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An Investigation of Technique and Equipment Factors Associated with Clubhead Speed in Golf

Christopher Joyce
Edith Cowan University

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Christopher Joyce
Edith Cowan University, c.joyce@ecu.edu.au

School of Exercise and Health Sciences

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Christopher Joyce

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Student:	Christopher Joyce 2011023
Supervisors:	Dr. Jodie Cochrane
	Associate Professor Angus Burnett

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USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

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Signature

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ABSTRACT

If golfers achieve long hitting distances whilst maintaining their accuracy they will gain a competitive advantage. To increase hitting distance, faster clubhead speed is required and this can potentially be achieved through a number of factors. Firstly, anthropometric factors such as height and physical factors such as trunk rotational power have been previously considered to be of importance. However, biomechanical factors such as; the X-factor (separation of the trunk-pelvis alignment when viewed in the transverse plane), have been a major focus of recent research. Further, the interaction of the golfer with the implement they hit with i.e. the golf club has also been examined in biomechanical studies. The broad aim of this doctoral research was to investigate how male high-level amateur golfers generate club head speed and this was examined in a series of five studies that examined technical and equipment factors.

The first study of this thesis (Study I) developed a valid three-dimensional Cardan / Euler model to examine the kinematics of the trunk and lower trunk during the golf swing. This validation study involved; developing and validating models and related algorithms as well as making comparisons to static and dynamic postures. It was concluded that a lateral bending / flexion-extension / axial rotation (ZYX) order of rotation was the most suitable to quantify the X-factor and lower trunk movement in the golf swing.

Previous research has shown conflicting relationships between golf swing kinematics (such as variables related to the X-factor) and clubhead speed, as well as what physical variables assist in generating clubhead speed. The second study of this thesis (Study II) had two aims.

The first aim was to determine whether significant between-club (driver and five-iron) differences existed for trunk and lower trunk kinematics as well as launch conditions. The second aim was to determine which anthropometric, physical and trunk and lower trunk kinematic variables were most strongly associated with clubhead speed. Fifteen high level amateur male golfers (2.5 ± 1.9 handicap) had their trunk and lower trunk three-dimensional kinematics data quantified using the methods developed in Study I. Nine significant ($p < 0.002$) between-club differences in swing kinematics were found; namely trunk and lower trunk flexion and lower trunk axial rotation, as well as ball velocity. Regression analyses explained 33.7 % and 66.7 % of the variance in clubhead speed for the driver and five-iron respectively, with both trunk and lower trunk variables showing associations with clubhead speed. No anthropometric (i.e. height) or physical (i.e. maximum trunk rotational speed) were associated with clubhead speed.

The low amount of variance explained by clubhead speed for the driver in Study II stimulated further investigation. Studies III and IV were designed to develop a method to locate the kick point during the golf swing and examine the effect of kick point location on swing parameters and their related launch conditions, respectively. Study III involved two phases, Firstly, the level of agreement between two methods of determining the static kick point was determined. This showed that an algorithm using three-dimensional locations of markers placed on the golf club was a valid method to determine the location of the static kick point. In the second phase of testing, this method was used to determine the location of the dynamic kick point during the golf swing. Excellent between-trial reliability was found for this method. Further, differences were found for the dynamic kick point location when compared to the static kick point location.

The main objective of Study IV was to determine whether drivers fitted with shafts having high and low kick points would alter selected swing parameters, and related launch conditions. Twelve high level amateur male golfers (1.2 ± 1.8 handicap) had three shots analysed for each of two drivers fitted with “stiff” shafts but these drivers had differing kick point location. Stiffness profiles of these shafts were also measured. Five swing parameters and their related launch conditions were measured using a real-time launch monitor. The driver fitted with the shaft containing the high kick point displayed a more negative (steeper) angle of attack, a lower launch angle and an increased spin rate when compared to a driver fitted with a low kick point

In Study II, a relatively small amount of variance in clubhead speed was explained by the driver and it was the overall intention of the last study of this thesis (Study V) to attempt to explain more of this variance by examining both trunk and wrist kinematics. This was undertaken using two drivers containing differing kick point locations (low and high), with two separate regression models being produced. Twenty high-level amateur male golfers (1.9 ± 1.9 handicap) had their trunk and lower trunk three-dimensional kinematics data quantified as in Study II, but with the addition of a wrist segment. Four significant ($p < 0.003$) between-driver differences were found, although only two of these variables showed to have practical relevance; a slower trunk axial rotation velocity, and a more delayed release (un-cocking) of the wrist during the downswing for the driver fitted with the high kick point shaft. Regression analysis explained 60 % and 67 % of the variability in clubhead speed for the low and high kick point drivers respectively, with lower trunk and wrist kinematics showing significant associations with clubhead speed. In the regression models two of the four variables for the low kick point driver and three of the four variables for the high kick point driver were related to the wrist segment. This showed the importance of the wrist joint during the downswing when attempting to maximise clubhead speed.

In conclusion, the methods developed for this thesis to analyse golf swing kinematics revealed a greater insight into how highly skilled golfers produce clubhead speed. Particularly, the results from Studies II and V revealed significant associations between lower trunk related variables and clubhead speed when using different clubs (driver vs. five-iron) and the same club fitted with two shafts of different kick point location (driver). Also, the methods developed in Studies III and IV to investigate dynamic shaft profiles (deflection) in the downswing provided possible explanations as to how shaft performance in the downswing can influence swing parameters and their related launch conditions at ball impact.

PUBLICATIONS RELATED TO THESIS

Joyce, C., Burnett, A., & Ball, K. (2010). Methodological considerations for the three-dimensional measurement of the X-factor and lower trunk movement in golf. *Sports Biomechanics, 9,* 206-221.

Joyce, C., Burnett, A., & Herbert, S. (2012). The effects of the deflection point and shaft mass on swing and launch parameters in the golf swing. In: *Proceedings of the 30th International Conference on Biomechanics in Sports* (Eds. Bradshaw, L., Burnett, A., & Hume, P.), Melbourne, Australia, July 2 - 6, International Society of Biomechanics in Sport. pp. 88-91.

Joyce, C., Burnett, A., Ball, K., & Cochrane, J. (2013). Three-dimensional trunk kinematics in golf: between-club differences and relationships to clubhead speed. *Sports Biomechanics, 12*, 108-120.

Joyce, C., Burnett, A., & Matthews, M. (2013). A new method to identify the location of the kick point during the golf swing. *Journal of Applied Biomechanics*, *29*, 779-784.

Joyce, C., Burnett, A., Herbert, S., & Reyes, A. (2014). A dynamic evaluation of how kick point location influences swing parameters and related launch conditions. *Proceedings IMechE Part P: Journal of Sports Engineering & Technology*, *228*, 111-119.

Joyce, C., Burnett, A., Cochrane, J., & Reyes, A. (2014). Trunk and wrist kinematics when maximising clubhead speed: Effect of changing the kick point. (In Review – International Journal of Sports Science & Coaching).

LIST OF ABBREVIATIONS

1 RM	One repetition maximum
2D	Two dimensional
3D	Three dimensional
BI	Ball impact
CMC	Coefficient of multiple correlation
EI	Flexural rigidity
HC	Handicap
HKP	High kick point
HLA	High level amateur
ICC	Intra-class correlation coefficient
JCS	Joint coordinate system
LKP	Low kick point
PGA	Professional golfers association
ROM	Range of motion
SEM	Standard error of measure
SKP	Static kick point
TOB	Top of backswing
USGA	United states golfers association
X-factor	Shoulder – pelvis separation angle (transverse plane)

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CHAPTER 1

INTRODUCTION

1.0 Chapter Overview

This Chapter contains a review of literature relating to the factors that may contribute towards producing clubhead speed in golf. These factors will be discussed in four broad sections (Sections 1.2 to 1.5) focusing on i) the golf swing, ii) the golfer, iii) the golf club, and iv) swing parameters (club) and related launch conditions (ball). The relationship between these factors is also discussed throughout. The opening section (Section 1.2) introduces the golf swing, and the role of clubhead speed in producing ball velocity and ultimately, ball distance. Section 1.3 describes factors that affect the production of clubhead speed, and includes; ability of the player (as determined by handicap), golf swing technique (classic and modern), and the golfer's kinematics. The role that anthropometric and physical traits golfers possess and how they may contribute to optimising clubhead speed are also discussed. Section 1.4 then presents the role the golf club may have in optimising ball velocity through the generation of clubhead speed. This section will present how specific properties of golf clubs can be modified. This information may be used to select various clubs for golfers so they are theoretically capable of optimising their golf swing and subsequent swing parameters and related launch conditions, relating to the ball. Section 1.5 then describes swing parameters and their related launch conditions, and how they may influence, and relate, to each other. The interaction between the golfer and the golf club is also discussed in this section so an understanding can be gained on how the player and striking implement may potentially influence each other.

The overarching objective of the thesis and the specific aims of the five studies within it are presented in Section 1.6 then the limitations and delimitations of these five studies are outlined (Section 1.7). The Chapter concludes with the significance of the thesis (Section 1.8).

1.1 Overview of the Game of Golf

The game of golf has evolved since its professional inception in 1901 as the Professional Golfers' Association (PGA) of Great Britain and Ireland (Vamplew, 2008). At the turn of the 21st century, 30,000 golf courses were thought to exist and at that time it was also believed that there were 55 million participants of all ages and abilities worldwide (Farrally et al., 2003).

Golf is a sport where physical, technical, equipment and psychological factors all combine to contribute towards performance (Hellstrom, 2009). With respect to the technical aspect of the game, the success of a golfer may be attributed to their long game (hitting off the tee or fairway) and also their short game (chipping and putting) (Doan et al., 2006; Hellstrom, 2009; Keogh et al., 2009). The aim of driving from the tee is to hit the ball with maximum distance and sufficient accuracy, so that the distance that the subsequent approach shot needs to be hit can be minimised and that the shot to the pin can be hit from the fairway. Driving distance and driving accuracy have been found to be stronger predictors of lower scoring average when compared to driving distance alone (Davidson & Templin, 1986; Belkin et al., 1994; Dorsel & Rotunda, 2001; Wiseman & Chaterjee, 2006).

1.2 The Golf Swing

Driving distance of professional golfers on the PGA Tour increased linearly over 20 years to 2005, with driving accuracy being relatively constant (Alexander & Kern, 2005; Wiseman & Chaterjee, 2006). This indicates that the approach shots to the green for elite players potentially become easier, although the greens in regulation statistics (landing on the green within the expected number of shots) have remained unchanged over 20 years (Wiseman & Chaterjee, 2006). The main reason for this being the case is that as elite golfers are increasing their driving distance, courses have been lengthened to maintain difficulty. For example, the Augusta National course had an extra 300 yards added to its original length (Alexander & Kern, 2005). For this reason, it still remains advantageous for golfers of all abilities to maximise clubhead speed through their golf swing to achieve maximum driving distance. Investigations suggest that clubhead speed at impact is the primary factor in determining the length of a shot and, each percentage gained in clubhead speed will result in a corresponding percentage increase in hitting distance (Penner, 2003; Fradkin et al., 2004; Wiseman & Chaterjee, 2006; Arnold, 2010). This is providing all other launch parameters remain equal. Specific details on the relationship between these two variables are discussed in more detail in Section 1.5.

Whilst the golf ball can be hit with either a driver or iron when playing off the tee, or from the fairway, there are common elements to the golf swing regardless of the club that is being used. Every drive or approach shot may be considered as having six phases and as Figure 1.1 shows these phases are: the set-up, backswing, top of backswing, downswing, ball impact and follow-through (Maddalozzo, 1987). These movement patterns, utilised for metal woods (i.e. driver) and irons, typically show low between-swing variability for highly skilled golfers who play with a low handicap (Egret et al., 2003; Langdown et al., 2012). A skilled golfer will also consistently produce desired shot outcomes but these outcomes will be dependent upon club selection, due to there being between-club differences (e.g. shaft length, angle of clubface) and the role that each club is used for in the game (Egret et al., 2003; Wallace et al., 2007; Worobets & Stefanyshyn, 2007; Kenny et al., 2008a; Wells et al., 2009). For instance, hitting the golf ball with a driver results in significantly greater ball velocities and carry distances when compared to using an iron (Egret et al., 2003). The differing properties of drivers and irons are discussed in detail in Section 1.4.

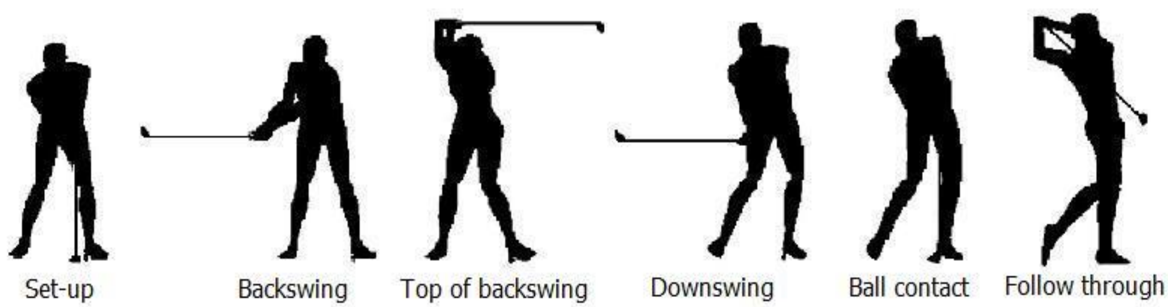

Figure 1.1 Events of the golf swing (Maddalozzo, 1987).

The golf swing involves the sequencing of a number of the body's segments to maximise ball velocity at impact. The biomechanical principle underlying this motion is termed “summation of velocity” and this is also evident in a number of striking/throwing activities such as the tennis serve and baseball pitching (Zatsiorsky, 2008) where larger, proximal segments (i.e. trunk) tend to proceed in a sequential manner to the smaller, more distal segments (Putnam, 1993). The purpose of the backswing is to position the body and the club in optimal postures so that the club can be accelerated through the downswing to impact (Maddazallo, 1987; Hume et al., 2005). In the downswing, a number of the body’s segments are then summated to maximise clubhead speed at impact (Putnam, 1993; Bechler et al., 1995; Zheng et al., 2008). Golfers initiate the downswing via hip and trunk rotation then they allow the arms and club to follow through to the completion of the swing (Watanabe et al., 1999; Gluck et al., 2007; Wallace et al., 2007). This is discussed further in Section 1.3.

There are considered to be two broad classifications of golf swing; the “classic” swing and the “modern” swing. Both swings have evolved in a bid to improve shot distance (McHardy et al., 2006; Gluck et al., 2007) and the “modern” swing has done this by increasing the amount of shoulder turn. The modern swing is also typified by restricted hip movement in the backswing, and therefore when compared to the classic swing a larger shoulder-pelvic segment separation (also known as the ‘X-factor’) occurs (Bulbulian et al., 2001; Cheetham et al., 2001; Gluck et al., 2007). Recent work has reported that a significant positive relationship exists between shoulder-pelvic segment separation and both ball velocity and driving distance (Myers et al., 2008; Hellstrom, 2009). Conversely, the classic swing, in which the heel of the forward foot is lifted, permits greater pelvic rotation in the backswing, resulting in a lesser magnitude of shoulder-pelvic segment separation (McHardy et al., 2006; Gluck et al., 2007). This smaller shoulder-pelvic segment separation is believed to adversely affect clubhead speed (Bulbulian et al., 2001; Gluck et al., 2007). Interestingly, there has been a surge of interest on the methods used to quantify shoulder-pelvic segment separation (Kwon et al., 2013) and this is discussed further in Sections 1.3.2 and 1.3.3.

1.3 The Golfer

The purpose of the majority of simulation and experimental investigations into golf swing biomechanics has been undertaken to quantify kinematic and kinetic variables that explain the most influential variables that generate clubhead speed (Watanabe et al., 1999; Keogh et al., 2009; Chu et al., 2010). This has been examined in players of all abilities. With clubhead speed seen as a key factor in determining ball velocity and influencing driving distance (Penner, 2003; Fradkin et al., 2004; Wiseman & Chaterjee, 2006; Arnold, 2010), the need to understand what kinematic variables relating to the golfer contribute to generating clubhead speed is important.

1.3.1 The Golfer's Ability - Handicap

Golfing handicap is the standard measure of a golfer's performance and it takes into account overall performance relating to their long game, short game and putting performance (Fradkin et al., 2004; Hellstrom, 2009). Golfers who possess a low handicap can generate fast clubhead speeds in a consistent manner and also exhibit greater driving ability off the tee. These are the most valid indicators of performance measures in golf (Fradkin et al., 2004; McHardy et al., 2006; Gluck et al., 2007; Horan et al., 2010). Fradkin et al. (2004) found clubhead speed to be highly correlated with golfing handicap ($r = 0.950$).

Golfers who participate in National Tour competitions such as the PGA and European PGA Tours are classified as elite (Robertson et al., 2013). Due to their travel commitments these players are therefore, difficult to recruit in research studies. Hence it is not surprising that experimental studies have typically recruited players who are classified as high level amateurs, who display a registered handicap of less than 5 (Robertson et al., 2013). The clubhead speeds of high level amateur golfers have previously been shown to be faster than golfer having a higher handicap (Fradkin et al., 2004). Further, driving ability (distance and accuracy or, total driving) has been shown to reduce the spread of shot dispersion on a fairway therefore, improving green in regulation ability (Wiseman & Chatterjee, 2006; Kenny et al., 2008a).

1.3.2 The Golfer's Technique - Kinematics

Both simulation and experimental studies which have compared golfers of low and high handicap, seem to agree with the idea that between-swing variability in kinematics is relatively low for golfers possessing a low handicap (Bradshaw et al., 2009; Langdown et al., 2012). Also, the golf swing kinematics for elite and high level amateur golfers have been shown to be comparable to one another, but significantly different to those of mid and high handicap golfers (Zheng et al., 2008). This helps to explain why high level amateur golfers can consistently produce optimal swing parameters and related launch conditions required for faster clubhead speed and accurate shot making (Bradshaw et al., 2009; Sweeney et al., 2013).

The examination of summation of body segments throughout the golf swing may provide some explanation behind the efficiency of the golf swing and how shot outcomes may be influenced (Milburn, 1982). The concept of the summation of segments principle seems to have support from previous work investigating high level amateur golfers. Specifically, previous studies investigating this group have reported faster, and less variable movement patterns such as maximal trunk rotational velocity (Cheetham, et al., 2001; Myers et al., 2008; Zheng et al., 2008; Langdown et al., 2012), and leading wrist velocities (Sprigings & Neal, 2000; Nesbit & Serrano, 2005; Sweeney et al., 2012) either at, or just before impact. Not only have faster segment velocities been reported for high level amateur golfers when compared to amateurs possessing a higher handicap, but there is also believed to be less variability in swing kinematics (Langdown et al., 2012). Cheetham et al. (2008) found that when comparing high level amateur and high-handicap golfers, the high-handicap golfers displayed non-optimal proximal to distal sequencing, with the arm velocity reaching a maximum before thorax velocity peaked. Efficient movement patterns during the downswing of high level amateur golfers are typified by faster thorax rotation when compared to the pelvis and also a strong ‘coupling’ between the thorax and pelvis segments (Horan & Kavanagh, 2012). This coupling may explain in part, the low variability in high level amateur kinematics, i.e. producing a highly repeatable, simplified motor control strategy to produce the same shot outcome, every shot (Bradshaw et al., 2009; Horan & Kavanagh, 2012; Langdown et al., 2012).

In comparison to high handicap players, the between-club differences in the golf swing kinematics of high level amateur golfers and their contribution to producing clubhead speed are less understood (Chu et al., 2010). Egret et al. (2003) examined whether between-club (driver, five-iron and pitching wedge) differences in swing kinematics and clubhead speed existed in seven players with very low handicaps (0-3). Differences between-club were found for swing timing ($p < 0.05$), with equal time spent on the backswing with the driver and the pitching wedge. Further, significantly greater clubhead speeds were developed using the driver when compared to the five-iron, as well as for the five-iron when compared to the pitching wedge. These latter findings were in agreement with previous experimental and simulation studies which have found between-club differences in clubhead speed (Libkuman et al., 2002; Kenny et al., 2008; Wells et al., 2009). The majority of experimental golf swing investigations have focused on analysing the golfer's kinematics when using the driver, and how golfers produce faster clubhead speeds (Chu et al., 2010). To the author's knowledge, no previous investigations have explained how faster clubhead speeds are produced when using an iron, rather these studies have only described the differences in kinematics between the driver and iron (Libkuman et al., 2002; Egret et al., 2003; Kenny et al., 2008; Wells et al., 2009).

One of the most extensively investigated kinematic phenomena in golf is the so called 'X-factor' (Cheetham et al., 2001; Lephart et al., 2007; Myers et al., 2008; Horan et al., 2010; Kwon et al., 2013). During the backswing, the shoulders of the golfer are rotated further away from the target than the pelvis (Myers et al., 2008). The resulting separation of the shoulder - pelvic alignment at the top of the backswing is referred to as the "X-factor" (McLean, 1992; Hume et al, 2005; Gluck et al, 2007). Experimental research tends to support the idea that high level amateur golfers who use a modern swing exhibit faster clubhead speeds (Fradkin et al., 2004). Further, high level amateur golfers tend to display an increased magnitude of the X-factor when than high-handicap golfers (Burden et al., 1998; Cheetham et al., 2001; Myers et al., 2008; Zheng et al., 2008). Another variable that is worthy of investigation is the X-factor stretch. This refers to the point after the top of the downswing where the shoulder-pelvis separation angle is maximised as the pelvis is known to counter-rotate prior to the shoulders (Cheetham et al., 2001). Maximising the X-factor may increase the potential to utilise the stretch shortening cycle during the golf swing and this has possible implications for increasing clubhead speeds and hitting distance (Cheetham et al., 2001; Myers et al., 2008). The X-factor stretch (Cheetham et al., 2001), has been found to be significantly larger in high level amateur players when compared to those with a higher handicap (Cheetham et al., 2001; Myers et al., 2008). Table 1.1 describes the various experimental studies that have investigated the X-factor, and this table also reports the findings for golfers of varying ability.

There has been recent interest in the role that the wrist plays in generating clubhead speed. Whilst early anecdotal evidence suggested that a “fixed” wrist position (Leadbetter, 1990; Wiren, 1990) may be effective when attempting to generate clubhead speed, subsequent simulation and experimental investigations have suggested that ‘un-cocking’ of the wrist (wrist flexion and ulnar deviation) of the lead arm during the downswing can influence clubhead speed (Sprigings & Neal, 2000; Teu et al., 2006; Suzuki et al., 2009; Sweeney et al., 2012). High level amateur golfers who utilise a late “release” of the wrist (i.e. the wrist will be radially deviated at the start of the downswing, and the point at which ulna-deviation begins is the ‘point of release’ (Sweeney et al., 2012) may in fact, increase their clubhead speed between 9-46 % (Sprigings & Neal, 2000; Sweeney et al., 2011; Fedorcik et al., 2012). Exactly how a low handicap golfer uses their wrist release to derive optimal launch conditions is not well understood. Further, more needs to be known regarding between-club differences exist in the timing of wrist release. Recent experimental investigations into the role of wrist kinematics and their role in producing clubhead speed are shown in Table 1.2.

Table 1.1 Experimental studies using various methods to quantify the X-factor, and their reported findings.

