be the least proficient putter (Table 7.17). The triangle represents the percentage at which ball contact occurred (59%). Significant very strong positive correlations on the Z axis were identified between the following segments; left right forearm (r = .99, p < .001), left forearm and pelvis (r = .98, p < .001) and the right forearm and pelvis (r = .96, p < .001). Significantly very strong negative relationships were identified between the trunk and left forearm ((r = -.99, p < .001), trunk and right forearm (r = -.99, p < .001) and trunk and pelvis (r = -.94, p < .001). A strong negative relationship was identified for X rotations between the left and right forearm (r = .75, p < .001). Putter Z rotations were all correlated to a very strong level with the following segments left forearm (r = .99, p < .001), right forearm (r = .99, p < .001), pelvis (r = .98, p < .001) and with the trunk negatively (r = -.91, p < .001). R values for all segment relationships are presented in Appendix H.

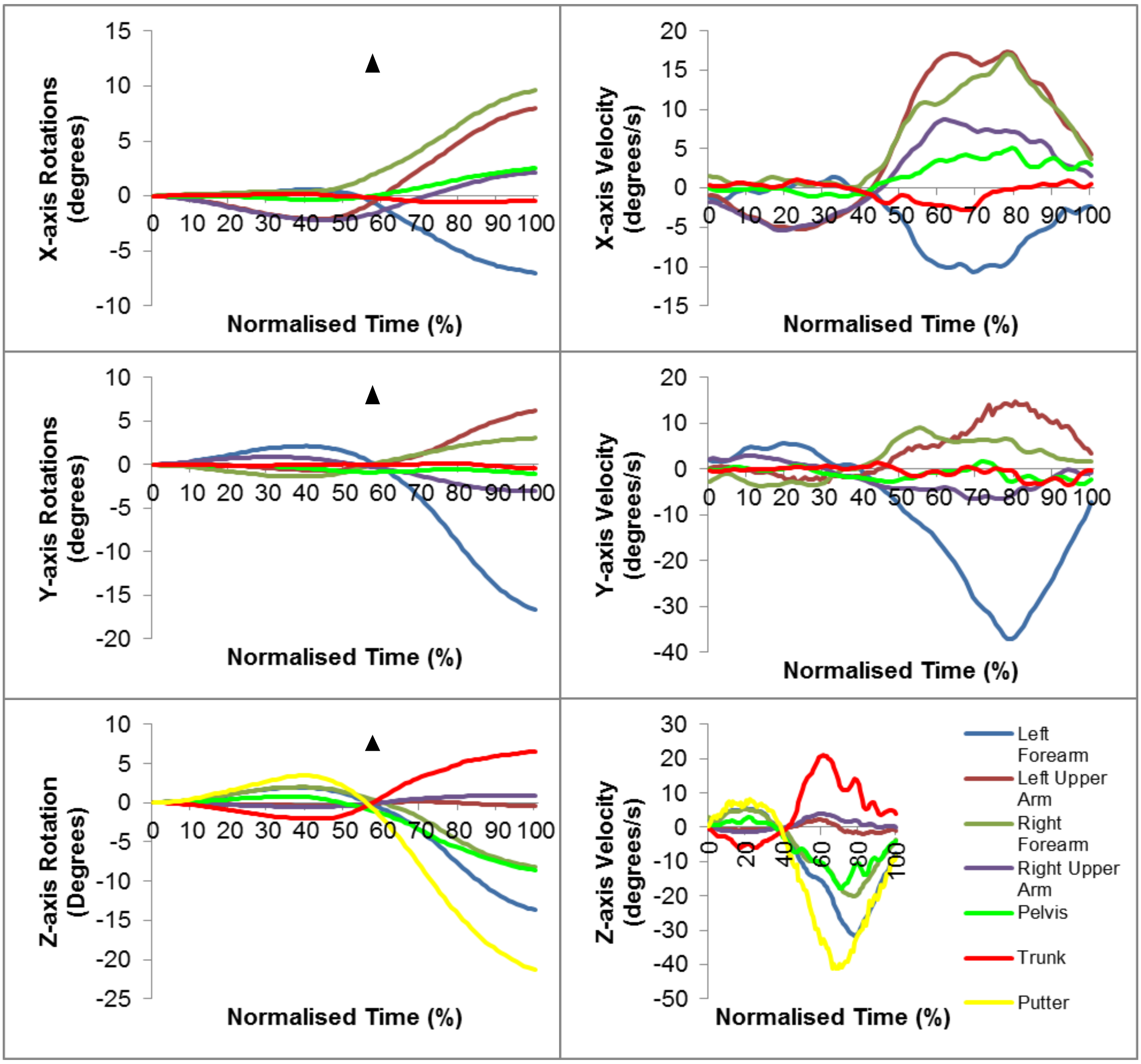

Figure 7.8. The displacement and velocities of Participant 3 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.

Figure 7.9 displays time-normalised segment rotations and segment velocities on the X, Y and Z axis for participant six who was identified to have an opposite movement pattern in comparison to all the other participants. The triangle represents the percentage at which ball contact occurred (72%). A range of strengths of correlations were observed for Z rotations between the following segments; left and right forearm (r = .88, p < .001), left forearm and pelvis (r = -.61, p < .001), right forearm and pelvis (r = -.31, p = .002), left forearm and trunk (r = .52, p < .001), right forearm and trunk (r = .17, p < .092) and the pelvis and trunk (r = -.97, p < .001). A strong significant correlation was identified left and right forearm for X rotations (r = .64, p < .001). A range of strength of relationships were identified between putter Z rotations and the following Z segment rotations; left forearm (r = .03, p = .767), right forearm (r = .34, p < .001), pelvis (r = .68, p < .001) and trunk (r = -.81, p < .001).

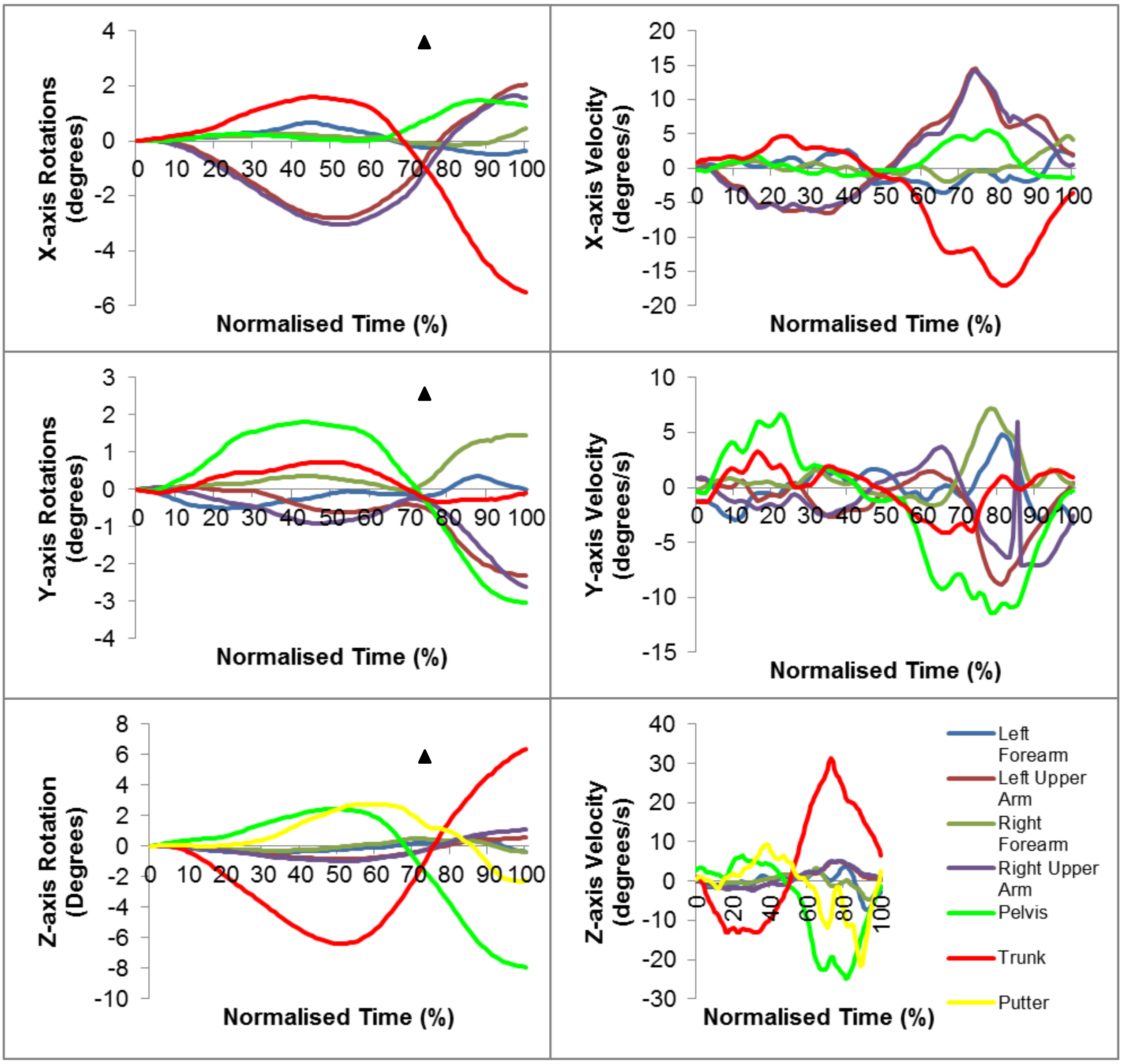

Figure 7.9. The displacement and velocities of Participant 6 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.

Figure 7.10 displays time-normalised segment rotations and segment velocities on the X, Y and Z axis for participant eight, who demonstrated the best putting proficiency (Table 7.17). The triangle represents the percentage at which ball contact occurred (63%). Very strong signficant postive correlations were observed for Z rotations between the left and right forearem (*r* = .99, *p* < .001), left forearm and pelvis (*r* = .99, *p* < .001) and right forearm and pelvis (*r* = .99, *p* < .001). Significant very strong negative correlations were identified between the trunk and the following segments; left forearm (*r* = -.98, *p* < .001), right forearm (*r* = -.99, *p* < .001) and pelvis (*r* = -.99, *p* < .001). A strong negative relationship between the left and right forearm for X rotations was identified (*r* = -.65, *p* < .001). Putter Z rotations demonstrated very strong positive correlations with the following segments; left forearm (*r* = .90, *p* < .001), right forearm (*r* = .92, *p* < .001) and pelvis (*r* = .93, *p* < .001). The opposite negative very strong correlation was identified between the putter and trunk (*r* = -.94, *p* < .001). Time-normalised rotations and velocities are presented in Appendix H.

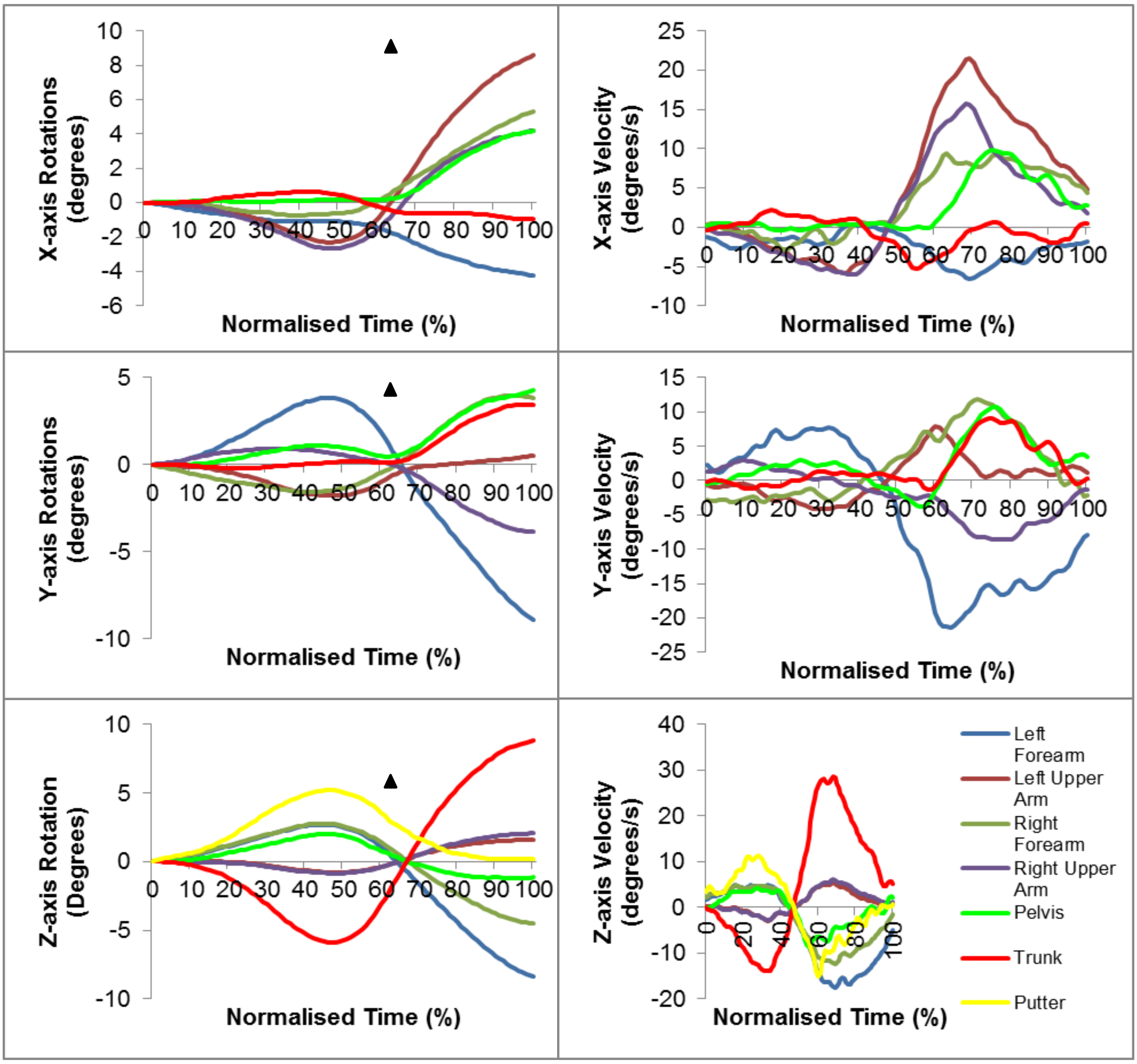

Figure 7.10. The displacement and velocities of Participant 8 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.

Ball Contact Correlations

Figures 7.8 – 7.10 and Appendix H display the segment rotations at ball contact along with time-normalised segment rotations. A range of different degrees of rotation were identified between participants for all segments. An example of this is for left forearm Z rotations, with -0.74 and 1.08 degrees observed between participant one and participant four. For the right forearm a similar range was observed between participant one and four at 0.01 degrees and 2.37 degrees respectively. Correlations between performance measures and segments rotations for X, Y and Z rotations are presented in Tables 7.21 – 7.23. One significant relationship was observed for right forearm X rotations (r = -.95, p = <.001), one very strong significant relationship was observed on the Y axis with the left forearm and ball velocity (r = .76, p = .028). For Z rotations, two significant relationships were observed between the left forearm velocity and side spin (r = -.81, p = .015) and the right forearm rotation and vertical launch angle (r = .76, p = .037).

A similar range of Z rotations was observed between the trunk and pelvis segments at ball contact (Figures 7.8 – 7.10, Appendix H). A range of 2.10 degrees were observed for Pelvis Z rotations between participant six (-1.39 degrees) and participant seven (0.71 degrees). The largest range for trunk Z rotations were observed between participant one (-2.16 degrees) and participant three (0.14 degrees). All participants excluding participant three had a negative trunk rotation at impact, rotation away from the target (right rotation). The velocity of Pelvis and Trunk segment Z rotations were larger in comparison to the forearm segments. The largest range for the pelvis rotation velocity was between participant five (-34.63 degrees/s) and seven (-4.82 degrees/s), for the trunk it were between participant six (30.13 degrees/s) and five (12.63 degrees/s). A number of relationships between the pelvis and trunk rotations and velocity at ball contact and performance measures were identified, however none of these were for Y rotations (or velocities) (Tables 7.21 – 7.23). For the X axis (Table 7.21) two significant very strong positive relationships were observed between the pelvis and whether the ball was pushed or pulled (r = .83, p = .010) and the horizontal launch angle (r = .83, p = .010). For Z rotations relationships were identified for the trunk segment (Table 7.23). Significant negative strong correlations were identified for trunk rotations and whether the ball was pushed or pulled (r = -.79, p = .021) and horizontal launch angle (r = -.79, p = .021). For trunk velocities four significant correlations were acknowledged; side spin ((r = -.71, p = .047), initial ball roll ((r = -.88, p = .004), forward roll ((r = .71, p = .047) and vertical launch angle ((r = .93, p = .001).

In comparison to other segments the left and right upper arm demonstrated less X, Y and Z rotations (Figures 7.8 – 7.10, Appendix H). Despite the low rotations and velocity (in comparison to the other segments) some relationships with the performance measures were identified. Two positive relationships were identified between the right upper arm and ball velocity ((r = .83, p = .010) and vertical launch angle (r = .74, p = .037) for X rotations (Table 7.21). For Y rotations relationships (Table 7.22) were identified between the left upper arm and initial ball roll (r = .74, p = .037), forward roll (r = .91, p = .002) and vertical launch angle (r = -.71, p = .047). Similarly relationships were identified between the left upper arms Z rotation velocity (Table 7.23) and whether the ball was pushed or pulled (r = .74, p = .037) and horizontal launch angle (r = .74, p = .037).

For Putter Z rotations a range of 2.08 degrees were observed, the most open putter face was recorded in participant eight at 2.84 degrees, the lowest was observed for participant one and for at 0.76 degrees. In regards to velocity of the putter face rotation at ball contact were -29.52 degrees/s for participant three, whereas the lowest were -2.34 for participant two. It should be noted that participant eight also demonstrated a low velocity at ball contact (-10.58). No significant correlations were identified between putter Z rotations and performance measures (Table 7.23).

Table 7.21. R values between performance measures (kinematic variables) and segment rotations on the X axis at point of ball contact for all participants (R = rotational displacement, V = velocity of displacement). (Significant differences denoted by a highlighted cell, $p < .05$).

	Left Forearm		Left Upper Arm		Right Forearm		Right Upper Arm		Pelvis		Trunk	
	R	V	R	V	R	V	R	V	R	V	R	V
Velocity	.21	.31	.05	-.55	-.95	.07	.83	- .21	.26	.10	.14	-.19
Side Spin	.24	-.45	-.29	.12	-.29	.52	.24	-.71	-.24	.14	.45	.29
Initial Ball Roll	.07	.02	.29	.36	-.48	.55	.52	-.64	-.62	.33	.07	.07
Forward Roll	.00	-.14	-.14	.29	.31	-.31	-.21	.57	.60	-.26	-.17	.00
Vertical Launch Angle	.05	.00	-.31	.48	.52	-.57	-.60	.74	.60	-.48	.02	-.02
Push/Pull	.10	.02	-.52	.41	-.14	-.64	-.17	.48	.83	-.41	.31	-.29
Horizontal Launch Angle	.10	.02	-.52	.41	-.14	-.64	-.17	.48	.83	-.40	.31	-.29

Table 7.22. R values between performance measures (kinematic variables) and segment rotations on the Y axis at point of ball contact for all participants (R = rotational displacement, V = velocity of displacement). (Significant difference denoted by a highlighted cell, $p < .05$).

	Left Forearm		Left Upper Arm		Right Forearm		Right Upper Arm		Pelvis		Trunk	
	R	V	R	V	R	V	R	V	R	V	R	V
Velocity	.76	-.12	.17	.48	.50	.38	.48	.29	.24	-.36	.24	-.41
Side Spin	.64	-.52	.24	.48	.68	.45	-.19	.21	.21	-.02	.38	-.24
Initial Ball Roll	.52	-.41	.74	.36	.67	.29	.41	-.12	-.33	-.19	.00	-.07
Forward Roll	-.45	.33	.91	-.05	-.60	-.33	-.52	.24	.21	.29	-.07	.07
Vertical Launch Angle	-.45	.38	-.71	-.33	-.76	-.14	-.36	.10	.29	.24	.10	.14
Push/Pull	.48	.07	-.36	-.05	-.17	.33	.07	-.17	.64	.41	.45	-.21
Horizontal Launch Angle	.48	.07	-.36	-.05	-.17	.33	.07	-.17	.64	.41	.45	-.21

Table 7.23. R values between performance measures (kinematic variables) and segment rotations on the Z axis at point of ball contact for all participants (R = rotational displacement, V = velocity of displacement). (Significant difference denoted by a highlighted cell, $p < .05$).

	Left Forearm		Left Upper Arm		Right Forearm		Right Upper Arm		Pelvis		Trunk		Putter (Z rotations)	
	R	V	R	V	R	V	R	V	R	V	R	V	R	V
Velocity	-.05	-.26	-.12	-.10	-.36	-.12	-.21	-.52	.38	-.26	-.48	-.62	.22	-.12
Side Spin	-.41	-.81	.12	-.38	-.69	-.24	.31	-.45	-.02	-.10	-.07	-.71	-.34	-.64
Initial Ball Roll	-.31	-.45	.21	-.41	-.67	.02	.19	-.62	.10	-.29	.17	-.88	-.04	-.55
Forward Roll	.31	.38	.05	.14	.62	-.05	.05	.38	-.02	.36	-.10	.71	.33	.43
Vertical Launch Angle	.41	.38	-.19	.50	.76	-.19	-.14	.67	.00	.38	-.24	.93	-.02	.50
Push/Pull	.41	-.26	-.60	.74	.36	-.36	-.50	.52	.24	.00	-.79	.36	-.23	.43
Horizontal Launch Angle	.41	-.26	-.60	.74	.36	-.36	-.50	.52	.24	.00	-.79	.36	-.23	.43

7.3.5 Discussion

Relationship between centre of mass and centre of pressure excursions

The first aim of this study was to identify whether a relationship exists between the CP excursions and COM displacement. Significant strong and moderate relationships (Table 7.14) were identified between the mean range of CP excursions and COM displacement, however the direction of the relationship changed between axes (ML, r = .61; AP, r = -.54) for the group average. Participants' range of CP excursions and COM displacement demonstrated large inter-subject variability of relationships for both axes (ML range of r = -.43 to .77; AP range of r = -.72 to .97). This large inter-subject variability was also apparent for the range of ML and AP CP excursions (ML, 9.71 – 34.59 mm; AP, 5.07 – 15.98 mm) and COM displacements (ML, 12.89 – 33.45 mm; AP, 4.80 – 11.03 mm) (Table 7.15). Participants COM displacement and CP excursion patterns demonstrated inter-subject variability. The average displacement pattern and scatterplot of COM and CP excursion at points of the golf putt of all participants (Figure 7.4 & Appendix I) does not resemble any of the individual participants displacement patterns or patterns (Figure 7.6 & Appendix I), therefore intra-subject variation may be masked if only average data is considered. The range of CP excursions and COM displacement and associated velocities for the three phases of the golf putt are presented in Table 7.16. Two significant differences were identified for range of displacement (Phase 2; range of anterioposterior displacement, p = .012) where increased CP excursions were observed and in Phase 3; range of mediolateral displacement, p = .025) where increased COM displacement was observed.