Study	Subjects	Methods	Findings
McTeigue et al. (1994)	131 males (51 US PGA, 46 Senior US PGA and 34 amateur) Mean age unknown 17.5 ± 18.5 HC	XF defined as the differential of the relative rotation of the shoulders to the hips. Data collected at 100 Hz from a rate gyroscope with six precision potentiometers placed on the posterior thoracic spine and pelvis.	US PGA subjects had an averaged XF of 87°, 78° Senior US PGA and 87° amateur. XF-stretch largest with PGA subjects (70 %). DD related to XF with top 10 PGA subjects showing larger XF than other subjects.
Cheetham et al. (2001)	19 males Mean age unknown 0 HC (10 subjects) 15 + HC (9 subjects)	XF defined as difference between the rotational position of the pelvis and T3 sensors at all points during swing. Data collected using electromagnetic sensors placed at two positions, sampling at 30 Hz.	XF not significantly* different for two groups. 0 HC group showed higher values of XF-stretch (19 %) than 15+ HC group (13 %).
Wheat et al. (2007)	10 males Mean 28.5 yrs < 18 HC	XF quantified by comparative methods of transverse plane projection of separation angle of upper thorax (C7, sternum, T8, xiphoid process, bilateral acromion processes) and pelvis (bilateral ASIS), as well as Cardan angles. Data collected using optoelectronic system sampling at 300 Hz.	XF similar (r = 0.97) for transverse angle projection and Cardan angles at set-up. Not similar at top of backswing (r = 0.32). Comments that transverse angle projection should not be used to estimate thorax alignment in the golf swing.
Myers et al. (2008)	100 males 45.1 ± 15.9 yrs 21 HBV 65 MBV 14 LBV	XF defined as the difference in angle between upper torso vector and pelvis (light reflective markers positioned; sacrum and bilaterally ASIS – pelvis, and C7 and bilaterally acromion – upper torso). Data collected using optoelectronic system sampling at 200Hz.	HBV groups had significantly* larger XF and XF-stretch than slower BV groups.
Horan et al. (2010)	19 males 26 ± 7 yrs (< 4 HC) 19 female subjects 25 ± 7 yrs (< 4 HC)	XF defined by Cardan angles of upper thorax (C7, clavicle, sternum and T10) and pelvis (bilateral PSIS and bilateral ASIS). Data collected using optoelectronic system sampling at 500 Hz.	No significant* differences in male and female XF. Cardan method reports XF not as important at < clubhead speed, rather, weight transfer and segment summation.
Kwon et al. (2013)	18 males 31.7 ± 10.4 yrs -0.6 ± 2.1 HC	Comparison of conventional projected plane XF to Cardan rotation-based method. Data collected using optoelectronic system sampling at 250 Hz.	XF not significantly** correlated to maximum clubhead speed in homogenous groups. Projected plane methods questionable at reporting < clubhead speeds for < XF.

XF = X-factor, HC = Handicap, HBV = high ball velocity, MBV = medium ball velocity, LBV = low ball velocity, BV = ball velocity, $*p < 0.05$, $**p < 0.001$.

Table 1.2 Simulation and experimental studies explaining the importance of wrist mechanics in producing clubhead speed.

Study	**Subjects**	**Methods**	**Findings**
Neal & Sprigings (2000)	None (simulation)	Simulation study using a 2D, three-segment model of the arm to create torque generators that adhered to force-velocity properties of upper limb musculature.	Maximal CHS achieved with sequential proximal to distal segment action. Specifically gains in CHS of 9 % achieved when wrist torque activated in latter stages of downswing.
Nesbit & Sorano (2005)	3 males, 1 female 21-42 yrs, 31 yrs 0-13 HC, 18 HC	Full body 15 segment simulation kinematic and kinetic model applied to human testing.	Wrist torque more active in lower handicap subjects, who produce faster CHS.
Teu et al. (2006)	1 male Single figure HC, semi professional	Experimental single subject using Cardan angles to model the left (leading) upper limb.	Highest angular velocity recorded for the wrist joint from all upper limb joints. Wrist "un-cocking" in the latter downswing second biggest predictor of CHS.
Suzuki et al. (2009)	Unknown	Simulation model comparison of 'natural' and 'late-hitting' (un-cocking), confirmed with experimental results.	"Late-hitters" use the contribution of other body segments to delay wrist release and promote faster CHS at impact.
Fedorcik et al. (2012)	15 males (0-5 HC) 13 males (≥ 10 HC)	Experimental marker placement of lower arm and hand to define wrist angle differences in radial deviation for low vs. high handicap players.	Peak radial deviation values and at ball impact were significantly* higher for higher handicap players.
Sweeney et al. (2012)	10 males 2.7 ± 1.6 HC	Experimental marker placement of lower arm and hand to define wrist angle changes in flexion and ulnar deviation in the downswing.	Lead (left) wrist underwent 46° (±10) of flexion, 44° (±10) ulnar deviation in the downswing.

HC = handicap, CHS = clubhead speed, * = significance value (p) set at $p \leq 0.001$

1.3.3 Kinematic Data Collection and Analysis Techniques

With the development of biomechanical measurement technologies from predominantly two-dimensional to three-dimensional methods over the last 15 years, the ability to accurately quantify complex movements such as the golf swing has improved. The magnitude and timing of the X-factor and wrist movement and their relationship to clubhead speed and ball velocity has been examined using various methodological approaches (Cheetham et al., 2001; Lephart et al., 2007; Myers et al., 2008; Hellstrom, 2009; Horan et al., 2010). Arguments against a two-dimensional approach for quantifying the X-factor (i.e. in the transverse plane) have been put forward because as well as the trunk being axially rotated it can also be laterally bent, flexed and extended (Hsu et al., 2008; Hellstrom, 2009; Horan et al., 2010). This results in movements being measured out of plane.

The use of high-speed optoelectronic devices to quantify three-dimensional golf swing kinematics is now common place in golf biomechanics (Egret et al., 2003; Egret et al., 2006; Lephart et al., 2007; Wheat et al., 2007; Myers et al., 2008; Zheng et al., 2008, Horan et al., 2010). These systems allow the use of customised modelling which involves placing light reflective markers over a series of anatomical locations to quantify kinematic and kinetic variables (Nesbit & Sorano, 2005; Suzuki et al., 2009). However, as seen in Table 1.1, few authors are using a true three-dimensional method to quantify three-dimensional kinematics in golf. Rather, raw three-dimensional data is collected and angles (i.e. joint separation angles) are determined by projecting angles in the transverse plane (Lephart et al., 2007, Myers et al., 2008). These differing methods may be problematic in obtaining consistent findings in studies investigating potential relationships with shot outcome parameters such as clubhead speed and ball velocity (Brown et al., 2013; Kwon et al., 2013). Regardless of reporting the X-factor using a projected plane (Myers et al., 2008) or Cardan angle (Horan et al., 2010) method, research has failed to establish a direct link between the X-factor and clubhead speed. Using what is essentially a two-dimensional method to determine the magnitude of the X-factor, there has been a difference in typical values reported for this variable. For example, Burden et al. (1998) found an average X-factor of 110°, with one subject displaying 130° when quantifying X-factor using the projected plane method. These values are on average 20° greater than X-factor values found in USPGA professionals as found using electromagnetic sensors placed along the spine (McTeigue et al., 1994).

As previously mentioned, strong and positive relationships have been reported between the magnitude of the X-factor and both clubhead speed and ball velocity (Lephart et al., 2007; Hellstrom, 2009). However, the numerous studies that have quantified the X-factor through three-dimensional modelling of the segments involved, have actually utilised methods that could be considered as dissimilar (Brown et al., 2013; Kwon et al., 2013). As reported in Table 1.1, Horan et al. (2010) and Kwon et al. (2013) used modern Cardan angle methods to determine X-factor. Both authors reported no correlation between X-factor and clubhead speed. Horan et al. (2010) concluded that weight transfer and summation of segments were more important in generating clubhead speed, that the position of the body at the top of the backswing. This may possibly affect the strength of the X-factor – clubhead speed relationship. A second explanation which could affect the X-factor – clubhead speed relationship may be the heterogeneous cohorts used in previous studies (Kwon et al., 2013). Kwon et al. (2013) reported a non-significant relationship for a homogenous cohort between X-factor and clubhead speed. It was suggested that X-factor be used to assess a golfers' skill level rather than relating to clubhead speed as heterogeneous groups displayed varied swing styles that influence X-factor and clubhead speed.

With reference to measuring wrist kinematics, experimental studies have shown consistent findings, specifically for more skilled golfers who show a more delayed un-hinging or, release of the wrist than lesser skilled golfers (e.g. Sprigings & Neal, 2000; Sweeney et al., 2012). However, potential inhibition of natural wrist movement by the obstruction of anatomical retro-reflective marker placement in the golf swing requires the use of ‘virtual markers’ as described elsewhere (Cappozzo et al., 1996). Using this approach involves a static calibration trial being recorded which has the participant being “marked up” with an anatomically placed marker set, as well as a ‘cluster marker set’ (often three to four markers positioned on a rigid base). The anatomical markers are then removed for subsequent dynamic trials. From recent experimental investigations into the importance of wrist kinematics during the golf swing (Sweeney et al., 2011 & 2012), similar methods seen in Table 1.2 may help to explain the comparable between-study findings.

1.3.4 The Golfer’s Anthropometric and Physical Traits

A recent review of literature revealed that faster clubhead speeds are associated with golfers who are flexible, strong and have good balance (Hellstrom, 2009). Further, high level amateur golfers who generate faster clubhead speeds may be taller, and have longer upper limbs when compared to those with higher golfing handicaps (Yoon et al., 1998; Kawashima et al., 2003). However, whilst having longer upper limbs may be advantageous for creating clubhead speed, the related moment of inertia may be such that is effects clubhead speed (Penner, 2003). Interestingly, upper limb length explained only 5 % of the variance in clubhead speed in previous work (Keogh et al., 2009) with a greater amount of variance explained by a high level amateur golfer's physical characteristics such as strength and rotational power.

Studies that have assessed physical characteristics and their relationship to golfing performance (i.e. total driving) have focused on physical performance and improving physical capacities (Fletcher & Hartwell, 2004; Doan et al., 2006; Lephart et al., 2007; Gordon et al., 2009; Hellstrom, 2009). Table 1.3 summarises these studies, and shows positive effect on golfing performance. Most researchers agree that flexibility and the ability to increase the range of motion (ROM) of the body segments related to the backswing, most importantly; axial rotation to the ipsilateral side, is important in achieving greater clubhead speeds (Doan et al., 2006; Lephart et al., 2007; Gordon et al., 2009; Moran et al., 2009). Conditioning programs that focus on improving flexibility (Doan et al., 2006) have yielded a 14.8 % increase in ipsilateral axial rotation, which equated to a significant ($p < 0.05$) change in clubhead speed of 1.6 %.

Strength has also been reported to be a strong indicator of clubhead speed (Lephart et al., 2007; Hellstrom, 2009). Differences in levels of strength between low and high handicap golfers has been examined (Keogh et al., 2009) and low handicap golfers (0.3 ± 0.5) demonstrated a 30 % greater upper body strength and this group had 12 % faster clubhead speeds when compared to subjects with a higher handicap (20.3 ± 2.4). Fletcher and Hartwell (2004) noted a 1.5 % increase in clubhead speed, and a 4.3 % increase in driving distance after completing an eight week periodised strength and power conditioning program, but they did not report on changes in axial rotation ROM. Lephart et al. (2007) completed a similar eight week conditioning program and although it was stated the program had similar increases in clubhead speed (5.2 %) and driving distance (6.8 %), decreases in ROM values for right axial rotation (-3.8 %) were found post-training. However, an increase in torso-rotational power (7.0 %) was the most likely reason for improvement in shot outcomes. Rotational power of the torso was also examined by Doan et al. (2006) and the authors found that; levels of this variable increased by 19.9 %, strength gains of 13 % (1RM squat) and 10.2 % (1RM bench press) and axial rotation ROM increased 14.8 %. Interestingly, a 1.6 % change in clubhead speed and 4.9 m increase in driving distance resulted. As described in Section 1.3.2, high level amateur golfers who display faster trunk segment rotational velocities can generate faster clubhead speeds (Lephart et al., 2007). Therefore, it is not surprising that high level amateur golfers exhibit physical traits such as greater strength and flexibility when compared to those with higher handicaps.

Table 1.3 Investigations examining correlations of anthropometric and physical conditioning methods with clubhead speed.

Study	Subjects	Methods	Findings
Yoon (1998)	41 males >3 HC	Single testing session to analyse correlations of anthropometric, strength and power variables to CHS.	CHS correlated with rotational power (r = 0.80), height (r = 0.51), arm length (r = 0.45).*
Kawashima et al. (2003)	128 males 11 professional 117 high level amateur to novice	Somatotype classification Anthropometric variables (girths, skinfolds, limb lengths).	Professional and high level amateurs had a mesomorphic somatotype and larger limb girths.*
Fletcher and Hartwell (2004)	11 males 29 ± 7.4 yrs 5.5 ± 3.7 HC	8 week strength and plyometrics program.	1.5 % increase in CHS and 4.3 % Increase in DD. No reported change in ROM.*
Doan et al. (2006)	10 males (19.8 ± 1.7 yrs, 0 HC) 6 females (18.5 ± 0.8 yrs, 5-10 HC)	11 week strength, power and flexibility program.	1.6 % increase in CHS, 4.9 m increase in DD. 10.2 % increase in Bench Press 1RM, 13.3 % increase in Squat 1RM, 14.8 % increase in right axial rotation flexibility.*
Lephart et al. (2007)	15 males 47.2 ± 11.4 yrs 12.1 ± 6.4 HC	8 week strength, flexibility and balance program.	5.2 % increase in CHS. Significant changes in whole body torque values, ROM and balance values.*
Gordon et al. (2009)	15 males 34.3 ± 13.6 yrs ≤ 8 HC	Single testing session to analyse correlations of strength, power and flexibility to CHS.	CHS correlated to chest strength (r = 0.69) and rotational power (r = 0.54).*
Keogh et al. (2009)	20 males 10 Low HC (0.3 ± 0.5) 10 High HC (20.3 ± 2.4)	Flexibility, muscular strength and endurance	Low HC group 12 % faster CHS and 30 % higher bench press strength than High HC group.
Moran et al. (2009)	18 males 23.3 ± 3.2 yrs 3.2 ± 2.3 HC	Dynamic flexibility program.	$1.9 m.s^{-1}$ increase in CHS, $3.5 m.s^{-1}$ increase in BV.*

HC = handicap, CHS = clubhead speed, DD = driving distance, ROM = range of motion, BV = ball velocity, * = significance value (p) set at < 0.05.

1.3.5 Summary points “The Golfer”

The following points summarise the measurement of golf swing kinematics and how golfers of high ability produce fast clubhead speeds. Of importance is how recent Cardan angle methods used to analyse X-factor have found low correlations between X-factor and clubhead speed. Also, if by using these methods, will different kinematic variables be identified as being highly associated with clubhead speed?

- Fast clubhead speeds, and lower variability in swing kinematics are typically seen in low handicap golfers, compared to high handicap golfers.
- Euler / Cardanic three-dimensional methods should be utilised when analysing golf swing kinematics due to combined multiple trunk movement during the golf swing.
- Golfers who demonstrate better physical traits such as increased flexibility and strength have been shown to have faster clubhead speeds.
- Between-club (drivers and irons) differences in golf swing kinematics exist.
- The magnitude of the X-factor and delayed wrist release may be two important variables in explaining variance in clubhead speed for the driver.
- It is unknown if similar, or different variables, may help to explain the amount of variance in clubhead speed in an iron club.
- It is unknown if multi-segment trunk modelling will add extra insight into investigations measuring the X-factor, as recent investigations using Cardan angle methods report low correlations between X-factor and clubhead speed.
- The association between clubhead speed and golf swing kinematics for irons are unknown.

1.4 The Golf Club

Different golf clubs are required for different shot requirements during a round of golf. With putters and short irons (i.e. wedges) being used for low speed / high accuracy such as putting and the short game respectively, the ‘long game’ not only focuses on driving ability from the tee, but also requires long and sufficiently accurate iron shots to be able to reach the green within ‘regulation’ (i.e. within the expected number of shots - Hellstrom, 2009). The design and manufacture of drivers and irons allows for a number of specific modifications to be made in an effort to improve clubhead speed. Further, there are a number of properties of drivers and irons which may assist golfers to optimise their long game potential.

1.4.1 Iron Properties

A golfer’s set of irons generally have consistent characteristics such as clubface size and shaft composition (steel or graphite). However, from a pitching wedge up to a three-iron, there is a decreasing clubface loft and an increasing shaft length (Jackson, 2001). The role of the iron clubs is to reach the green within the required number of shots (i.e. one for a par three, two for a par four, and three for a par five). The choice of which of the iron clubs is used to reach the green depends upon the distance from the green. However, while the iron club may potentially be swung with varying speed with varied irons (3-iron to pitching wedge), elite and high level amateur golfers seem to produce similar swing speed using a long or short iron (Egret et al., 2003). With swing speed being maintained for all clubs, increases in clubhead speed for longer irons and drivers are a result of the increase in angular velocity produced from longer shafts (Lacy et al., 2012) and also the difference in clubface angle of each of the irons would be the main contributors towards launch conditions of the ball (Jackson, 2001; Egret et al., 2003; Poulin et al., 2004). Golfers who hit long, straight drives will tend to use a more lofted and shorter iron to promote increased vertical ball height, a steep angle of descent and a greater spin rate. These factors prevent the ball from rolling excessively away from the intended target when it lands on the green (Jackson, 2001; Poulin et al., 2004). Golfers who hit longer, straighter drives are also more likely to record a lower score (Wiseman & Chatterjee, 2006). Conversely, a golfer who hits their drive a shorter distance from the tee will be required to hit a longer approach iron shot to the green with a less lofted, longer iron. This typically results in lower vertical ball height, a shallower angle of descent and decreased spin rate, and this may result in reduced accuracy when hitting to green (Poulin et al., 2004).

The material that the shaft of the golf club is made from may also influence the launch conditions of the ball. Shafts made from steel allow for reduced bending in the downswing and promote straighter, more accurate ball flights when compared to less stiff graphite shafts as used by golfers with slower swing speeds (Van Gheluwe et al., 1990). A comparison of steel and graphite shafts in five-irons and seven-irons revealed no difference in hitting distance for low handicap golfers, although a difference in hitting distance did exist with a three-wood fitted with a stiff graphite shaft hitting longer than that of the same three-wood fitted with a steel shaft (Van Gheluwe et al., 1990). Another investigation of steel and graphite shafts revealed that drivers fitted with graphite shafts revealed less straight and inaccurate ball flights but increased hitting distance (Pelz, 1990). Both these studies recommended steel shafts for use with irons clubs, as their role requires accurate hitting to smaller greens; however, graphite shafts which tend to bend more than steel shafts, were recommended for woods to promote increased hitting distance to wider fairways (where the accuracy demands are not as great) (Butler & Winfield, 1994; Worobets & Stefanyshyn, 2007).

1.4.2 Driver Properties

With driving distance being a key indicator of lower scoring (Dorsel & Rotunda, 2001; Wiseman & Chatterjee, 2006), the importance of maximising clubhead speed is paramount. The use of graphite shafts has been shown to provide bending profiles in the downswing which can facilitate faster clubhead speeds at impact (Butler & Winfield, 1994). However, there is a slight downside with graphite shafts as they tend to produce shots with less accuracy (Van Gheluwe et al., 1990; Pelz, 1990). Graphite shafts used in modern-day drivers may be manufactured with variable length, qualitative rating of stiffness, flexural rigidity, mass and may also possess a differing location of the maximum deflection point (also termed the kick point) (Wallace & Hubbell, 2001; Brouillette, 2002; Hocknell, 2002; Cheong et al., 2006). These properties of the shaft as well the design of the clubhead are discussed below.

1.4.2.1 The Clubhead

The design of the clubhead in drivers has developed radically since the inception of stainless steel designs in the early 1990's. Since this time, titanium alloy heads have been used. The original size of a stainless steel head was 190 cm^3, although the R&A (Royal & Ancient, Scotland) standards allowed legal limits of 460 cm^3 (R&A, 2014). With larger clubheads came the design of more aero-dynamic heads to help maximise clubhead speed (Jackson, 2001; Hocknell, 2002; Hellstrom, 2009). The flexibility of the clubhead's face has also increased which results in higher coefficients of restitution, which in turn, produces higher ball velocities after impact (Hellstrom, 2009). However, the benefits of faster clubhead speeds with clubfaces of higher restitution are also associated with increased rates of metal fatigue which, over time, reduces clubhead speed. This relationship has been shown to be linear (measured by clubface thickness and coefficient of restitution), as clubfaces producing impact-speeds of 190 km.h^{-1} plus are three times more likely to induce metal fatigue than clubfaces designed to generate impact-speeds of 130 km.h^{-1} (Hocknell, 2002).

1.4.2.2 Club Length

The length is defined as the distance from the point of the intersection between the two planes to the top of the grip, with driver length not allowed to exceed 1.22 m (R&A, 2014). Modifying the length of the club can be undertaken by increasing shaft length (Lacy et al., 2012). Simulation studies using a double-pendulum model (Penner, 2003) have been conducted to determine whether increases in clubhead speed at impact are possible when shaft length is lengthened (Reyes & Mittendorf, 1999; Werner & Greig, 2000). By keeping all other properties of the club fixed, these studies have found significant increases in clubhead speed of 2.4 - 8.5 % and this evidence tends to be supported by experimental studies (Wallace et al., 2007; Lacy et al., 2012). The optimal length of the club was identified by Werner and Greig (2000) to be 1.28 m, when considering driving distance as the outcome variable. While this seems like an obvious avenue for improving golfer's performance, a larger dispersion of ball impact location on the clubface has also been shown to be present when using longer shafts (Lacy et al., 2012). This will then mean that there will be a negative effect on total driving performance based on the higher variability in swing parameters and their related launch conditions. Golfers also find it difficult to produce the strength required to continue to angularly accelerate a club with a longer shaft, thus increasing its moment of inertia (Milne & Davis, 1992; Mather et al., 2000; Cheong, 2006; Hellstrom, 2009).

1.4.2.3 Shaft Stiffness and its Profiling

There are a number of graphite shafts available which vary with respect to their qualitative grading of stiffness (Jackson, 2001). These are categorised from least to most flexible; ladies, amateur, regular, stiff and extra stiff (Worobets & Stefanyshyn, 2007); however, no industry standards exist therefore, one manufacturer's "regular" flex may not be the same as another manufacturer (Swanek & Carey, 2007).

Understanding the shaft's resistance to dynamic deformation (flexural rigidity) provides an opportunity to use a standard quantitative measure to define points of deflection along the shaft (Brouillette, 2002; Huntley et al., 2006). The flexural rigidity (also called *EI*) of a shaft is dependent on its modulus of elasticity (*E*) and it's cross sectional area (*I*). To determine a shaft's EI profile, a piece of equipment called an EI Shaft Profiler (Fit2Score, Texas, USA) (Figure 1.2) is typically used to grip and balance the shaft and then apply a set amount of force directly onto the shaft at regular intervals from the butt to the tip. This process reveals variations in stiffness along the length of a shaft and these differences are thought to be due to reasons such as differences in wall thickness of the shaft (Brouillette, 2002; Huntely et al., 2006; Betzler et al., 2012).

Figure 1.2 Flexural rigidity (EI) Shaft Profiler (Fit2Score, Texas, USA) http://blog.hirekogolf.com/2013/01/new-shaft-testing-equipment-added-to-hirekos-rd-lab/

Generating an EI profile of a shaft can also be done by suspending a known load from the tip end of a shaft whilst the grip is clamped (Figure 1.3). The shaft is then moved away from the clamp at regular intervals and the same load and is applied. This results in a greater amount of deflection as the shaft is further extended.

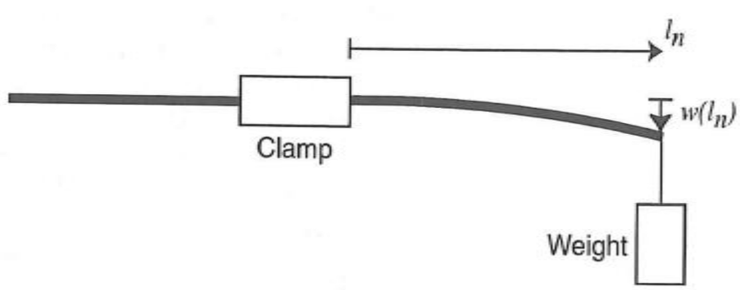

Figure 1.3 Brouillette's third method of attaining EI values (Brouillette, 2002).

The resulting deflection distances at a series of n points are entered into Brouillette's equation (2002) to determine the EI of the shaft.

$$EI_n = \frac{\frac{1}{3}\,F[l_n^3 - l_{n-1}^3]}{w(l_n) - \frac{1}{3}\,\frac{M_{n-1}l_{n-1}^3}{\overline{\overline{EI}}_{n-1}}}$$

Where F is the weight suspended from the tip of the shaft, whilst l_n and $w(l_n)$ are the cantilever length and the deflection distance sampled at each point respectively. Further, M_n is the bending moment of each point sampled as determined by $F(l_n - l_{n-1})$ and EI_{n-1} is considered as $Fl_{n-1}^3\,/\,3w(l_{n-1})$.

Club-fitters typically recommend changes in shaft stiffness based on swing speed (Worobets & Stefanyshyn, 2007). Golfers of higher ability who generate higher clubhead speeds when compared to players of lesser ability (Fradkin et al., 2004) tend to use drivers fitted with stiffer shafts (Jackson, 2001; Worobets & Stefanyshyn, 2007). This is so that bending of the shaft in the lead / lag plane (Figure 1.4) is reduced and the clubface can be better controlled at ball impact (Betzler et al., 2012). Shafts of greater qualitative stiffness have been shown to translate into faster clubhead speed (Betzler et al., 2012). However, experimental and simulation studies have concluded that faster clubhead speeds are not necessarily associated with stiffer shafts (Wallace & Hubbell, 2001; MacKenzie, 2005; MacKenzie & Sprigings, 2009b; Betzler et al., 2012). In contrast, faster 'kick velocities' which have shown to contribute to faster clubhead speeds have been found for less stiff shafts, as they are able to store and release more energy through larger amounts of deflection in the lag-lead plane during the downswing (Butler & Winfield, 1994; Betzler et al., 2012).

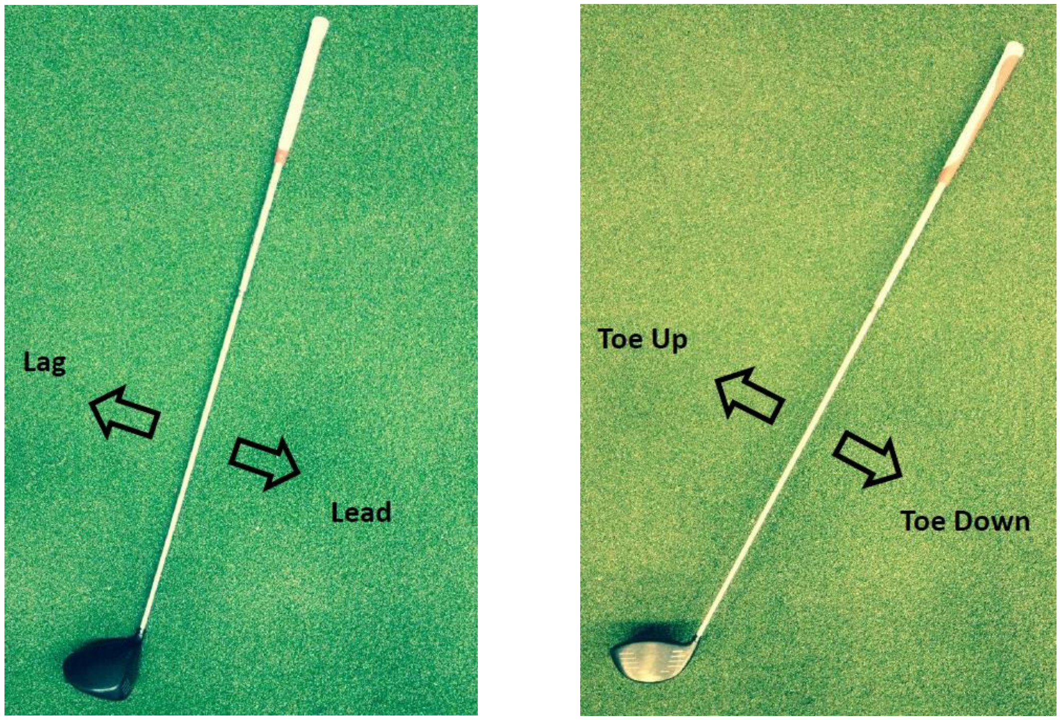

Figure 1.4 Bending planes of the golf shaft; lag and lead (left), and toe up and toe down (right).

The main reason why elite golfers (who exhibit faster clubhead speeds) use stiff shafts is that controlling an excessive of deflection in the lead / lag plane may be detrimental to the optimal timing of wrist release (Betzler et al., 2012). The majority of shaft deflection is seen in the toe up / toe down plane, with smaller values seen in the lead / lag plane (Butler & Winfield, 1994; Betzler et al., 2011). It has even been postulated that highly skilled golfers are able to adapt their swing kinematics to optimise swing parameters and their related launch conditions when using shafts of different stiffness (Milne & Davis, 1992; Wallace & Hubbell, 2001; MacKenzie, 2005).

1.4.2.4 Shaft Mass, Swing-weighting and Kick Point Location

Shaft mass is a property influenced by mass distribution and flexural rigidity (Milne & Davis, 1992; Brouillette, 2002; Penner, 2003; Harper, 2005; Huntley et al., 2007). Simulation studies note that decreasing the mass of the shaft can result in faster clubhead speed and increased hitting distance due to the reduction of inertial forces experienced by the shaft in the downswing, and the ability of the shaft to 'kick' forward at impact (Butler & Winfield, 1994; Maltby, 1995; Werner & Greig, 2000; Penner, 2003). This has yet to be demonstrated from an experimental point of view for high level amateur golfers who are capable of generating fast clubhead speed (Fradkin et al., 2004). With simulation studies finding negligible increases in clubhead speed with lighter shafts, minimising the shaft mass to such a point for elite and high level amateur golfers may result in a detrimental effect on swing tempo, and changes in swing kinematics due to the greater 'lag' of the clubhead (Butler & Winfield, 1994; Penner, 2003; Lee & Kim, 2004; Cheong et al., 2006). However, the dynamic bending profile during the downswing is yet to be investigated experimentally. Elite and high level amateur golfers generally use heavier shafts to better control the clubface at impact whilst also maintaining faster swing speeds (Egret et al., 2003; Fradkin et al., 2004; Lee & Kim, 2004).

Whilst the stiffness of two shafts may be consistent, heavier shafts are shown to have their extra mass positioned towards the tip of the shaft (Huntely et al., 2006; Betzler et al., 2011). This extra mass may be due to differences in the fabrication of each shaft, for example, shaft geometry, and / or a difference in the number of layers and the fibre alignment in these layers (Cheong et al., 2006; Slater et al., 2010). Shaft mass distribution is a result of both fabrication processes and swing-weighting from the butt to the tip (Jackson, 2001; Harper et al., 2005;

Haeufle et al., 2012). A club's swing-weighting is related to the 'feel' of the club and is quantified using a qualitative, alpha-numeric value, within the range C9 to D8, with each swing-weight equivalent to 'two inch-ounces' (Jackson, 2001; Harper et al., 2005). Further, swing-weight is related to the distribution of mass about a fulcrum point which is a known distance from the butt of the shaft, such that heavier shafts have a higher swing-weighting (Harper et al., 2005). During the golf swing, the effect of swing-weighting is subjective, with previous work reporting that a club's swing-weight is not a good predictor of clubhead speed, and shows no correlation to dynamic performance (Mather et al., 2000; Jackson, 2001; Harper et al., 2005; Haeufle et al., 2012).

The qualitative grading of shaft stiffness is determined through static testing methods. Such methods will reveal a greater amount of bending or, an increased perpendicular distance from a line joining two ends of a loaded shaft (bottom of grip to shaft tip) for more flexible shafts, and reduced bending for stiffer shafts (Figure 1.5). This point of maximum perpendicular distance is the static deflection point or 'kick point' (Jackson, 2001). From previous studies (Mather et al., 2000; Cheong et al., 2006), the maximum kick point of clubs used by elite and high level amateur players may be located anywhere between 44 – 60 % of shaft length when expressed as a distance from the end of the shaft. The kick point is an important consideration when aiming to optimise swing parameters and related launch conditions. A high kick point is believed to decrease the launch angle of the ball at impact, due to an increase in the lag of the clubhead associated with higher inertial forces experienced in the downswing due to the increased mass at the tip (Milne & Davis, 1992; Mather et al., 2000; Cheong et al., 2006).

Little experimental evidence exists to support the claim that kick point has an effect on launch angle, and other swing parameters and related launch conditions. It has also been suggested by various researchers (Chou & Roberts, 1994; Mather et al., 2000; Summit, 2000; Cheong et al., 2006) that the location of the kick point during the golf swing (the dynamic kick point) may differ from the kick point determined in a static manner (the static kick point). Previous research (Chou & Roberts, 1994) reported that the static kick point showed no relationship with swing parameters and related launch conditions such as; clubhead speed, ball velocity and spin rate. It is unknown how the dynamic bending profiles of shafts of different kick points differ from static values, and how they contribute to changing swing parameters and their related launch conditions.

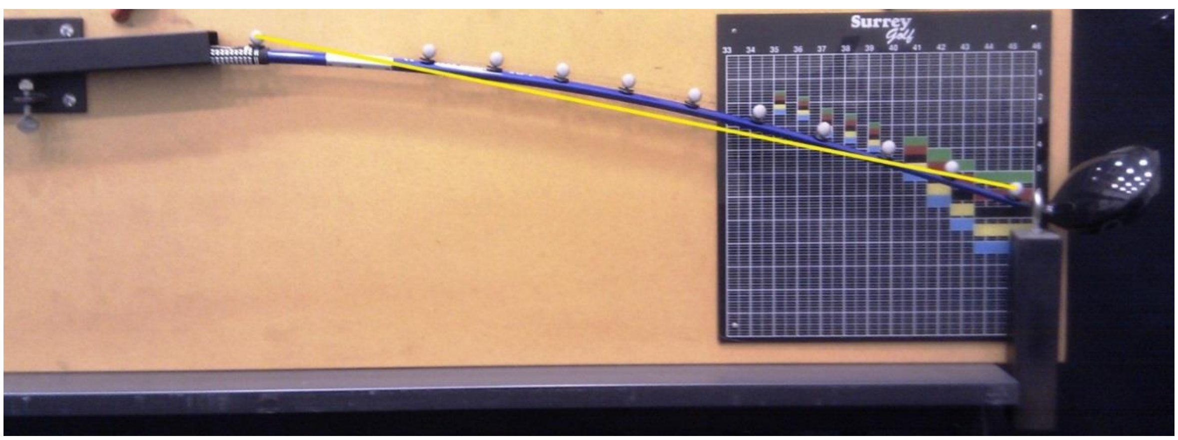

Figure 1.5 Determining the static kick point of a loaded shaft.

As previously mentioned, investigations examining whether high level amateur golfers modify their swing kinematics in response to changes in shaft stiffness are inconclusive (Milne & Davis, 1992; Stanbridge et al., 2003; Worobets & Stefanyshn, 2007; Suzuki et al., 2008; MacKenzie & Sprigings, 2009b; Betzler, 2011). It is of interest that research examining biomechanical variables that explain modified swings has been largely inconclusive (Milne & Davis, 1992; Stanbridge et al., 2004; Worobets & Stefanyshn, 2007; Suzuki et al., 2008; MacKenzie & Sprigings, 2009a; Betzler, 2010). To the author's knowledge, no investigations have been undertaken to explain the biomechanical differences in swing kinematics when using shafts of differing kick point location.

1.4.3 Summary points "The Golf Club"

The following points describe the design and manufacturing methods used in the club-making industry. It is reported that modifiable properties of a golf club, such as driver shafts, can have multiple modifiable properties which reveal differences in performance under static conditions. What is unknown is how shafts perform dynamically (during the golf swing) and if these reflect results from static testing conditions, and how these could affect swing parameters and related launch conditions?

- Driver shafts have many modifiable properties including; stiffness, kick point, mass and length. This is also the case for driver heads; clubhead size, shape and clubface angle.
- Alteration of shaft properties such as stiffness grading, flexural rigidity and length has resulted in changes to swing parameters and their related launch conditions in both simulation and experimental studies.
- No experimental evidence exists to show if static kick point location differs from dynamic kick point location using three-dimensional motion analysis methods. It is also unknown if the bending profile differs for shafts of differing kick point location, and the amount of deflection in the principal bending plane.
- No experimental evidence exists to show whether kick point location has an effect on the likes of; clubhead speed, launch angle and spin rate.
- Although qualitative shaft stiffness may not influence golf swing kinematics, it is unknown whether differences exist for changes in kick point location.

1.5 Swing Parameters, Their Related Launch Conditions, and Their Inter-Relationships

Maximum hitting distance tends to be achieved if maximum clubhead speed is delivered to the ball at impact causing a high ball velocity (Kemp 2005; Hume et al., 2005; Doan et al., 2006; Wallace et al., 2007; Gordon et al., 2009; Hellstrom, 2009). However, as ball velocity is influenced by other factors such as impact location on the clubface and ball spin (Tanaka et al., 2013; Sweeney et al., 2013), clubhead speed has been used as the outcome variable of choice in studies examining the biomechanics of the golf swing (Barrentine et al., 1994; Lephart et al., 2007).

Changing one or more of the modifiable properties of the golf club may affect the 'swing parameters' at impact (Jackson, 2001; Cheong et al., 2006; Worobets & Stefanyshyn, 2007). These parameters include clubhead speed and attack angle or, descending or ascending angle of the clubface on the ball at impact. Considered simply, the swing parameters are what influence the movement of the golf ball post-impact, and this movement can be described by the 'launch conditions'. Launch conditions include launch angle, ball velocity and spin rate (Tuxen, 2008). It is important to know how launch conditions are influenced by swing parameters, so clubhead speed can be maximised at impact. Ball velocity is influenced by clubhead speed, but also other swing parameters and related launch conditions such as, attack angle and ball spin rate (Tuxen, 2008; Tanaka et al., 2013). Hence, this makes clubhead speed the outcome variable of choice in previous research (Barrentine et al., 1994; Lephart et al., 2007).

When measuring swing parameters and their related launch conditions, recent experimental studies have used Doppler radar devices to track the swing parameters (club) and launch conditions (ball) (Myers et al., 2008; Tuxen, 2008). Unfortunately, few of these devices have been shown to be reliable and valid (Rankin & Winfield, 2004; Betzler et al., 2012; Sweeney et al., 2012).

1.5.1 Swing Parameters

In this thesis, measurement of both swing parameters and their related launch conditions were undertaken using a Doppler radar real-time launch monitor. The swing parameters are associated with the clubhead and its delivery into the ball at the point of impact, from which the launch conditions are then predicted (Rankin & Winfield, 2004; Tuxen, 2008). The two swing parameters examined in this thesis were clubhead speed and attack angle. Clubhead speed is typically defined as how fast the clubhead is travelling at the point of ball impact (Arnold, 2010). The attack angle (see Figure 5.1) is determined by whether the clubface is either descending (negative values), or ascending (positive values) into the ball in relation to the ground at the point of ball impact (Tuxen, 2008). Launch conditions such as ball velocity, and launch angle are affected by the presentation of the clubhead into the ball at impact (Butler & Winfield, 1994; Maltby, 1995; Penner, 2003; MacKenzie & Sprigings, 2009b).

With respect to the two swing parameters used in this thesis, previous simulation and experimental studies have found little difference in clubhead speed for shafts of differing stiffness rating and flexural rigidity (Milne & Davis, 1992; Wallace & Hubbell, 2001; Worobets & Stefanyshn, 2007; MacKenzie & Sprigings, 2009b; Betzler et al., 2011; Betzler et al., 2012). However, anecdotal evidence suggests that shafts of varying static kick point are shown to produce different attack angles due to the way the shaft bends in the downswing (Mather et al., 2000; Cheong et al., 2006). Heavier, stiffer shafts with a high kick point tend to experience higher inertial loading in the downswing and create lagging of the clubhead. As a result the clubface is presented at a steeper angle into the ball at impact (Butler & Winfield, 1994; Mather et al., 2000; Cheong et al., 2006; Betzler et al., 2011). Conversely, lighter, less stiff shafts with a low kick point will experience a more positive attack angle. This may be due to one of two reasons. Firstly, the increased kick velocity resulting from a shaft of reduced stiffness tends to deflect more than a stiffer shaft in the downswing, promoting a more positive attack angle (Butler & Winfield, 1994). Secondly, the lower kick point reduces the amount of lag associated with players of slower clubhead speeds who use lighter shafts (Lee & Kim, 2004; Cheong et al., 2006).

1.5.2 Launch Conditions

Three important launch conditions that have a major part in determining ball distance are ball velocity, launch angle and ball spin rate (Penner, 2003). Ball velocity (v_{ball}) is directly related to clubhead speed (v_{club}), but other factors such as clubface coefficient of restitution (c_R), mass of the club (m_{club}), and the mass of the ball (m_{ball}) need to be considered (Arnold, 2010). The equation below demonstrates from a simulation perspective, how faster ball velocities are generated from optimal impact conditions. However, optimal contact is dependent on multiple factors such as clubhead speed, ball velocity, clubface angle, coefficient of restitution, finite masses and centeredness of strike on the clubface ($miss$), and is difficult to achieve experimentally. The equation below demonstrates from a simulation perspective, how ball velocity is generated from other impact conditions (Tuxen, 2012).

$$v_{ball} = \frac{(1 + c_R)\, v_{club}}{1 + m_{ball} / m_{club}}$$

Launch angle is defined as the angle the ball leaves the tee in relation to the ground. Launch angle has been previously discussed as it is strongly influenced by clubhead presentation (attack angle) into the ball at impact. A steeper clubface into the ball at impact will result in a lower launch angle, as described in the previous 'swing parameters' section (Section 1.5.1). Ball spin rate describes the amount of back-spin (revolutions per minute) the golf ball has imparted on it at the point of impact. Spin rate influences the total distance the ball will travel upon landing as high spin increases angular momentum of the ball and decreases linear momentum (Shaw, 1995). This is important, as reduced spin is important for maximising driving distance, and high spin important when using irons, aiming to reduce total carry when hitting to a green (Penner, 2003).

1.5.3 Optimising Swing Parameters and Related Launch Conditions

A club-fitter's aim is to optimise swing parameters and related launch conditions through testing different combinations of shafts with varying stiffness rating, flexural rigidity, static kick point, and clubhead properties (i.e. face angle, lie angle). The golfer's subjective view of the swing parameters and related launch conditions based on 'feel' and satisfactory shot outcome can be quantitatively assessed with the use of real-time launch monitors, or radars

(Rankin & Winfield, 2004). Previous club-fitting methods which were more subjective in nature, were based on visual feedback of ball speed and hitting distance (Rankin & Winfield, 2004). However, launch monitors allow real-time feedback, by means of camera, or Doppler radar feedback, and algorithms to measure the launch conditions based on the swing parameters (Rankin & Winfield, 2004; Sweeney et al., 2011).

Real-time launch monitors are widely used by club-fitters when fitting the correct combination of shaft and clubhead for a golfer (Rankin & Winfield, 2004; Bertram & Guadagnoli, 2008). With club-fitting now commonplace in the process of purchasing a set of golf clubs, it is not only beneficial to elite players, but also important for amateurs to be fitted for the most suitable clubs (Bertram & Guadagnoli, 2008). Bertram & Guadagnoli (2008) investigated the (blinded) effects of a pre-fitted six-iron against a standard, non-custom six-iron for skilled golfers (handicap 3 - 8.6) using a real-time launch monitor. Results showed that the fitted six-iron had significantly ($p < 0.05$) faster clubhead speed and lower variability in clubhead speed and shot dispersion. This tends to support the need for club-fitting. With launch monitors being used in numerous studies to report swing parameters and related launch conditions, the need for valid measures is important for club-fitting, for example. The authors are aware of a single study (Sweeney et al., 2009) that has validated a launch monitor to be used to report accurate swing parameters and related launch conditions in further investigations (Sweeney et al., 2012). Sweeney et al. (2009) used a three-dimensional motion analysis system to validate the variables; clubhead speed, attack angle, launch angle and ball velocity. Reflective marker tracking allowed for all variables to be calculated although, ball spin would prove difficult with reflective marker tracking.

Golfers who are “fitted” with correct clubs familiarise themselves during the fitting process, and in practice for competition. It is recommended that experienced golfers need time to familiarise themselves with a new club, so that lower variability in shot outcome is expected (Kenny et al., 2008a; Langdown et al., 2012). This could suggest the use of drivers in previous investigations have not yielded significant between-shaft differences in swing kinematics, due to a large variability in shot outcomes. With limited success of ‘non-familiar’ between-shaft studies involving shaft stiffness alone, investigation into shaft kick point location, mass and its influence on golf swing kinematics when aiming to achieve maximum clubhead speed is required.

1.5.4 Summary points "Swing parameters and related launch conditions"

The previous section (1.4) identified possible differences between static and dynamic testing conditions relating to modifiable golf club properties, such as shafts. This section described how delivery of the clubface into the ball at ball impact affects the swing parameters and related launch conditions of the golf ball. With previous investigations reporting relationships between these conditions, it is unknown if drivers fitted with shafts of differing kick point location and mass would induce differences for these conditions? Also of importance was the validity of launch monitors used in recent investigations, also of which are used by club-fitting professionals to match club properties to individuals.

- Relationships exist between how the clubface is presented to the ball at impact (swing parameters) and the resulting effect of ball flight characteristics (launch conditions).
- Modifications to drivers (i.e. qualitative shaft stiffness and flexural rigidity) have produced different swing and launch conditions in experimental studies. The effect of changing the location of the kick point of the shaft is unknown.
- Elite and high level amateur golfers will modify driver properties in an attempt to maximise clubhead speed and desired launch conditions. Experimental evidence behind this idea is not as widespread as evidence provided by simulation-based investigations.
- Although several investigations have reported strong relationships between swing and launch conditions such as clubhead speed and ball velocity, the swing parameter attack angle, has not been rigorously examined to date.
- It is unknown experimentally, if drivers containing a low kick point shaft produce higher launch angles of the ball.

- The swing parameters and related launch conditions used in this thesis have not been previously discussed for between-shaft differences in kick point. These factors are also important based on the shaft deformation profiles at different stages of the downswing.
- The lack of validity of launch monitors used in investigations where swing parameters and related launch conditions are reported is important when linking these to swing kinematics and dynamic shaft movement.

1.6 Overall Objective and Specific Aims of the Thesis

The overarching objective of this thesis was to determine variables that assist in generating clubhead speed in golf. This objective was examined in male, high level amateur golfers. The first two studies of this thesis examined this issue from the perspective of the golfer while the following two studies (Studies III and IV) examined this issue in regard to the golf club. The final study of the thesis (Study V) was informed by the methodology developed and knowledge gained from Studies I - IV. The titles of each of these studies and their specific aims are outlined below.

Chapter 2 – Study I. "Methodological considerations for the three-dimensional measurement of the X-factor and lower trunk movement in golf"

i) To identify the most appropriate method of examining the X-factor and lower trunk movement in the golf swing via a three-dimensional approach.

Chapter 3 – Study II. "Three-dimensional trunk kinematics in golf: between-club differences and relationships to clubhead speed"

i) To determine whether significant differences existed between a driver and a five-iron club for three-dimensional trunk kinematic variables measured during the golf swing,
ii) To determine the anthropometric, physical and trunk kinematics variables most strongly associated with clubhead speed for high level amateur male golfers,

Chapter 4 – Study III. "A new method to identify the location of the kick point during the golf swing"

i) To develop an algorithm using three-dimensional coordinate data from markers placed on a golf club to calculate the location of the deflection point on a golf club

ii) To determine the between-shaft reliability of the dynamic kick point location for two drivers fitted with shafts of differing mass,

iii) To assess whether differences existed between the location of the static and dynamic kick point for two shafts of differing mass.

Chapter 5 – Study IV. "A dynamic evaluation of how kick location influences swing parameters and related launch conditions"

i) To determine whether changes in the location of the kick point of a driver resulted in differences in clubhead speed and attack angle (swing parameters), and indirectly affected; ball velocity, launch angle and spin rate of the ball (related launch conditions).

ii) To determine whether significant associations existed between the five swing parameters and their related launch conditions for each driver.

iii) To determine whether the amount of shaft bend changed as a result of kick point location and whether the amount of shaft bend changed throughout the downswing.