Benda, Riley and Krebs (1994) outline that the CP is the single point at which the resultant force vector of the GRF would act. As Palmieri et al. (2002) outlines, the position of the CP also depends on projections of muscle forces that are required to control or produce the movement. Therefore, CP excursion patterns do not directly represent the displacement pattern of the COM (Benda et al., 1994; Winter, 1995; Zatsiorsky & King, 1997). The CP position will vary about the COM position due to the higher frequency content (Benda et al., 1994), which will manifest in different patterns being observed between parameters. This difference between the positions of the CP and COM represents a moment arm of the weight force vector (COM) and ground reaction force vector (CP) (Benda et al., 1994; Riley, Mann & Hodge, 1990). One association between the displacement patterns is that CP excursion should always be greater than COM displacement in an attempt to maintain balance when alterations to the COM occur (Palmieri et al., 2002). Within, the current study, this was not the case. A number of other studies have expressed caution when interpreting CP excursions and COM displacement, especially when matching time histories (Benda et al., 1994; Gutierrez-Farewick, Bartonek & Saraste, 2006; Lafond, Duarte & Prince, 2004).

Figures in Appendix I display the CP excursion and COM displacement patterns, and it is visually evident that the CP excursion patterns are smaller to the COM displacement pattern. This may be different due to more variability being associated with the position of the CP (Table 7.15), masking the excursion when presented as the participants' average. Increased variation was also observed in velocities of the CP excursion in comparison to COM displacement. In addition to this, as previously reported, the CP excursion oscillations will be of a higher frequency than the COM (Benda et al., 1994). Significantly, different peak velocity between CP excursion and COM displacement patterns support this (Table 7.16). With the data being time-normalised using a cubic spline algorithm these oscillations may have been occurring at different time frequencies and therefore potentially cancelling each other out.

When the total range for all three phases of the putt are considered for CP excursions (32.67 mm) and COM (32.91 mm) (no significant difference, p = .902), the two variables seem more closely related than Figures in Appendix I suggest. The difference between the COM displacement and CP excursion time frequencies may be due to the projections of the lower limb muscle contractions during the execution of the putting stroke (Palmieri et al., 2002). Whilst the upper body is rotating (Delphinus & Sayers, 2012) the lower limb remains predominantly static. It may be the case that there are contractions of the lower limb muscles 'stabilising' the CP excursions during the golf putt, whereby, a portion of the excursion occurs after the putting stroke has been executed to maintain balance during the stroke. This delay of CP excursions in comparison to COM displacement has been observed in quiet standing of up to 100 ms (Winter, Patla, Prince, Ishac & Gielo-Perczak, 1998). Small amounts of CP excursion have been observed to occur during the golf putt in this study and previous literature (Hurrion & Hurrion, 2008; McLaughlin et al., 2008; McLaughlin & Best, 2013). The delay of the CP excursion occurring may be occurring like observed in quiet standing. This additionally may increase the variability observed between trials for the CP excursions, where less variability would be observed if the golfer were to not try and control CP excursions in an attempt to increase stability, particularly with the small value of excursions observed.

Gatev, Thomas, Kepple and Hallet (1999) termed the muscle activation in the lower limb to maintain balance during quiet standing as 'ankle strategy'. The ability to maintain balance was reduced when narrower stances were adopted (Gatey et al., 1999). Generally, the putting stance will be wider than a quiet standing position widths of 24.21 – 28.84 cm has been previously observed (Hurrion & Hurrion, 2008). This wider stance may give the golfer an increased ability to minimise the CP excursions during the putting stroke. This conscious controlling of CP excursions potentially could have a negative effect on performance. Previously Toner & Moran (2011) identified conscious monitoring of the putting stroke technique had a negative effect on putting performance.

This attempt at controlling CP excursions may have contributed to the varied results observed during the putting stroke amongst the previous literature (Hurrion & Hurrion, 2008; McLaughlin et al., 2008; McLaughlin & Best, 2013) and study two of this thesis. More accurate golfers were found to have marginally larger CP excursions than less accurate golfers (not significant), suggesting that reducing CP excursions may not necessarily benefit performance (McLaughlin & Best, 2013). Additionally, McLaughlin and Best (2013) observed no significant differences between the peak velocity of CP excursions on the X axis (accurate = 41.9 ± 24.5 $mm \cdot s^{-1}$, less accurate = 42.0 ± 27.9 $mm \cdot s^{-1}$), which is in contrast to when participants were grouped by handicap (low handicap = 33.4 ± 24.4 $mm \cdot s^{-1}$, high handicap = 60.4 ± 26.6 $mm \cdot s^{-1}$). Again this emphasises that CP excursions may not be as important as other parameters regarding putting performance. In the current study, similar peak CP velocities during phase two of the golf putting stroke (Table 7.16) to that of those observed in McLaughlin and Best (2013). The projection of lower limb muscle contractions (Palmieri et al., 2002) may also explain the differences between the COM displacement and CP excursions that occur on the ML and AP axes (Table 7.15). On the AP axis, an increase of 3.83 mm was observed for the CP excursions in comparison to the COM displacement. Considering the body predominantly translates on the ML axis during putting the increase in CP excursions on the AP axis in comparison to COM displacements may be due to the golfer attempting to stabilise the body during the putting stroke. Delphinus and Sayers (2012) demonstrated that more proficient putters move their COM along the ML axis, whereas, less proficient golfers exhibit increased sagittal movement on the AP axis, it may be the case golfers need to replicate this with CP excursions, by not trying to consciously control them (Toner & Moran, 2011).

Another implication of the results is the efficacy of grouping participants by handicap previously identified by McLaughlin & Best (2013) but also by statistically clustering through CP excursion parameters as carried out by McLaughlin & Best (2013). The rationale for this is that high inter-subject variability reduces the suitability of averaged results. In the current study, it is clear from CP excursion and COM displacement that a number of different CP and COM patterns were evident and therefore potentially different techniques (Figure 7.6) which did not reflect the CP or COM patterns when averaged (Figure 7.4). Therefore, inferences identified from the averaged data may not have true practical implications with errors in interpretation of the data. The relationship between time-normalised range of displacement for CP excursions and COM displacement also supports this (Table 7.14). When averaged, an r value of .61 (p = .001) for the range of displacement between CP excursions and COM displacement on the ML axis. Despite this, negative r values were observed for participant two, four, five and eight demonstrating a negative relationship between the variables. Therefore, practical implications suggested from the averaged data potentially would not apply to half of the participants that formulated the average. With no clear consensus of optimal technique having been identified for the golf putt within the literature (Delphinus & Sayers, 2012; Hurrion & Hurrion, 2008;

Karlsen et al., 2008; McLaughlin et al., 2008; Mclaughlin & Best, 2013, Pelz, 2000) other than the putter face should be square to the target at impact, this has potentially large implications. Literature examining the full golf swing has identified the benefit of individual based analysis regarding CP excursions (Ball & Best, 2012). It was concluded that individual based analysis should be used in conjunction with group based analysis, with differences observed between individuals (Ball & Best, 2012). These inter-individual differences could potentially be masked if analysed only as an averaged group. Additionally, Tucker et al. (2013) stated that it may be more beneficial to examine movement variability on an individual basis. To date, published golf putting literature has not considered participants on an individual basis.

The current study raises doubts into the results and implications of McLaughlin & Best (2013) particularly. McLaughlin & Best (2013) used cluster analysis on CP excursion data to group golfers into particular styles. Two styles were identified; arm putters and body putters, where reduced displacement of the CP excursion is observed for arm putters in comparison to body putters who have a relatively large CP excursion and an increased velocity of CP excursion at impact (McLaughlin and Best, 2013). As McLaughlin and Best (2013) state there was no statistical differences observed for success rate or accuracy between two different styles of technique (arm and body), raising questions into the importance of CP excursions. Despite being statistically arranged into groups, large variability was observed for CP excursion variables for the three phases of the golf putt (expressed as a percentage of the mean: range = 45 - 190%; peak velocity = 55 - 71%). Again this raises doubts as to the implications being applicable to all participants. These results of variability are slightly larger to the current study where the eight participants were not grouped (expressed as a percentage of the mean: range = 38 – 68%; peak velocity (ML axis) = 34 – 43%) (Table 7.16). In addition to this, it is questionable as to whether it is appropriate for McLaughlin and Best (2013) to term the groups ‘arm’ and ‘body’ putters when body kinematic parameters were not measured. As this study demonstrated that the relationship between the COM displacement and CP excursions is not a simplistic one. All body movements and rotations will contribute to alterations in the displacement of COM and therefore it may be unsuitable to interpret body movement from only assessing CP excursion parameters.

Effect of segment rotation variability on ball kinematic variables and performance

The second aim of this study was to determine whether segment rotations and variability in segment and putter rotations affect performance measures (kinematic ball roll variables). Individual performance variability for body segments are presented in Figure 7.7 and putter Z rotation variability is presented in Table 7.17. A range of variability was observed between participants, with low variation observed for participant two, four, five, six and eight. The largest amount of variation was observed for participant three left forearm segment with a value of 2.85 degrees^3/degrees. In regards to putter Z rotations the lowest variability observed was in participant four (0.13 degrees), the most proficient golfer (participant eight) had the equal highest putter face angle variability of 0.28 degrees. With participants averaged (Table 7.18) the most variability was observed in the COM (0.73 ± 0.70 degrees^3/degrees) followed by the left forearm (0.57 ± 0.95 degrees^3/degrees) although this is elevated by participant three. The pelvis and trunk had very similar variability observed (0.19 and 0.18 degrees^3/degrees) respectively. Correlations coefficients between performance measures variability and segment variability are presented in Table 4. The performance measure (ball roll variable) that had the most significant relationships with segment rotations was the horizontal launch angle (*r* = .73 to .93). However, no significant relationship was identified for the putter head angle (*r* = -.20). For whether the ball was pushed or pulled, significantly strong correlations were identified with the variability of the left and right forearm (*r* = .51 to .69).

Time-normalised displacement and velocities for individual participants for the three orthogonal planes are presented in Figures 7.8 – 7.10 and Appendix H. Inter-subject variability was apparent for all rotations, particularly at ball contact for Z rotations, where minor differences in putter face angle will affect the horizontal launch angle (Hurrion & Mackay, 2012). A number of trends between participants was however evident. For seven of the eight participants it was identified that the left forearm, right forearm, pelvis and putter rotate in the same direction on the Z axis (left forearm pronates, right forearm supinates, pelvis rotating to the right, putter face opening during backswing, opposite for downswing and follow though) with very strong positive correlation coefficients identified (Appendix H). The trunk rotated in the different direction (left rotation) with very strong negative correlations with the left forearm, right forearm, pelvis and putter (Appendix H). The only anomaly to this was participant six, where significant correlations were observed for Z rotations between the left and right forearm, pelvis and trunk but to varying strengths. Less Z rotation was observed for the left and right forearm, resulting in a negative relationship for both segments with the pelvis, and a positive relationship with the trunk (Appendix H), the opposite to all other participants. The putter segment, however, had a strong positive correlation with the pelvis and very strong negative correlation with the trunk for Z rotations.

Relationships between the degree of segment rotations and velocities at ball contact (X, Y and Z) and performance measures (kinematic ball roll variables) are presented in Tables 7.20 – 7.23. No discernible trends between the forearm of upper arm segments (left and right) were identified with any of the performance measures. Additionally, no putter Z rotations were significantly correlated with any ball roll variable, previously highlighted as an important factor of the putting stroke (Hurrion & Mackay, 2012; Karlsen et al., 2008; Pelz, 2000). This may be due to how the putter face angle was calculated however.

To date no literature has considered movement variability in regards to the golf putt, studies have only considered the full golf swing (Bradshaw et al., 2009; Langdown et al., 2012; Horan et al., 2011; Tucker et al., 2013). Despite this, the desired outcome for the putt is very similar to that of the full swing shot, being an accurate shot with the correct power. Therefore to obtain this sought after outcome, a movement system must be a balance of stable (persistent) and flexible motor outputs (Davids et al., 2003), allowing the golfer to adapt to the requirements of each shot (Langdown et al., 2012). Tucker et al., (2013) reported performance variability (mm^3/mm) for the full golf swing for individual body landmarks, a wider range of variability was observed across the markers analysed in comparison to the current study. There are a number of reasons this may be the case. Firstly, the full golf swing has increased amounts of movement involved in terms of displacement and rotations of the body and club (Zheng et al., 2008); with these rotations occurring at faster velocities (Karlsen et al., 2008; Zheng et al., 2008) which may cause increased variability. Secondly, Tucker et al., (2013) analysed individual body landmarks separately, which may inflate the variability. It may be more suitable to analyse body segments as in the current study, since this would be easier for coaches to interpret. This is due to the fact when coaching, individual landmarks would rarely be mentioned, whereas, body segments would be referred to.

It has been reported that a reduction in the variability of the hand trajectory from mid-downswing to impact improved performance for the full golf swing (Horan et al., 2011; Tucker et al., 2013). This may also be applicable to the putting stroke, where increased variability of forearm rotations increased the variability of the putter face angle at impact. Previously, the putter face angle has been deemed to be essential regarding the initial direction of the golf putt (Karlsen et al., 2008; Pelz, 2000; Hurrion and Mackay, 2012). Hurrion and Hurrion (2012) accounted 92-95% of the starting direction (horizontal launch angle) of a putt to putter face angle, Karlsen et al. (2008) accounted 80% of direction variability to putter face angle and Pelz (2000) accounted 83% to putter face angle. In the current study very strong significant correlations were observed between the horizontal launch angle variability (putt direction) and right and left forearm rotation variability (r = .78 and .93) (Table 7.20). These very strong positive relationships were also apparent for the closely related variable whether the ball was pushed or pulled (left forearm, r = .98; right forearm r = .93).

This suggests that increased variability of forearm rotations is detrimental to the initial direction of the golf putt, increasing the variability will reduce the accuracy and therefore success rate of the golf putt. No significant correlation for the putter Z rotations was observed, which may be due to the normalisation process whereby Z rotations were normalised to the putter at set up being 0 degrees in accordance with Karlsen et al. (2008). When considered separately a weak correlation was identified between putter Z rotation variability and putting proficiency, in fact, the most proficient golfer (participant eight) with 83% success rate had one of the higher performance variability values for the putter of 0.28 degrees. Additionally, the worst performing participant (52% success rate) had a variability of 0.18 degrees (Table 7.17). The differences may be due to variation of putter face angle at set-up. This provides tentative support for Karlsen et al. (2008) that the putting stroke may only have a minor effect on performance outcome, with original green reading and lining up the putt more important. However, with the margin of error in golf putting very small, the putter face angle clearly being a key factor in the initial putt direction (Hurrion & Mackay, 2012; Karlsen et al., 2008; Pelz, 2000) and variability associated between rotations and the initial direction of the golf putt it would be unwise to disregard technique. Additionally, this study gives contrasting evidence to Karlsen et al. (2008) that the segment variability of the forearms did increase variability of the initial putt direction.

Along with the forearms, the left and right upper arm, pelvis and trunk variability all demonstrated strong to very strong relationships with the variability of the horizontal launch angle (Table 7.20). However, unlike the forearms, no significant relationships with the variance of whether the ball was pushed or pulled were observed, the strength of correlation was moderate to strong however (Table 7.20). Delphinus and Sayers (2012) observed greater movement variability of the pelvis and trunk in less proficient golfers (< 79% success rate) in comparison to more proficient golfers (> 79% success rate). The current study's results are in contrast to this, although not statistically analysed in a similar fashion (Delphinus and Sayers (2012) adopted the use of Cohen's effect sizes between two groups). Golfers in the current study had a consistent variability of the pelvis (0.01 – 0.19 degrees^3/degrees) and trunk (0.01 – 0.11 degrees^3/degrees), this however, excludes participant one where elevated levels of variation were observed (Figure 7.7). Additionally, no significant correlations were observed for performance variability of the pelvis (r = -.05) and trunk (r = -.37) with putting success rate. Differences between the current study and Delphinus and Sayers (2012) may be due to the analysis techniques, whereby individual putting events during the stroke were assessed whereas the current study totalled variation for all three planes and normalised the data by the rotational displacement of each segment. It also may be due to the large intra and inter-subject variability observed in both this study and Delphinus and Sayers (2012) that differences actually existed between each study, especially as low numbers of participants were used in both.

Despite Tucker et al. (2013) suggesting that highly skilled players use their own strategies to exploit their movement variability to minimise shot outcome variability, this is not valid when considering the putter as a segment. Due to the aforementioned role of the putter face angle has on the initial direction and therefore accuracy of the putt (Hurrion & Mackay, 2012; Karlsen et al., 2008; Pelz, 2000). It may however, apply to body segment rotations, whereby a different combination of rotations result in a square putter face at impact being equally as desirable as minimal variability. Therefore, it may be more suitable in future studies to measure the putter face angle (Z rotations) as an outcome variable along with the horizontal launch angle. Unrelated to golf, Bernstein (1967) reported a large inter-trial variability in hammer trajectory with no increase in end-point variability. Emphasising the fact it is possible to have varied patterns ending in a consistent outcome (Bernstein, 1967; Tucker et al., 2013). Results in this study seem to contradict this with significant positive correlations identified in segment rotations and horizontal launch angle, suggesting less variability is beneficial for the golf putt. This however may only be applicable to participants within the study, more participants would need to be analysed to confirm this. Bradshaw et al. (2009) also states less variability is important in the full golf swing; however a clear limitation of this study is that the 3D videography was only sampled at 50 Hz. In contrast no relationship was observed between performance (movement) variability and outcome (velocity) variability (Tucker et al., 2013). It may be the case that the less displacement the club or putter makes during a swing or stroke will increase the effect variability has on outcome variables such as putt direction. Tucker et al. (2013) concedes that accuracy of the full golf shot and movement variability need to be investigated further.

Figure 7.8 – 7.10 and Appendix H displays the time-normalised rotations and velocities for all body segments and putter (Z rotations only). Despite some similarities being observed between participants, inter-subject variability is evident for displacement of rotations and velocities associated with the rotation. These results echo the findings from the earlier discussed results (COM and CP excursion relationships), that it is beneficial to include individual based analysis along with group based analysis, similar to the methodology utilised in the full swing by Ball and Best (2012). In regards to grouping participants, cluster analysis may be suitable, however, more established relationships between body kinematics and performance measures would need to be established so groups could be clustered using the most important body kinematics. Therefore, practical implications are more likely to apply to all participants rather than a select few.

An example of individual based analysis being beneficial is participant six, who did not display the strong relationships identified in the other participants. The typical relationships identified in the other participants in the Z plane was for the forearms to rotate in the same direction, the pelvis rotates to the right along with the putter face opening, and the trunk rotated in the opposite direction (left) during phase one of the golf putt. The reverse movements were observed in phase two (downswing) and three (follow through) of the putt (Figures 7.8 – 7.10, Appendix H). This was not evident in participant six, where the trunk was identified to have a positive relationship with the forearms and the pelvis the negative, the reverse to all other participants. Delphinus and Sayers (2012) is the only other study to have examined the role of the pelvis and trunk during putting. Within Delphinus and Sayers' (2012) study it was not reported as to whether as much inter-subject variation of rotations was observed across participants like the current study, or if any participants showed entirely different patterns of Z rotations such as participant six. One conclusion of Delphinus and Sayers (2012) is that less proficient golfers exhibit more movement in the sagittal plane (Y), whereas more proficient golfers move towards the target in the frontal plane (X). This increased movement in the sagittal plane has potential to cause back extensor fatigue which could impair performance (Delphinus & Sayers, 2012; Evans, Refshauge, Adams & Barrett, 2008). Although direct comparisons cannot be made, no relationships were observed between performance measures and the trunk segment Y rotation at ball contact (Table 7.22). At ball contact the majority of participants had extended the trunk marginally (-0.13 to -0.72 degrees), the largest amount of flexion observed in the trunk at ball contact was 0.31 degrees in participant four. Generally less rotation was observed on the Y axis for the trunk in comparison to the other planes of motion (Figures 7.8 – 7.10, Appendix H). However, neither this current study or Delphinus and Sayers (2012) induced fatigue or used a protocol until fatigue was evident, so more research into this hypothesis is needed.

In the current study it was evident that a pattern of pelvic-torso separation (whereby the segments rotate in opposing directions) was evident (Figures 7.8 – 7.10, Appendix H). Previously this has been identified to occur in the full golf swing in an attempt to generate more power to maximise driving distance (Cheetham et al., 2000; Hume et al., 2005; McTeigue et al., 1994; Zheng et al., 2008). Pelvic-torso separation in the golf putt is not likely to be to be an attempt to maximise power, as less force is needed to impart the required amount of velocity to displace the ball to be successful at putting. The degree of the maximum separation is also very different in the putt in comparison to the full golf swing, values of 34 – 50 degrees pelvic-torso separation has been reported (McTeigue et al., 1994; Horan et al., 2010). In the current study a range of 5 – 12 degrees was observed and generally this occurred at approximately 50% of the golf putting stroke. A potential hypothesis for this separation is not to maximise power but an attempt to control it. As Pelz (2000) states, body rotation is used as power generation along with the muscles of the fingers, hands, wrists and forearms and upper arms and shoulders that can be used to impart impulse on the golf ball. Pelz (2000) outlines that body rotations are the least desirable as it is more difficult to control the power produced from larger muscle groups than say the muscles of the forearm. Rotating the trunk and the pelvis in opposite directions may be in attempt to minimise the power recruited from rotations of the torso and pelvis, allowing the ball to be displaced using the controlled contractions of the forearms and hands.