Chapter 6 – Study V. "Trunk and wrist kinematics when maximising clubhead speed: Effect of changing the kick point"

i) To determine if differences in trunk and wrist kinematics exist in drivers containing differing kick point location.

ii) To determine which trunk and wrist kinematic variables were most strongly associated with clubhead speed. This was examined when hitting with two drivers containing differing kick point locations.

1.7 Limitations of the Thesis

i) As this thesis examines high level amateur golfers, the findings of this thesis are applicable to this group only.

ii) All testing was conducted at an indoor biomechanics laboratory therefore, the findings may not be representative of the outdoor environment, despite an outdoor familiarisation session in Study V.

iii) Whilst the golfer uses multiple clubs, to examine clubhead speed only the driver and five-iron were tested. Further, only two variations of a driver were used.

iv) While a multi-segment trunk model and a wrist model from the leading arm during the golf swing were used in this thesis the lower limbs were not considered.

v) When examining the effect of kick point on swing parameters and related launch conditions, for reasons related to feasibility, the effect of other factors such as shaft stiffness profile, shaft mass and swing-weighting could not be separated.

vi) For Studies III and IV, despite the shaft being able to bend in two bending planes of toe up / toe down and, lead / lag, only the principle bending plane, where maximum deflection of the shaft was analysed.

vii) Clubhead orientation (open / closed) and impact location on the clubface of the drivers and five-irons used within this thesis were not measured. Therefore, clubhead speed was the most suitable outcome variable.

1.8 Significance of the Thesis

The golf swing is a complex motor skill in which an elite player's shot making ability is superior to those who possess a higher handicap (Hellstrom, 2009). The production of clubhead speed may be influenced by many factors and these may include; the golfer, the technique used by the golfer and the golf club they are using to hit the ball. It is important to collect kinematics of the golf swing while the player is not impeded (Cheetham et al., 2001; Lindsay & Horton, 2002). The use of three-dimensional optoelectronic systems as opposed to systems that use an exo-skeleton or electromagnetic tracking systems achieves this goal. Only recently have Euler / Cardanic methods been used to describe three-dimensional kinematics of the golfer during the golf swing (Horan et al., 2010). Further, the trunk while known to move in different ways in its various regions has yet to be analysed in this way. Use of such methods may provide greater understanding of the importance of trunk and wrist movements in the golf swing, as well as between-club differences in swing kinematics with the aim of producing clubhead speed.

Recent advances into the design of components of the golf club such as the shaft and clubhead have allowed for superior shot making by reducing the overall loss in mechanical energy at impact for both drivers and irons (Hocknell, 2002; Poulin et al., 2004). Previous studies have found differences in swing parameters and related launch conditions when using shafts of different stiffness (Betzler et al., 2012; MacKenzie & Sprigings, 2009b; Worobets & Stefanyshyn, 2007), although whether differences exist in swing parameters and related launch conditions for shafts possessing differing kick point location has yet to be investigated. It is possible this has not been investigated as there is currently no method to identify kick point location during the golf swing.

The selection of golf clubs is largely based on the subjective nature of the perceived ‘feel’ and shot outcome of an individual. The effect of between-driver differences in shaft stiffness have failed to find significant differences for swing kinematics (Betzler, 2010). There is currently no understanding of the biomechanical parameters used by high level amateur golfers concerning the golfer, the golf club, and the golfer’s interaction and manipulation of these biomechanical parameters when hitting different golf clubs such as drivers and irons, as well as the modifiable property of kick point of shaft kick point. This research will lead to a greater understanding of the contribution of multiple body segments involved in deriving clubhead speed, and also how golfers manipulate these when using different golf clubs.

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CHAPTER 2

STUDY I

It has been reported that increasing the segment angular displacement of the shoulders relative to the pelvis during the backswing in the golf swing, has a significant positive relationship with clubhead speed, and driving distance (Myers et al., 2008; Hellstrom, 2009). This segment separation is termed the 'X-factor', and occurs at the top of the backswing, where an initial counter-rotation of the pelvis to commence the downswing momentarily increases this further, and this reports the maximum value of axial rotation, or 'X-factor stretch' (Cheetham et al., 2001).

Various methods have been used to quantify the X-factor, with indefinite associations to clubhead speed and driving distance by using different methods such as electro-magnetic devices (Cheetham et al., 2001; Lindsay et al., 2002) and opto-electronic systems (Lephart et al., 2007; Myers et al., 2008). With various anatomical positioning of retro-reflective markers being used to quantify X-factor, no configuration, or marker set has been validated against a 'gold standard' method of three-dimensional motion analysis, when used to analyse the kinematics of the golf swing. Further, with current marker sets being employed to define the trunk and pelvis segments, no study has defined or investigated the kinematics of the lower trunk in the golf swing.

Methodological considerations for the three-dimensional measurement of the X-factor and lower trunk movement in golf

This Chapter is presented in the pre-publication format adapted from:

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2.1 Abstract

It is believed that increasing the X-factor (movement of the shoulders relative to the hips) during the golf swing can increase ball velocity at impact. Increasing the X-factor may also increase the risk of low back pain. The aim of this study was to provide recommendations for the three-dimensional measurement of the X-factor and lower trunk movement during the golf swing. This three-part validation study involved; 1) developing and validating models and related algorithms 2) comparing three-dimensional data obtained during static positions representative of the golf swing to visual estimates and 3) comparing three-dimensional data obtained during dynamic golf swings to images gained from high speed video. Of particular interest were issues related to sequence dependency. After models and algorithms were validated, results from parts two and three of the study supported the conclusion that a lateral bending / flexion-extension / axial rotation (ZYX) order of rotation was deemed to be the most suitable Cardanic sequence to use in the assessment of the X-

factor and lower trunk movement in the golf swing. The findings of this study have relevance for further research examining the X-factor and its relationship to clubhead speed and lower trunk movement and low back pain in golf.

2.2 Introduction

While the golf ball can be hit with a variety of woods and irons, every golf shot from the tee or the fairway involves a backswing phase and a downswing phase. At the completion of the backswing, the body and the club are positioned in an optimal posture to accelerate the club through the downswing (Hume et al., 2005; Hellstrom, 2009). During the downswing, a number of the body's segments are sequenced together to maximise ball velocity at impact (Bechler et al., 1995; Zheng et al., 2008). The biomechanical principle underlying this motion is termed "summation of velocity" and this is evident for a number of striking/throwing activities such as the tennis serve and baseball pitching (Putnam, 1993).

During the backswing, the shoulders of the golfer are rotated further away from the target than the hips (Myers et al., 2008). The resulting separation of the hip-shoulder alignment at the top of the downswing is referred to as the "X-factor" (McLean, 1992; Hume et al, 2005; Gluck et al, 2007). Another related concept called the "X-factor stretch" refers to the point after the top of the downswing where the hip-shoulder separation angle is maximised as the hips are known to counter-rotate prior to the shoulders (Cheetham et al., 2001). Maximising the hip-shoulder separation angle may increase the potential to utilise the stretch shortening cycle during the golf swing and this has possible implications for increasing hitting distance (Cheetham et al., 2001; Myers et al., 2008). However, a marked hip-shoulder separation angle also has the potential to elevate the risk of developing, or exacerbating low back pain by producing excessive strain on the passive structures of the spine such as the inter-vertebral disc and the facet joints (Lindsay et al., 2002; Gluck et al., 2007). Therefore, the pathomechanics of low back injury in golfers has also been previously investigated in three dimensions (Morgan et al., 1998; Lindsay et al., 2002).

There have been various biomechanical approaches utilised when investigating the X-factor (Hellstrom, 2009). Previous researchers have collected three-dimensional coordinate data and projected the hip-shoulder separation angle (defined as the angle between a line joining the two hip joints and a line joining the two shoulder joints) onto the transverse plane (Myers et al., 2008; Zheng et al., 2008). However, the golf swing is a complex three-dimensional movement with the torso being axially rotated, laterally bent and flexed during the golf swing (Hellstrom, 2009). To this end, the X-factor was recently been reported in a true three-dimensional manner (Horan et al., 2010). However, with regards to quantification of three-dimensional rotations, previous studies have yet to examine multiple body segments [i.e. comparison of shoulders to pelvis (trunk), and lower thoracic to pelvis (lower trunk)]. In previous golf research Wheat et al. (2007) utilised a multi-segment model projected onto the transverse plane of the trunk. Further, multi-segment models have been used in cricket to investigate lumbar segment kinetics (Ferdinands et al., 2009). Hence, development of a three-segment trunk model for examination of the golf swing is of importance.

When relative rotations of body segments in three dimensions are described, a concept called "sequence dependency" needs to be considered (Rundquist & Ludewig, 2004; Senk & Cheze, 2006). When defining the position of a rigid body in space, three translations (displacements along the X, Y and Z axes) and three independent and successive rotations (rotation about the X, Y and Z axes - referred to as Cardan angles) are commonly used in biomechanics (Wu et al., 2002, 2005). In human movement applications these three rotations typically correspond to flexion/extension, lateral bending and axial rotation. To provide anatomical meaning these angles need to be defined in a specific order of rotation (ZYX, ZXY, YZX, YXZ, XYZ or XZY). It is the order in which these angles are defined which may affect the actual value of the rotations reported. Whilst previous authors (Wheat et al., 2007; Horan et al., 2010) have stated the order of rotations utilised when reporting three-dimensional trunk kinematics data during the golf swing the reason for using their Cardanic sequences were not provided. This is of importance as for movements with large magnitudes of rotations about each orthopaedic axis (such as golf), as the magnitude of rotation reported for each Cardanic sequence may vary considerably as the choice of which rotational sequence is appropriate for a particular movement pattern. Lees et al. (2010), identified a Cardanic sequence of XYZ when analysing the hip and leg movements of the in-step (support) leg of the soccer kick. The integrated angular velocity and orientation angles were superimposed on each graph and when compared to the other five Cardanic sequences, the XYZ sequence produced the lowest Root Mean Square (RMS) value.

Therefore, the aim of this study was to identify the most appropriate method of examining the X-factor and lower trunk movement in the golf swing via a three-dimensional approach. This was undertaken using a multi-trunk model and examining the X-factor (trunk) and the magnitude of lower trunk movement, and these estimates were compared to visual estimates to ensure anatomical meaningfulness.

2.3 Methods

2.3.1 Experimental Protocol

The experimental protocol used in this study consisted of three parts; 1) algorithm and model development and validation using a wooden model 2) a comparison of visual estimates of three-dimensional trunk posture and the six Cardanic orders of rotation during representative moments of the golf swing and 3) examination of sequence dependency in real golf swings. To undertake the first part of this study, two motion analysis systems were used as described below. This study was undertaken indoors in the Biomechanics Laboratory at the School of Exercise, Biomedical and Health Sciences, Edith Cowan University. Permission to undertake this research was granted by the Institutional Human Research Ethics Committee.

2.3.2 Data Collection

2.3.2.1 Description of Motion Analysis Systems

Two motion analysis systems were used in this study; an optoelectronic motion analysis system and an electromagnetic tracking system. The optoelectronic system used was a 10-camera MX-F20 Vicon-Peak Motion Analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz. The electromagnetic tracking system was a 3-Space Fastrak^{TM} (Polhemus Navigation Science Division, Vermont, USA). Whilst the Vicon system was primarily used to define the position and orientation of the segments of interest in this study (pelvis, lower thorax and shoulders) the 3-Space Fastrak^{TM} was used as a “gold standard” in part one of the study (the wooden model trials).). The Fastrak has a reported angular accuracy of 0.9-1.2° (Audette et al., 2010). The 3-Space Fastrak™ consists of a systems electronics unit, a source and four sensors. The source emits a low frequency magnetic field that the sensors use to detect their relative three-dimensional position and orientation. Angular displacement data from the three Fastrak sensors used in this study were output in a ZYX order of rotation at a sampling rate of 30 Hz. With this system positive Z axis points forward, positive Y points right and positive X points up. The coordinate system held within each Fastrak sensor are relative to a global reference point (0,0,0) held within a "base" sensor.

2.3.2.2 Part One - Algorithm and Model Development and Validation

Each of the coordinate systems for the pelvis, lower thorax and shoulders were mimicked on a life-size wooden model in the first part of this study (Figure 2.1). Representative markers for these coordinate systems were also attached to a human participant during parts two and three of the study. The location of these markers and markers placed on the golf club (used in parts two and three) are shown in Table 2.1. The wooden model was constructed so that flexion/extension and/or lateral bending could be created by purposely bending the flexible wooden rod which simulated the spine (Figure 2.1). Furthermore, axial rotation could be created in each of the anatomical regions. Consequently, true three-dimensional movement could be created using this model. For the wooden model trials, sensors from the Fastrak system were attached to the simulated "spinous processes" of the three anatomical regions (pelvis, lower thorax and shoulders) (Figure 2.1). As each of the simulated pelvis, lower thorax and shoulders on the wooden model were effectively rigid bodies, relative movement measured by the Fastrak was equivalent to that measured by the Vicon system.

Table 2.1 Anatomical placements of light-reflective markers.

Markers	Anatomical Marker Placement
Shoulder Ref. Frame	
Left Shoulder	Left Acromion Process
Right Shoulder	Right Acromion Process
Lower Thorax Ref. Frame	
Sternum	Xiphoid Process, distal end of the Sternum
T10 vertebrae	Tenth Thoracic Spinous Process (T10)
L1 vertebrae	First Lumbar Spinous Process (L1)
Pelvis Ref. Frame	
Left Anterior Pelvis	Left Anterior Superior Illiac Spine (LASIS)
Right Anterior Pelvis	Right Anterior Superior Illiac Spine (RASIS)
Left Posterior Pelvis	Left Posterior Superior Illiac Spine (LPSIS)
Right Posterior Pelvis	Right Posterior Superior Illiac Spine (RPSIS)
Golf Club	
Upper Shaft	1/3 length of shaft from grip
Lower Shaft	2/3 length of shaft from grip

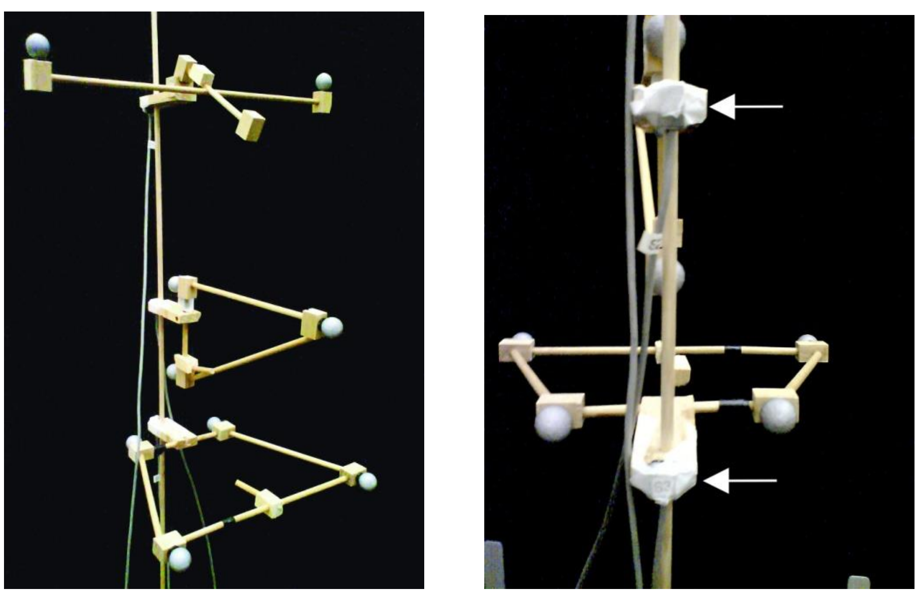


Figure 2.1 Wooden model used for the validation in part one of the study. Figure shows model with Vicon markers attached (left) and an example of a Fastrak™ sensor attached to the simulated "spinous processes" (right).

After volume calibration for the Vicon system, a series of uni-axial and multi-axial rotation trials were conducted where “shoulders” of the wooden model were moved relative to its “pelvis” (trunk segment). During these trials, synchronised kinematic data from the two motion analysis systems were collected. Synchronisation of the Fastrak and Vicon systems was achieved by sending a voltage signal generated from triggering the Fastrak’s customised data collection program, to the Vicon’s Ultranet unit. The trials for this part of the study included; uni-axial rotations (flexion, extension, left and right lateral flexion, left and right axial rotation) and a multi-axial rotation (a simulated golf back-swing trial). Whilst the design of the wooden rod couldn’t completely eliminate the coupling of rotation during the single-axis trials, they were conducted so that a vast majority of rotation occurred about the axis of interest. In each of these trials, data were collected for approximately 5-8 seconds. Data from these trials were smoothed using a Woltring filter with a mean square error of 20 mm^2 (Woltring, 1986). All data from these trials were then exported to text files for further analysis.

2.3.2.3 Part Two – Visual Estimations of Three-dimensional Posture

A comparison of visual estimates of three-dimensional trunk posture and the six Cardanic orders of rotation was conducted at five distinct moments of the golf swing (address, take-away, top of backswing, impact and follow-through). The purpose of this part of the study was to conduct a “face-validity” type analysis prior to conducting dynamic analysis of the golf swing. Visual estimates of range of motion (in two-dimensions) is routinely used in clinical practice and in previous research investigating shoulder pain (Terwee et al., 2005) and passive range of motion in the lower limbs of children (Rachkidi et al., 2009).

In the current study a single examiner (an experienced Sports and Clinical Biomechanist with knowledge of the relevant mathematical procedures) estimated the three-dimensional trunk posture of a male subject who was asked to assume the five static positions. These postures were assessed as being representative of the golf swing by the head teaching professional from a private golf club with over seven years of golf coaching and swing analysis. For each of the five static positions, the visual examiner was asked to report the three-dimensional trunk posture (flexion / extension, lateral bending and rotation) for the trunk and the lower trunk to the nearest 5° (Terwee et al., 2005; Rachkidi et al., 2009).

Vicon data were collected whilst the subject was in an anatomical position, and for each of the five static positions. Once the static position was set and the Vicon data were collected, the examiner was able to move around the subject to estimate their three-dimensional trunk posture. This process was repeated for each of the five static positions. Three observers watched this process and agreed the subject displayed minimal movement whilst being observed. The analysis of the visual estimates and the Vicon data was conducted in a blinded manner.

2.3.2.4 Part Three - Golf Swing Trials

Dynamic golf swing trials were carried out with the Vicon system using a single participant. The participant for this part of the study was a male golfer who played with a seven handicap. Retro-reflective markers were attached to the golfer and for the purpose of identifying the top of the backswing, two markers were also added to the golf club (Table 2.1). Furthermore to identify impact, a small piece of retro-reflective tape was attached to the golf ball. After a suitable warm up and volume calibration, the participant was then filmed performing six range of motion trials (same single –plane movements as in part one of the study). A trial was also captured with the participant standing in an anatomical position so that movements during the golf swing could be measured relative to the neutral position. The participant then hit a total of 10 maximal effort shots using a leading brand driver and a five-iron. These clubs were used as they are representative of the two types of clubs (i.e. a driver and an iron) used in golf (Wells et al., 2009). All shots involved hitting the same leading brand of golf ball off an artificial turf surface into a net placed positioned 5 m in front of the hitting area. From the 10 golf swings recorded, two trials (one for the driver, one for the five-iron) were chosen for analysis based on maximal clubhead velocity and minimal marker loss. No variables pertaining to hitting accuracy were quantified in this study.

In this phase of testing, the golf swing trials were also recorded using two Sony HDRFX7 (HD1080i) high speed video cameras operating at a 300 Hz with a shutter speed of 1/3000 s. These cameras were positioned perpendicular to the hitting area and from behind the participant. The footage from these cameras was used to visually confirm which order of rotation provided the closest estimate of what was happening anatomically. The Vicon system and high speed cameras were synchronised using impact as the critical event. Vicon data from these trials were smoothed using a Woltring filter with a mean square error of 20 mm^2 (Woltring, 1986) and the resulting data were then exported as a text file.

2.3.3 Data Analysis – Algorithm and Model Development and Validation

2.3.3.1 Part One - Fastrak Data

Relative rotations (flexion/extension, lateral bending and axial rotation) in each of the six Cardanic orders of rotation were determined for the trunk and the lower trunk. To calculate these variables, the following process was undertaken.

Firstly, the three Cardan angles for each sensor (relative to the source) were used to determine the direction cosine matrix for each sensor. Secondly; the transposed direction cosine matrix of the proximal sensor and the direction cosine matrix of the distal sensor were multiplied and the relative rotations (still in ZYX order) were recovered. Finally; in order to calculate the rotations relative to a zero reference (0,0,0) the direction cosine matrix from where the Cardan angles were reduced was multiplied by the direction cosine matrix derived from the first frame of data from each trial (Burnett et al., 1998). Fastrak data captured at 30 Hz were time-matched to Vicon data recorded at 250 Hz using cubic spline interpolation.

2.3.3.1 Part One - Vicon Data

Smoothed coordinate data from the retro-reflective markers were used to construct the joint coordinate systems (JCS) (Grood & Suntay, 1983; Wren & Mitiguy, 2007). To be consistent with the coordinate system of the Fastrak the same axes definition was used for the Vicon data. These were defined as outlined in Table 2.2. After these JCS were constructed, the Cardan angles related to the shoulders relative to the pelvis (trunk) and the lower thorax relative to the pelvis (lower trunk) were calculated by the same means as the Cardan angles reduced from the Fastrak.

Table 2.2 Joint Coordinate Systems (JCS) for Shoulder, Lower Thorax and Pelvis.

JCS	Origin	X - vector	Y (temp) - vector	Z - vector	Y - vector
Shoulder	Coincident with the mid-acromion and halfway to T10	Mid-acromion point, with the unit vector pointing to the right	Mid-point of the mid-acromion and T10, a distal unit vector, perpendicular to X	The common perpendicular of X and Y (temp), a proximal unit vector, perpendicular to X	Cross-product of X and Z, unit vector perpendicular and anterior to X
Lower Thorax	Coincident with the mid-point of L1 and T10 and halfway to Sternum	Mid-point of L1 and T10, with the unit vector pointing to the right	Mid-point of the L1 and Sternum, a distal unit vector, perpendicular to X	The common perpendicular of X and Y (temp), a proximal unit vector, perpendicular to X	Cross-product of X and Z, unit vector perpendicular and anterior to X
Pelvis	Coincident with the mid-point of mid-ASIS and mid-PSIS	Mid-point of mid-ASIS and mid-PSIS, unit vector pointing to the right	Mid-point of the mid-ASIS and mid-PSIS, a distal unit vector, perpendicular to X	The common perpendicular of X and Y (temp), a proximal unit vector, perpendicular to X	Cross-product of X and Z, unit vector perpendicular and anterior to X

2.3.3.2 Part Two – Visual Estimations of Three-dimensional Posture

To examine the effect of sequence dependency during the static posture trials, the three angles were calculated for the six Cardanic orders of rotation. The results from the visual examination of trunk posture; flexion/extension (Y), lateral bending (Z) and axial rotation (X) for each of the five static trials were compared against each order of rotation (ZYX, ZXY, YXZ, YZX, XZY, and XYZ), reduced as outlined above.

2.3.3.3 Part Three – Golf Swing Trials

To examine the effect of sequence dependency on dynamic golf swing trials, the Y, Z and X values were calculated for the six Cardanic orders of rotation. These values were calculated at the top of the backswing and at impact. The top of the backswing was defined as the frame where the two club markers changed direction to initiate the downswing (Lephart et al., 2007; Myers et al., 2008). From the Vicon algorithm, the maximal value of axial rotation in the back swing was also consistent with the transition point or frame, which could be seen. Impact was defined as the frame where the ball was first seen to move after contact. The identification of the top of the backswing in the high speed video footage was determined by time matching back from the moment of impact as determined by the Vicon system. This and all previous analyses were undertaken using Microsoft Excel.

2.4 Statistical Analysis

In part one of the study, to determine the similarity between Fastrak and Vicon kinematic data for the six uni-axial trials and the multi-axial trial, two indices were used; the adjusted coefficient of multiple correlation (CMC), R_a^2, (Kadaba, et al, 1989) and the Mean Absolute Variability (MAV) (e.g., Noonan et al., 2003). CMC values of 1 indicate identical waveforms whilst lower MAV values (data are in degrees) indicate more similarity between two sets of kinematic data. In part two of the study, comparisons of the visual estimates of trunk posture and the six orders of rotation were quantified by calculating the averaged magnitude of the vector from the three angles for the two methods of analysis. In part three of the study descriptive data from the six Cardanic sequences were presented in combination with images taken from the high speed footage at transition and impact.

2.5 Results

2.5.1 Part One – Algorithm and Model Development and Validation

CMC and MAV values for the six range of motion trials and the one multi-axis trial are shown in Table 2.3. The average CMC value obtained for all seven trials was 0.998 which demonstrated a very high level of similarity between the Vicon and Fastrak data. Furthermore, the average MAV value obtained from all seven trials was 0.6º. These results confirmed that the algorithms and models developed in part one of this study were valid.

Table 2.3 Comparisons of Vicon and Fastrak data.

ROM	Coefficient of Multiple Correlation (CMC)	Mean Absolute Variability (MAV) (°)
Trunk Flexion	0.999	1.1
Trunk Extension	0.997	0.9
Right Lateral Flexion	0.999	0.1
Left lateral Flexion	0.999	0.2
Right Axial Rotation	0.998	0.2
Left Axial Rotation	0.998	1.4
Set-up to Top of Backswing (right axial rotation for golf specific movement pattern)	0.999	0.4
Average Scores	**0.998**	**0.6**

Coefficient of Multiple Correlation (CMC) and Mean Absolute (MAV) statistics.

2.5.2 Part Two – Visual Estimations of Three-dimensional Posture

The averaged magnitude of the differences between the visual estimations and the six Cardanic orders of rotation (from Vicon analysis) for the static positions of the golf swing are presented in Table 2.4. From these data it can be seen that when the trunk and lower trunk data are summed together, the ZYX (Lateral Bend-Flexion/Extension-Axial Rotation) order of rotation shows the closest agreement between visual estimates and motion analysis derived data. Whilst it would be ideal to conclude from these results that the ZYX sequence most closely approximates what is seen visually, the precision of visual estimates prevented the selection of one sequence from this phase of analysis.

2.5.3 Part Three – Golf Swing Trials

After obtaining angle-time data for the dynamic trials (see samples in Figure 2.4), data related to the trunk and lower trunk position at the top of the backswing and impact for the driver and five-iron trials were derived. From these data a great disparity in the flexion-extension, lateral bending and axial rotation angles between the six rotational sequences was evident (Tables 2.5 and 2.6). The process of determining the most appropriate Cardanic sequence to analyse dynamic golf swing trials involved eliminating orders of rotation that did not represent what was seen visually (Figures 2.2 and 2.3). As this study was predominantly interested in quantifying rotational (X) values (e.g. X-factor) a closeness in approximation of X values was seen as the most important priority.

In the XYZ, XZY and ZXY sequences there were major discrepancies between Vicon data and what was seen in the images obtained from high speed film for both trunk and lower trunk movement. With these three orders of rotation eliminated, lateral bending (Z) was then assessed from the three remaining Cardanic sequences. On the basis that the YXZ order of rotation showed over-estimated values at the top of the backswing (Tables 2.5 and 2.6) this sequence was then eliminated.

Table 2.4 Averaged visual estimation values of the static three-dimensional trials using magnitude of difference.

	Trial	**ZYX**	**YZX**	**XYZ**	**XZY**	**ZXY**	**YXZ**
Trunk	Address	13.7	14.6	14.4	24.8	20.6	17.5
	Take Away	11.7	9.3	22.1	39.8	28.2	30.2
	Top of Backswing	10.8	42.1	51.3	50.5	6.4	49.4
	Ball Impact	14.7	15.9	23.1	32.6	29.4	31.0
	Follow Through	17.7	18.5	60.0	48.6	96.8	40.8
	Mean	**13.7**	**20.1**	**34.2**	**39.3**	**36.3**	**33.8**
Lower Trunk	Address	6.8	8.6	24.2	8.1	4.7	8.6
	Take Away	4.6	12.6	9.9	10.7	13.8	13.7
	Top of Backswing	13.7	32.6	29.1	22.7	29.2	29.4
	Ball Impact	7.2	4.8	12.3	5.4	9.7	5.7
	Follow Through	15.4	15.6	16.9	15.4	46.3	17.9
	Mean	**9.5**	**14.8**	**18.5**	**12.5**	**20.7**	**15.0**

From the two remaining orders of rotation (ZYX and YZX), flexion / extension values (Y) were examined and due to the position of the shoulders relative to the pelvis at the top of the backswing (Figures 2.2a, 2.2b and 2.3a, 2.2b), flexion (negative) values were determined to be more representative rather than extension (positive) values. More representative data is also seen in the driver and five-iron trials at the top of the backswing (Tables 2.5 and 2.6), where the longer club (driver) causes lesser values of flexion. Negative flexion values were also seen at impact (Tables 2.5 and 2.6). To further support the choice of the ZYX sequence, the YZX sequence also showed relatively small and positive values of rotation (X) for the lower trunk at the top of the backswing (Figures 2.2a, 2.2b and 2.3a, 2.3b) when there is a clear flexed trunk posture at this point for the trunk. Finally, angle-time data for the ZYX order of rotation (Figures 2.4 and 2.5) appeared to most closely match what was seen visually.

Table 2.5 Cardan angles (°) for each of the six rotational sequences of the driver swing.

	Trial	**ZYX**	**YZX**	**XYZ**	**XZY**	**ZXY**	**YXZ**
Trunk (Top of Backswing)	Flexion	-15.0	12.8	-13.2	-23.4	29.7	-2.1
	Lateral Bend	3.8	23.7	-64.2	72.8	-3.3	48.3
	Rotation	-71.9	-70.6	-46.7	-17.2	-123.5	-72.3
Lower Trunk (Top of Backswing)	Flexion	-17.7	31.1	157.8	-15.4	-40.0	31.7
	Lateral Bend	19.9	26.9	28.0	22.3	44.8	30.9
	Rotation	-42.2	13.1	-13.2	-12.6	23.4	14.0
Trunk (Ball Impact)	Flexion	-22.5	-27.6	-39.8	1.4	3.2	-49.2
	Lateral Bend	-35.4	-36.3	-40.5	21.7	-65.9	-29.4
	Rotation	-17.8	-16.7	-13.0	-35.8	-71.1	7.6
Lower Trunk (Ball of Impact)	Flexion	-0.9	-14.2	131.1	-17.5	-18.5	14.3
	Lateral Bend	-16.1	-13.9	-10.9	-13.2	-16.8	-15.9
	Rotation	-18.4	-8.1	-8.1	-3.5	-4.3	-3.6

The angles are consistent with the top of the backswing and ball impact. Positive values indicate right lateral bending, trunk extension and left axial rotation.

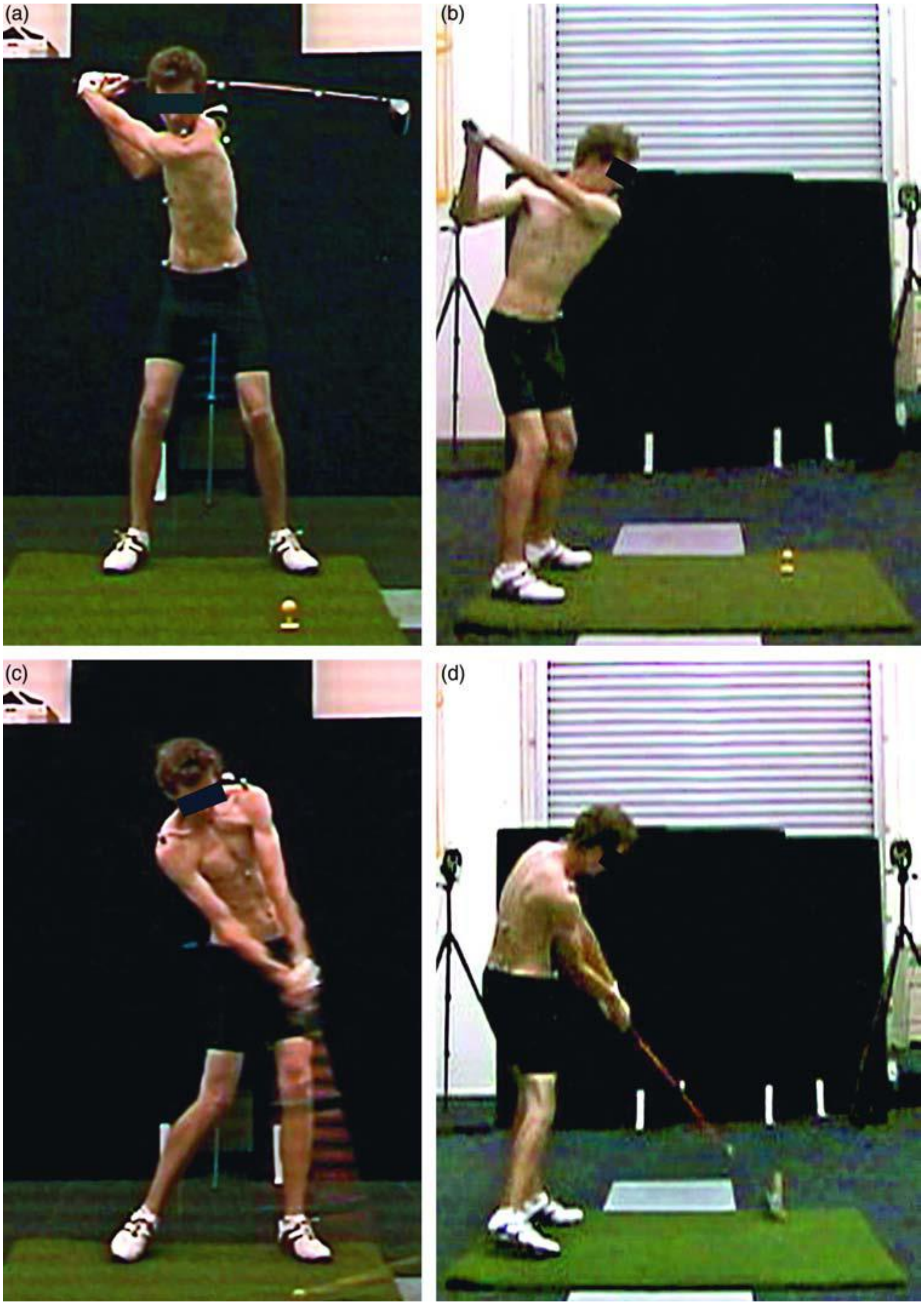


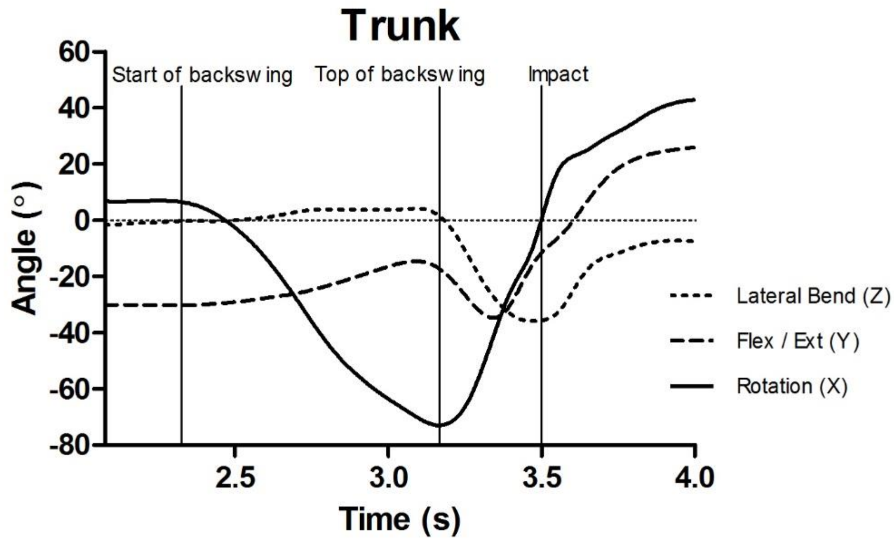
Figure 2.2 Frames from the high-speed footage for the (a) sagittal view for the top of the backswing (b) rear view for top of the backswing (c) sagittal view at impact and (d) rear view at impact for a selected driver trial.

Table 2.6 Cardan angles (°) for each of the six rotational sequences of the five-iron swing.

	Trial	ZYX	YZX	XYZ	XZY	ZXY	YXZ
Trunk (Top of Backswing)	Flexion	-19.1	1.6	-9.1	-39.0	28.0	-11.8
	Lateral Bend	3.8	18.1	40.9	68.4	-5.9	-61.7
	Rotation	-70.3	-69.3	-69.4	-24.3	-124.5	-45.3
Lower Trunk (Top of Backswing)	Flexion	-18.3	27.7	27.9	-13.0	-39.5	160.3
	Lateral Bend	19.3	24.8	29.5	21.7	41.4	28.8
	Rotation	-40.4	12.4	13.6	-11.0	19.6	9.4
Trunk (Ball Impact)	Flexion	-32.5	-37.9	-48.4	-11.2	5.7	-49.6
	Lateral Bend	-36.3	-38.0	-43.9	30.0	-65.1	-34.0
	Rotation	-27.4	-26.0	4.2	-38.2	-91.0	-35.6
Lower Trunk (Ball Impact)	Flexion	-7.8	11.8	12.0	-16.0	-28.3	151.5
	Lateral Bend	-12.7	-10.1	-9.8	-7.9	-11.7	-12.6
	Rotation	-22.7	-3.2	-2.8	-3.0	3.9	1.8

The angles are consistent with the top of the backswing and ball impact. Positive values indicate right lateral bending, trunk extension and left axial rotation.

Figure 2.3 Frames from the high-speed footage for the (a) sagittal view for the top of the backswing (b) rear view for top of the backswing (c) sagittal view at impact and (d) rear view at impact for a selected five-iron trial.



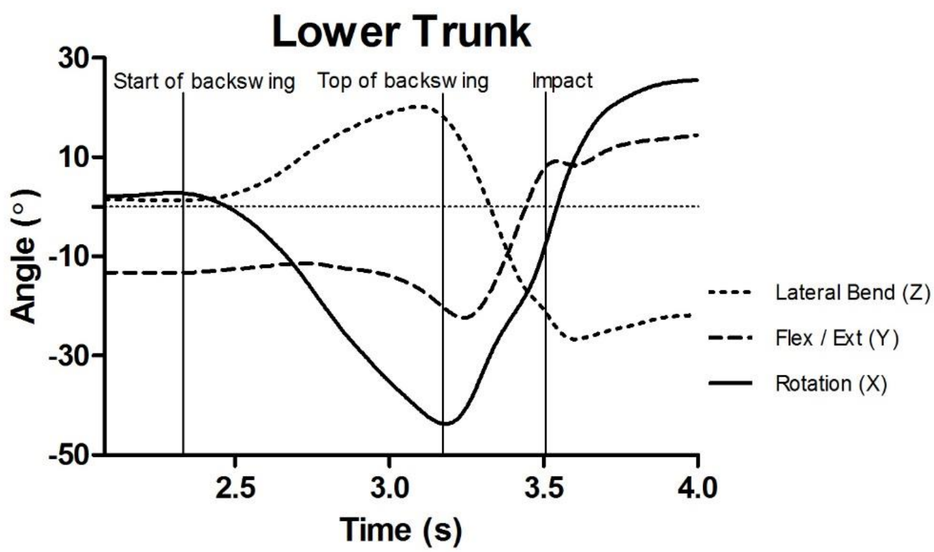
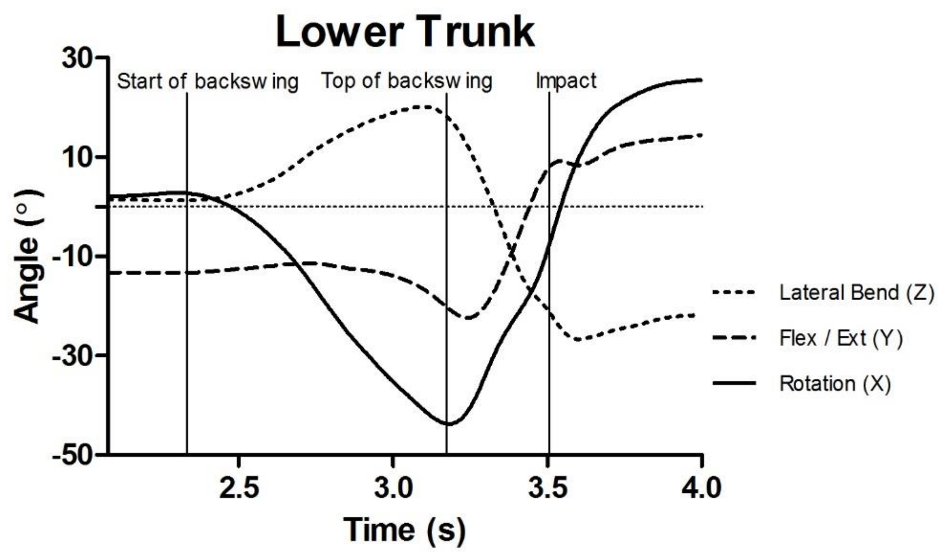


Figure 2.4 Angle-time data for the dynamic golf swing trials in Part 3 of testing. Shown are the angles from the ZYX Cardanic sequence for the trunk (above) and lower trunk (below).



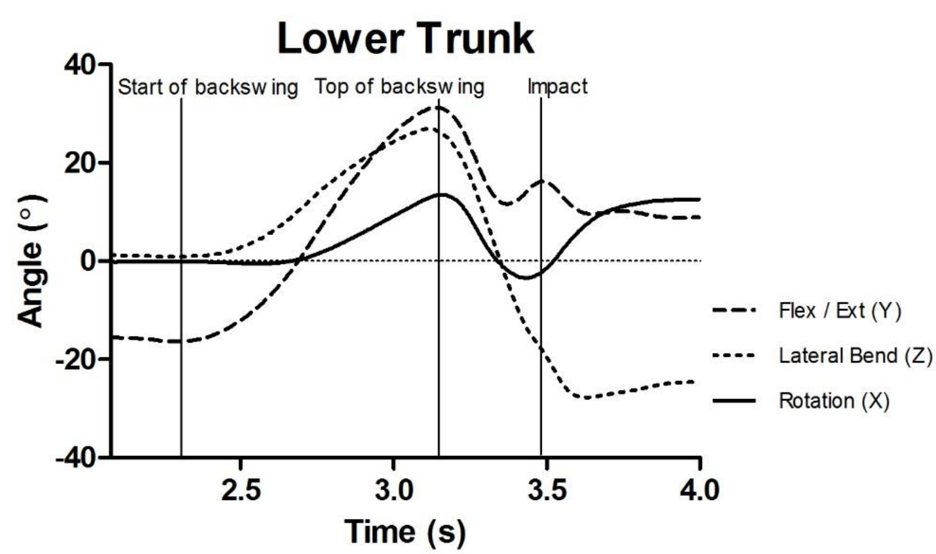


Figure 2.5 Angle-time data for the dynamic golf swing trials in Part 3 of testing. Shown are the angles from the lower trunk ZYX Cardanic sequence (above) and lower trunk YZX Cardanic sequence (below).

2.6 Discussion

Recently there has been an increased amount of attention paid to the biomechanics of the golf swing and particularly phenomena such as the X-factor (e.g. Hume et al, 2005; Gluck et al, 2007). However, there are few recommendations on how to report such data in a true three-dimensional manner. It has been previously reported that for small joint rotations, the choice of Cardanic sequence is relatively unimportant (Crawford et al, 1996; McGill et al, 1997); however, as Cardan angles approach 90°, large coupled rotations appear and the choice of Cardanic sequence becomes more important. (Rundquist & Ludewig, 2004). As the golf swing involves large rotational motion of the trunk, the aim of this study was to investigate methodological considerations for examining the X-factor and lower trunk movement in three dimensions during the golf swing. Previous biomechanical analyses of movement have rarely justified the choice of a Cardanic sequence for three-dimensional analyses.

In this study, the choice of what Cardanic sequence to utilise in three-dimensional biomechanical analysis was undertaken using a multi-step validation procedure. Specifically, after validating the algorithms and model (part one) using a similar approach to that reported in previous research (e.g. Cutti et al., 2008), visual estimation of three-dimensional trunk posture at five critical points during the golf swing (part two), and visual comparison to two critical points during actual golf swings (as taken from high speed footage in part three) was used as a basis for comparison. From these procedures it was determined that the ZYX order of rotation (corresponding to lateral bending, flexion/extension, and axial rotation) seemed the most suitable for analysis of a rotation-dominant movement such as the golf swing.

Some recommendations for the reporting of three-dimensional kinematic data have been previously provided in the literature. Firstly, the International Society of Biomechanics (ISB) (Wu & Cavanagh, 1995; Wu et al, 2002; Wu et al, 2005) suggest that kinematic data should be reported so that angles remain as close as possible to the clinical definitions of joint and segment motions. These guidelines also mention that proximal and distal segments be clearly defined, and that the choice of the centre of origin of the segments can drastically affect angular displacement values (Wu & Cavanagh, 1995). Crawford et al. (1996) utilised both Cardan and projected angles for finding the most representative Cardanic sequence for assessing spine motion. It was stated that whilst any of the six orders of rotation could be used, for spinal motion of small magnitude the flexion-extension, lateral bending and axial rotation sequence was recommended. The choice of an appropriate order of rotation has previously been reported for movements with large movements of the trunk such as fast bowling in cricket. In this study a Cardanic sequence of lateral bending, flexion-extension and axial rotation order was recommended (Ferdinands et al., 2009).

The findings of this study provide evidence that some previous recommendations should be adopted with caution. For instance, McGill et al. (1997) stated that the axis first experiencing 90º of rotation should be defined first in a sequence of three rotations so that errors in the other two axes are minimised. With axial rotation being the largest value of rotation in golf (Figures 2.3 and 2.4) this would mean that either of the XYZ or XZY orders of rotation could be chosen. From the data reported in this study, this would have created data sets that do not describe what is seen visually. Wheat et al. (2007) using a dual-segment model, used the Cardan sequence YZX for determining hip-shoulder rotations, which does not support McGill's recommendations. Lees et al. (2010) suggested the largest movement of the soccer kick was flexion-extension of the hip (Y), which also does not support McGill's recommendations, as they recommended either the XYZ or XZY as the *de facto* standard through analysis of the six Cardanic sequences, and also the support of multiple references.

A limitation of this study was that a face-validity process was utilised. That is, the angles reported needed to be consistent with what was visualised. A more precise gold standard may have been achieved by using a goniometer. An example of such an approach would be the mechanical arm study of Elliott et al. (2007). However, with the reporting of estimated angles in increments of 5° in part two of this study (Terwee et al., 2005; Rachkidi et al., 2009) there were sufficiently large differences evident between Cardanic sequences to enable the elimination of certain sequences of rotation.

A second limitation was that the two-dimensional method in which the X-factor has been previously reported (McLean, 1992; Myers et al., 2008) which requires a vector to be created through the left and right acromion processes. However, for three-dimensional analysis of X-factor in this study, the shoulder coordinate system was constructed from both acromion landmarks and T10. There are some difficulties with such a representation of shoulder alignment. For example, movement of the landmarks used in the reconstruction of shoulder alignment, such as scapula retraction, can lead to large calculation errors (Elliott et al., 2002). However, this representation of the shoulder alignment typifies the concept of the X-factor and two-dimensional projection of shoulder alignment in certain phases of the fast bowling motion are still used (Elliott et al., 2002). Results from the two studies that used transverse projected angles showed a projected X-factor of 61.8° ± 7.8° (Myers et al., 2008) and 55° ± 10° (Zheng et al., 2008) for high velocity swings. These values were consistent with what was found in this study for the Cardanic sequence ZYX (Tables 2.5 and 2.6).

Calculation errors due to shoulder alignment may also influence the choice of Cardanic sequence. Wheat et al. (2007) used the YZX order of rotation as the most appropriate, although the thoracic segment was made up of five individual markers, whereas the shoulder segment used in this study was made up of only three. The fact that the closeness of the ZYX and the YZX Cardanic sequences seen in this study suggest that the choice of markers, number of markers used to construct a segment and the number of segments may influence the Cardanic sequence used. Lees et al. (2010) suggested that either the XYZ or the XZY sequence support dynamic leg movements in soccer, although multiple studies had suggested the XYZ sequence to be the *de facto* standard. With this in mind, more studies are needed to support the choice Cardanic sequence for the golf swing.