Another factor of what body segment the participant recruits to generate power; is that it may potentially influence the putter face rotations and velocities of the rotation during the putting stroke. At ball contact, a range of putter face angles were demonstrated (0.76 – 2.84 degrees (calculated from position at address)) and velocity of the rotation at impact (-2.34 to -29.52 degrees/s). A range of variation was also evident (putter face angle: 0.89 – 2.02 degrees; velocity of rotation: 6.13 – 20.82 degrees/s) (Figures 7.8 – 7.10, Appendix H). With rotations of the trunk and pelvis more difficult to control than the forearms (Pelz, 2000), this may lead to an increase in the variance of putter face angle and velocity of the rotation at impact. This is potentially important as contact time between the putter and the ball has been recorded at half a millisecond (Hurrion & Hurrion, 2008). An increase in the velocity of rotation of the putter during this period around ball contact will increase the difficultly of obtaining a consistent putter face angle at impact (Hurrion & Hurrion, 2008). For a putt of 12 feet Hurrion and Mackay (2012) state a putt with a horizontal launch angle of 0.75° will be successful, which would be produced with a putter face angle of 0.69°, therefore the margins between success and failure are very small. The results regarding the variance of body segments affecting the horizontal launch angle and therefore direction of the golf putt support this (Table 7.20).

Practical Implications

The practical implications of this study are that coaches should use a combination of kinematic analysis, preferably 3D analysis and CP excursions, as one may not necessarily match the pattern of the other. Additionally, coaches should focus on reducing variability of body segment rotations particularly on the Z plane in an attempt to minimise the variability of the horizontal launch angle of the golf putt, the most important performance measure. However, it should be appreciated that individual golfers need to be analysed and treated separately from one another. The segments recruited to generate power which the golfer is using to impart impulse on the ball (Pelz, 2000) may be a factor that increases this variation of putter face angle at impact and therefore technique of the stroke may need to be altered.

Limitations & Future Recommendations

A limitation of the current study was the calculation of the putter face angle, normalising to the angle at address, despite this being previously utilised within the literature (Karlsen et al., 2008). Due to the variation of the angle at address between participants and between the participants' trials, this made it difficult to correlate to the outcome variables and between participants. Two retro reflective markers were placed on the putting line and aligned using a laser line; however during analysis it was identified that this needed to be more accurate. Putter face angles were identified that did not match the outcome of the golf putt, suggesting that there was variability of the placement of the markers between participants, this therefore not accurate enough as aforementioned small differences of putter face angle dramatically influence the direction and therefore result of the putt (Hurrion & Mackay, 2012). Additionally, it would have been beneficial to include the putter within the centre of mass model; despite being lightweight in comparison to the body it may influence the displacement of the COM.

Future research should investigate a larger number of participants to reaffirm the different styles identified in the current study, or as to whether more exist. Additionally it would be beneficial to look at segment rotation variability in larger number of participants; this would increase the power of the statistical analysis undertaken in the current study. It may also clarify some of the anomalies observed in the current study, where, putter face angle could be calculated from the putting line. The variation calculated could also be segmented into the different phases of the golf putt, like it has previously been observed for CP excursions (Hurrion & Hurrion, 2008; McLaughlin & Best, 2008).

7.3.6 Conclusion

The relationship between COM displacement and CP excursions is not as simple as originally hypothesised. Centre of pressure excursions when plotted as a scatter graph appeared to be smaller than that of COM displacement, which may be due to the larger variation observed in the CP oscillations being negated when time-normalised and averaged. The total CP excursions and COM displacement were very similar (32.67 and 32.91 mm respectively) and therefore supports this suggestion. Centre of pressure excursions should exceed that of the COM displacement; however, that was not observed in the current study. It is hypothesised that golfers employ strategies to minimise CP excursions whilst executing the putting stroke in an attempt to optimise stability to varying levels of success. These results raise doubts with previous literature that has interpreted body kinematics from CP excursion parameters. A large inter-subject variation was observed suggesting that putting studies should consider adopting individual based analysis as conclusions gained from group analysis may not have practical implications for even all of the participants who undertook the study.

This is the first study to have considered movement variability effect on performance measure in the golf putt. A very strong significant positive relationship was identified between performance variability of segment rotations (left and right forearm, left and right upper arm, pelvis and trunk) and the variability of performance measure horizontal launch angle. Only the forearms were significantly correlated with whether the ball was pushed or pulled; moderate to strong relationships for the other segments were not significant. This suggests that the lower variability of segment rotations in a golfers technique the more successful putts that will be executed. Similarities between time-normalised segment rotations and velocities were evident between participants excluding participant six. This suggests that individual based analysis should be adopted along with group-based analysis, similar to that being utilised in the full golf swing. One similarity demonstrated between participants was pelvic-torso separation. Unlike the full golf swing this is not likely to be to produce increased power, but may be an attempt to control power generated by body rotations allowing for the finer muscles of the hand, wrist and forearm produce the power needed to impart the correct amount of impulse to the golf ball. Additionally this may allow for more consistency in putter face angle at impact, which is essential for the initial direction of the golf putt.

7.4 Development of Research

The work in this chapter completed two studies that fulfilled the original aims of the thesis and the aims developed throughout the thesis. Study Six contributes to the literature by identifying that the impact point on the golf ball does not affect the horizontal launch angle and whether the ball was pushed or pulled when a human subject completes the golf putt. This is in contrast to Study Five, which identified significant associations between horizontal launch angle and whether the ball was pushed or pulled and the impact point on the golf ball. Study Seven identified that variability of segment rotations cause increased variability in the horizontal launch angle, which is a detriment to performance. Additionally, that COM displacement patterns and CP excursions do not always reflect one another and therefore any interpretations of body movement from only analysing CP excursions need to be considered with caution. The practical implications of both studies, is that less proficient golfers should aim to develop movement patterns that reduce variability from putt to putt, allowing for a more consistent putter face angle at impact resulting in more successful putts.

Chapter Eight

Discussion

8.1 Introduction to Discussion

The original aims of this thesis were to examine CP excursion during the full golf swing and golf putting stroke. Throughout the thesis and observing results from earlier studies, the following aims were formulated:

- To assess the reliability and validity of a novel new piece of software, Quintic Ball Roll v2.4.
- To assess the effect of golf ball dimples on the ball roll kinematics with a mechanical putting robot (whereby putter path and putter face angle will remain constant) and human participants.
- To assess the relationship between COM displacement and CP excursions during the putting stroke.
- To examine the effect of segment rotation variability on golf putting performance outcomes (ball roll kinematic variables).

The following aims are addressed over seven studies, initially identifying trends between different proficiencies of golfers, moving on to theories as to why or what is causing these significant differences. The studies that used a mechanical putting robot assessed reliability of methods and software and raise complex theories concerning ball roll kinematics. This discussion will review the aims of this thesis, gauge practical implications, identify contributions to the literature, consider limitations of the research undertaken and make recommendations for future research.

8.2 Aim: To examine CP excursion and it's relationship with CHV during the full golf swing

The aim to examine the CP excursion during the full golf swing was addressed in Study One. Following an extensive literature review, it was identified that to a degree there was limited published work regarding the CP excursions with the majority of work being conducted by the same authors (Ball & Best, 2007a; Ball & Best, 2007b; Ball & Best, 2011; Ball & Best, 2012). Comparisons between three different golf clubs (4-iron, 8-iron and pitching wedge) were presented.

Before Study One commenced a thorough pilot study was completed analysing the relative and absolute reliability of the AMTI force platforms performance with the extension board fitted. Strong reliability was observed for both vertical (Fz) forces and CP coordinates. ICC scores observed suggested reduced day-to-day reliability of the AMTI force platform with the extension board fitted in comparison to the change in mean and the SEM scores. However, this was accounted to the fact data was collected without human participants, and therefore as the ICC ranks the data in combination with measuring the similarity between scores (McDowell, 2006) the ICC can be held in less regard to the SEM and change in mean. It was concluded that strong to very strong reliability was observed for Fz force and X and Y coordinates for the CP data, and the extension board has minimal influence on the AMTI force platform.

Study One was consequently completed using the AMTI force platform with the extension board fitted. The main finding from the results of Study One was significant differences in CP excursions along the ML axis during phase three of the golf swing, between the 8-iron and 4-iron, and the 8-iron and pitching wedge. Ball and Best (2011) identified no significant differences between a driver, 3-iron and 7-iron, so the results in Study One are of a contrast to this. The differences between the results of Study One and Ball and Best (2011) may be due to that stance width may influence the amount of CP excursions observed between the golf clubs. However, it would be expected that the club in the middle of the three tested (8-iron within this thesis) would not be the club that the others would be significantly different to. As the smallest stance width would generally be adopted with the pitching wedge (shortest club used) and the widest stance adopted with the 4-iron, and a stance width between the two other clubs adopted with the 8-iron, as stated by Leadbetter (1995). An additional possible rationale for the observed finding may be stance width influences which phase of the swing the majority of CP excursions occurs, with total CP excursions for the 4-iron being 101.54 mm in comparison to the 8-iron being 73.31 mm and pitching wedge (66.70 mm). For the 4-iron 59.2% of CP excursions along the ML axis occurred in the follow through phase of the golf swing, this was 30.8% for the 8-iron and 31.7% for the pitching wedge. Therefore, more research would be needed to clarify these results. Ball and Best (2011) identified that 96% of golfers used the same style of golf swing (front foot or reverse) for all of the three clubs tested. Within this study all subjects used the same swing style with the 4-iron, 8-iron and pitching wedge, which therefore supports the results previously published.

Although found to be non-significant (likely because of low subject numbers and moderate inter-subject variation) another potentially important finding relates to the 95% elliptical scores. The 4-iron demonstrated a larger score (451.1 cm^2) than the 8-iron (334.01 cm^2) and pitching wedge (335.02 cm^2). Generally within golf the longer irons such as the 4-iron golfers of all levels will display less accuracy; this is supported by PGA Tour statistics gathered in 2011. Larger CP excursions and greater intra-subject variability with those excursions may be correlated with accuracy of golf shots. This leads to a practical recommendation that golfers of all abilities should attempt to reduce the intra-subject variability of golf shots that may lead to increased accuracy. Future research should also analyse intra-subject variability of the CP excursion parameters between golfers of different proficiencies and identify whether there is a correlation between CP excursion and long game performance.

8.3 Aim: To examine CP excursion and weight distribution during the golf putting stroke

Study Two originally assessed CP excursion and weight distribution comparing three different abilities of golfers (LH, MH and HH). This was preceded by Pilot Study Two, which examined the reliability of the RS FootScan, and found the RS FootScan to be reliable when compared to an AMTI force platform. This Pilot Study was based on the ease it could be conducted, and that hard based force platforms are considered more accurate than PMDs within the literature (Giacomozzi, 2010a).

Study Two was conducted, as during the literature review it was apparent that putting performance is a very important contributor to the overall golf score. A number of studies identified a correlation between putting and overall performance (Dorsel & Rotunda, 2001; Quinn, 2006; Wiseman & Chatterjee, 2006). It was also identified during the literature review that the area of golf with the least amount of research available was the golf putting stroke. This provided strong rationale to complete the study and have putting as the major theme of the thesis. Two papers had been published prior to when Study Two was conducted that analysed the putting stroke. Firstly, by Hurrion and Hurrion (2008) where CP excursions along the ML and AP axis were totaled and analysed together, and secondly, McLaughlin et al. (2008) where only CP excursions along the ML axis were discussed. Therefore, providing data for the CP excursions observed along the AP axis would be a positive contribution towards the literature.

The main finding of Study Two was that LH golfers demonstrated significantly smaller CP excursions in comparison to the HH group along the AP axis for all three phases of the golf putt (Start to top of backswing, Top of backswing to impact, Impact to follow through). No significant differences were observed along the AP axis between the LH and MH groups, or between any groups along the ML axis. This is potentially important as significantly higher putting success rates were found for the LH group in comparison to the MH and HH group. The MH group were also identified to be significantly more proficient than the HH group, despite no significant differences observed between the two groups CP excursion parameters. In addition to this no significant differences were observed between the groups for weight distribution at any of the swing events. This suggests that CP excursions may influence putting performance but are unlikely to be the most important factor contributing to putting success rate.

The results of Study Two are in contrast to McLaughlin et al. (2008), where significant differences were identified along the ML axis. The differences between the results may be because of the differences in putt length used; Study Two used a putt length of 2.5 m, whereas McLaughlin et al. (2008) used a putt length of 4 m. This suggests that the focus of reduced CP excursions may differ for different lengths of putt. Hurrion and Hurrion (2008) also observed more proficient golfers to produce significantly less total (ML and AP) CP excursions in comparison to a less proficient group. Hurrion and Hurrion (2008) suggest that the smaller the CP excursions the greater the balance the golfer has during the putting stroke. Less total CP excursions were observed in Study Two in comparison to Hurrion and Hurrion (2008), again this is likely to longer putt being analysed in the prior study (7.6 m). Despite, some small differences, the results from Study Two support both Hurrion and Hurrion (2008) and McLaughlin et al. (2008) that smaller CP excursion are associated with more proficient golfers.

Larger CP excursions may have been observed in HH golfers due to differences in technique and how the player generates power to project the golf ball as originally discussed by Pelz (2000). It was suggested in Study Two that HH golfers may predominantly generate power due to body rotation, whereas, LH golfers would predominantly use their fingers, hands and wrists to generate power. As the increased body rotation would increase CP excursion more so than movement of the hands and wrists. Findings by Delphinus and Sayers (2012) also provide a suggestion as to why increased CP excursions along the AP axis were observed for HH golfers in Study Two. Using 3D video analysis, it was identified that less proficient golfers COM moved more within the sagittal plane in comparison to more proficient golfers. More recently, McLaughlin and Best (2013) identified two types of putting stroke putters (arm and body) and found no significant differences between the two styles in terms of putting success rate. No analysis of the CP excursion along the AP axis was presented as none of the AP parameters were influential during cluster analysis, and therefore the results in Study Two seem to be irrelevant to types of putting style. In addition to this, McLaughlin and Best (2013) did not measure any body movement and therefore more data is needed regarding the different putting techniques.

8.4 Aim: To assess the reliability of the Quintic Ball Roll software with a mechanical putting robot

The aim to assess the reliability and validity of the Quintic Ball Roll v2.4 software was addressed in Study Three, where the day-to-day reliability was assessed using a mechanical putting robot. This extensive reliability testing needed to be completed before future research could be conducted as to whether CP excursions have a relationship with ball roll kinematics, and whether more proficient golfers display preferable ball roll kinematics in comparison to less proficient golfers. Two types of putters were used, one a traditional faced putter and the other a grooved faced putter, which is designed to hold the ball to the putter face longer improving the initial ball roll and reduce skid during the initial phase of the putt. Within the literature there is disagreement as to whether grooves do improve ball roll kinematics or not (Hurrion & Hurrion, 2002; Brouillette, 2010). The Quintic Ball Roll software was found to be reliable and the variables of velocity and horizontal launch angle were identified to be valid. The data provided additional information on whether grooves do improve ball roll kinematics. The GEL® putter (grooved faced) produced preferable ball roll kinematics for the initial ball roll and forward roll variables in comparison to an Odyssey putter (traditional faced). This supports Hurrion and Hurrion (2002) despite a small reduction in velocity as observed by Brouillette (2010).

All variables demonstrated strong day-to-day reliability. However, with significant differences being observed between different ball conditions it was regarded that when using the Quintic Ball Roll software, to minimise software error it is imperative that the ball is aligned correctly with regards to the target line the software was originally calibrated to. Importantly, no significant differences were observed between test – retest values for the horizontal launch angle and whether the ball was pushed or pulled for four putter-ball combinations as significance for these two kinematic variables were identified in later studies within the thesis.

The conclusion of Study Three was that all measurement variables did show strong day-to-day reliability, however, this was not solely accountable to measurement error. There was large output variability in comparison to input variability (stroke kinematics), which was controlled for. This prompted further analysis of the images created by the Quintic Ball Roll software. Along with the large output variance in comparison to input variance visual analysis of the three marks on the golf ball (used to calculate the ball roll variables) were in different positions at the end of recording, which suggested that some of the variability being observed may have been actual variability and not software error. The hypothesis formulated as to the reason why this actual variability was being observed, was the influence of the impact point between the putter and ball striking different points of the dimple. This topic had extremely limited published literature on, with only Pelz (2000) and Cross (2006) acknowledging that dimples causes some variability in the horizontal launch angle of the golf ball. This led to the completion of Studies Four, Five and Six which assessed the variability of the impact point on the golf ball and its effect of ball roll variables.

8.5 Aim: To assess the effect of golf ball dimples on the ball roll kinematics during a golf putt, with a mechanical putting robot and human participants

Due to the variability of the ball roll variables observed in Study Three; the potential effects of impact point on the golf ball formulated three studies within this thesis. Study Four presents the second analysis method used and reliability statistics of this method. Study Five assessed the effect of golf ball dimples on the ball roll kinematics during the initial stages of the golf putt with a mechanical putting robot, and Study Six assessed this with human participants.

Pilot Study Three assessed whether visually determining the impact point was a suitable method to assess the effect of the impact point on ball roll kinematics. During the protocol however, it was apparent that the method was not suitable due to the difficulty of undertaking statistical analysis on the data sets therefore Study Four was then designed using a more appropriate statistical method. This allowed for a far more objective and accurate method of identification of impact point to be completed. The method involved the identification of a centroid location of a dimple pattern; from this the distance and angle (or distance of the X and Y coordinates) of the centre of the impact zone (area of the ball that came into contact with the putter during impact) could be measured. As well as the surface area of the impact zone itself. Study Four analysed the day-to-day reliability of this method.

It was identified that both methods used (distance and angle from the centroid location) or (distance of the X and Y coordinates from the centroid location) demonstrated very strong relative and absolute reliability. Therefore the method can be considered reliable in the assessment of the impact point on the golf ball. It was suggested that if other authors undertook the data processing and analysis a period of reliability testing should be taken to ensure that no subjective variability is observed during the main analysis.

Study Five assessed the effect of the impact point on the ball roll kinematics using a mechanical putting robot. The rationale for this study was previously it has been only been identified that putter face angle, putter path and horizontal impact point on the putter affect the initial direction of the golf ball (Karlsen et al., 2008; Pelz, 2000). Therefore, to isolate the effect caused by the impact point on the golf ball, these variables needed to remain constant which could be achieved by using a mechanical putting robot. The two kinematic variables to show significant associations with the impact variables (distance, angle and surface area from the centroid location) were the horizontal launch angle and whether the ball was pushed or pulled. This was observed for three of four putter ball combinations tested. This could have been important as variance in the horizontal launch angle will directly affect whether a putt is successful since whether the ball was pushed or pulled resembles the final position of the ball at 10 feet in relation to the centre of the hole. Weak associations were observed between the impact variables and the following kinematic ball roll variables; velocity, side spin, initial ball roll, forward roll, true roll and vertical launch angle.

Despite significant associations being observed for three of the four putter-ball combinations, dimple error solely is unlikely to affect the putting success rate of a golfer. As Karlsen et al. (2008) stated, a putting stroke with a horizontal launch angle variability of 0.39° will miss 5% of putts from 13 feet. The variability of the horizontal launch angle accountable to the impact point on the golf ball for the three of the four putter-ball combinations fell well within this range (0.04° - 0.15°). Results from Hurrion and MacKay (2012) additionally support this, stating from 15 feet the largest horizontal launch angle that will still result in a successful putt is 0.60°. It was suggested that this variance observed was due to the placement of the golf ball during the protocol. The increased variability observed in the X and Y coordinates of the impact point on the golf ball in comparison to the putter face demonstrates this. This was the only human component during the protocol and therefore was subject to error causing dissimilarities. The external validity of the findings is however increased, as golfers would not be able to control for ball placement during putting during a golf round.

Study Six analysed the effect of the impact point on the golf ball roll kinematics using human subjects. It was identified that the only significant associations with both putters (GEL® and Odyssey) were found to exist between the impact variables and the kinematic ball roll variable velocity. This was in contrast to Study Five whereby significant associations were identified between the impact variables and horizontal launch angle and whether the ball was pushed or pulled. A reason for no significant associations being identified for the horizontal launch angle and whether the ball was pushed or pulled may be due to the fact that the variance in the putter face angle and putter path may negate the effects of dimple error when a putt is performed by a human cohort. As Karlsen et al. (2008), Pelz (2000) and Hurrion and MacKay (2012) have all identified that putter face angle has the largest effect on the horizontal launch angle of the ball (80 - 92%). A second hypothesis was also formulated to explain the differences in findings between Study Five and Study Seven regarding the horizontal launch angle of the golf ball. This is where a small amount of rotation occurs during impact when a human performs the putt. This relates to the impulse imparted on the golf ball, whereby, the human participant applies the same amount of force over a longer period of time than the mechanical putting robot. It is hypothesised that this has the potential to occur due to the human being able to manipulate grip pressure. Pelz (2000) states it is often taught that a light grip is more beneficial that a tight one, which allows the golfer to ‘stroke’ the putt rather than ‘hit’ the putt. These rotations of the putter face at impact may explain the large amount of variation observed in the side spin of the human participants. The practical implications of Study Five and Study Six are that golfers should not be concerned with the effects of dimple error. This is because when putts are completed by a human participant the variability of the putter face angle and putter path negate the effects of dimple error or human participants have the ability to control the impact between the putter and golf ball causing mini rotations at impact negating the effect of dimple error on horizontal launch angle. Therefore, golfers should focus on areas of the putting stroke previously identified to significantly contribute to putting success rate, such as the intra-subject variability of the putter face angle.