Whilst this study is a methodological investigation, it is of importance to both practitioners and coaches as it provides the methodological basis for examining issues related to analysing the golf swing such as the summation of segments. The results shown from this study have further strengthened the use of multi-segment models due to the kinematics of the trunk during the golf swing, and the potential for its use alongside X-factor type analyses.

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CHAPTER 3

STUDY II

Faster clubhead speed is required for golfers who aim to increase driving distance (Hume et al., 2005; Kemp, 2005; Doan et al., 2006; Gordon et al., 2009; Hellstrom 2009). The technique variables related to the generation of ball velocity have been investigated (Chu et al., 2010). However, as ball velocity is influenced by swing parameters (clubhead speed and attack angle), it is unknown what technique, anthropometric and physical factors are responsible for producing clubhead speed alone.

Previous research has reported between-club differences in golf swing kinematics (Egret et al., 2003) although, using a multi-segment model to quantify trunk and lower trunk kinematics, using a Cardan / Euler approach has been reported to more accurately analyse golf swing kinematics such as ‘X-factor’ (Brown et al., 2013; Kwon et al., 2013). From using the methods developed in Study I, this investigation may lead to understanding how multiple trunk segments interact with the aim of producing clubhead speed for different golf clubs.

Three-dimensional trunk kinematics in golf: between-club differences and relationships to clubhead speed

This Chapter is presented in the pre-publication format adapted from:

Joyce, C., Burnett, A., Ball, K., & Cochrane, J. (2013). Three-dimensional trunk kinematics in golf: between-club differences and relationships to clubhead speed. *Sports Biomechanics, 12*, 108-120.

3.1 Abstract

The aims of this study were (i) to determine whether significant three-dimensional trunk kinematic differences existed between a driver and a five-iron during a golf swing, and (ii) to determine the anthropometric, physical and trunk kinematic variables associated with clubhead speed. Trunk range of motion and golf swing kinematic data were collected from 15 high level amateur male golfers (handicap: 2.5 ± 1.9). Data were collected using a 10-camera motion capture system operating at 250 Hz. Data on clubhead speed and ball velocity were collected using a real-time launch monitor. Paired t-tests revealed nine significant ($p \leq 0.0019$) between-club differences for golf swing kinematics; namely trunk and lower trunk flexion/extension and lower trunk axial rotation. Multiple regression analyses explained 33.7 % and 66.7 % of the variance in clubhead speed for the driver and five-iron respectively, with both trunk and lower trunk variables showing associations with clubhead speed. Future

studies should consider the role of the upper limbs and modifiable features of the golf club in developing clubhead speed for the driver in particular.

3.2 Introduction

Golfers gain a competitive advantage when they are able to achieve long hitting distances with drivers and irons. Different clubs produce different shot outcomes due to characteristics such as shaft length and face angle (Wallace et al., 2007; Kenny et al., 2008) composition (Worobets & Stefanyshyn, 2007), and clubface composition and angle (Hocknell, 2002). Trunk kinematics can differ with club type (Egret et al., 2003), although how this interaction influences clubhead speed is an area under-researched.

To increase hitting distance, a faster clubhead speed is required (Hume et al., 2005; Kemp, 2005; Doan et al., 2006; Gordon et al., 2009; Hellstrom 2009), and this is related to physical traits such as trunk rotational power (Doan et al., 2006; Gordon et al., 2009; Keogh et al., 2009; Wells et al., 2009) and anthropometric factors such as height (Kawashima et al., 2003; Fradkin et al., 2004; Hellstrom, 2009). Whilst investigating key biomechanical predictors of driving distance, Chu and colleagues (2010) explained 44-74 % ball velocity variance with five biomechanical variables: X-factor (separation of the trunk-pelvis alignment when viewed in the transverse plane); lateral bending and flexion of the trunk; weight shift during the downswing; and delayed arm and hand release. The biomechanical, anthropometric and physical traits that are most strongly associated with clubhead speed, however, have yet to be identified.

The golf swing has evolved to improve shot distance (McHardy et al., 2006; Gluck et al., 2007) and the modern swing is characterised by large trunk rotation. This movement pattern restricts hip movement in the backswing, resulting in a larger trunk-pelvic segment separation than in the older, ‘classic’ golf swing (Bulbulian et al., 2001; Cheetham et al., 2001; Gluck et al., 2007). Recent work has reported that a significant positive relationship exists between trunk-pelvic segment separation and ball velocity, and driving distance (Myers et al., 2008; Hellstrom, 2009). Conversely, the older golf swing, in which the heel of the forward foot was lifted, permitted greater pelvic rotation in the backswing, resulting in a smaller trunk-pelvic segment separation (McHardy et al., 2006; Gluck et al., 2007). This smaller trunk-pelvic segment separation is believed to have adversely affected clubhead speed (Bulbulian et al., 2001; Gluck et al., 2007).

Whilst many biomechanical studies of trunk movement have utilised a two-dimensional approach, reporting of three-dimensional Cardan/Euler angles may be more informative for relating modern swing kinematics, such as trunk-pelvic segment separation, and clubhead speed. Specifically, this kind of modelling of the trunk as a rigid body is less prone to overestimation than two-dimensional transverse plane projections, because it is not affected by out of plane motion and yields lower values for trunk-pelvic segment separation (Wheat et al., 2007; Horan et al., 2010). Three-dimensional multi-segment models of the trunk have now been validated by the examination of a single participant for typical golf swing positions (Joyce et al., 2010). This is important, as the thoracic (trunk) and thoracolumbar (lower trunk) regions do not move uniformly when undergoing axial rotation (Hsu et al., 2008). The kinematics of the lower trunk and their importance in creating clubhead speed have yet to be investigated. Axial rotation of the trunk is a key component of the kinetic chain because of its large range of motion (ROM) during the golf swing (e.g. Lindsay et al., 2002; Horan et al., 2010). Although Horan et al. (2010) reported that increases in angular velocity of the trunk are related to larger clubhead speed, trunk rotation in their study was reported relative to a global coordinate system located between the feet, rather than to the pelvis segment.

To the author's knowledge, there has been no previous investigation into variables associated with the generation of faster clubhead speeds using multi-segment trunk Cardanic modelling in homogenous cohorts. Homogeneous cohorts (such as low handicap golfers using a certain swing type) may be more appropriate when attempting to explain variance, as the 'pooling' of heterogeneous data exaggerates the r^2 value (Atkinson & Nevill, 1997). As previously mentioned, Chu et al. (2010) were able to explain 44-74 % of the variance in clubhead speed, but their results were determined from a large heterogeneous cohort, their trunk kinematics values were derived from transverse plane projections, and their study only considered one type of club, that being a driver.

The aims of this study were twofold: (i) to determine whether significant differences existed between a driver and a five-iron club for three-dimensional trunk kinematic variables measured during the golf swing, using a previously validated model (Joyce et al., 2010); and (ii) to determine the anthropometric, physical and trunk kinematics variables most strongly associated with clubhead speed in the participants (low handicap golfers). It was hypothesised that (i) there would be significant differences between clubs for trunk and lower trunk segment rotation variables; and (ii) greater participant height, and increased trunk axial rotational velocity (of both trunk and lower trunk regions) would be most strongly associated with increased clubhead speed.

3.3 Methods

3.3.1 Participants

Participants recruited for this study included 15 right handed high level amateur male golfers (M ± SD: age = 22.7 ± 4.3 years, height = 1.80 ± 0.10 m, mass = 72.9 ± 12.2 kg, and handicap = 2.5 ± 1.9). At the time of testing, participants had a golfing handicap of 5 or lower, were aged between 18 and 30 years, had no low back pain in the previous 12 months prior to testing (as assessed by a modified Nordic Low Back Pain questionnaire), and were using a modern (as opposed to a classic) golf swing. To determine whether participants were using this swing type, videos of potential participants' golf swings were recorded and independently assessed by two Professional Golf Association (PGA) teaching professionals. The teaching professionals utilised key discriminating factors to categorise swing type, namely shoulder turn, hip movement and heel raise (as outlined in the introduction). Five of the 20 potential participants were excluded from the study after the teaching professionals disagreed on how to classify their swings. The remaining 15 participants were recruited for the study. Ethical approval to conduct the study was sought from the relevant Institutional Human Research Ethics Committee.

3.3.2 Data Collection

3.3.2.1 Medicine Ball Test - Release Velocity

Before the data on golf swing kinematics was collected, a medicine ball throw test using a 2 kg ball was conducted. The release velocity during this test was determined to provide an indication of the rotational power of the trunk. To make the test golf-specific the medicine ball was thrown as fast as possible in a simulated full golf swing movement during three maximum velocity trials. A digital video camera (Samsung VP-D371WI, Japan) operating at 25 Hz and positioned 4 m from the participant and perpendicular to the line of the throw was used to estimate release velocity during this test.

3.3.2.2 Range of Motion and Golf Swing Kinematics

A 10-camera MX-F20 Vicon-Peak Motion Analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz was used to capture each participant's static range of motion (ROM) of the trunk, as well as all three-dimensional swing kinematics during the golf swing trials. A previously validated multi-segment trunk model (Joyce et al., 2010) was created from the retro-reflective markers attached to participants (Table 3.1). The model consisted of three anatomical reference frames: trunk (left and right acromian processes and tenth thoracic vertebra), lower trunk (tenth thoracic vertebra, sternum and first lumbar vertebra), and pelvis (left and right anterior superior iliac spine and left and right posterior superior iliac spine). Table 3.2 indicates how the anatomical markers were used to construct the segment reference frames. Two markers were also attached to the shaft of the golf club (1/3 and 2/3 of the length of the club). A small piece of retro-reflective tape attached to the golf ball was used to identify ball impact. A real-time launch monitor (PureLaunch™, Zelocity, USA) was positioned at a distance of 3 m adjacent to the participant's target line to determine clubhead speed and ball velocity at ball impact.

Table 3.1 Placement of retro-reflective markers.

Markers	Anatomical Marker Placement
Trunk Reference Frame	
Left Shoulder	Left Acromion Process (LACRM)
Right Shoulder	Right Acromion Process (RACRM)
T10 vertebra	Tenth Thoracic Spinous Process (T10)
Lower Trunk Reference Frame	
Sternum	Xiphoid Process, distal end of the Sternum
T10 vertebra	Tenth Thoracic Spinous Process (T10)
L1 vertebra	First Lumbar Spinous Process (L1)
Pelvis Reference Frame	
Left Anterior Pelvis	Left Anterior Superior Illiac Spine (LASIS)
Right Anterior Pelvis	Right Anterior Superior Illiac Spine (RASIS)
Left Posterior Pelvis	Left Posterior Superior Illiac Spine (LPSIS)
Right Posterior Pelvis	Right Posterior Superior Illiac Spine (RPSIS)
Golf Club	
Upper Shaft	1/3 length of shaft from grip
Lower Shaft	2/3 length of shaft from grip

Table 3.2 Joint Coordinate Systems for Trunk, Lower Trunk and Pelvis.

JCS	Origin	X - vector	Y (temp) - vector	Z - vector	Y – vector
Shoulder	Coincident with the mid-acromion and halfway to T10	Mid-acromion point, with the unit vector pointing to the right	Mid-point of the mid-acromion and T10, a distal unit vector, perpendicular to X	The common perpendicular of X and Y (temp), a proximal unit vector, perpendicular to X	Cross-product of X and Z, unit vector perpendicular and anterior to X
Lower Thorax	Coincident with the mid-point of L1 and T10 and halfway to Sternum	Mid-point of L1 and T10, with the unit vector pointing to the right	Mid-point of the L1 and Sternum, a distal unit vector, perpendicular to X	The common perpendicular of X and Y (temp), a proximal unit vector, perpendicular to X	Cross-product of X and Z, unit vector perpendicular and anterior to X
Pelvis	Coincident with the mid-point of mid-ASIS and mid-PSIS	Mid-point of mid-ASIS and mid-PSIS, unit vector pointing to the right	Mid-point of the mid-ASIS and mid-PSIS, a distal unit vector, perpendicular to X	The common perpendicular of X and Y (temp), a proximal unit vector, perpendicular to X	Cross-product of X and Z, unit vector perpendicular and anterior to X

A static trial was captured using the Vicon system with participants standing in the anatomical position so that the multi-segment model could be attached to the participant and all ROM and golf swing kinematic data collection could be measured relative to a neutral position (defined as 0º, 0º, 0º). For maximum ROM trials (from which normalised golf swing kinematic data could be obtained), participants were instructed to perform three maximum ROM trials for trunk flexion, extension, left and right lateral bending, and left and right axial rotation. The maximum value from the three trials was used. Participants were instructed to stand in an upright starting position with arms held out to the side, and to bend as far as possible forwards, then backwards, then asked to bend as far as possible to the left, then to the right, also from the same starting position. Finally, they were asked to rotate as far left, then as far right as possible, again from the same starting position. They were told to complete all trunk movements with a static pelvis position and straight legs, specifically for trunk flexion and extension. All movements were practised, and the investigators were confident that the participants reached end ROM for each movement (Ranson et al., 2008; Joyce et al., 2010).

In the subsequent golf swing trials, participants were instructed to use their own clubs to hit a golf ball as straight as possible with maximum velocity from an artificial turf surface into a net positioned 5 m in front of the hitting area. Data from five driver and five five-iron swings were collected using the same golf ball, and these ten swings were monitored. Trials were disregarded if the launch monitor failed to record clubhead speed or ball velocity, or if the participant felt that improper contact was made with the ball.

3.3.3 Data Analysis

3.3.3.1 Medicine Ball Test - Release Velocity

The centre of the medicine ball during the 2 kg medicine ball throw test was digitised using SiliconCoach data analysis software (SiliconCoach PRO, Wellington, NZ) from the point of maximal trunk counter rotation to release. A maximal value for ball release velocity was obtained from three digitised trials.

3.3.3.2 Range of Motion and Golf Swing Kinematics

The coordinate data from each of the anatomical reference frames (Table 3.2) for the three-dimensional ROM and golf swing trials were smoothed using a Woltring filter with a mean square error of 20 mm^2 (Woltring, 1986) . Smoothed coordinate data were exported as a text file and subsequent data analyses were undertaken in Microsoft Excel using a previously defined algorithm (Joyce et al., 2010) in which Cardan angles for the trunk relative to pelvis and lower trunk relative to pelvis could be calculated. Cardan angles recovered for each of the two segments were reported using a ZYX (lateral bending, flexion/extension and axial rotation respectively) order of rotation (Joyce et al., 2010). In order to calculate the rotations relative to a zero reference (0, 0, 0) for each segment, Cardan angles derived from the direction cosine matrix were multiplied by the direction cosine matrix derived from the first frame of data from each trial (Burnett et al., 1998).

The maximal value from three trials for each of the six pre-swing ROM trials was used to normalise trunk kinematics during the golf swing trials in each of the respective movements. Positive values indicated trunk extension, right lateral bending and left axial rotation and negative values indicated trunk flexion, left lateral bending and right axial rotation. From the ten golf swings recorded, six trials (three trials for each club) were chosen for analysis based on maximal clubhead velocity and minimal marker loss. Ensemble averages for absolute trunk and lower trunk angular displacement data from top of the backswing to ball impact were created. In preparation for the ensemble average process, all data were time normalised (0-100 %) using cubic spine interpolation. An average of the three trials for each variable was used for subsequent analysis.

Three downswing events were used in extracting variables: top of the backswing, at the point of trunk maximum axial rotation, and at ball impact. The top of the backswing was defined as the frame where the two club markers changed direction to initiate the downswing (Lephart et al., 2007; Myers et al., 2008). The instant of trunk maximum axial rotation was determined to be the frame when the trunk segment began to counter-rotate, which occurs shortly after the frame where the pelvis counter-rotates (Cheetham et al., 2001). The time point when segment axial rotation velocity for the trunk, and lower trunk segments was maximised was also calculated. Ball impact was defined as the frame where the ball was first seen to move after contact (Joyce et al., 2010).

3.3.4 Statistical Analysis

There were a total of 34 dependent variables related to; segment ROM and normalised ROM, segment angular velocities and normalised angular velocity, and also clubhead speed and ball velocity for both the driver and five-iron clubs (Tables 3.3 and 3.4).

Intra-class correlation coefficient (ICC) and standard error of mean (SEM) statistics were used to determine the within-trial reliability of all variables listed in Tables 3.3 and 3.4.

According to Fleiss (1986), ICC values greater than 0.75 were considered as excellent, ICC values between 0.40 and 0.75 were considered as fair to good, and ICC values less than 0.4 were considered as poor. As Fleiss' fair to good values spanned a large range, reliability for the purposes of this study was considered to be good when ICC values ranged from 0.60 to 0.74 (Gstoettner et al., 2007). To determine whether between-club differences existed for all variables collected in the study, multiple paired t-tests were conducted. Pre-screening of the data revealed that assumptions regarding normality of population difference scores were met. As 34 between-club comparisons were conducted, a Bonferroni adjustment of the p-value ($p \leq 0.0019$) was made to correct the family wise error rate.

Stepwise linear regressions were conducted for the driver and five-iron clubs, in which trunk kinematic variables, participant height and the release velocity obtained during the trunk rotational power test were the independent variables and clubhead speed was the dependent variable. Assumptions regarding normality, linearity, homeoscedasticity and independence of residuals were met for the driver and five-iron models. These assumptions were checked by normal P-P plot distribution, and random scatter-plots showing independent errors, with casewise diagnostics showing low standardised residuals. A correlation matrix was also generated for trunk kinematic variables to check for multicollinearity. Consequently, normalised lateral bending and flexion/extension variables were removed due to the high level of association with their absolute counterparts. Normalised axial rotation variables were retained.

As there were 15 participants, and as the sample size should be at least five times the number of independent variables (Norman & Streiner, 2003) a maximum of three variables were retained in the regression analysis. The final model reported for the driver and five-iron was that with the highest amount of variance explained (to a maximum of three independent variables) while attempting to achieve the lowest p-value possible. Finally, Pearson's product moment correlation coefficients between selected variables were calculated to help assist with the discussion of regression findings. All statistical analyses were performed using SPSS V17.0 for Windows (SPSS Inc, Seattle, WA, USA).

3.4 Results

The average release velocity for the medicine ball was 9.2 ± 1.3 $m.s^{-1}$. There was good to excellent reliability for variables derived for both clubs for the trunk (ICC = 0.608–0.984, SEM = 1.2-7.1°) and the lower trunk (ICC = 0.618–0.935, SEM = 1.4-12.2°) (Table 3.3). There was good to excellent reliability for velocity and angular velocity related variables (ICC range = 0.609–0.909) (Table 3.4).

Results from the paired t-tests revealed that there were nine significant ($p \leq 0.0019$) differences between-club for trunk kinematics (Table 3.3). Six of these nine significant differences were related to trunk flexion/extension and three were related to lower trunk axial rotation. Further, five of these differences were for variables quantified at the top of the backswing while four variables were at ball impact. Normalised values of trunk and lower trunk axial rotation at the top of the backswing were greater than 100 % for both clubs indicating that participants moved beyond the relative position achieved during the static ROM trials. Ensemble average data for trunk and lower trunk segments from the top of the backswing (0 %) to ball impact (100 %) for both the driver and five-iron are shown in Figure

3.1. From this figure, the differing movement patterns of the trunk and lower trunk segments are evident.

There were no between-club differences for angular velocity-related trunk kinematics or for clubhead speed, although ball velocity was shown to be significantly different between-clubs (Table 4.4). For the driver, trunk and lower trunk segment axial rotation velocity was maximised 0.09 (± 0.16) s and 0.10 (± 0.15) s before ball impact, respectively. For the five-iron these variables were maximised 0.06 (± 0.15) s and 0.06 (± 0.15) s prior to ball impact.

Three trunk kinematic variables each explained 33.7 % and 66.7 % of the variance in clubhead speed for the driver and five-iron respectively (Table 3.5). From examination of the beta coefficients, the variable most related to clubhead speed for the five-iron was maximal axial rotation of the lower trunk (β = -0.665) while for the driver, lower trunk flexion-extension at the top of the backswing was identified as being most strongly associated variable with clubhead speed (β = 0.340). Neither anthropometric (standing height) nor physical (release velocity of the medicine ball) variables were selected by the regression models.

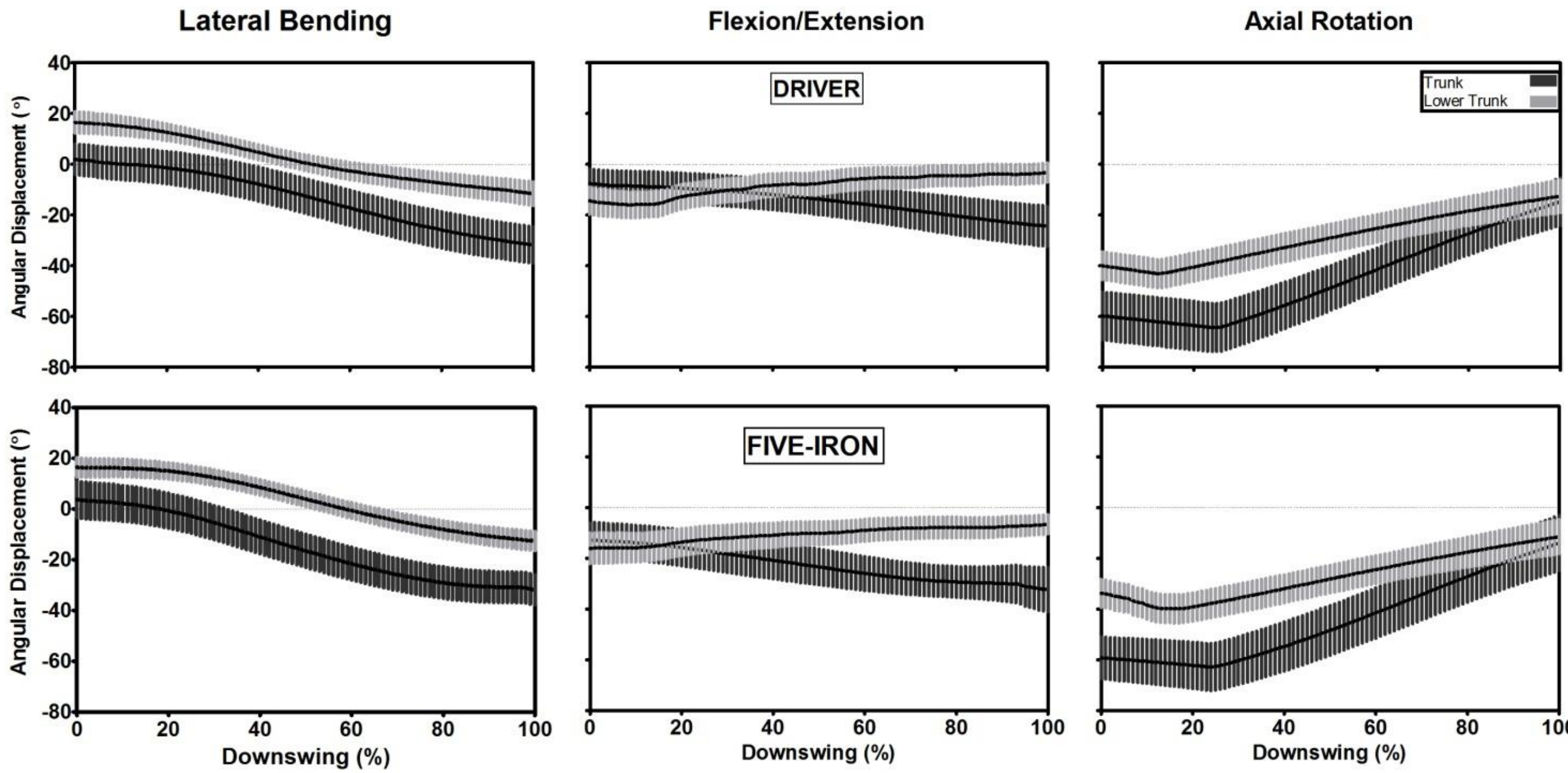

Figure 3.1 Ensemble averages of lateral bending, flexion/extension, and axial rotation angular displacement data. The ensemble averages are shown for the trunk and lower trunk segments from the top of the backswing (0 %) to ball impact (100 %) for both the driver and five-iron. Shaded areas represent one standard deviation from the mean.

Table 3.3 Trunk kinematics measured at the top of backswing (TOB) and at ball impact (BI) for the driver and five-iron trials (M ± SD). Negative values for absolute trunk kinematics indicate flexion, right lateral bending and left axial rotation. Indices of reliability are also reported.

		Driver			Five-iron		
Lateral Bend		**Absolute (°) / Relative (% ROM)**	**ICC**	**SEM**	**Absolute (°) / Relative (% ROM)**	**ICC**	**SEM**
TOB	Trunk	1.9 ± 6.0	0.738	3.1	3.7 ± 7.2	0.618	4.4
		4.5 ± 14.1	0.750	7.1	8.7 ± 16.7	0.629	10.2
	Lower Trunk	16.3 ± 4.3	0.898	1.4	16.4 ± 3.9	0.879	1.4
		87.5 ± 24.1	0.891	8.0	89.1 ± 24.9	0.911	7.4
BI	Trunk	-31.8 ± 7.2	0.960	1.4	-31.8 ± 5.9	0.897	1.9
		72.8 ± 15.7	0.957	2.3	73.1 ± 15.3	0.934	4.0
	Lower Trunk	-11.7 ± 4.7	0.884	1.6	-12.6 ± 3.9	0.751	2.0
		61.7 ± 22.2	0.819	9.5	68.1 ± 20.1	0.635	12.2
Flexion / Extension							
TOB	Trunk	-7.7 ± 5.7	0.854	2.2	-13.6 ± 6.8*	0.775	3.2
		14.7 ± 11.0	0.862	4.1	25.8 ± 14.1*	0.812	6.1
	Lower Trunk	-14.3 ± 5.3	0.954	1.2	-16.1 ± 6.0	0.921	1.7
		37.6 ± 12.7	0.952	2.8	42.2 ± 14.5	0.901	4.6
BI	Trunk	-24.4 ± 7.9	0.817	3.4	-32.3 ± 8.8*	0.855	3.4
		45.7 ± 15.8	0.813	6.9	60.7 ± 18.5*	0.896	6.0
	Lower Trunk	-3.2 ± 3.8	0.608	2.4	-6.6 ± 3.8*	0.608	2.4
		8.0 ± 9.4	0.757	4.6	17.3 ± 10.0*	0.861	3.7
Axial Rotation							
TOB	Trunk	-59.5 ± 9.6	0.980	1.4	-59.3 ± 8.2	0.880	2.9
		102.5 ± 17.9	0.984	2.3	102.4 ± 17.5	0.914	5.1
	Lower Trunk	-39.9 ± 5.5	0.951	1.2	-37.1 ± 5.5*	0.735	2.7
		118.0 ± 17.5	0.946	3.5	110.0 ± 19.5*	0.917	5.6
BI	Trunk	-14.8 ± 11.0	0.845	3.9	-14.1 ± 10.8	0.845	4.2
		25.8 ± 19.6	0.882	6.7	24.6 ± 19.3	0.832	7.9
	Lower Trunk	-12.6 ± 6.4	0.919	1.8	-11.6 ± 6.8	0.933	1.8
		37.2 ± 18.4	0.888	5.8	34.8 ± 20.2	0.935	5.1
Max. Axial Rotation							
	Trunk	-64.4 ± 10.3	0.981	1.4	-62.6 ± 8.2	0.891	2.7
	Lower Trunk	-43.0 ± 5.2	0.930	1.4	-40.8 ± 4.8*	0.865	1.7

* Indicates a significant difference ($p \leq 0.0019$) exists when compared to the driver.

Table 3.4 Angular velocity of trunk kinematic variables, clubhead speed and ball velocity. Indices of reliability are also reported.

	Driver	**ICC**	**SEM**	**Five-Iron**	**ICC**	**SEM**
Trunk max axial rotation velocity (°/s)	449.3 ± 84.9	0.735	47.5	446.6 ± 57.6	0.609	41.3
Trunk axial rotation velocity at impact (°/s)	327.8 ± 73.2	0.776	36.8	315.7 ± 70.5	0.868	26.2
Normalised trunk velocity (% of max)	74.3 ± 15.7	0.767	7.6	71.6 ± 14.9	0.816	6.7
Lower trunk max axial rotation velocity (°/s)	228.8 ± 45.5	0.741	36.5	227.5 ± 45.7	0.785	22.5
Lower trunk axial rotation velocity at impact (°/s)	142.7 ± 35.5	0.757	18.8	142.6 ± 33.6	0.892	11.2
Normalised lower trunk velocity (% of max)	64.7 ± 16.7	0.832	7.1	64.0 ± 17.2	0.909	5.2
Clubhead speed (m/s)	46.7 ± 4.5	0.809	2.1	43.9 ± 4.7	0.902	1.5
Ball velocity (m/s)	64.8 ± 4.2	0.679	2.7	54.0 ± 3.8*	0.753	2

* Indicates a significant difference ($p \leq 0.0019$) exists when compared to the driver.

Table 3.5 Linear regression models explaining clubhead speed for the driver and five-iron trials. Statistics relating to model fit and variance explained are reported as well as the beta coefficients (ß) and standard errors for the independent variables.

Model	Independent Variables	ß	Standardised Error	P-value	Variance Explained (%)
Driver	Lower trunk flexion (TOB)	0.340	0.241		
	Lower trunk flexion (BI)	0.288	0.362		
	Trunk lateral bending (TOB)	-0.194	0.200	0.194 n/s	33.7
Five-Iron	Lower trunk max. axial rotation	-0.665	0.179		
	Trunk max. segment velocity	-0.374	0.015		
	Trunk flexion (BI)	-0.246	0.101	0.006*	66.7

* Indicates a significant amount of variance explained ($p \leq 0.05$), n/s – not significant.

3.5 Discussion

This study had two main aims: (a) to determine whether significant differences existed between-club for three-dimensional trunk kinematic variables measured during the golf swing and (b) to determine the anthropometric, physical and trunk kinematics variables most strongly associated with clubhead speed for participants using a driver and five-iron.

The movement patterns recorded during the downswing (Figure 3.1) appear to have vindicated the approach used in this study to examine both the kinematics of the trunk and lower trunk segments. Although a visual inspection detected minimal differences between these segments for the movement pattern for lateral bending, there were clear differences between these segments in flexion/extension and axial rotation.

Besides the logical between-club difference in ball velocity (Table 3.4), several between-club differences were observed for trunk kinematics variables (Table 3.3). For shots hit with the driver, greater values of absolute and relative lower trunk axial rotation at the top of the backswing and lower trunk segment maximum axial rotation were found. Previous investigations agree that an increase in axial rotation is associated with increased clubhead speed, and this association is particularly strong in the case of the driver (Cheetham et al., 2001; Myers et al., 2008), as it is used to achieve maximum distance off the tee. The five-iron, however, is normally used not to maximise distance but to place a shot accurately on the green (Egret et al., 2003; Wiseman & Chatterjee, 2006). Interestingly, there was a greater difference in the magnitude of axial rotation evident for the lower trunk when compared to the trunk. While at first glance these differences appear to be small (approximately 2°) it should also be considered that participants went beyond the statically measured ROM in axial rotation where there would be little available range. With regard to trunk flexion/extension, a greater magnitude of both trunk and lower trunk flexion (both absolutely and relatively) was seen for the five-iron when compared to the driver. This was the case at both the top of the backswing as well as at ball impact, as the length of the five-iron is shorter than that of the driver (Egret et al., 2003) and increased trunk flexion is required to return the clubface to the initial set-up position, at ball impact for accurate contact with the ball.

From the regression analyses performed, different variables were selected for the driver and five-iron models (see Table 3.5). Further, the model generated for the five-iron explained a greater amount of variance in clubhead speed when compared to the driver. The low amount of variability found by the driver model can partly be explained by the higher standardised errors reported for the beta coefficients.

The three variables most strongly associated with clubhead speed for the driver were: (a) lower trunk flexion/extension at the top of the backswing; (b) lower trunk flexion/extension at ball impact; and (c) lateral bending of the trunk at the top of the backswing. Positive beta coefficients for lower trunk flexion/extension at the top of the backswing and at ball impact indicate that a lesser amount of trunk flexion was associated with faster clubhead speed. In the standing position, increased trunk flexion has been shown to decrease the amount of available axial rotation (Burnett et al., 2008). Therefore, decreased flexion of the lower trunk may have been responsible for increased axial rotation at the top of the backswing. In fact, there was a near-significant association between trunk flexion/extension and normalised lower trunk axial rotation at the top of the backswing ($r = 0.461$, $p = 0.084$). It is possible that the small homogenous sample recruited for this study precluded this association from being significant. A right handed golfer whose trunk is more axially rotated to the right at the top of the backswing may be able to develop greater clubhead speed. However, there was no significant association between the amount of axial rotation of the trunk at the top of the backswing and clubhead speed ($r = -0.038$, $p = 0.894$). This tends to support the idea that there are a number of factors that contribute to the development of clubhead speed during the downswing.

A variable from the regression analysis for the driver that is difficult to explain is lower trunk flexion/extension at ball impact. This variable may not actually be directly associated with increased clubhead speed, but may have been a by-product of the fact that lower trunk flexion at the top of the backswing was significantly associated ($r = 0.521$, $p = 0.047$) with the amount of lower trunk flexion at ball impact. The final variable selected by the regression model for the driver, lateral bending of the trunk at the top of the backswing, indicated that golfers with a lesser magnitude of left lateral bending of the trunk tended to display greater club head speed. It has been previously shown that an upright trunk position at the top of the backswing may enable greater rotation of the trunk, and that this in turn may result in faster clubhead speed (Adlington, 1996; McHardy et al., 2006). A relatively neutral trunk position at the top of the backswing is a feature of the modern golf swing (McHardy et al., 2006). It is clear from Figure 3.1 that the trunk is laterally bent to the right through to ball impact, and this is in agreement with the findings of previous research (Chu et al., 2010).

The three variables found to be most associated with clubhead speed for the five-iron were: (a) lower trunk maximal axial rotation; (b) trunk segment maximum axial rotation velocity; and (c) trunk flexion/extension at ball impact. The negative beta coefficient for lower trunk axial rotation indicates that a greater magnitude of axial rotation to the right (for right handed-golfers) during the backswing is associated with faster clubhead speeds. A similar finding has been reported in previous investigations (Lephart et al., 2007; Myers et al., 2008;

Chu et al., 2010). Trunk segment maximum axial rotation velocity also had a negative beta coefficient, so that greater values for this variable were associated with lesser clubhead speed. This finding has not been reported by previous studies. However, the value of this variable was maximised 0.060 s prior to ball impact. Due to the relatively late occurrence of this maximal value, it is possible that the wrists play an important role in generating clubhead speed late in the downswing, and this hypothesis seems to be supported by recent research (Chu et al., 2010; Fedorcik et al., 2012). The last variable derived from the regression analysis for the five-iron was increased trunk flexion at ball impact, which was associated with faster clubhead speed. This result contrasted with the results found for the driver. The findings from the regression analyses for the driver and five-iron should be confirmed with future studies and consideration should be given to other segments such as the wrists to determine whether these findings can be reproduced.

It should be noted that differences in the regression models generated both in this and earlier studies may be due to the kinematic models and statistical methods used. This study generated a single regression model for each club by which all variables regardless of phase of the golf swing, were simultaneously entered into the regression models. Previous investigations have compartmentalised the golf swing into its different events and phases (i.e. top of the backswing, downswing, pre-ball impact and ball impact) and generated a regression model at each of these points (Watanabe et al., 1999; Chu et al., 2010).

The findings of this study should be considered along with its limitations. Firstly, due to the difficulty in recruiting the homogenous cohort, the sample size in this study was small. This meant that only three variables could be retained from the regression analysis. Norman & Streiner (2003) recommended that the sample size should be at least five times the number of independent variables. Using homogenous groups in regression statistics produces a range of variables that are smaller than in studies of heterogeneous groups (Tabachnick & Fidell, 1996). This reduces the effect size, and thus the statistical power in regression analysis, as seen with the driver (p = 0.194), and by Ball and Best (2007) when studying centre of pressure patterns in elite level golfers. Secondly, Garcier et al. (1999) found that the ROM of the thoracic and lumbar spine is influenced by other segments, namely the lower extremities. Our multi-segment model focused on quantifying the kinematics of both the trunk and lower trunk, and position of the lower extremities at different stages of the golf swing may have contributed to the ROM of this segment. Thirdly, the lesser amount of variance explained for the driver model might reflect the fact that a driver has a greater number of modifiable properties than an approach iron (Hocknell, 2002), Participants in this study used their own driver, so it is possible that factors such as shaft length, shaft mass and shaft stiffness contributed to the lesser amount of variance explained for this club. This result warrants further investigation, as previous studies have failed to find a significant interaction between golf swing kinematics, shaft properties and their influence on clubhead speed (Betzler, 2010). Finally, the kinematics of the upper limbs were not examined in this study. This too may be an important limitation, as previous studies (Teu et al., 2006) have indicated that the kinematics of the upper arm, lower arm and wrist explain 60 % of variance in clubhead speed.

In conclusion, five of the nine between-club differences found in this study were related to the lower trunk segment. Further, most of the between-club differences were seen for axial rotation and flexion/extension-related variables, and the driver showed larger values of axial rotation and smaller values of flexion at the top of the backswing and at ball impact. The regression model for the five-iron explained a greater amount of variance in clubhead speed than did the regression model for the driver. However, the regression models that were generated found that only kinematic variables were associated with clubhead speed. Three of the six variables used to explain the variance in clubhead speed were from the lower trunk, which shows in part, the importance of including segments such as the lower trunk when examining the golf swing. Finally, it is recommended that modelling of the upper limb and modifiable factors related to the golf club should be examined in an attempt to explain a greater amount of variance in clubhead speed.

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CHAPTER 4

STUDY III

The non-significant driver model from Chapter 3 required further investigation into how more variance could be explained for high level amateur male golfers producing clubhead speed. Drivers are shown to have more modifiable properties than irons (Jackson, 2001; Hocknell, 2002), namely numerous modifications to graphite shafts such as; length, (Lacy et al., 2012) stiffness (Betzler et al., 2012) and mass (Haeufle et al., 2012). This may explain the low amount of variance explained for the driver in Chapter 3, as participants used their own drivers and such modifiable properties were not controlled for.

Another modifiable shaft property which has received little attention is the point of maximum bend (kick) point along the shaft. As with most classification of shaft properties, these are based on static measures. The golf swing is a highly dynamic movement; therefore, the statically measured kick point location may be different under dynamic conditions as the golf club experiences large inertial forces during the downswing (Milne & Davis, 1992; Mather et al., 2000; Summitt, 2006). There were multiple aims of this study in developing an algorithm, assessing its reliability and comparing static kick point location as a percentage of shaft length from the tip with dynamic values for a between and within-club analysis for two shafts of known different static kick point location. The methods used in this study may lead to a greater understanding of the swing parameters of the club, and the related launch conditions of the ball at impact.

A new method to identify the location of the kick point during the golf swing

This Chapter is presented in the pre-publication format adapted from:

Joyce, C., Burnett, A., & Matthews, M. (2013). A new method to identify the location of the kick point during the golf swing. *Journal of Applied Biomechanics*, *29*, 779-784.

4.1 Abstract

No method currently exists to determine the location of the kick point during the golf swing. This study consisted of two phases. In the first phase, the static kick point of 10 drivers (having identical grip and head but fitted with shafts of differing mass and stiffness) was determined by two methods; 1) a visual method used by professional club fitters and 2) an algorithm using three-dimensional locations of markers positioned on the golf club. Using level of agreement statistics, we showed the latter technique was a valid method to determine the location of the static kick point. In phase two, the validated method was used to determine the dynamic kick point during the golf swing. Twelve high level amateur male golfers had three shots analysed for two drivers fitted with stiff shafts of differing mass (56 g and 78 g). Excellent between-trial reliability was found for dynamic kick point location. Differences were found for dynamic kick point location when compared to; static kick point location, as well as between-shaft and within-shaft. These findings have implications for future investigations examining the bending behaviour of golf clubs, as well as being useful to examine relationships between properties of the shaft and launch conditions.

4.2 Introduction

There have been suggestions that the interaction between the golfer and the shaft of a golf club may influence clubhead speed, mainly due to modified swing kinematics (Mather et al., 2000; MacKenzie & Sprigings, 2009a; McGinnis et al., 2010; Betzler et al., 2012). Understanding how the shaft performs under dynamic conditions (i.e. during the golf swing) may provide better insight when compared to evaluation of the shaft under static conditions alone (Milne & Davis, 1992; Wallace & Hubbell, 2001; MacKenzie & Sprigings, 2009b; Betzler et al., 2011). Important properties of the golf club's shaft include; stiffness, damping, torsional stiffness, mass, and maximum bending point of the shaft (Jackson, 2001; Wallace & Hubbell, 2001; Cheong et al., 2006). The location of the maximum bend point of the shaft, which has also been termed the minimum radius of curvature or herewith, the kick point, is typically considered the furthest point from a line joining the two ends of a loaded shaft (Jackson, 2001). The kick point determined in a static manner (herewith termed the static kick point) of clubs used by high level players has been reported to be located between 44-60 % of shaft length when measured from the shaft's tip (Mather et al., 2000; Cheong et al., 2006). It has been postulated that heavier shafts provide a higher static kick point (Mather et al., 2000; Jackson, 2001; Cheong et al., 2006), but little objective evidence exists to support these claims.

Findings from studies using motion analysis (Mather et al., 2000; Wallace & Hubbell, 2001; Huntley et al., 2006; Villasenor et al., 2006) and computer simulation (Milne & Davis, 1992; McGinnis & Nesbit, 2010) suggest that the bending profile of the shaft measured under dynamic conditions differs to that under static conditions. This may be due to inertial forces generated during the downswing (Milne & Davis, 1992; Mather et al., 2000; Summitt, 2006), although examining the dynamic deflection point (herewith known as the dynamic kick point) of the shaft from information based on static performance.

This study had several aims. The first aim was to develop an algorithm using three-dimensional coordinate data from markers placed on a golf club to calculate the location of the static kick point on a golf club. The second aim was to determine the between-shaft reliability of the dynamic kick point location for two drivers fitted with shafts of differing mass. The third aim was to assess whether differences existed between the location of the static kick point and the dynamic kick point for two differently weighted golf club shafts. The final aim was to determine whether the location of the dynamic kick point differed between-shaft for each subject, and within-shaft for each trial.

4.3 Methods

4.3.1 Participants and Experimental Protocol

Twelve right-handed high level amateur male golfers (M ± SD; age 24.7 ± 6.0 y, handicap 1.2 ± 1.8 score) participated in this study. The inclusion criteria were a registered golfing handicap ≤ 5 and being aged 18-35 years. All participants provided informed consent and the Institutional Human Research Ethics Committee approved the study.

This study consisted of two phases. In the first phase, the static kick point for 10 drivers of differing mass and stiffness grading (Table 4.1) was determined using two methods: 1) a method used by a professional club-fitter and 2) an algorithm that used three-dimensional coordinates of markers positioned on the golf club's shaft, measured by a motion analysis system. The 10 drivers had the same grip and head and were of identical length (1.19 m); however, they were fitted with interchangeable shafts. To confirm that no differences in stiffness were evident for shafts graded within the same category, a shaft frequency analyser (Surrey Golf, Australia) was used. Further, the club's swing weighting was also determined. During the second phase of testing, the dynamic kick point of two of these drivers (56 g Stiff and 78 g Stiff) was determined and a validation of the location of the dynamic kick point location was undertaken. The 56 g and 78 g shafts were chosen as they are used by elite-level players and provided a discernible difference in shaft mass.

Table 4.1 Grouped shaft properties (light to heavy) for drivers fitted with the 10 differing shafts. M ± SD locations (reported as a percentage of shaft length from tip) of static kick point determined by the professional club fitter and motion analysis and maximum Euclidean distance are shown.

		SKP (% from tip)		**Distance (mm)^**	**Stiffness (Hz)***	**Shaft Weighting (category)**
		Club Fitter	Motion Analysis			
Light	53 g Amateur	54.0 ± 0.8	53.7 ± 0.6	40.7 ± 0.8	3.1	D0
	56 g Regular	53.5 ± 1.8	54.0 ± 2.0	37.1 ± 1.0	3.7	D1
	56 g Stiff	54.0 ± 1.0	55.3 ± 1.5	31.9 ± 1.1	4.0	D1
Medium	65 g Amateur	55.3 ± 0.6	57.7 ± 0.6	39.8 ± 0.9	3.2	D1
	65 g Regular	55.0 ± 1.0	57.0 ± 1.0	33.1 ± 1.0	3.8	D0.05
	66 g Stiff	55.0 ± 1.0	56.3 ± 0.6	29.5 ± 0.8	4.1	D0.05
Heavy	77 g Regular	57.7 ± 1.2	58.0 ± 1.0	25.8 ± 1.1	3.8	D0.25
	78 g Stiff	58.3 ± 0.6	58.4 ± 1.5	31.5 ± 1.0	4.0	D3
	79 g Extra Stiff	58.7 ± 0.6	58.7 ± 1.5	23.6 ± 0.8	4.6	D3
	95 g Stiff	60.3 ± 1.5	60.3 ± 1.2	23.4 ± 1.1	5.3	D4.5

^ - indicates maximum Euclidean distance at the static kick point for motion analysis.
* - Stiffness / frequency trials are reported as average of two trials.

4.3.2 Data Collection

A 10-camera MX-F20 Vicon-Peak Motion Analysis system (Oxford Metrics, Oxford, UK) operating at 500 Hz was used to capture three-dimensional coordinate data. The average calibration residual was 0.15 for all trials. Further, the standard deviation of the distance between two markers placed 0.80 m apart on a rigid steel pole during simulated golf swing was 0.0006 m. During real golf swing trials, 11 lightweight retro-reflective markers (1.4 cm diameter) were positioned approximately in line along the shaft of each driver tested using double-sided adhesive tape (Figure 4.1). One marker (P1) was placed at the bottom of the grip, while another 10 markers (P2-P11) were equi-spaced (every 7 cm) from the tip of the shaft (P11).

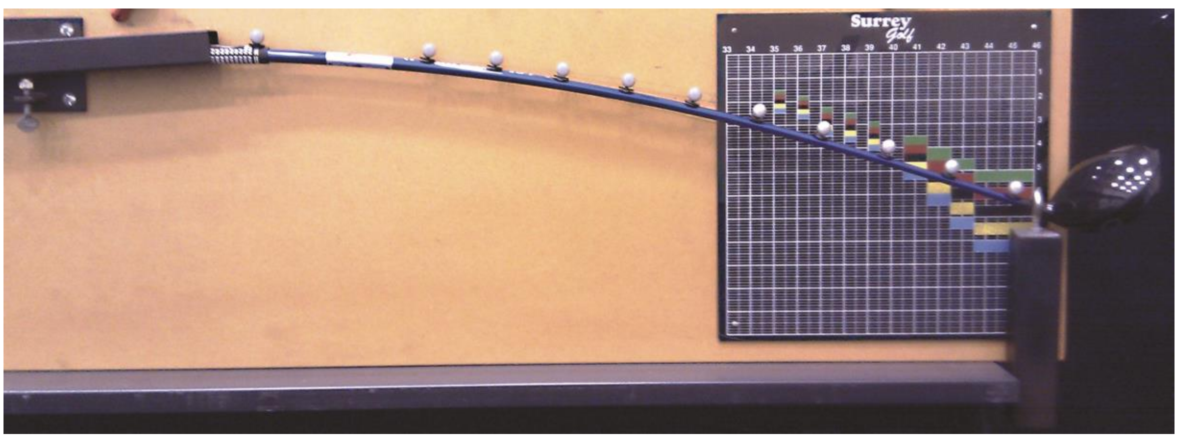

Figure 4.1 The experimental set up to determine the static kick point. Shown in the figure are the 11 retroreflective markers (P1-P11 from left to right).