8.6 Aim: To assess the relationship between the centre of mass and centre of pressure excursions during the putter stroke

Study Seven examined the relationship between CP excursions and COM displacement, this was to identify whether it is appropriate to make assumptions on body kinematics from CP parameters like previously utilised (McLaughlin & Best, 2013). It was identified that that the relationship between CP excursions and COM displacement is a complicated one, with a large degree of inter-subject variability evident, meaning assumptions of body kinematics from CP excursions should be interpreted with caution. This raises doubts into previous literature including Study Two, particularly those of McLaughlin and Best (2013). Where assumptions were made about body kinematics, despite only CP parameters being analysed. It may not be suitable to group golfers to different movement patterns, when no kinematic body variables were analysed.

It was hypothesised that the reason for this inter-subject variability occurring is the golfer attempts to minimise CP excursions during the trial to optimise stability to varying levels of success. This may explain why the CP excursions were not larger than the COM displacement during the putting trial. The mechanism of why this is occurring may be the following; whilst the upper body is rotating, the lower limb is predominantly static (Delphinus & Sayers, 2012). It may be the case that there is contractions of the lower limb that 'control' the CP excursions during the trial (Palmieri et al., 2002), with a portion of the CP excursion then occurring after the trial (Gatev et al., 1999; Winter et al., 1998). Trying to consciously control CP excursions may in fact be a detriment to performance, previously Toner & Moran (2011) identified conscious monitoring of the golf putt had a negative effect on performance. Additionally, this hypothesis of the golfers attempting to control the CP excursions may have contributed to the varied results observed between Study Two, Seven and the previous literature (Hurrion & Hurrion, 2008; McLaughlin et al., 2008; McLaughlin & Best, 2013).

The second main implication of Study Seven is that it will be beneficial for future research to include individual based analysis along with group based analysis as previously adopted within the full golf swing literature (Ball & Best, 2012). This is due to the different CP excursion and COM displacement patterns being demonstrated across the participants. With no clear optimal technique being identified within the literature, practical implications from studies may not be applicable to all participants even within the study if they displayed different patterns of movement. The inclusion of individual based analysis will help resolve this. Practical implications of this study are that coaches should not necessarily employ the same strategies of technique to all golfers. Additionally, if technology is being used a combination of 3D analysis and force platforms should be utilised.

8.7 Aim: To assess to what degree putter face and body segment variability affects putting performance

Study Seven utilised 3D motion analysis was used to examine the variability of body segment rotations and whether these influence the variance of putting performance measures (ball roll kinematics). An additional aim of whether different patterns of segment rotations between participants existed were assessed. To date no literature has examined the effect of movement variability on putting performance. A method to calculate variability expressed as one number was used developed by Tucker et al. (2013). This allowed for an easy comparison between participants and has the added benefit of being easy to interpret in a practical sense. In comparison to the full golf swing (Langdown et al., 2012; Tucker et al., 2013), less variability was observed in Study Seven. This is likely due to the reduced displacement and velocities associated with the golf putt.

Previously it has been proposed that a reduction in movement variability from mid-downswing to impact improves performance for the full golf swing (Horan et al., 2011; Tucker et al., 2013). This may also be relevant for the golf putt, due to aforementioned importance of the putter face angle on the initial direction of travel for the golf ball (Karlsen et al., 2008; Pelz, 2000; Hurrion and Mackay, 2012). It was identified in Study Seven that increased variability of segment rotations increased the variability of the horizontal launch angle, which reduces the putting proficiency of the participant. However, no significant relationship was identified for variability between the horizontal launch angle and putter head rotations. This is likely due to putter head rotations being normalised to the angle at address, which variation would be evident from trial to trial. Tucker et al. (2013) outlined that within the full golf swing, highly skilled players exploit movement variability to minimise outcome variability. This may apply for the golf putt also, whereby a combination of different segment rotations resulting in a square putter face is as desirable as no variation of segment rotations at all.

This section of Study Seven also supports the use of individual based analysis accompanying group-based analysis, like the CP excursion and COM section. Pelvic-torso separation were evident in all participants but it was evident for one participant that opposite directions of pelvic-torso separation were occurring during all phases of the putting stroke compared to the other participants, meaning practical applications of the results may not be suitable for all participants to adopt. Within the full golf swing this pelvis-torso separation is used to generate more power maximising driving distance (Cheetham et al., 2000; Hume et al., 2005; McTeigue et al., 1994; Zheng et al., 2008). It is hypothesised within the golf putt that pelvic-torso separation is utilised by the golfer to do the opposite and to control power. The opposite rotations allow power to predominantly be generated by the smaller muscles of the hands and forearms, rather than the larger muscles of the torso and pelvis. The practical implications of this study are that, golfers should aim to reduce movement variability of segment rotations to reduce the variability associated with the horizontal launch angle and direction of the golf ball. This is due to the very small variation needed to result in a successful putt; previously it has been identified differences of less than 1 degree can result in a missed putt (Hurrion & Mackay, 2012). Additionally, generating power from the torso and pelvis may increase the variability putter face angle at impact, with the contractions more difficult to control.

8.8 Limitations

The main limitation in this work is subject numbers. A range of 8 - 19 subjects was used in each study that included human participants. Although this is in line with a lot of similar published research, the large inter-subject variability being observed may have affected the statistical output, which provides support for the use of individual based analysis accompanying group-based analysis. With an increased sample size, there is greater statistical power and other significances may have been identified. It is important however, that if larger cohorts are used they are matched based on similar techniques. An increase in subject numbers would have also strengthened the overall findings of this thesis, providing additional support for hypotheses raised within the work. In addition to this, another limitation of the research is the restrictions of available equipment and software for the thesis. Using a lot of novel software it was difficult to compare some of these measures to criterion measures, so whilst all methods were identified to be reliable, not all measures could be determined to be valid.

8.9 Recommendations for Future Research

Further research is needed into movement variability within the putting stroke. Hypotheses generated from this thesis could then be tested amongst a larger number of participants. Additionally, the putting stroke could be broken into phases, to identify whether variability is less desirable at certain points of the golf putting stroke. Rationale for this is the large inter-subject variability observed in this thesis along with the low number of participants. This would additionally provide more information to combinations of segment rotations, with different strategies identified in Study Seven. More research is needed into whether more biomechanical investigations need to adopt individual based analysis as well as group based analysis due to the large inter-subject variability observed in this thesis and within the literature also.

A number of interesting hypotheses were formulated during this thesis, due to a lack of previously published work, such as the rotations that may be occurring during impact of the putter and golf ball during the putting stroke. Research using high-speed recordings could be used to prove or disprove this theory. In addition to this, some research undertaken within this thesis could be undertaken on outdoor putting greens to increase the ecological validity of the findings.

8.10 Conclusion

This thesis has provided an insight into performance measures during the golf swing and golf putt. Initially the work was split into investigating the full golf swing and golf putting stroke. However, more conclusive findings concerning the golf putting stroke drove the focus of the thesis to concentrate on the golf putting stroke along with the limited amount of previous literature in this area. For the full golf swing, it was hypothesised that increased variability of CP excursions may decrease accuracy. Whereas in Study Three it was concluded that LH golfers demonstrate smaller CP excursions along the AP axis in comparison to a HH group, therefore coaches should aim to eliminate unnecessary movement during the putting stroke. This lead to investigations into kinematic ball roll variables and what factors influence them, this was following finding the software used to be reliable and valid. The impact point on the golf ball was assessed as a potential influencing variable on ball roll kinematics; a significant association was identified with the horizontal launch angle and whether the ball was pushed or pulled, but only with the putting robot and not human participants. This provides support to previous research that the putter face angle is the most important stroke characteristic to determine the horizontal launch angle of the golf ball. Therefore, golfers should not focus on the potential influence of the impact point on the golf ball. Within Study Seven it was identified that CP excursion and COM displacement patterns have a complicated relationship and that increased segment rotation variation increased the variability of the horizontal launch angle. Golfers and coaches should therefore aim to reduce variability associated with segment rotations, which will increase accuracy across a number of golf putts and subsequently increase performance.

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Appendices

Appendix A – Pilot Study One

Pilot Study One: Test Retest Reliability of the for Force Platform

Abstract

Background: The force platform available at the University of Hertfordshire has 0.4 x 0.4 metre dimensions. To allow a golfer to adopt a stance of the correct width an extension board was placed on the force platform. **Aim:** To assess the day to day reliability of the vertical force and centre of pressure coordinates with the extension board fitted to the force platform. **Method:** The protocol was completed over a two day period. To assess the vertical ground reaction force (Fz) a 20 kg weight was placed at fifty locations at 5 cm intervals on the extension board placed on the force platform. The centre of pressure coordinates were assessed by activating a 20 N trigger with a metal pointer at six locations on the extension board placed on the force platform. Day to day reliability was assessed using the ICC, SEM and change in mean statistics. **Results:** Strong to very strong day to day reliability was demonstrated for the vertical forces for all three sections of the force plate (ICC > 0.71, SEM < 1.02 N, change in mean < 0.44 N). Very strong day to day absolute reliability was observed for the centre of pressure coordinates (SEM 0.03 – 0.16 cm, change in mean 0.00 – 0.22 cm). Weak to very strong relative reliability was observed for the centre of pressure excursion coordinates (ICC 0.18 – 0.89). **Conclusion:** Very strong day to day reliability was observed for both the vertical forces and centre of pressure excursion coordinates. As the ICC is calculated by ranking the data, it may not be suitable for this pilot study as human measurements were not recorded.

Introduction

The AMTI force platform (AMTI, MA, USA) at the University of Hertfordshire has the dimensions of 0.4 x 0.4 metres. Typically for the large majority of golfers, their stance while addressing a driver, iron or wedge shot would be wider than 0.5 metres. Therefore an extension board was constructed out of high-density fibreboard with the dimension 0.60 x 0.65 metre and was securely bolted to the AMTI force platform to increase the surface area that could be analysed and allow the subject to adopt a natural stance while completing the trial. The aim of this pilot study was to test the day-to-day reliability of the extension board placed on the AMTI force platform effect on the centre of pressure measurements and vertical (Fz) forces.

Methods

Protocol

The protocol was completed twice over a two-day period. The AMTI force platform was sampling at 1000 Hz. To test the effect of the extension board had on the vertical Fz a 20kg weight placed on a bar with a circumference of 8cm was placed as accurately as possible at 5cm intervals (Figure 9.1) over the extension board. Measurements were taken in the following directions 90° (upwards in direction from the centre location), 0° (right in direction from the centre location), 180° (left in direction from the centre location), 270° (downwards in direction from the centre location) and each intersecting diagonal (45°, 135°, 225° and 315°). The testing protocol started with the weight being placed at the centre of the platform after a 20 second period had elapsed 1 second of data was recorded, from which a mean was formulated. For each location on the extension board this process was completed 16 times on each day.

To accurately assess the day-to-day reliability of the CP measurements a metal pointer was used. The origin of the coordinate system (X = 0, Y = 0) was the centre of the AMTI force platform and this location was termed centre. Measurements were then taken at the centre of AMTI force platform, and 20 cm diagonally, and 30 cm left and right (Figure 9.1) using the visual guide of the CP screen on the AMTI BioAnalysis software and a grid drawn on the extension board to limit the external inaccuracies to a minimum. A 20 N trigger was set, and once this figure was met 1 second of data was recorded. For each day 16 trials were completed for each of the five locations.

Data Analysis

For analysis of the Fz data, the force platform was split into three sections. The Fz Inner, which was comprised of the centre location and locations at 5 and 10 cm in each direction, the Fz Middle segment was comprised of the locations measured 15 and 20 cm away from the centre location and the Fz Outer segment combined the remaining locations at 25 and 30 cm away from the centre location.

Data were exported to statistical software package Microsoft Excel 2011. The reliability between day one and day two for CP measurements and Fz forces was assessed using the following reliability measures:

- The SEM calculated using the formula $SEM = SD\sqrt{1 - ICC}$.
- The change in mean between day one and day two.
- A two – way mixed ICC, calculated using the formula $\frac{1-SD^{\wedge}2}{SD^{\wedge}2}$.

The intraclass coefficient statistic boundaries were; *r* = 0.8 – 1.0, very strong, *r* = 0.6 – 0.8, strong, *r* = 0.4 – 0.6, moderate, *r* = 0.2 – 0.4, weak, *r* = 0.0 – 0.2, no relationship (Salkind, 2011).

Results

Vertical (Fz) forces

The test retest reliability for the vertical Fz forces is displayed in Table 9.1; additionally Fz percentages are presented in Figure 9.1. Strong to very strong day to day reliability was demonstrated for all Fz sections. The SEM and change in mean were very low for all Fz sections, however, both got progressively larger from the inner section to the outer section. There was a five-fold increase in the SEM between the inner section and outer section, however the SEM (1.02 N) remains very low in the outer section, reflecting in a 0.5% difference. The ICC also progressively reduced throughout the sections, with the lowest ICC being observed in the Fz outer section at 0.71. This still demonstrates strong relative reliability however.

Table 9.1 Test retest reliability of the effect of the extension board on vertical force values.

	Day One Mean ± SD (N)	Day Two Mean ± SD (N)	ICC	SEM (N)	Change in Mean (N)
Fz Inner	196.87 ± 0.23	197.07 ± 0.04	.97	0.19	0.20
Fz Middle	197.77 ± 0.13	197.52 ± 0.22	.81	0.25	-0.25
Fz Outer	198.81 ± 0.34	199.25 ± 1.10	.71	1.02	0.44

Centre of pressure coordinates

Test retest reliability scores for the X and Y coordinate CP data is presented in Tables 9.2 and 9.3. Very strong absolute day to day reliability was demonstrated for the X and Y coordinate CP data. Very low SEM and change in the mean was observed for each location. The SEM was slightly elevated for the X coordinate data in comparison to the other locations for the 30 cm left and right locations, at 0.16 cm and 0.14 cm respectively. This was not observed for the Y coordinate data, where an SEM and change of mean of 0.03 and 0.01 cm respectively was observed for the 30 cm left location. For the 30 cm right location and SEM of 0.05 cm and change in mean of -0.03 cm was observed. Despite very strong SEM and change in mean measurements, low to moderate ICCs were observed. The ICC measurements did not however get progressively lower at points further away from the centre location. The best ICC observed was for 30 cm left location at 0.89, interestingly this coupled with the largest SEM.

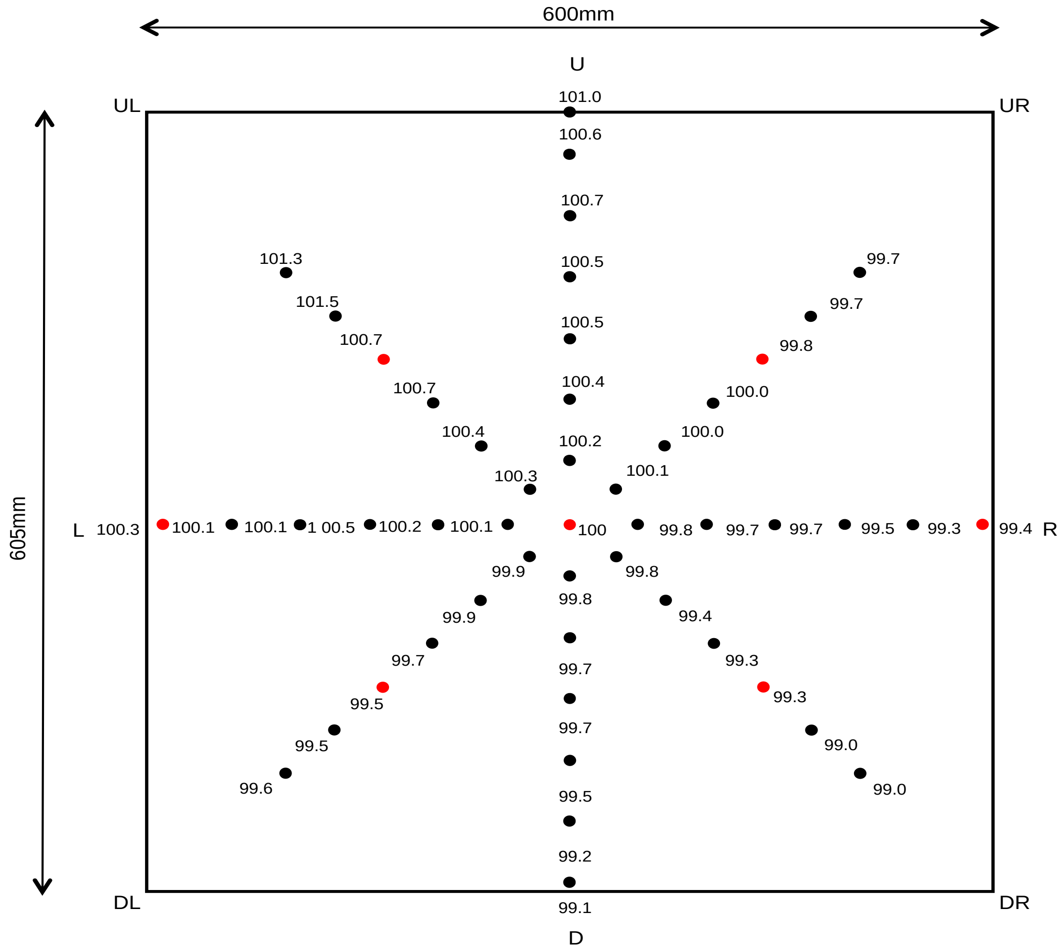


Figure 9.1 Fz Values for Day 1 and Day 2 expressed as a percentage of the centre. Red markers denote locations of measurements taken for CP accuracy. The letters on the border of the extension board represent the direction away from centre location; U = up (90°), D = down (270°), L = left (180°), R = right (0°), UR = upper right (45°), UL = upper left (135°), DR = down and right (315°) and DL = down and left (225°).

Table 9.2 Test retest reliability of the effect of the extension board on CP accuracy for the X-axis.

	Day One Mean ± SD (cm)	Day Two Mean ± SD (cm)	ICC	SEM (cm)	Change in Mean (cm)
Centre (0 cm)	0.69 ± 0.09	0.66 ± 0.07	.25	0.09	-0.03
Upper Right (45°, 20 cm)	20.78 ± 0.11	20.95 ± 0.07	.28	0.08	0.17
Upper Left (135°, 20 cm)	-19.25 ± 0.05	-19.32 ± 0.11	.40	0.07	-0.07
Down and Right (315°, 20 cm)	20.96 ± 0.09	20.99 ± 0.13	.31	0.11	0.04
Down and Left (225°, 20 cm)	-19.45 ± 0.15	-19.45 ± 0.08	.54	0.15	0.00
Left (180°, 30 cm)	-29.34 ± 0.11	-29.33 ± 0.12	.89	0.16	0.01
Right (0°, 30 cm)	31.01 ± 0.16	31.19 ± 0.08	.20	0.14	0.18

Table 9.3 Test retest reliability of the effect of the extension board on CP accuracy for the Y-axis.

	Day One Mean ± SD (cm)	Day Two Mean ± SD (cm)	ICC	SEM (cm)	Change in Mean (cm)
Centre (0 cm)	-0.22 ± 0.09	-0.24 ± 0.07	.33	0.09	-0.02
Upper Right (45°, 20 cm)	19.62 ± 0.08	19.78 ± 0.10	.42	0.07	0.16
Upper Left (135°, 20 cm)	19.51 ± 0.09	19.62 ± 0.08	.18	0.07	0.11
Down and Right (315°, 20 cm)	-20.09 ± 0.14	-20.14 ± 0.07	.37	0.09	-0.04
Down and Left (225°, 20 cm)	-19.72 ± 0.18	-19.94 ± 0.07	.38	0.16	-0.22
Left (180°, 30 cm)	-0.52 ± 0.04	-0.51 ± 0.04	.58	0.03	0.01
Right (0°, 30 cm)	0.06 ± 0.06	0.03 ± 0.03	.36	0.05	-0.03

Discussion

The results indicate that very strong absolute reliability was demonstrated for the vertical (Fz) forces and X and Y CP coordinates. Strong to very strong relative reliability was observed for the Fz forces with all three force plate sections having an ICC of > 0.70. Weak to very strong ICCs were demonstrated for the X and Y CP coordinates and therefore it is clearly apparent that the extension board affected the CP coordinates more than the vertical forces.

Figure 9.1 shows that the largest percentage difference of Fz in comparison to the centre was 1% observed at the upper 35 cm point. This is one of the points that sit outside the perimeter of the force platform. Originally it was a concern that Fz forces would in fact reduce, however this was not the case. The largest difference observed from day one to day two, when each point was analysed individually, occurred at the location 10 cm down (270°) with a change of 0.84%.

More variance was observed in the CP data in comparison to the Fz data, however this was only reflected in the reduced ICC scores. The reduction was not observed in the SEM or change in mean, which suggested very strong reliability. The reduction in the ICC may have been affected due to the nature of the reliability statistic. As McDowell (2006) states, the ICC ranks the data in combination with measuring the average similarity between scores, as this protocol purely assessed the reliability of a piece of equipment without the use of human movement the difference between scores was naturally very small. Therefore any day to day differences would likely affect the rank of the score within the data set and absolute differences exaggerated reducing the ICC. When it is considered how an ICC is interpreted (the value represents the percentage attenuable to true variance (Weir, 2005)), very small amounts of variance were observed between day one and day two, so the ICC is relatively insignificant in this case. This particularly comes to the forefront when the SEM is considered, the equation for the SEM takes the ICC and standard deviation into account and in this protocol remains very low for all locations CP data. The range of SEMs expresses this point (0.07 – 0.16 cm). In addition to this the ICC did not decrease at the data points located outside the perimeter of the force platform, which was an initial concern before undertaking the protocol.

Conclusion

Strong to very strong reliability was observed for the vertical (Fz) force and X and Y coordinates for the CP data when the method to calculate the ICC is considered. It can be concluded that the extension board has minimal influence on the reliability of Fz forces and CP measurement while using the force platform.

Appendix B – Dynamic warm up routine

Exercise 1 – Reverse Woodchop

Exercise used to warm up muscles used for rotation and large muscle groups of the shoulders and hips.

Start Phase: Feet positioned shoulder width apart, flex forward at the hips and flex knees to approximately 20°. Raise your hand and position over the right knee. Begin movement by tracing a diagonal line with the ball across your body simultaneously bracing your abdominals and rotating the hips and knees allowing the opposite knee to fall in. Perform 15 reps for each side.

Exercise 2 – One Arm Swing

Prepares the shoulder in the required ROM and velocity of the golf swing.

Start Phase: Position feet together, hold the golf club just below the grip. Start swinging the club in the pendulum motion in front of your body getting progressively higher once reached the highest point perform 12 reps, and then perform with the other arm.

Exercise 3 – Torso-Twist with shoulder stretch

Designed to warm up the back, shoulders and abdominal muscles in the ROM of the golf swing.

Start Phase: Stand with feet shoulder width apart, grasp the club with the arms crossing over (Refer to picture) twist your body around in an attempt to look behind you, do not bounce but hold at the end of stretch. Perform 15 reps.

Exercise 4 – Windmills

Used to stretch the trunk, shoulder, hamstrings and back.

Start Phase: Spread your feet wide apart; hold the club at either end. Keeping your arms straight bend at the waist aiming your left hand at your right foot, come back up to start position, then aim your right hand at your left foot. Perform for 20 reps.

Exercise 5 – Practice Swings with 2 clubs

Used to warm up the whole body, performing full swings with the overload of 2 clubs.

Start Phase: Take normal golf stance, swing clubs at a comfortable level (70-80%), perform 15 reps.

Appendix C - Summary tables of significant differences for the Quintic Ball Roll

Velocity p – values between the different ball conditions for the Odyssey putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.002*	0.001*	0.050
Aligned 10° left	0.002*	-	0.940	0.417
Aligned 10° right	0.001*	0.940	-	0.292
Random position	0.050	0.417	0.292	-

*Significant difference ($p < 0.05$)

Velocity p – values between the different ball conditions for the GEL® putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	<0.001*	<0.001*	<0.001*
Aligned 10° left	<0.001*	-	0.675	0.500
Aligned 10° right	<0.001*	0.675	-	0.271
Random position	<0.001*	0.500	0.271	-

*Significant difference ($p < 0.05$)

Spin p – values between the different ball conditions for the Odyssey putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.562	0.170	0.014*
Aligned 10° left	0.562	-	0.520	0.071
Aligned 10° right	0.170	0.520	-	0.186
Random position	0.014*	0.071	0.186	-

*Significant difference ($p < 0.05$)

Spin p – values between the different ball conditions for the GEL® putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.170	0.182	0.385
Aligned 10° left	0.170	-	0.013*	0.732
Aligned 10° right	0.182	0.013*	-	0.029*
Random position	0.385	0.732	0.029*	-

*Significant difference ($p < 0.05$)

Initial Ball Roll p – values between the different ball conditions for the Odyssey putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.064	0.822	0.135
Aligned 10° left	0.064	-	0.086	0.536
Aligned 10° right	0.822	0.086	-	0.164
Random position	0.135	0.536	0.164	-

Initial Ball Roll p – values between the different ball conditions for the GEL® putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.255	0.586	0.955
Aligned 10° left	0.255	-	0.397	0.187
Aligned 10° right	0.586	0.397	-	0.529
Random position	0.955	0.187	0.529	-

Forward Roll p – values between the different ball conditions for the Odyssey putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.609	0.488	0.286
Aligned 10° left	0.609	-	0.201	0.102
Aligned 10° right	0.488	0.201	-	0.565
Random position	0.286	0.102	0.565	-

Forward Roll p – values between the different ball conditions for the GEL® putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.766	0.453	0.167
Aligned 10° left	0.766	-	0.689	0.318
Aligned 10° right	0.453	0.689	-	0.403
Random position	0.167	0.318	0.403	-

True Roll p – values between the different ball conditions for the Odyssey putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.005*	0.735	0.124
Aligned 10° left	0.005*	-	0.038*	0.002*
Aligned 10° right	0.735	0.038*	-	0.090
Random position	0.124	0.002*	0.90	-

*Significant difference ($p < 0.05$)

True Roll p – values between the different ball conditions for the GEL® putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.028*	<0.001*	0.025*
Aligned 10° left	0.028*	-	<0.001*	0.906
Aligned 10° right	<0.001*	<0.001*	-	<0.001*
Random position	0.025*	0.906	<0.001*	-

*Significant difference ($p < 0.05$)

Launch Angle p – values between the different ball conditions for the Odyssey putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	0.855	0.015*	0.058
Aligned 10° left	0.855	-	0.008*	0.94
Aligned 10° right	0.015*	0.008*	-	0.001*
Random position	0.058	0.094	0.001*	-

*Significant difference ($p < 0.05$)

Launch Angle p – values between the different ball conditions for the GEL® putter.

	Correctly aligned	Aligned 10° left	Aligned 10° right	Random position
Correctly aligned	-	<0.001*	<0.001*	0.840
Aligned 10° left	<0.001*	-	0.292	<0.001*
Aligned 10° right	<0.001*	0.292	-	<0.001*
Random position	0.840	<0.001*	<0.001*	-

*Significant difference ($p < 0.05$)

Appendix D - Pilot Study Four

Analysis method one to analyse the impact point on a golf ball during putting

Abstract

Background: No published literature to date has analysed the impact point on a golf ball, this is a method that visually identified the type of impact and assigned a group for analysis. **Aim:** To determine whether visually identifying the impact point is a suitable method to analyse the effect of the impact point on ball roll kinematics. **Method:** A layer of pigmented emollient was applied to the golf putter face, which left an imprint of contact on the putter and the golf ball. A 3.2 metre golf putt was simulated using a mechanical putting robot. Each trial was then visually assigned to an impact group based on how much of a dimples surface came into contact with the putter based on the imprint of pigmented emollient (< 35%, 35-75%, >75%) and which dimples on the golf ball made contact with the golf putter. **Results:** No statistical analysis was undertaken on the different impact groups due to problems with the analysis technique. Visually assigning the trials to impact groups resulted in an uneven number of trials in each group affecting the original statistical analysis that was planned to take place. Additionally, the data analysis technique was subject to bias. **Conclusion:** Visually determining the impact groups was not a suitable method to analyse the effect of the impact point on ball roll kinematics. A new method using the statistical technique multiple regression analysis for statistical analysis needed to be developed.

Introduction

There is no published literature on the variability or effect of the impact point on the golf ball, therefore there was no established method how to analyse this contact mechanism. Before Study Four was undertaken the method to analyse the impact point was to visually determine the type of impact and assign a group, to which comparisons of the kinematic variables could be statistically compared.

Method

Protocol

Testing was completed in the Quintic Golf Laboratory on an artificial putting surface registering 12 on the stimpmeter. The Quintic mechanical putting arm mounted on an 360 kg bearing (Chapter 5.2a) was set up to simulate a level 3.2 metre putt. Forty trials were undertaken for the Odyssey-Titleist putter ball combination.

An Odyssey White Hot #3 putter and Titleist Pro V1 (Acushnet Europe Ltd., Cambridgeshire, UK) golf ball was used and analysed for the protocol. The golf ball was aligned for each trial using two Superline 2D line lasers. With one placed directly behind the golf ball and the other placed 90˚ to the path of the golf ball (Chapter Five, Figure 5.2b). This ensured the same positioning of the golf ball for each trial. A thin layer of pigmented emollient was applied to the putter face, leaving an imprint of contact made during impact with the golf ball. A Quintic high speed camera sampling at 220 fps was positioned perpendicular to the putting line. The Quintic Ball Roll v2.4 Launch monitor software was used to analyse the recorded videos. A Canon (Canon Europe Ltd, Uxbridge, UK) EOS 1000d camera was situated on a stationary Velbon CX-440 tripod 2.5 metres away from impact. An image was taken of the impact point on the golf ball after each trial. The ball was subsequently cleaned of all pigmented emollient and the process was repeated.

Data Processing

Since the golf ball was placed in the same position for all trials seven dimples were identified and numbered on the golf ball (Figure 9.2) to classify the location of impact on the golf ball. After visually analysing a number of trials it was clear that at least a partial section of three dimples generally came into contact with the putter during each trial. The following guidelines were used to identify the amount of contact made with each dimple; < 35% of the dimple made contact during impact, 36-75% of the dimple made contact during impact and > 75% of the dimple made contact during impact. These categories were visually determined by estimating the amount of contact made with each dimple, each trial was then assigned a group based on the amount of contact made with the three dimples. Different examples of group classifications are shown in Figure 9.3.

A total of six impact variations were observed and defined as follows:

- Impact group 1; dimple 1 < 35% contact, dimple 2 < 35% contact and dimple 3 < 35% contact
- Impact group 2; dimple 1 < 35% contact, dimple 2 > 75% contact and dimple 3 < 35% contact
- Impact group 3; dimple 1 < 35% contact, dimple 2 35-75% contact and dimple 3 < 35% contact
- Impact group 4; dimple 2 35-75% contact, dimple 3 < 35% contact and dimple 7 < 35% contact
- Impact group 5; dimple 2 < 35% contact, dimple 3 < 35% contact and dimple 7 < 35% contact
- Impact group 6; dimple 2 > 75% contact, dimple 3 < 35% contact and dimple 7 < 35% contact

Figure 9.2. The numerical representation for each dimple to identify the type of contact (the three primary dimples that made contact with the putter face by identifying the pigmented emollient mark), so the trial could be assigned to the appropriate impact group.

Figure 9.3. Three examples of the different impact point group classifications (dimple 1 is outlined in yellow, dimple 2 outlined in black, dimple 3 outlined in red and dimple 7 outlined in blue). Image A) shows an impact imprint that was classified as dimple 1 < 35% contact, dimple 2 < 35% contact and dimple 3 < 35% contact; Image B) shows an impact imprint that was classified as dimple 1 < 35% contact, dimple 2 36-75% contact and dimple 3 < 35% contact; Image C) shows an impact imprint that was classified as dimple 2 > 75% contact, dimple 3 < 35% contact and dimple 7 < 35% contact.

Results

Results are presented in Table 9.4. No statistical analysis was undertaken on the different impact groups for reasons explained in the discussion. Having observed the data it is apparent that differences may occur in the kinematic variables between all of the different impact groups for side spin and initial ball roll. Additionally, potential differences may occur in the kinematic variable start of forward rotation where impact group one and impact group two clearly differed from the collective mean of the whole data set. Impact groups two and four were noticeably different from the collective mean for the variable horizontal launch angle. For whether the ball was pushed or pulled impact group four was noticeably different from the collective mean. The kinematic variables velocity, true roll and vertical launch angle did not noticeably differ from the collective mean.

Table 9.4 Mean ± SD values of the kinematic variables for the different impact point groups.

Impact Group	Number of Trials	Velocity (ms^{-1})	Side spin (Cut (+), Hook (-), rpm)	Initial Ball Roll (rpm)	Start of Forward Rotation (cm)	True Roll (cm)	Vertical Launch Angle (°)	Horizontal Launch Angle (°)	Push or Pull (cm)
All	40	2.13 ± 0.04	-17.24 ± 12.55	-4.03 ± 13.18	1.73 ± 1.65	67.14 ± 5.95	1.46 ± 0.25	0.15 ± 0.45	0.17 ± 0.62
1	11	2.11 ± 0.05	-2.53 ± 10.39	0.38 ± 12.27	0.96 ± 1.05	64.42 ± 4.99	1.31 ± 0.31	0.04 ± 0.37	0.13 ± 0.48
2	3	2.12 ± 0.01	-17.33 ± 12.37	-5.63 ± 2.32	2.65 ± 2.44	67.73 ± 5.87	1.62 ± 0.28	0.28 ± 0.32	0.47 ± 0.54
3	8	2.13 ± 0.04	-24.54 ± 13.06	-11.32 ± 14.41	1.69 ± 2.38	67.31 ± 5.43	1.58 ± 0.12	0.17 ± 0.37	0.24 ± 0.55
4	3	2.13 ± 0.02	-11.46 ± 6.78	-6.17 ± 17.82	1.50 ± 1.39	67.73 ± 1.47	1.38 ± 0.12	-0.21 ± 0.63	-0.61 ± 0.28
5	5	2.16 ± 0.07	-11.60 ± 16.14	2.76 ± 15.92	1.64 ± 1.78	65.53 ± 5.79	1.14 ± 0.08	0.19 ± 0.44	0.16 ± 0.47
6	10	2.14 ± 0.03	-16.58 ± 11.54	0.46 ± 10.32	1.52 ± 0.91	66.55 ± 7.55	1.53 ± 0.25	0.18 ± 0.56	0.26 ± 0.74

Discussion

While analysing the data it became apparent that there was too much bias involved with the identification of which dimples on the golf ball came into contact with the putter to assign an appropriate impact group. Additionally, as the amount of contact (< 35%, 36-76% or > 75% contact) was visually determined, this was open to the authors' interpretation. As this problem was identified after analysing one putter-ball (Odyssey-Titleist) combination, analysis was not completed for the other putter ball combinations. During post analysis it was gauged that a number of trials could equally have been identified as a different amount of contact, which would have then changed the impact group the trial fell in. In addition to this it was arguable that some trials had more than three dimples that came into contact with the putter. At the start of analysis, however, three dimples were selected to identify the impact group, so that the data did not get too 'diluted' with an increased number of groups with very few trials in each impact group.

Another problem that was identified after processing the data was the statistical analysis methods that were originally planned to statistically analyse the data. Grouping the data by visually determining the impact type left the number of trials in each impact group uneven, which would have impacted on the subsequent ANOVA analysis. For example group one had eleven trials with the impact point; dimple 1 < 35% contact, dimple 2 < 35% contact and dimple 3 < 35% contact, whereas, group two had three trials with the impact point; dimple 1 < 35% contact, dimple 2 > 75% contact and dimple 3 < 35% contact. In addition, statistical comparisons to the whole data set would not have been statistically appropriate. It was initially thought that to determine whether the impact point on the golf ball influenced the roll of the golf ball, statistical differences between the defined impact groups and overall data set would allow for an insight into whether this affected the ball roll kinematics. The difference in the number of trials in each impact group was not considered a factor before the data was processed. However, the problem was identified before all putter ball combinations were processed and analysed.

To solve the problem of uneven data sets two main other areas of statistical analysis were considered; firstly, cluster analysis and secondly, multiple regression analysis. Essentially, cluster analysis would of allowed for the data to be analysed more objectively by grouping the data by their similarity (Everitt, Landau & Leese, 2001). The cluster analysis technique was however quickly eliminated from consideration as although the groups would have been determined more objectively from grouping the trials by their kinematic variables (velocity, side spine, initial ball roll, true roll, horizontal and vertical launch angle and whether the ball was pushed or pulled). The grouped data still could have resulted in uneven data sets for further analysis of statistical differences between impact groups. Additionally, linking the groups back to the type of contact still would have been visually determined and subject to error. Therefore, it was deemed more appropriate to use multiple regression analysis, as the statistical technique is simpler to interpret than cluster analysis and it removes the problem of uneven groups. This is because the data are not grouped and then analysed for statistical differences, but analysed as a whole data set in attempt to identify relationships between a number of independent variables to a dependent variable (Field, 2013; Vogt & Johnson, 2011).

For multiple regression to be completed the data needed to be reanalysed in a more objective manner eliminated bias and generating independent variables identifying the type of impact, which then could be compared to the kinematic (dependent) variables. The reliability of the method developed is discussed in Study Four and the results of the analysis of whether the impact point on a golf ball affects the ball roll kinematics is presented in Study Five.

Conclusion

Visually determining the impact groups by which dimple and what amount of area of that dimple came into contact with the golf putter was not a suitable method to analyse the effect of the impact point on ball roll kinematics. This was because of the bias involved with the identification process and the resultant uneven number of trials in each data set, which made statistical analysis very difficult.

Appendix E – Normality Statistics for Study Five

Interpretation of statistics for the impact variables

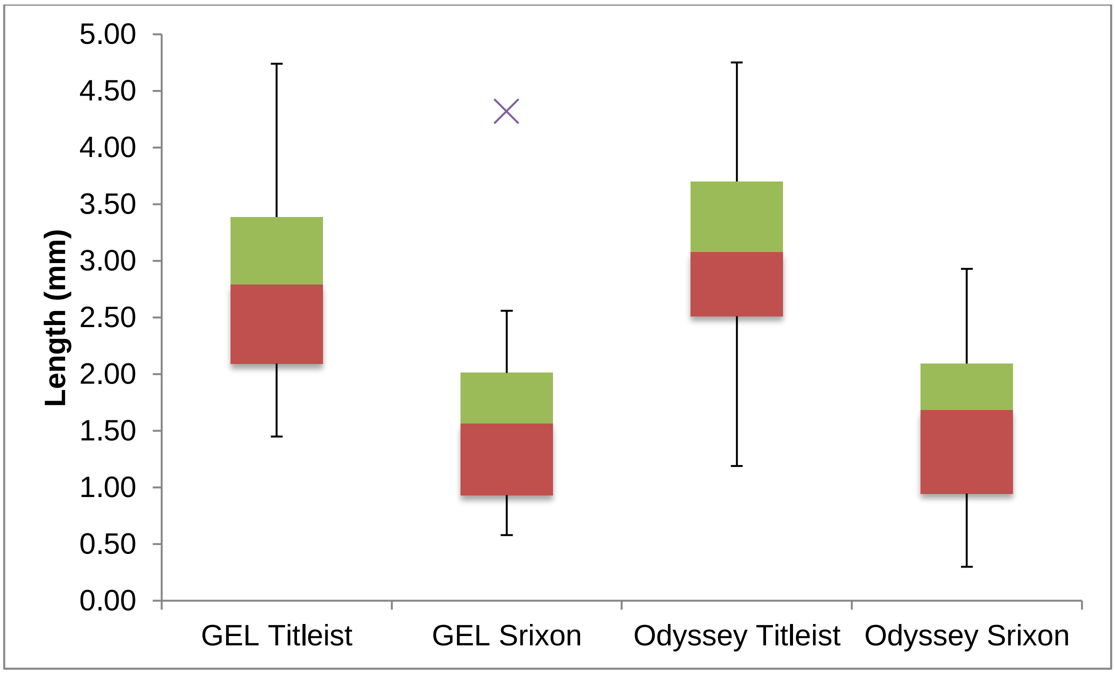
The results of the normality statistics shows that certain variables needed to either be log transformed or have outlying data points removed from the data set. The box and whisker diagrams identified that three trials from the GEL® Srixon and GEL® Titleist putter-ball groups. One trial was identified as an outlier in the GEL® Srixon data set for the variable length (4.32 mm). Two trials were identified as outliers for the GEL® Titleist putter-ball combination for the variable surface area (30.33 mm^2, 28.34 mm^2). These data points were found to have Z scores ($z = \frac{X - \bar{X}}{sd}$) above a value of two.

The GEL® Srixon data was log transformed using the log transformation LG10 function as the data was identified as having a positive skew as outlined by Field (2013). The only other indication of non-uniformity was in the Odyssey Srixon group, which had a kurtosis score of -1.047. The LG10 function would not be suitable to transform this data, as it is only appropriate for transforming data sets that display positive kurtosis or skewness. None of the main four types of transformation (log, square root, reciprocal and reverse score transformation) are recognised at being effective of correcting negative kurtosis (Field, 2013). As the data was found to be symmetrical in terms of skewness (-.072), with no multicollinearity observed between the impact variables and just outside the bracket of normality of kurtosis (> 1.0). The Odyssey Srixon group was not log transformed or cleansed of certain data points.

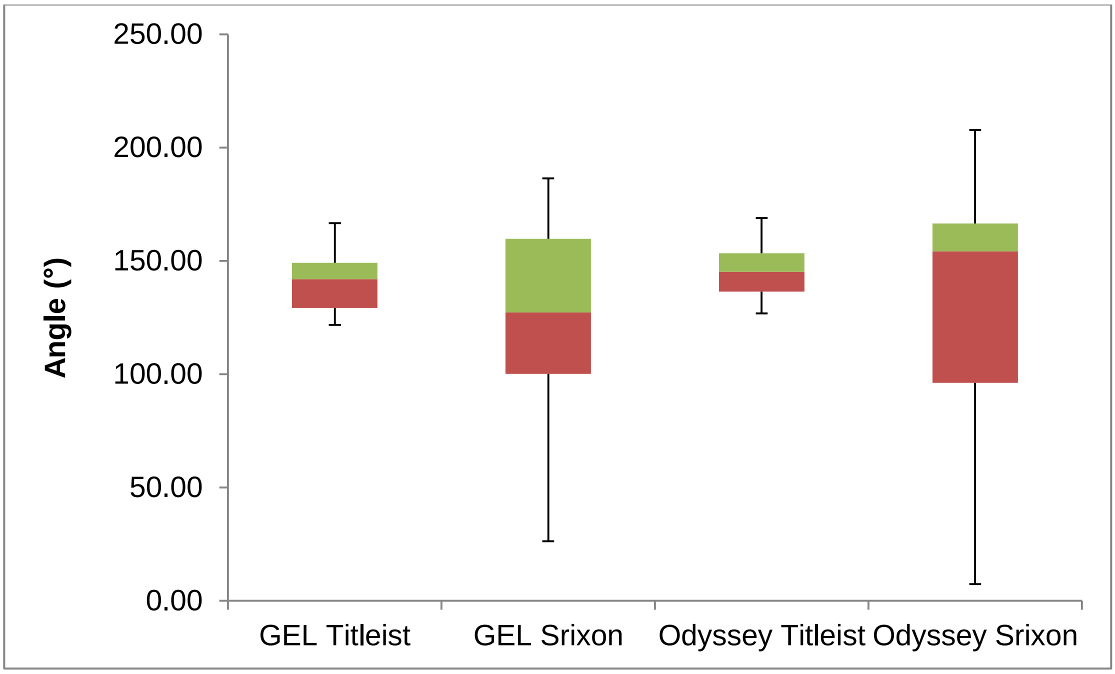
Bivariate analysis identified significant relationships between the impact variables; however, no correlations were identified as very strong (r = 0.8 – 1.0). Therefore, primary component analysis was not undertaken as this met the assumption of not displaying multicollinearity as suggested by Ntoumanis (2001).

Descriptive normality statistics for the impact variable length from the centroid location.

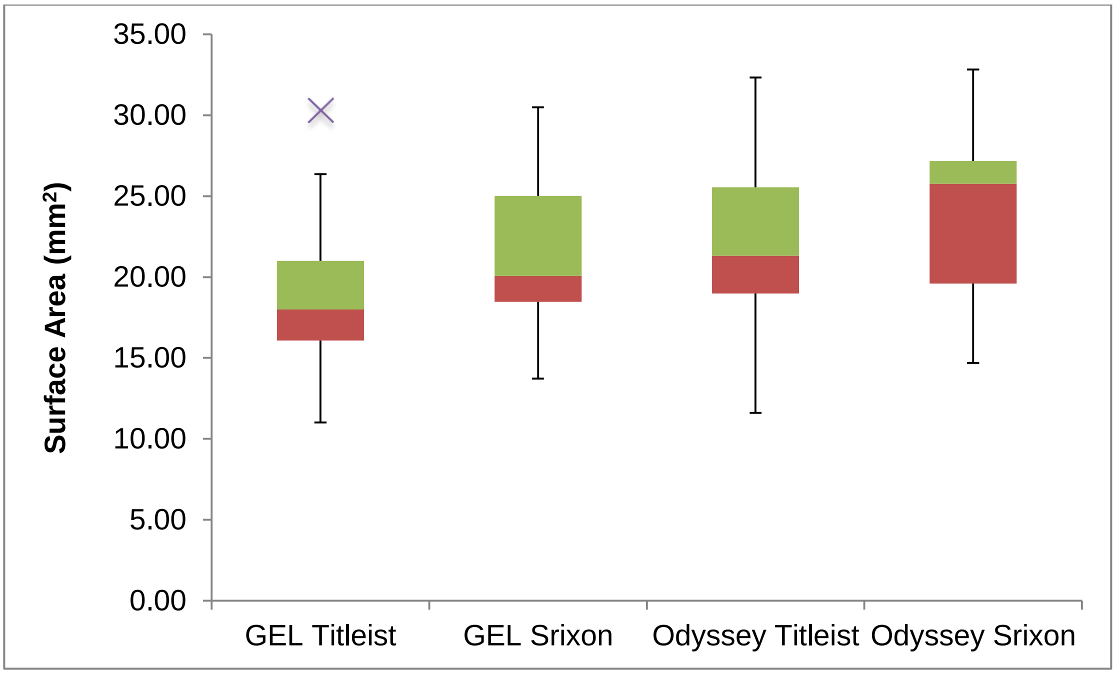
	Mean ± SD (mm)	Median (mm)	Skewness	Kurtosis
GEL® Titleist	2.82 ± 0.85	2.80	.376	-.525
GEL® Srixon	1.56 ± 0.73	1.57	1.263	3.471
Odyssey Titleist	3.09 ± 0.74	3.08	.070	-.006
Odyssey Srixon	1.59 ± 0.70	1.68	-.072	-1.047



Box and whisker diagrams for the impact variable length from the centroid location. The purple X denotes an identified outlier in the data set and was removed from analysis.



Box and whisker diagrams for the impact variable angle from the centroid location.



Box and whisker diagrams for the impact variable surface area. The purple X denotes an identified outlier in the data set and was removed from analysis.

Descriptive normality statistics for the impact variable Angle from the centroid location.

	Mean ± SD (°)	Median (°)	Skewness	Kurtosis
GEL® Titleist	140.94 ± 12.38	142.00	.193	-.826
GEL® Srixon	122.60 ± 41.06	127.30	-.660	-.335
Odyssey Titleist	145.37 ± 11.57	145.20	.176	-.982
Odyssey Srixon	131.77 ± 54.73	154.33	-.851	-.351

Descriptive normality statistics for the impact variable surface area of the impact zone.

	Mean ± SD (mm^2)	Median (mm^2)	Skewness	Kurtosis
GEL® Titleist	18.88 ± 4.34	17.99	.833	.351
GEL® Srixon	21.36 ± 4.04	20.07	.646	-.391
Odyssey Titleist	21.83 ± 4.63	21.31	.020	-.297
Odyssey Srixon	23.95 ± 4.72	25.76	-.301	-.829

Multicollinearity statistics for the GEL® Titleist putter-ball combination (significant relationship = highlighted cell, $p < 0.05$).

	Length (r)	Angle (r)	Surface Area (r)
Length (r)	-	-	-
Angle (r)	.585	-	-
Surface Area (r)	.507	.677	-

Multicollinearity statistics for the GEL® Srixon putter-ball combination (significant relationship = highlighted cell, $p < 0.05$).

	Length (r)	Angle (r)	Surface Area (r)
Length (r)	-	-	-
Angle (r)	.378	-	-
Surface Area (r)	.336	.061	-

Multicollinearity statistics for the Odyssey Titleist putter-ball combination (significant relationship = highlighted cell, $p < 0.05$).

	Length (r)	Angle (r)	Surface Area (r)
Length (r)	-	-	-
Angle (r)	.584	-	-
Surface Area (r)	.173	.665	-

Multicollinearity statistics for the Odyssey Srixon putter-ball combination (significant relationship = highlighted cell, $p < 0.05$).

	Length (r)	Angle (r)	Surface Area (r)
Length (r)	-	-	-
Angle (r)	.586	-	-
Surface Area (r)	.418	.265	-

Interpretation of statistics for the kinematic variables

Normality statistics are not presented, as all kinematic variables are analysed individually from one another and therefore are not as important for the main multiple regression analysis as the normality of the impact variables. However, no outliers were identified for any of the kinematic variables. The majority of variables displayed normality for all four putter-ball groups. The only variable that was log transformed due to extreme non-uniformity was the forward roll variable, via the LG10 method. Non-uniformity was expected in this variable due to the nature that the majority of the golf putt observed started rolling forward immediately and therefore had a score of 0.00.

Bivariate analysis revealed significant correlations between a number of the kinematic variables. All variables displayed moderate to high correlations (r = 0.4 – 0.8) apart from the variables horizontal launch angle and the push and pull variable for the GEL® Titleist (r = .99), Odyssey Titleist (r = .89) and Odyssey Srixon (r = .89) groups. Principle component analysis could have been undertaken on the variables, however, in the multiple regression analysis the variables would be analysed separately from one another. It was not considered to be appropriate to eliminate one variable from the analysis as it increases understanding of how much the horizontal launch angle influences the final position of the golf ball. This is in terms of what degree the horizontal launch angle has to be to influence the success rate of a golf putt. Therefore, principle component analysis was not undertaken.

Multicollinearity statistics for the GEL® Titleist putter-ball combinations kinematic variables (significant relationship = blue highlighted cell, $p < 0.05$, significant relationship/very strong relation = orange cell, $p < 0.05$).

	Velocity (*r*)	Side spin (*r*)	Initial ball roll (*r*)	Forward roll (*r*)	True roll (*r*)	Vertical Launch Angle (*r*)	Horizontal Launch Angle (*r*)	Push or Pull (*r*)
Velocity (*r*)	-	-	-	-	-	-	-	-
Side spin (*r*)	.168	-	-	-	-	-	-	-
Initial ball roll (*r*)	.082	.772	-	-	-	-	-	-
Forward roll (*r*)	.056	-.474	-.500	-	-	-	-	-
True roll (*r*)	.391	-.082	-.185	-.033	-	-	-	-
Vertical Launch Angle (*r*)	.167	-.326	-.315	.131	.179	-	-	-
Horizontal Launch Angle (*r*)	.053	-.362	-.294	.272	.356	.092	-	-
Push or Pull (*r*)	.054	-.362	-.295	.274	.358	.092	.999	-

Multicollinearity statistics for the GEL® Srixon putter-ball combinations kinematic variables (significant relationship = blue highlighted cell, p < 0.05).

	Velocity (r)	Side spin (r)	Initial ball roll (r)	Forward roll (r)	True roll (r)	Vertical Launch Angle (r)	Horizontal Launch Angle (r)	Push or Pull (r)
Velocity (r)	-	-	-	-	-	-	-	-
Side spin (r)	-.144	-	-	-	-	-	-	-
Initial ball roll (r)	-.298	.414	-	-	-	-	-	-
Forward roll (r)	.218	-.340	-.736	-	-	-	-	-
True roll (r)	.235	.306	-.183	-.030	-	-	-	-
Vertical Launch Angle (r)	.059	-.409	-.323	.138	-.137	-	-	-
Horizontal Launch Angle (r)	.178	.281	.096	-.022	-.158	-.326	-	-
Push or Pull (r)	-.037	-.373	-.037	.166	-.301	.141	-.160	-

Multicollinearity statistics for the Odyssey Titleist putter-ball combinations kinematic variables (significant relationship = blue highlighted cell, $p < 0.05$, significant relationship/very strong relation = orange cell, $p < 0.05$).

	Velocity (*r*)	Side spin (*r*)	Initial ball roll (*r*)	Forward roll (*r*)	True roll (*r*)	Vertical Launch Angle (*r*)	Horizontal Launch Angle (*r*)	Push or Pull (*r*)
Velocity (*r*)	-	-	-	-	-	-	-	-
Side spin (*r*)	-.318	-	-	-	-	-	-	-
Initial ball roll (*r*)	-.183	.590	-	-	-	-	-	-
Forward roll (*r*)	.190	-.510	-.685	-	-	-	-	-
True roll (*r*)	.614	-.413	-.384	.362	-	-	-	-
Vertical Launch Angle (*r*)	.045	-.340	-.002	.016	.115	-	-	-
Horizontal Launch Angle (*r*)	-.152	.031	.323	-.157	.068	.107	-	-
Push or Pull (*r*)	-.160	.058	.228	-.090	.110	.167	.894	-

Multicollinearity statistics for the Odyssey Srixon putter-ball combinations kinematic variables (significant relationship = blue highlighted cell, $p < 0.05$, significant relationship/very strong relation = orange cell, $p < 0.05$).

	Velocity (*r*)	Side spin (*r*)	Initial ball roll (*r*)	Forward roll (*r*)	True roll (*r*)	Vertical Launch Angle (*r*)	Horizontal Launch Angle (*r*)	Push or Pull (*r*)
Velocity (*r*)	-	-	-	-	-	-	-	-
Side spin (*r*)	-.092	-	-	-	-	-	-	-
Initial ball roll (*r*)	-.117	.360	-	-	-	-	-	-
Forward roll (*r*)	.021	-.160	-.693	-	-	-	-	-
True roll (*r*)	.493	-.224	-.202	.153	-	-	-	-
Vertical Launch Angle (*r*)	-.236	.121	-.070	-.044	-.007	-	-	-
Horizontal Launch Angle (*r*)	.041	-.064	.099	-.157	-.030	.251	-	-
Push or Pull (*r*)	-.026	.008	.168	-.139	-.108	.195	.889	-

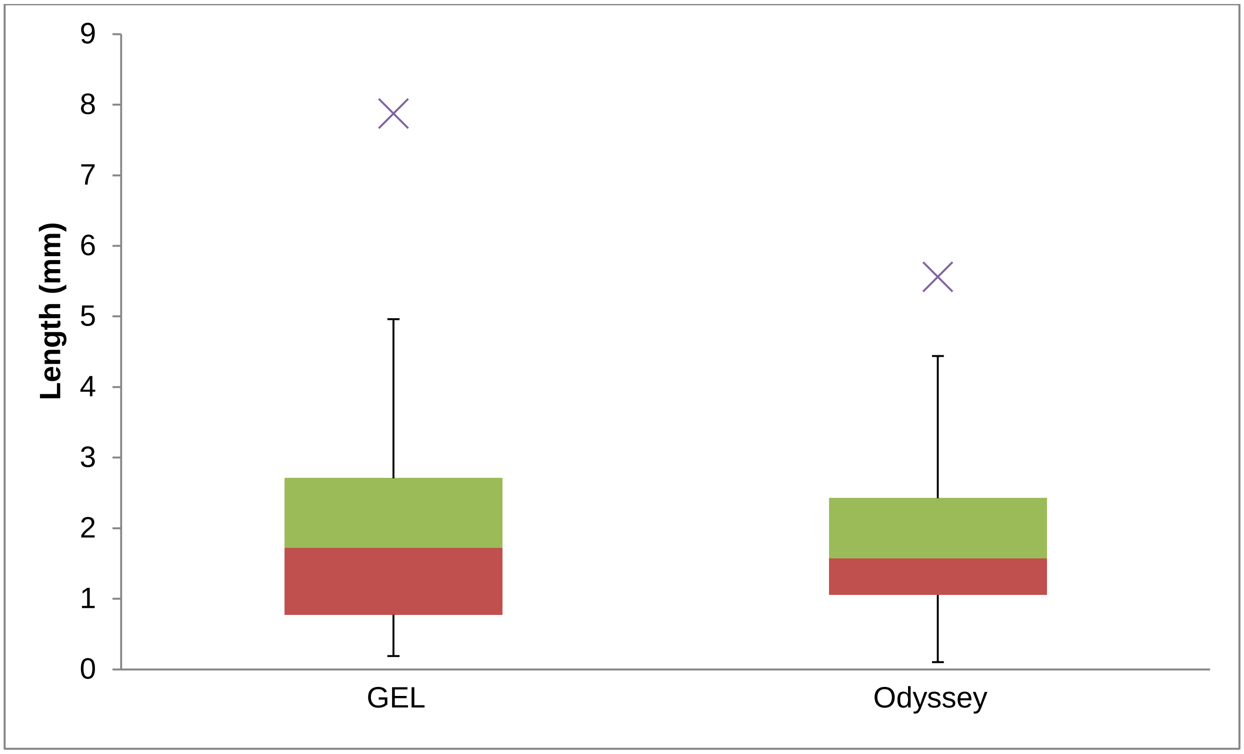
Appendix F – Normality Statistics for Study Six

Interpretation of statistics for the impact variables

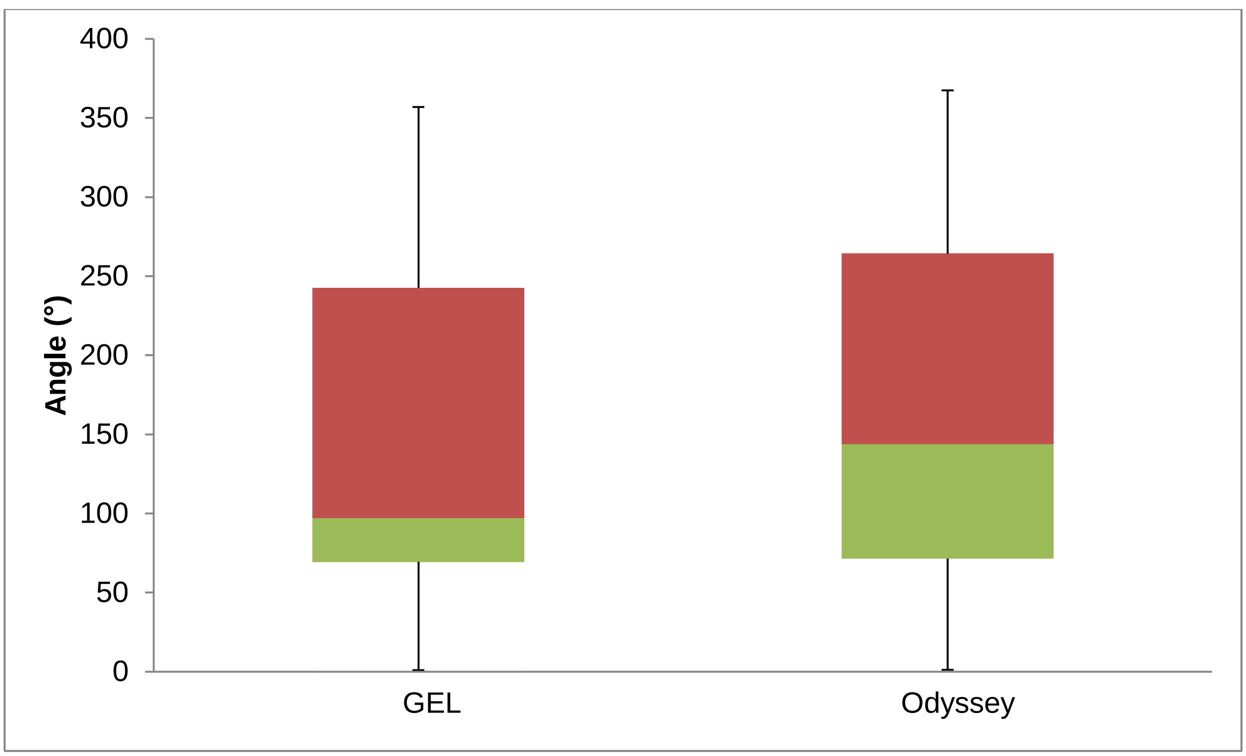
The results of the normality statistics demonstrates that certain variables displayed slight non-uniformity, and needed to either be log transformed or have outlying data points cleansed from the data set. It was identified using the box and whisker diagrams that two trials from the Odyssey data set needed to be removed. Both trials were identified as outliers for the length from the centroid location (5.56 mm and 5.26 mm). In addition to this both data points were found to have a Z score of greater than two (Z = 3.58 and Z = 3.30). Two trials were also eliminated from the GEL® data set (7.87 mm (Z score = 4.71) and 5.27 mm (Z score = 2.66)). All the trials were completed by separate participants and can be accounted to errors in the data collection process.

The GEL® data set was log transformed using the LG10 function as the data set was identified as having a positive skew and being positively kurtosed (Field, 2013). The Odyssey data set was found to be negatively kurtosed for the angle from the centroid location and surface area of the impact zone, however, this was not as severe as the length variable for the GEL® data set. An attempt was made to log transform this data whereby firstly the scores were reversed (each score was subtracted by the highest score +1) then the LG10 function was applied to the data set, however, although this eliminated the negative skew and kurtosis the data set became positively kurtosed, more so than the original negative kurtosis. Therefore, as both data sets were only just outside the bracket for normality (> 1.0) and there was no multicollinearity observed the Odyssey data was not log transformed. To identify the data sets where not a problem a multiple regression was completed for additional collinearity statistics, the variance inflation factor (VIF) and tolerance statistic. Both of which were observed to be below the levels set for VIF and above the tolerance statistic (Bowerman & O'Connell, 1990; Menard, 1995).

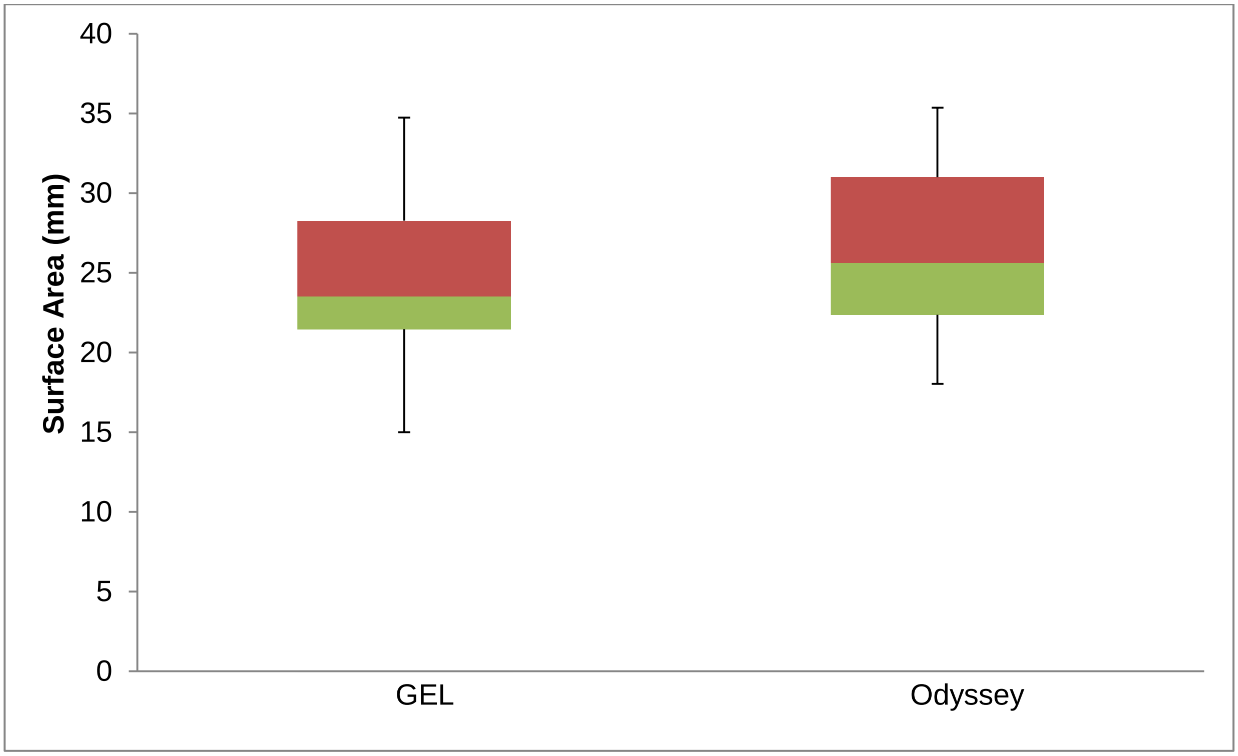
Bivariate analysis identified significant relationships between the impact variables, however all correlations were identified as weak (r = 0.2 – 0.4) or no correlation (r = 0.0 – 0.2). This meets the assumption that none of the dependent variables display multicollinearity, so principle component analysis was not undertaken (Ntoumanis, 2001).



Box and whisker diagrams for the impact variable length from the centroid location. The purple X denotes the largest outlier within the data set which was subsequently removed from analysis.



Box and whisker diagrams for the impact variable angle from the centroid location.



Box and whisker diagrams for the impact variable surface area.

Descriptive normality statistics for the impact variable length from the centroid location.

	Mean ± SD (mm)	Median (mm)	Skewness	Kurtosis
GEL®	1.89 ± 1.27	1.72	1.116	2.309
Odyssey	1.80 ± 1.05	1.57	.986	.922

Descriptive normality statistics for the impact variable angle from the centroid location.

	Mean ± SD (°)	Median (°)	Skewness	Kurtosis
GEL®	149.61 ± 110.00	97.00	.563	-.988
Odyssey	169.53 ± 112.75	143.80	.263	-1.35

Descriptive normality statistics for the impact variable surface area of the impact zone.

	Mean ± SD (°)	Median (°)	Skewness	Kurtosis
GEL®	24.90 ± 4.91	23.55	.526	-.545
Odyssey	26.71 ± 5.00	25.63	.294	-1.09

Multicollinearity statistics for the GEL® putter (significant relationship = highlighted cell, $p < 0.05$).

	Length (r)	Angle (r)	Surface Area (r)
Length (r)	-	-	-
Angle (r)	-.174	-	-
Surface Area (r)	.275	.310	-

Multicollinearity statistics for the GEL® putter (significant relationship = highlighted cell, $p < 0.05$).

	Length (r)	Angle (r)	Surface Area (r)
Length (r)	-	-	-
Angle (r)	-.136	-	-
Surface Area (r)	.371	.053	-

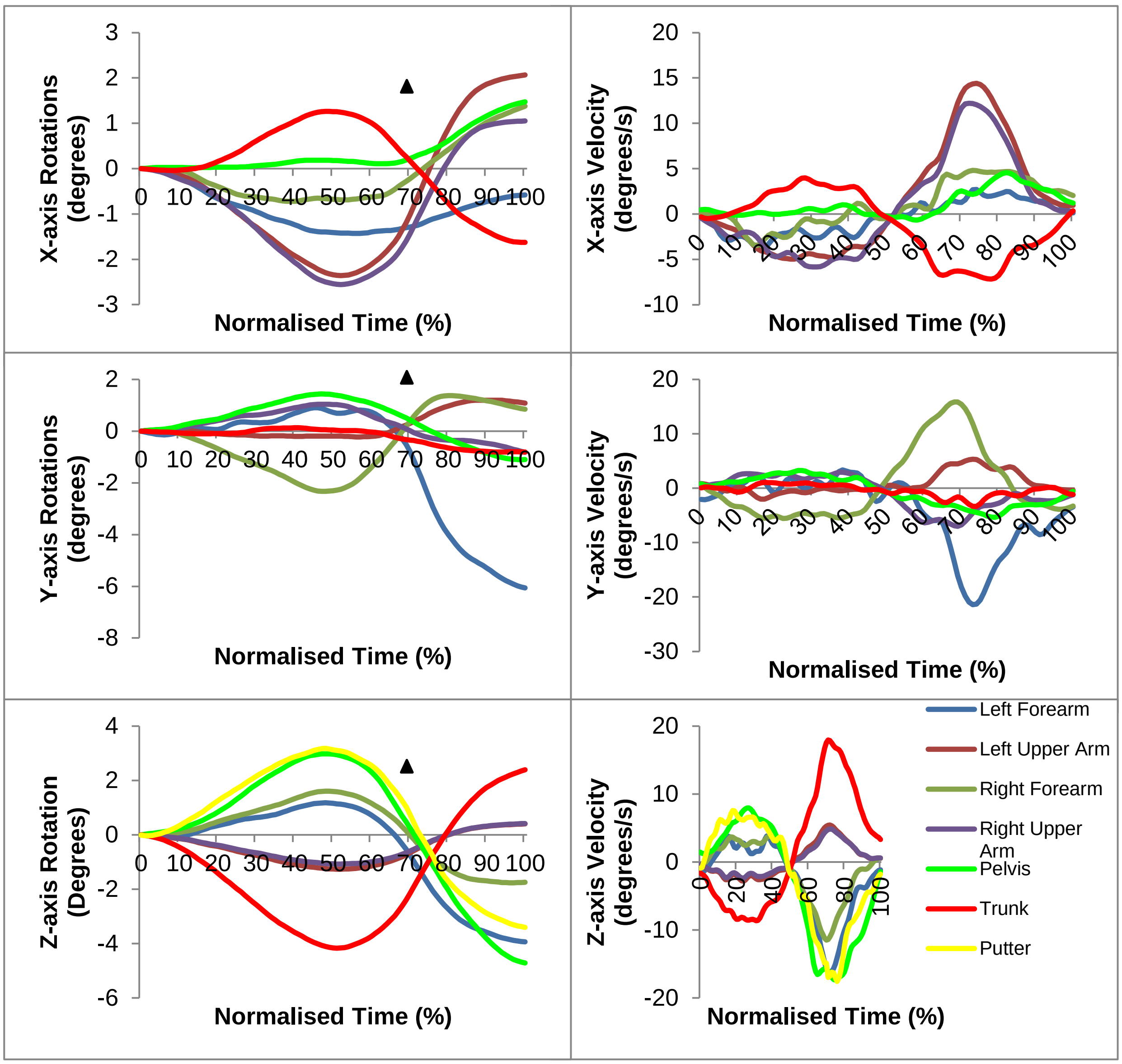
Interpretation of statistics for the kinematic variables

Kinematic variables were tested for normality, however, are not presented as all variables are analysed separately from one another and therefore multicollinearity is more important. Outliers were identified for all kinematic variables (velocity, side spin, initial ball roll, forward roll, true roll, vertical launch angle, whether the ball was pushed or pulled and horizontal launch angle). Outliers were removed from subsequent analysis for the variable it was originally identified for and not the whole trial like Study Five. The rationale for this is the large majority (> 80%) of trials were identified as outliers for the forward and true roll variables and as identified by bivariate analysis forward and true roll had little to no correlation with the other variables. Therefore it was deemed unnecessary to remove the whole trial.

The variables that showed non-uniformity was the forward roll and true roll variable for both the GEL® and Odyssey data set, in addition to this the horizontal launch angle for the GEL® data set. These variables were log transformed using the LG10 method to reduce the effects of non-uniformity. Bivariate analysis identified one very strong relationship between the variables horizontal launch angle and whether the ball was pushed or pulled for both the GEL® and Odyssey data set. This mirrors the results for normality statistics performed for Study Five, and likewise principle component was not performed on the variables. This is because the variables are analysed separately from one another during multiple regression, it will increase understanding of how much the horizontal launch angle influences the final position of the golf ball.

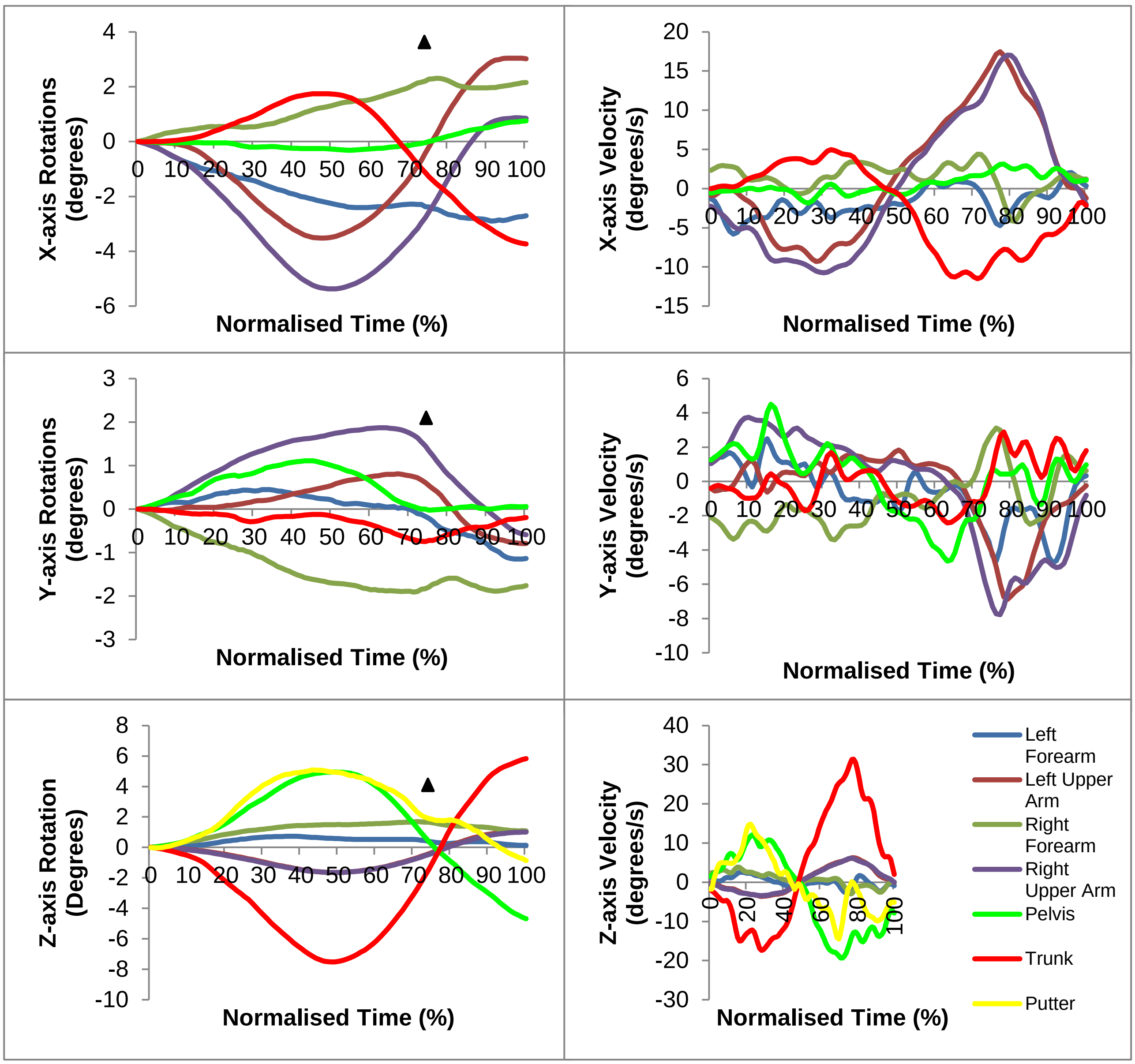
Appendix H – Segment Rotations and associated *r* values

The triangle shows the percentage at which ball contact occurred (70%). A number of significant relationships were identified. Very strong significant postive relationships were identified on the Z axis between the left forearm and right forearm (r = .99, p < .001), left forearm and pelvis (r = .99, p < .001), right forearm and pelvis (r = .99, p < .001). A very strong negative relationship on the Z axis was apparent between the trunk and left forearm (r = -.93, p < .001), trunk and right forearm (r = -.96, p < .001) and trunk and pelvis (r = -.97, p < .001). A strong relationship was identified for X rotations between the right and left forearm (r = .65, p < .001). Putter Z rotations were very strongly correlated with the Z rotations of the left forearm, right forearm, pelvis and trunk (r = .98, .99, .99 and -.97) respectively.



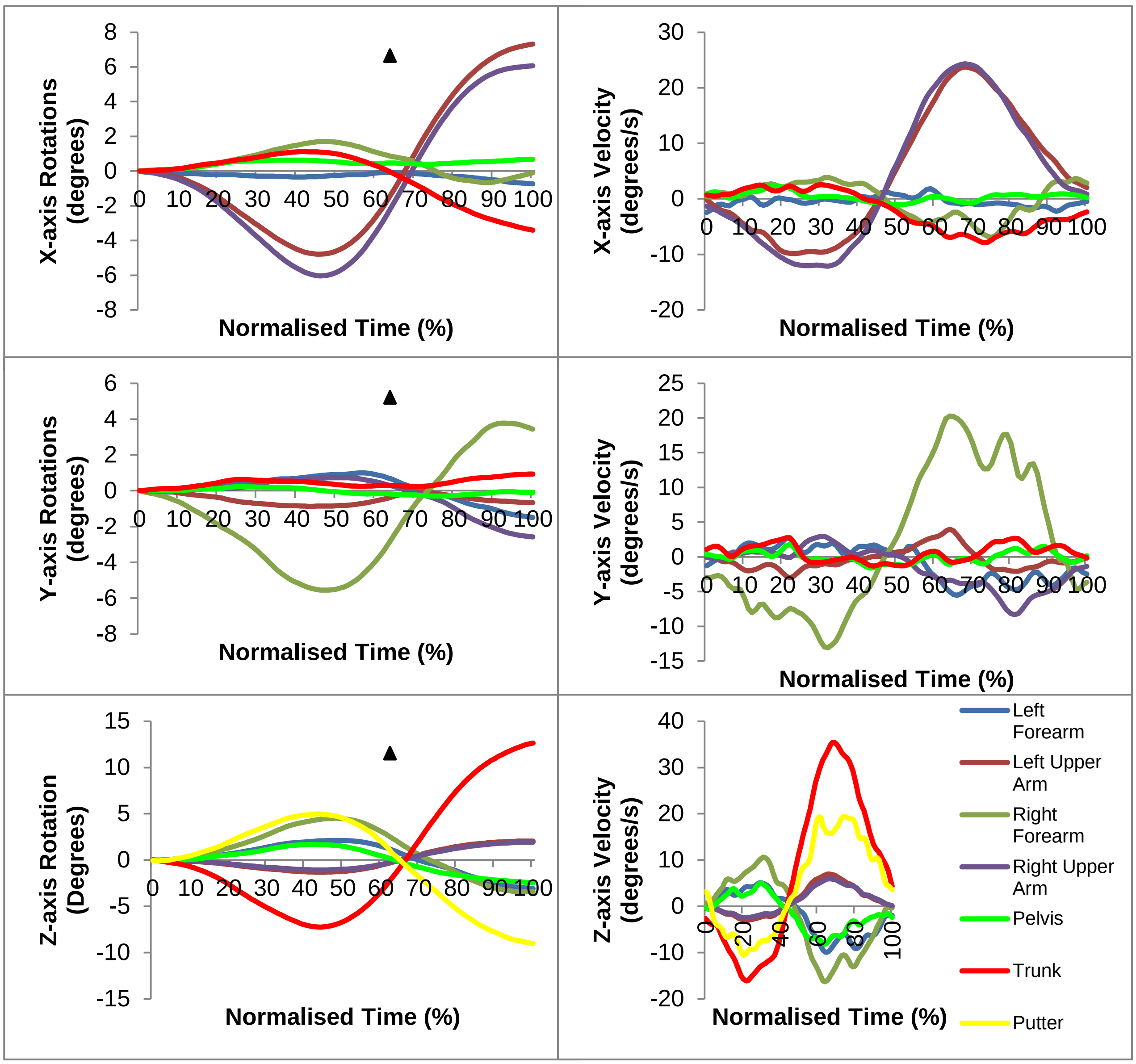
The displacement and velocities of Participant 1 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.

The triangle represents the percentage at which ball contact occurred (75%). Significant postive relationship on the Z axis were, left forearm and pelvis (r = .80, p < .001), left forearm and right forearm (r = .52, p < .001), right forearm and pelvis (r = .41, p < .001). Significant negative relationships were identified between the trunk and left forearm (r = -.81, p < .001), trunk and right forearm (r = -.49, p < .001) and trunk and pelvis (r = -.99, p < .001). A very strong negative relationship was identified for X rotations between the right and left forearm (r = -.91, p < .001). Putter Z rotations were either very strongly or strongly positively correlated with the Z rotations of the left forearm (r = .92, p < .001), right forearm r = .60, p < .001) and pelvis (r = .93, p < .001). A very strong negative correlation was apparent for the putter Z rotations and the trunk Z rotations (r = -.88, p < .001).



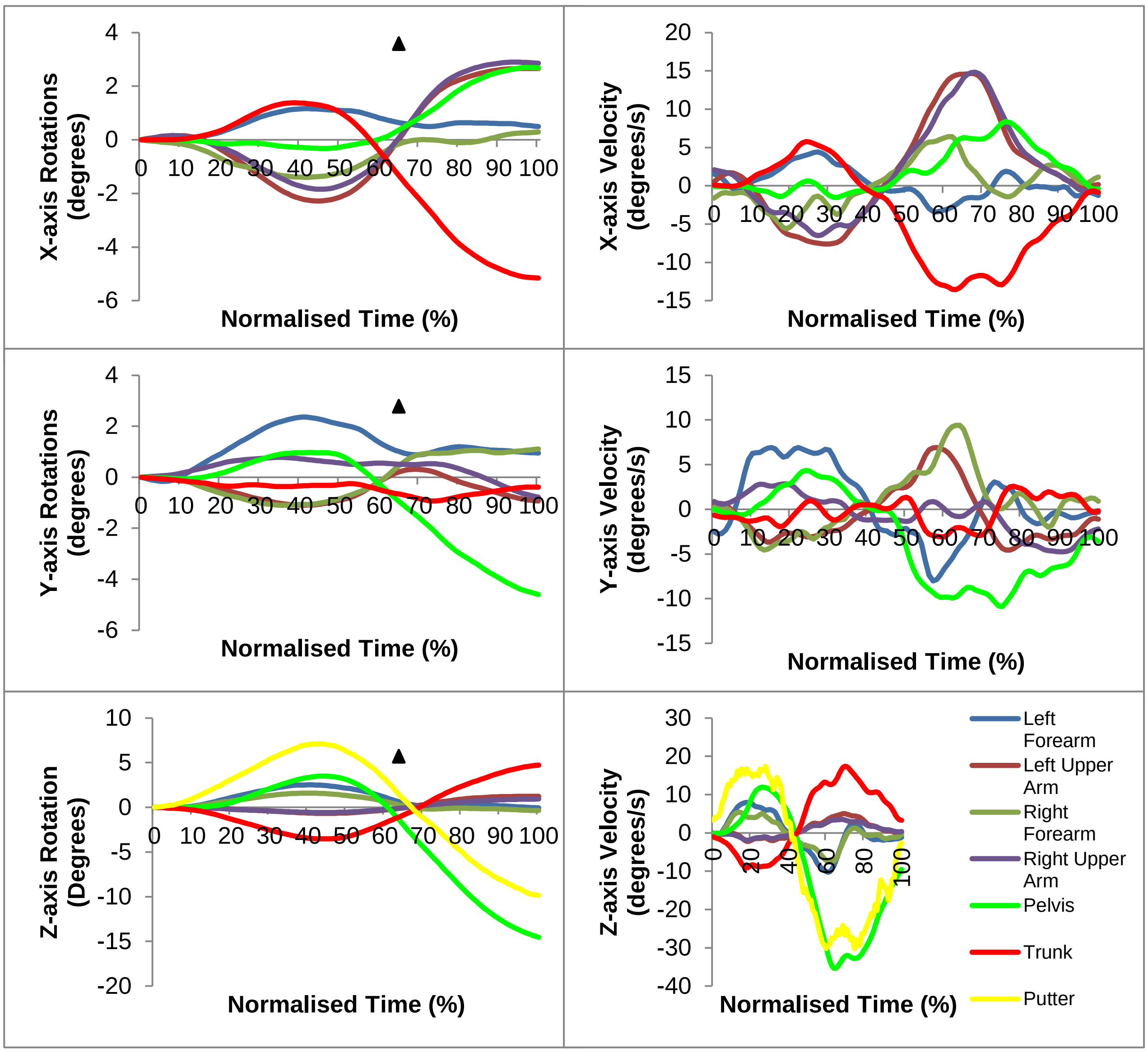
The displacement and velocities of Participant 2 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.

The triangle represents the percentage at which ball contact occurred (63%). Significant very strong positive relationships were identified for Z rotations between the left and right forearm (r = .99, p < .001), left forearm and pelvis (r = .96, p < .001) and right forearm and pelvis (r = .94, p < .001). Very strong negative relationships were identified between the trunk and the following segments left forearm (r = -.98, p < .001), right forearm (r = -.97, p < .001) and pelvis (r = -.99, p < .001). A weak significant relationship was identified between the left and right forearm segments on the X axis (r = .20, p = .044). Putter Z correlations demonstrated very strong positive correlations with the segments left forearm (r = .97, p < .001, right forearm (r = .96, p < .001) and pelvis (r = .99, p < .001). A very strong correlation was demonstrated with the trunk, this was negative however (r = -.91, p < .001).



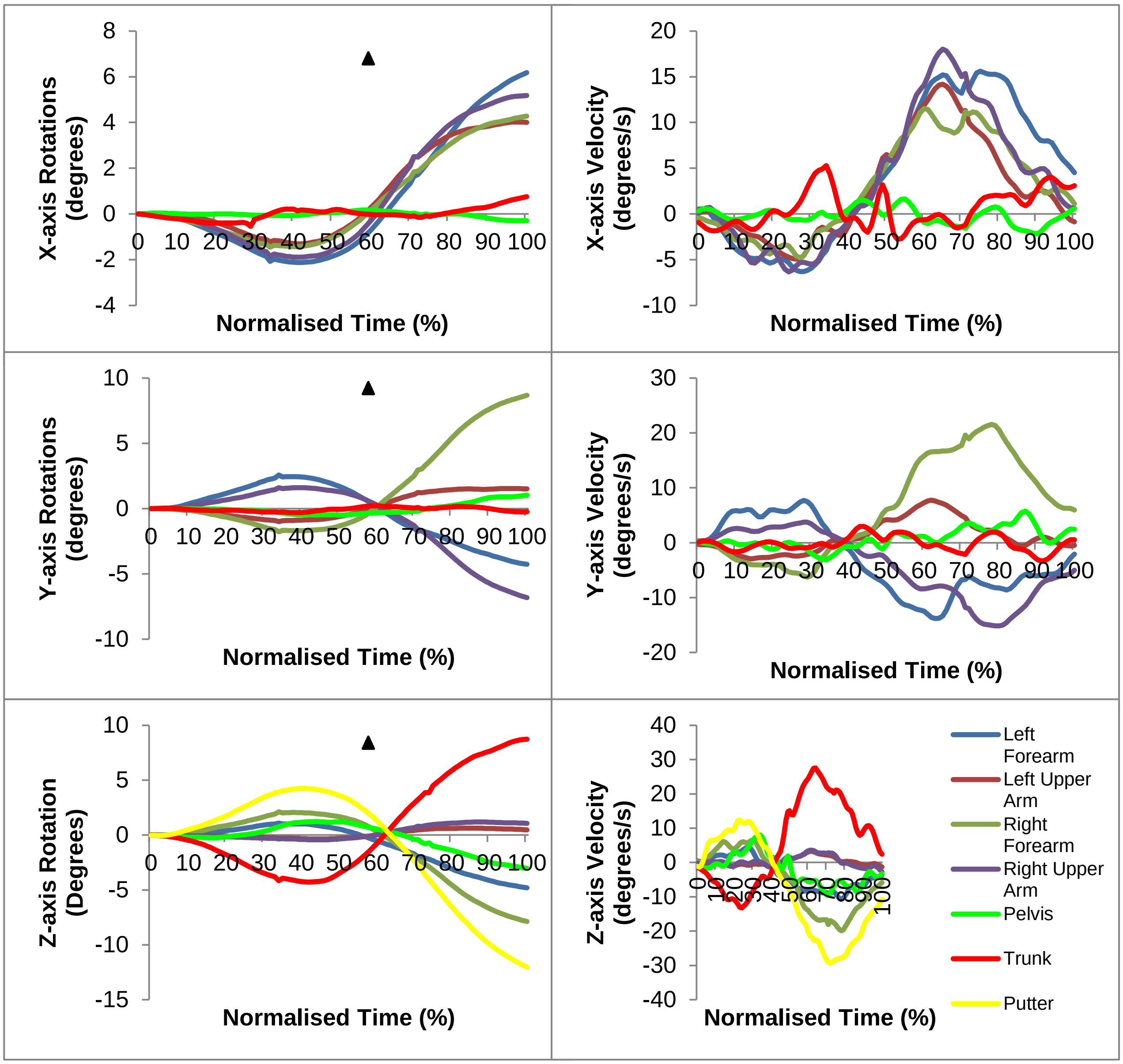
The displacement and velocities of Participant 4 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.

The triangle represents the percentage at which ball contact occurred (63%). Significant very strong positive relationships were demonstrated for Z rotationss between the following segments left forearm and right forearm (r = .91, p < .001), left forearm and pelvis (r = .85, p < .001) and right forearm and pelvis (r = .97, p < .001). Very strong negative relationships were demonstrated between the trunk and the following segments; left forearm (r = -.89, p < .001), right forearm (r = -.97, p < .001) and pelvis (r = .98, p < .001). A strong negative relationship was identified between the left and right forearm for X rotations (r = -.64, p < .001). Putter Z rotations showed very strong positive correlations with the left forearm (r = .88, p < .001), right forearm (r = .98, p < .001) and pelvis (r = .99, p < .001). A very strong negative correlation was seen for the putter and trunk (r = -.91, p < .001).

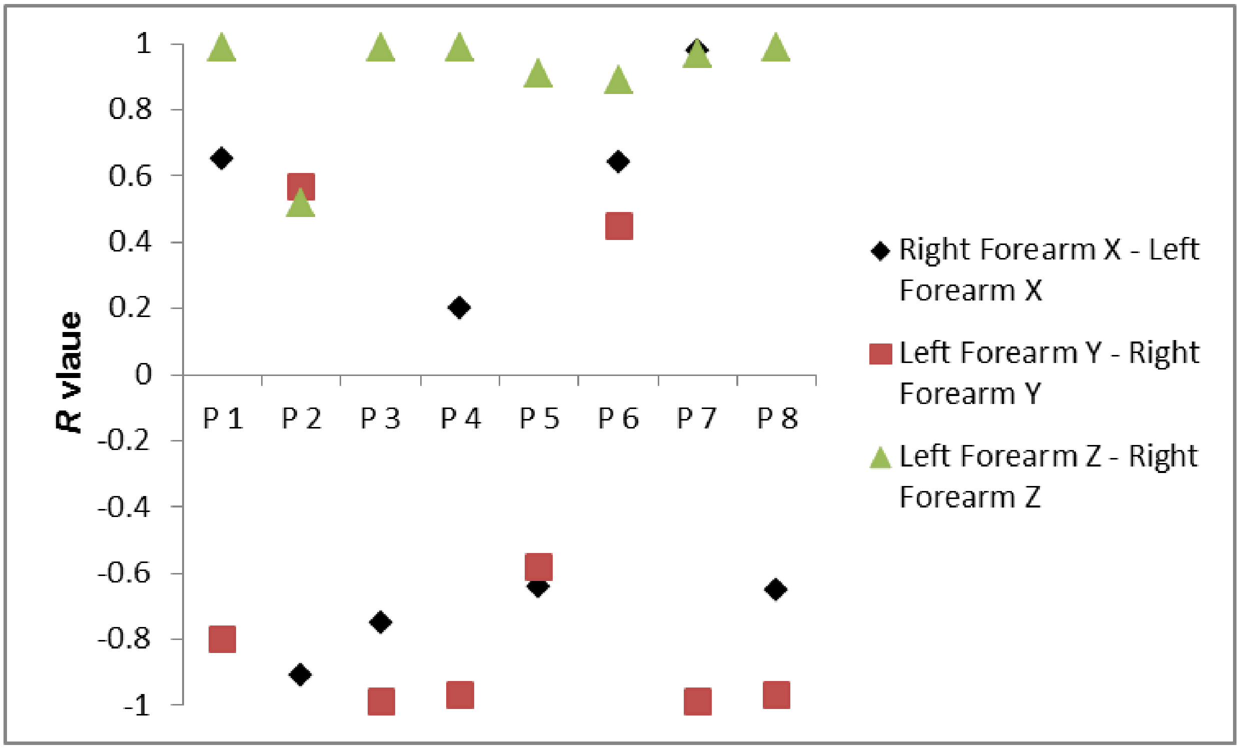


The displacement and velocities of Participant 5 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.

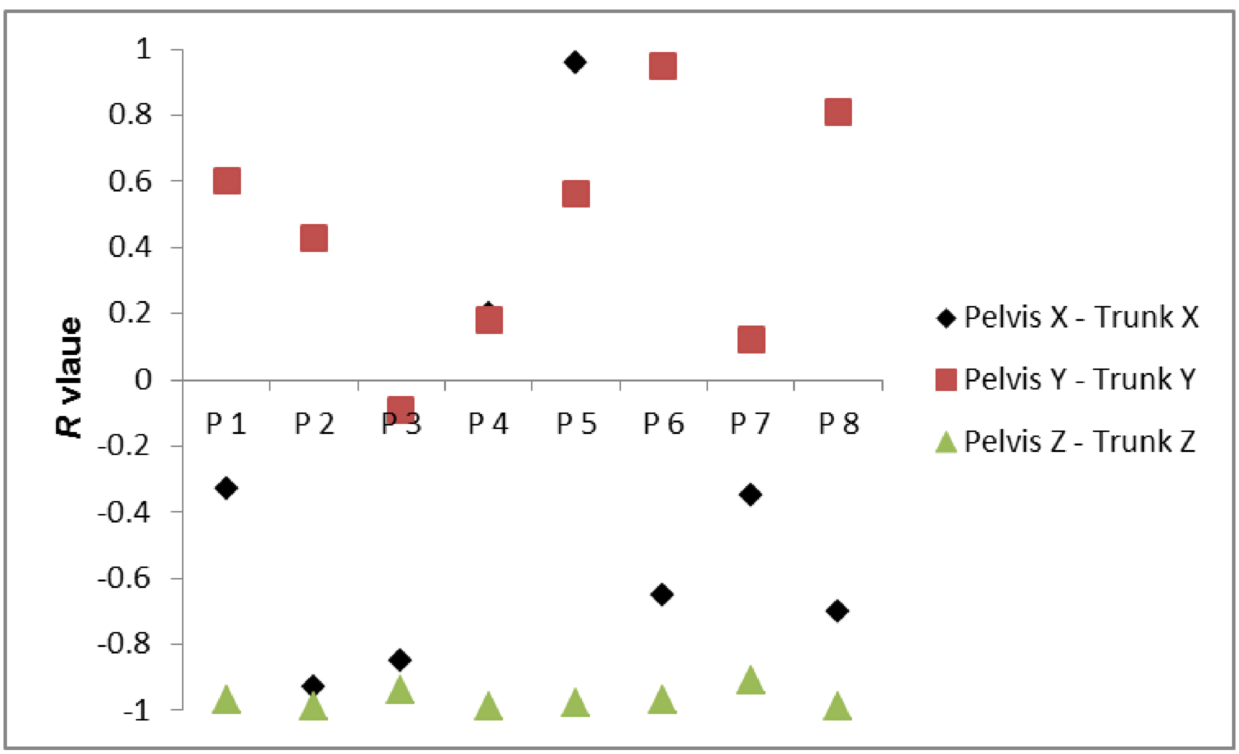
The triangle represents the percentage at which ball contact occurred (58%). Very strong significant postive relationship were demonstrated for Z rotations between the following segments left and right forearm (r = .98, p < .001), left forearm and pelvis (r = .83, p < .001) and right forearm and pelvis (r = .90, p < .001). Very strong significant negative correlations were observed between the trunk and the following segments left forearm (r = -.97, p < .001), right forearm (r = -.99, p < .001) and pelvis (r = -.91, p < .001). A very strong relationship for X rotations was observed between the left and right forearm (r = .98, p < .001). Putter Z rotations demonstrated very strong positive correlations with the following segments; left forearm (r = .96, p < .001), right forearm (r = .99, p < .001) and pelvis (r = .92, p < .001). A strong negative relationship was identified between the putter and the trunk (r = -.99, p < .001).



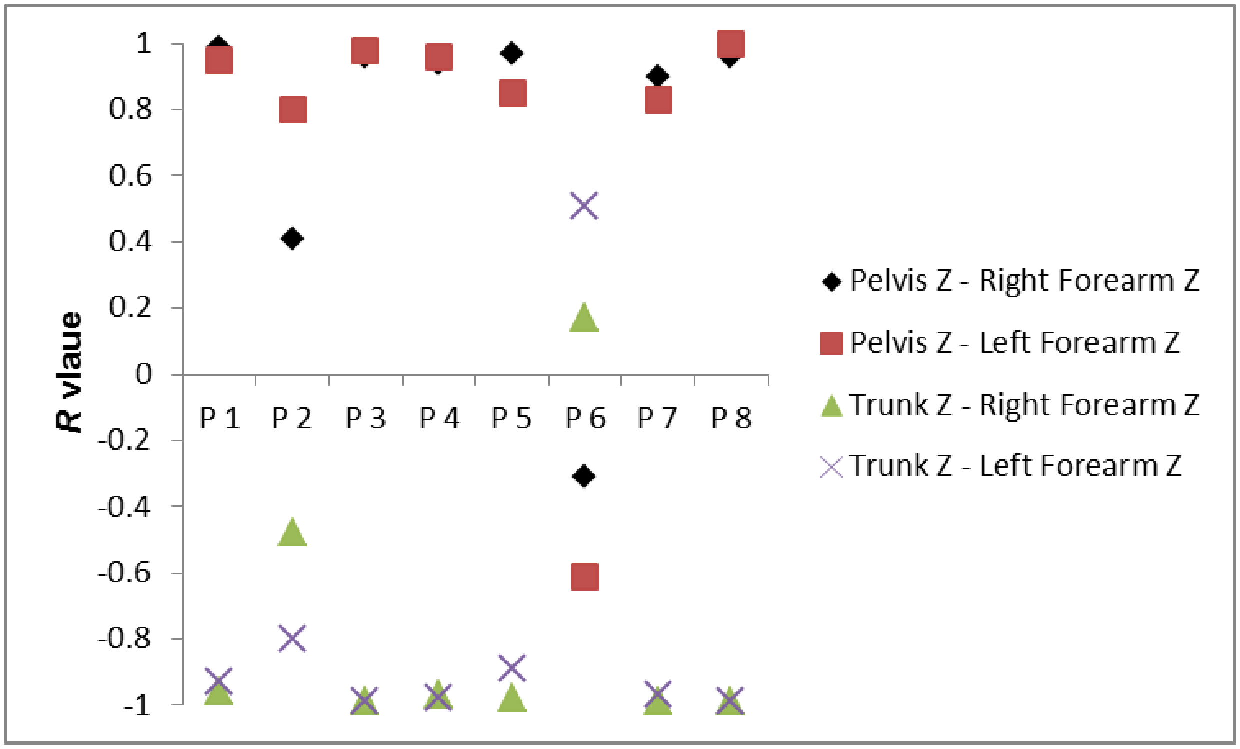
Figure?? The displacement and velocities of Participant 7 segment rotations on the X, Y and Z axis for the putting stroke. The triangle shows the mean time of ball contact.



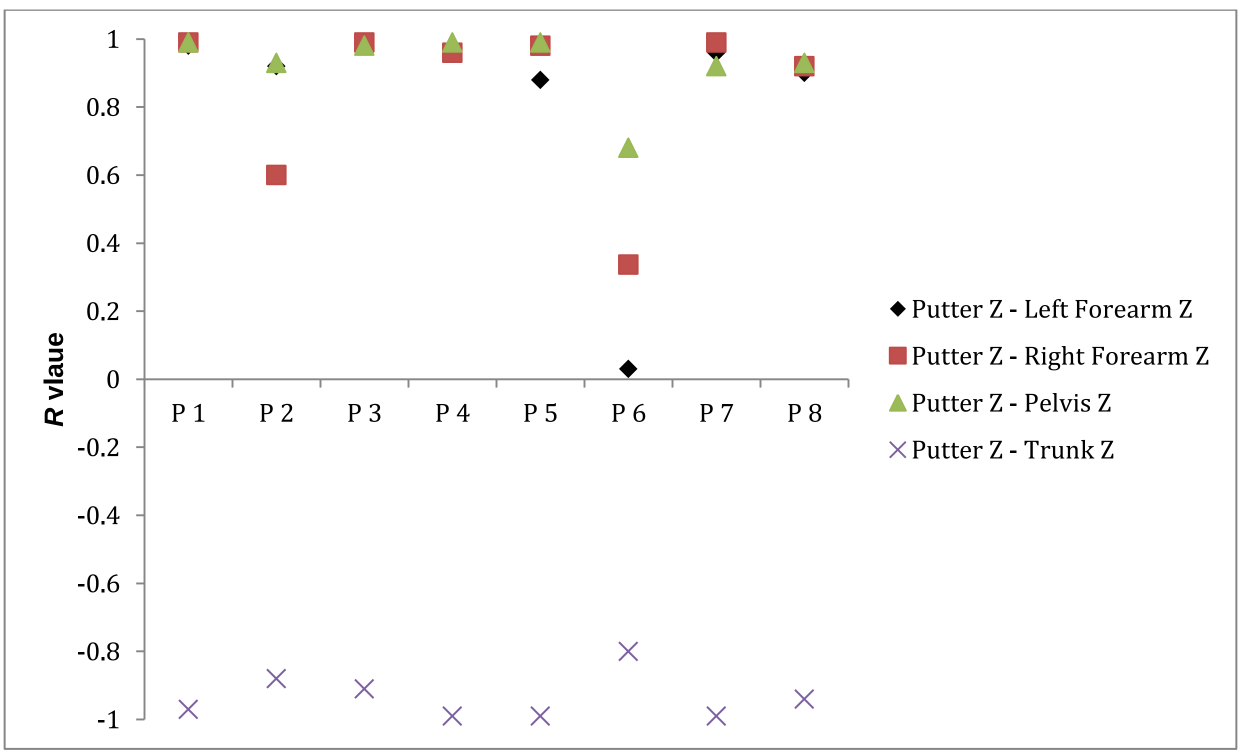
Correlation coefficients between the left and right forearm segments (P = participant). (All relationships significant, $p < .01$).



Correlation coefficients between the pelvis and trunk segments (P = participant). (All relationships significant between X and Z segment rotations, $p < .01$).

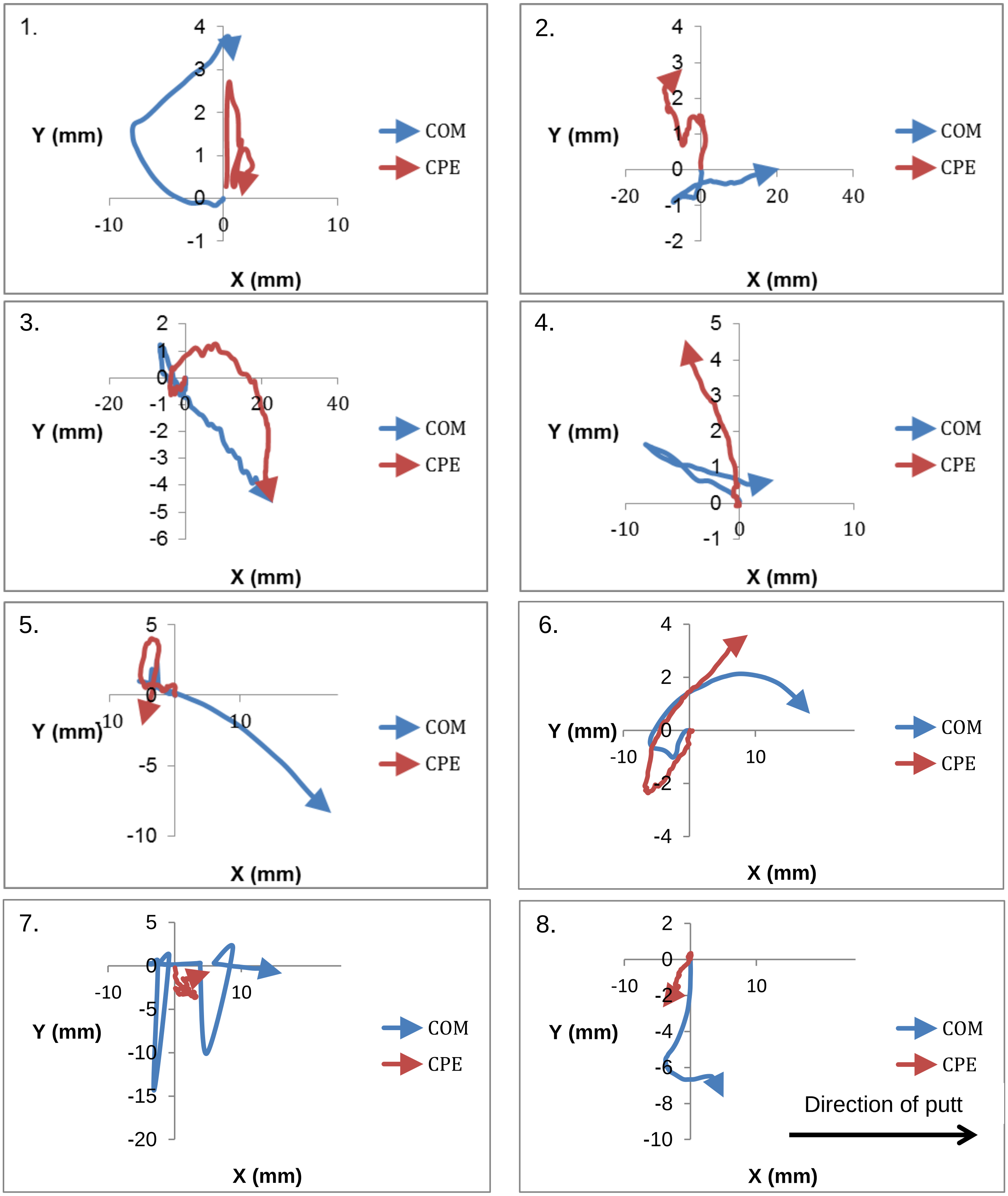


Correlation coefficients between the left and right forearm, pelvis and trunk Z rotations. (P = participant). (All relationships significant excluding participant six, $p < .01$).

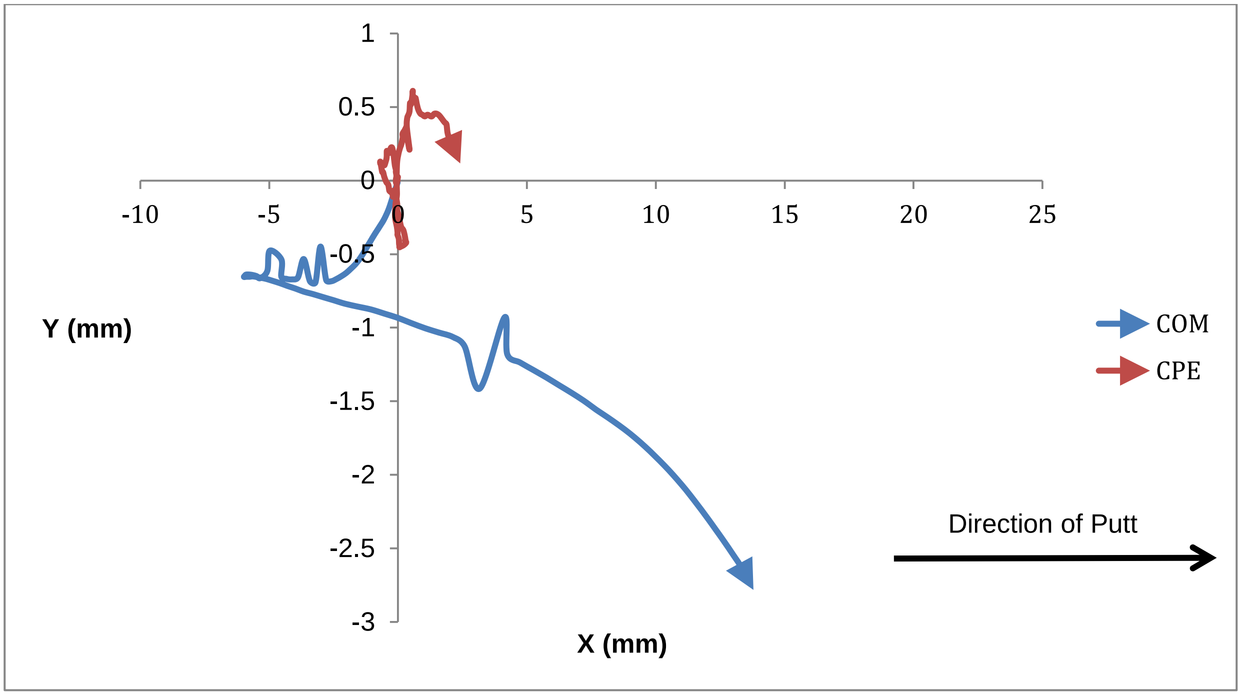


Correlation coefficients between the left and right forearm, pelvis and trunk segments and putter Z rotations. (P = participant). (All relationships significant excluding participant six, $p < .01$).

Appendix I – Figures demonstrating relationship between COM displacement and CP excursions



Time-normalised relative COM and CP excursion displacement patterns for participants one – eight. Axis Y denotes displacement in the anterioposterior direction and axis X denotes displacement in the mediolateral axis.



Mean time-normalised relative COM and CP excursion displacement patterns. Axis Y denotes displacement in the anterioposterior direction and axis X denotes displacement in the mediolateral axis.