In a similar manner to previous research the static kick point for 10 drivers was determined by the club fitter who fixed the grip in a vice, then suspended a 2.3 kg load from the distal end of the shaft (Jackson, 2001). The club fitter identified the static kick point with the aid of a tape measure held at markers P1 and P11 and the point on the shaft where the maximum distance from the tape measure was determined. This value was subsequently reported to the nearest 1 % of shaft length. The positions of the retro-reflective markers in space were then recorded using the motion analysis system for a period of 5 s (MacKenzie & Sprigings, 2009b). These processes were repeated five times per driver. For each trial, the load was removed and reset.

For the dynamic kick point trials, the 56 g and 78 g stiff shafts were used. Twelve trials were conducted for each participant (six shots per driver). Shots were hit from a tee positioned on an artificial turf surface and hit into a net placed 5 m in front of the player. Participants were instructed to hit the ball as straight as possible with maximum velocity. A real-time launch monitor (PureLaunch™, Zelocity, USA) was used to determine whether the ball would have landed within the confines of a standard 37 m wide fairway. Participants were informed if the trial was successful by landing the ball within the fairway. Participants were blinded to which shaft was fitted to the driver by covering any visual markings.

4.3.3 Data Analysis

From the five static kick point trials collected, three trials were randomly selected for analysis. Coordinate data for these trials were averaged over all frames. For dynamic kick point trials, three trials per shaft were analysed and the trials selected were those with maximum clubhead speed and minimal marker drop out. For these trials, raw data from the end of the address position through to the completion of the follow through were smoothed using a Woltring filter with a mean square error of 20 mm^2 (Woltring, 1986). Data from 10 frames prior to top of the backswing to 10 frames past ball impact were then exported as text files.

4.3.4 Determining Kick Point Location

An algorithm was designed to determine the location of the point on the shaft with a maximum perpendicular distance from the vector V connecting the most proximal marker on the club P_1 to the most distal marker P_{11}. These two points have coordinates;

$$P_1 = (x_1, y_1, z_1) \quad \text{and} \quad P_{11} = (x_{11}, y_{11}, z_{11}),$$

then the vector equation of the line is

$$V = \begin{bmatrix} x_1 + (x_{11} - x_1)t \\ y_1 + (y_{11} - y_1)t \\ z_1 + (z_{11} - z_1)t \end{bmatrix}$$

for some parameter t.

To find the maximum distance between vector V and the remaining markers lying on the club with coordinates $P_i = (x_i, y_i, z_i)$ where $i = 2,3,\ldots,10$, the Euclidean distance is calculated and differentiated with respect to t to obtain the critical point (which can be shown corresponds to a minimum since the second derivative is always positive). The value of t is then substituted back into the formula for the Euclidean distance, and the following formula for the minimum distance d between a point P_i and the vector line V connecting the points P_1 and P_{11} is determined as

$$d = \frac{\left|\left(\mathrm{P}_i - \mathrm{P}_1\right) \times \left(\mathrm{P}_i - \mathrm{P}_{11}\right)\right|}{\left|\mathrm{P}_{11} - \mathrm{P}_1\right|} \quad , \quad i = 2,3,\ldots,11,$$

For both the static and dynamic kick point trials, the three-dimensional shape of the shaft was approximated using a cubic spline interpolation for each frame. This process generated 101 data points per frame between P1 and P11. For each trial, the dynamic kick point was calculated at maximum (the frame where the perpendicular distance of a marker Pi from vector V was maximised) and at the frame before ball impact. The location of the kick point was reported to 0.1 % of shaft length. All coding was performed using Microsoft Excel.

4.3.5 Validation – Dynamic Kick Point Location

To validate the algorithm determining kick point location during a real golf swing, a controlled evaluation with a fixed kick point location was conducted. A standard clubhead from a driver was welded to a rigid steel pole of length 1.19 m and a grip was also attached. A rigid steel pole was utilised to minimise the chance of bending to the shaft. The 11 markers as mentioned above were positioned on the shaft and a total of six golf swing trials performed by a participant swinging with maximal effort were conducted. The first set of three trials involved the golfer hitting a foam ball the size of a standard golf ball (to simulate a minimal clubhead-ball collision) and the second set of these trials involved hitting a standard golf ball. A simulated kick point was created by offsetting marker P4 which was precisely positioned at 73 % of the simulated shaft’s length. All trials were smoothed using the same approach as stated above. An ensemble average for ball condition trials was created after data from top of backswing to impact were time-normalised 0- 100 %. Further, data were processed from impact to 10 frames post-impact.

4.3.6 Statistical Analysis

Unless specified, all statistical analyses were performed using SPSS V19.0 for Windows (SPSS Inc, Seattle, WA, USA). Between-method agreement to quantify static kick point location from club fitter and motion analysis was assessed using a Bland–Altman plot with multiple observations per trial, where the true value is constant (Bland & Altman, 2007). This analysis was performed using MedCalc V12.1.4 (MedCalc Software, Mariakerke, Belgium). Between-trial reliability of static kick point location for all 10 shafts, for both methods (club fitter and motion analysis system), as well as for dynamic kick point locations at maximum and ball impact was determined using intra-class correlation coefficients (ICC (3,3)) and absolute Standard Error of Measurement (SEM).

A one-sample t-test was used to determine whether the location of the static kick point (determined from motion analysis) differed from the maximum dynamic kick point location for the clubs fitted with 56 g and 78 g shafts. Independent t-tests were then conducted to determine whether the dynamic kick point location differed between-club (56 g and 78 g shafts). To determine whether the location of the dynamic kick point differed within-club (i.e. between maximum and ball impact), paired t-tests were used. Standard assumptions for parametric tests were met. Bonferroni adjustments were made for independent and paired t-tests therefore, the alpha levels were set at 0.025 for these comparisons.

4.4 Results

From examining the Bland-Altman plot, a slight systematic bias was evident when determining the location of the static kick point using the motion analysis method (Figure 4.2) for the 10 shafts. Excellent between-trial reliability was seen for both the Club Fitter (ICC = 0.956, SEM = 0.2 %) and the Motion Analysis system (ICC = 0.965, SEM = 0.2 %) for locating the static kick point.

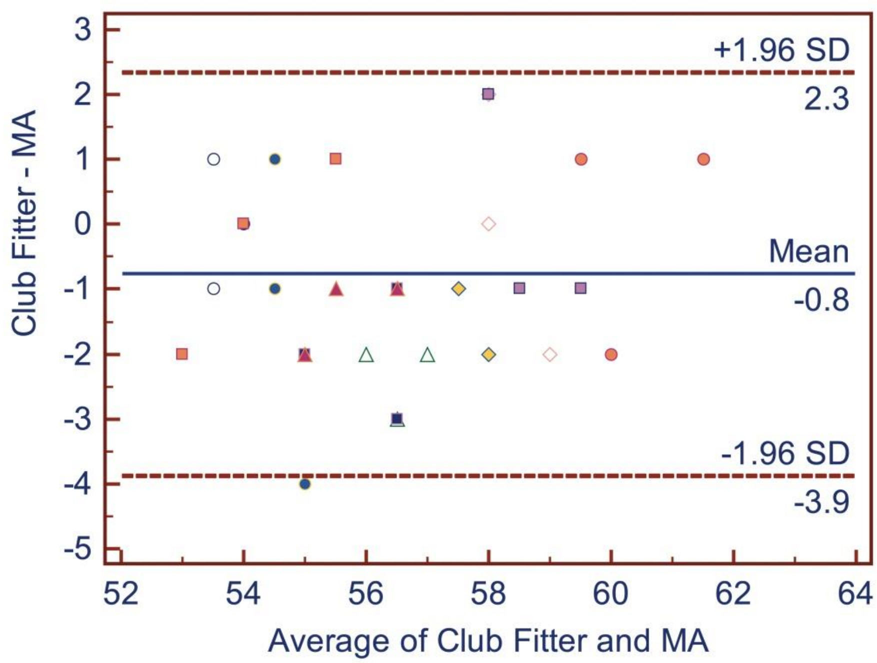

Figure 4.2 Bland-Altman plot with multiple measurements per shaft showing the 95 % limits of agreement between the professional club fitter and motion analysis (MA) methods used to determine the location of the static kick point on the 10 drivers. Different symbols in this figure represent the different drivers tested.

The effect of the collision between the clubhead and a golf ball is evident when comparing the foam-ball and standard golf ball trials (Figure 4.3). There was remarkable consistency between the gold standard value of 73 % and the foam-ball trial (standard deviation <0.01 %). From the standard golf ball trials, deviations from the gold standard value can be seen after ball impact (Figure 4.3).

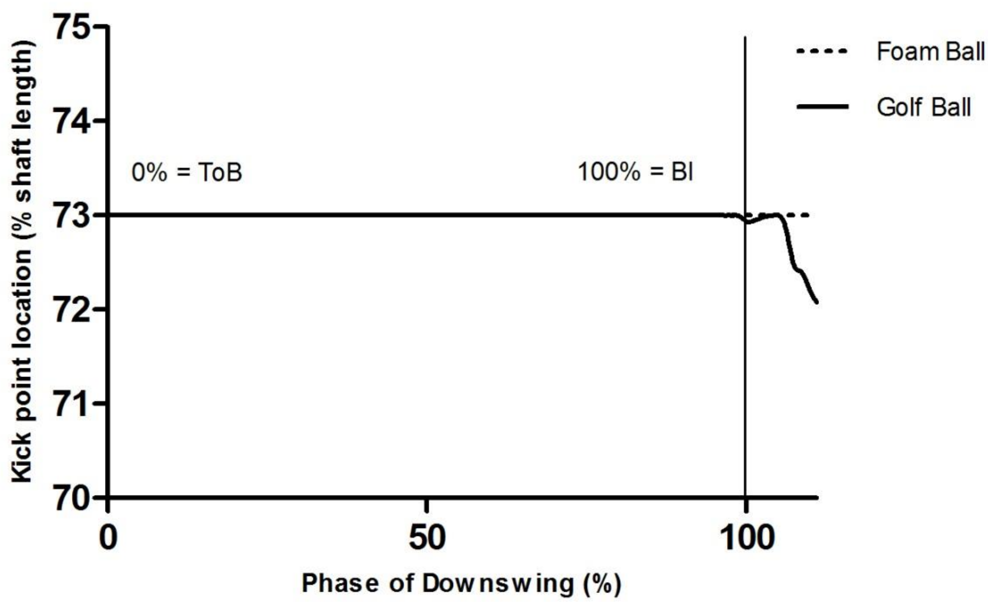

Figure 4.3 Comparison of the foam-ball and standard golf ball trials. Simulated kick point is at 73 % of shaft length. Data are shown from Top of Backswing (TOB) to Ball Impact (BI). Values greater than 100 % on the x-axis are the 10 frames recorded post-impact.

Reliability of the between-trial location of maximum dynamic kick point (ICC range = 0.936–0.957, SEM range = 0.4–1.1 %) and for ball impact (ICC range = 0.901–0.913, SEM range = 1.1–1.2 %) was excellent (Table 4.2). Due to these levels of reliability, the three shots hit by each participant were averaged to provide a single data point.

Table 4.2 Comparison of the static kick point, and dynamic kick point at maximum and ball impact for the 56 g and 78 g "stiff" shafts (M ± SD locations – reported as a percentage of shaft length from tip).

	SKP (% from tip)	DKP Max. (% from tip)	DKP Impact (% from tip)	Distance (mm)^
56 g Stiff	55.3 ± 1.5	58.7 ± 3.2*[1]	50.9 ± 5.5[2]	21.5 ± 4.3
78 g Stiff	58.4 ± 1.5	62.1 ± 2.0*[1]	55.2 ± 4.3[2]	19.1 ± 2.2

^ - indicates maximum Euclidean distance at the maximum dynamic kick point.
* - indicates significant difference ($p \leq 0.05$) when compared to SDP location.
[1] - indicates between-club difference ($p \leq 0.025$) at DDP (maximum).
[2] - indicates within-club difference ($p \leq 0.025$) of DDP at maximum and ball impact.

The mean maximum dynamic kick point for the 56 g and 78 g shafts was significantly higher than the static kick point for both shafts ($p = 0.016$ and $p < 0.001$ respectively). A between-shaft difference ($p = 0.019$) was evident for dynamic kick point at maximum, but no significant difference ($p = 0.033$) was evident for dynamic kick point location at ball impact. Table 4.2 shows that for both shafts, the dynamic kick point moved significantly closer to the tip of the shaft from maximum to ball impact ($p < .001$ – 56 g, $p < .001$ – 78 g). This pattern can be seen from an ensemble average of three trials from one participant (Figure 4.4). The dynamic kick point at maximum was shown to have occurred at 7.24 (± 6.63) % of the downswing for the 56 g shaft, and at 11.46 (± 5.48) % of the downswing for the 78 g shaft.

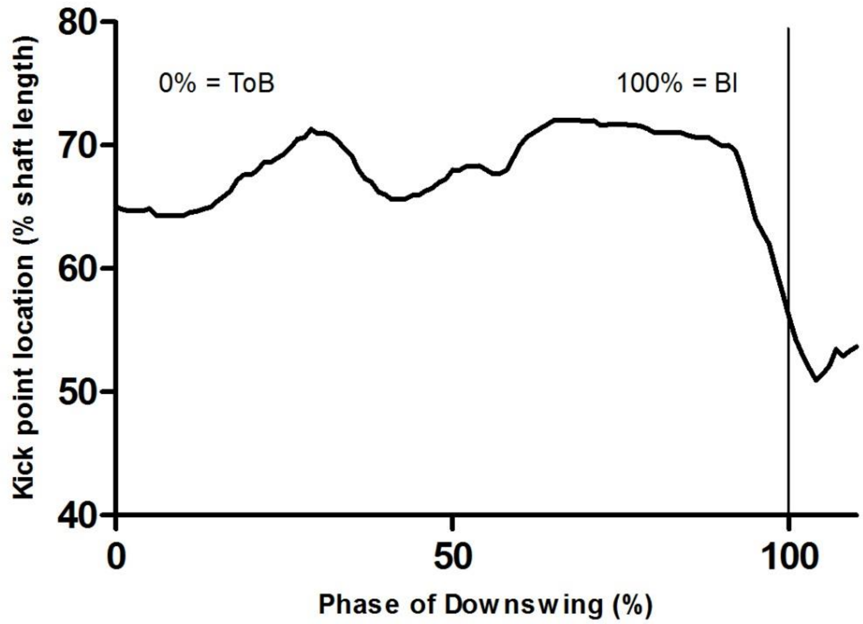

Figure 4.4 Ensemble average of three dynamic golf swing trials from Top of Backswing (TOB) to Ball Impact (BI). Values greater than 100 % on the x-axis are the 10 frames recorded post-impact.

4.5 Discussion

Methods used to quantify and locate dynamic deflection of golf shafts have previously utilised a two-dimensional approach and did not analyse the full downswing (Mather et al., 2000). Therefore, a method was developed to estimate the location of the dynamic kick point with the aid of a commonly used three-dimensional motion analysis system. Comparison between a conventional method and the algorithm-based motion analysis system to locate the static kick point showed that this method was both valid and reliable, so that examination of the dynamic deflection of golf shafts could be undertaken.

Anecdotal reports have stated that both the location of the static and dynamic kick points may not be the same for a golf club (Chou & Roberts, 1994; Jackson, 2001). In this study, the location of the dynamic kick point (maximum) for both shafts was found to be significantly higher up the shaft when compared to the static kick point. The higher bend point of the heavier shaft may be due to it experiencing a higher moment of inertia, and an increased lag (Mather et al., 2000; Jackson, 2001; Cheong et al., 2006) during the downswing which may explain the point of maximal bending occurring later after the top of the backswing, when compared with the lighter shaft. This explanation may also be consistent with the shaft weighting. While the stiffness of both shafts may be consistent (Table 4.1) the heavier shaft is shown to have its extra mass towards the tip of the shaft. This extra mass may be due to differences in the fabrication of each shaft for example, shaft geometry, a difference in the number of layers and the fibre alignment in these layers (Betzler et al., 2011). Not previously mentioned in the literature, is the significant within-club difference found between the dynamic kick point at maximum and at ball impact, for both shafts. These findings have potential application for analysing the shaft bending behaviour with optimal positioning of strain gauges to give maximum values of strain.

A limitation of this study was that the plane in which the shaft was deflecting was not defined. Although bending of the shaft occurs in two planes (lead/lag, toe-up/down) (MacKenzie & Sprigings, 2009b), this study only focused on the principal bending plane. The validation of the dynamic kick point location revealed that even with a rigid steel shaft, some difference, albeit a small ± 0.13 %, existed in dynamic kick point location at the point of impact in the principal bending plane – similarly seen in two-dimensional analysis (Mather et al., 2000). Interestingly, while filtering through ball impact is not typically recommended (Hocknell et al., 1996; Knudson & Bahamonde, 2001) this had little bearing on the validity of our estimates of the dynamic kick point during the downswing. However, data post-impact were effected; therefore, we utilised the frame before impact as a proxy of impact.

In conclusion, this investigation has revealed a valid and reliable method to determine the location of the dynamic kick point during the golf swing. Understanding the dynamic kick point of a golf shaft and how it changes during the golf swing may assist in enabling golfers to achieve optimal launch conditions.

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CHAPTER 5

STUDY IV

Understanding the role of the golf shaft in the downswing has shown to be important in simulation research (MacKenzie & Sprigings, 2009b) at predicting the presentation of the clubhead at ball impact, for shafts of different stiffness (MacKenzie & Sprigings, 2009b), length (Lacy et al., 2012), swingweight (Harper et al., 2005) and mass (Haeufle et al., 2012). Anecdotal evidence claims that swing parameters (club) and their related launch conditions (ball) are affected by hitting with drivers fitted with different kick point locations (Cheong et al., 2006; Wishon, 2011). No experimental evidence exists to support these claims, or describe how the bending profile of the shaft also (developed in Study III) influences the swing parameters and their related launch conditions.

This study aimed to investigate the effect of hitting with drivers fitted with shafts of different kick point location on swing parameters (clubhead speed, attack angle) and their related launch conditions (ball velocity, launch angle and spin rate). Further, this study aimed to determine whether significant associations existed between the swing parameters and their related launch conditions for each driver, and if kick point location influenced the amount of shaft bend throughout the downswing.

A dynamic evaluation of how kick point location influences swing parameters and related launch conditions

This Chapter is presented in the pre-publication format adapted from:

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5.1 Abstract

In golf, many parameters of the driver can be modified to maximise hitting distance. The main objective of this study was to determine whether drivers fitted with shafts having high and low kick points would alter selected swing parameters, and related launch conditions. Twelve high level amateur male golfers (handicap 1.2 ± 1.8) had three shots analysed for two drivers fitted with "stiff" shafts with differing kick point location. Stiffness profiles of these shafts were also measured. Five swing parameters and their related launch conditions were measured using a real-time launch monitor. The locations of the low and high kick points on each shaft during the golf swing (the dynamic kick points) were confirmed via motion analysis. The driver fitted with the shaft containing the high kick point shaft displayed; a more negative (steeper) angle of attack ($p < 0.01$), a lower launch angle ($p < 0.01$) and an increased spin rate ($p < 0.01$) when compared to a driver fitted with a low kick point shaft. It is possible that the attack angle differed between-driver due to the greater

amount of shaft bending found late in the downswing (80 % of the downswing and just before impact). Future work is needed in this under-researched area to determine why these differences occurred.

5.2 Introduction

In golf, driving ability consists of driving distance and driving accuracy and is associated with lower overall score (Belkin et al., 1994; Dorsel & Rotunda, 2001; Wiseman & Chaterjee, 2006). Technique factors, such as the so-called “X-factor” which is defined as the angular displacement between the pelvis and shoulders (Cheetham et al., 2001; Myers et al., 2008; Joyce et al., 2013), and equipment factors such as the shaft of the driver, may influence driving distance. Shaft properties can be altered to help optimise swing parameters and related launch conditions (Werner & Greig, 2000; Wallace & Hubbell, 2001; Cheong et al., 2006; Haeufle et al., 2012). These properties include shaft length (which may only be altered within a certain range), shaft stiffness, shaft mass, location of the point of maximum bend (kick point) and the distribution of mass in the shaft, and can influence parameters such as centre of mass and moment of inertia.

Researchers (Worobets & Stefanyshyn, 2007; MacKenzie & Sprigings, 2009b; Betzler et al., 2012a) have claimed that shaft stiffness influences swing parameters, for example, increased stiffness may lead to higher clubhead speed at ball impact (Worobets & Stefanyshyn, 2007). However, determining shaft stiffness is a complex issue. Probably, the most commonly used description of shaft stiffness in the golfing market is stiffness grading (e.g. ladies, amateur, regular, stiff, extra stiff). However, no industry standards exist for these categories (Huntley et al., 2006; Swanek & Carey, 2007). To address this problem, flexural rigidity (EI) testing may be used as a more comprehensive method to determine shaft stiffness. The EI profile of a shaft depends on its modulus of elasticity (E) and its cross sectional area (I) and EI values for a shaft will change along its length (Brouillette, 2002; Huntley et al., 2006). This method should be utilised in this area of research.

Researchers have postulated that shaft mass influences swing parameters and related launch conditions such as launch angle of the ball (Mather et al., 2000; Cheong et al., 2006). However, as with shaft stiffness, despite quantitative values for actual shaft mass, manufacturers also use alpha-numeric values to describe the distribution of mass (Harper et al., 2005). There are two moments of the shaft with the first being about the wrist-cock axis (termed the swingweight) and the second being the moment of inertia about the club's centre of mass (Wallace et al., 2007). A driver's swing-weighting is related to the 'feel' of the club and is quantified alpha numerically within the range C9 to D8, with each swingweight equivalent to 'two inch-ounces' (Jackson, 2001). Further, swing-weight is related to the distribution of mass about a fulcrum point which is a known distance from the butt of the shaft, such that heavier shafts have a higher swing-weighting (Harper et al., 2005). However, a club's swingweight is not a good predictor of clubhead speed, and shows no correlation with dynamic performance (Mather et al., 2000; Jackson, 2001; Harper et al., 2005; Haeufle et al., 2012).

The location of the kick point is typically determined in a static manner by applying a known load to the tip of the shaft and finding the maximum perpendicular distance between the bent shaft and a line joining the shafts two ends when not bent (Jackson, 2001). From previous work examining elite golfers (Mather et al., 2000; Cheong et al., 2006), the static kick point may be located anywhere between 44–60 % of shaft length (when expressed from the club's tip). However, the golf swing is a highly dynamic movement and motion analysis (Wallace & Hubbell, 2001; Huntley et al., 2006; Villasenor et al., 2006; Haeufle et al., 2012; Joyce et al., 2013) and computer simulation (Milne & Davis, 1992; McGinnis & Nesbit, 2010) have suggested that the dynamic bending profile of a golf club differs to that determined under static conditions. Despite claims that clubs with higher kick points (closer to the grip) tend to produce lower ball launch angles (Mather et al., 2000; Summitt, 2000), little experimental evidence has been provided. Further, to our knowledge no research has examined whether kick point location affects swing parameters and related launch conditions such as clubhead speed and launch angle. Other important related issues include the magnitude of bending of the shaft in the downswing as shaft bend and the timing of it, will determine the presentation of the clubhead to the ball (Wallace et al., 2007; Betzler et al., 2012). A higher swing speed is also known influence the amount of shaft bending (MacKenzie & Sprigings, 2009a).

The first of three aims of this study was to determine whether changes in the location of the kick point of a driver caused differences in clubhead speed and attack angle (swing parameters), and indirectly influenced ball velocity, launch angle and spin rate of the ball (related launch conditions). The second aim was to determine whether significant associations existed between the swing parameters and their related launch conditions for each driver. The final aim was to determine whether the kick point location was associated with the amount of shaft bend throughout the downswing.

5.3 Methods

5.3.1 Participants and Experimental Protocol

The 12 right-handed high level amateur male golfers from Chapter 4 (M ± SD; age 24.7 ± 6.0 years, handicap 1.2 ± 1.8 score) were recruited based on the following criteria; being a male aged between 18-35 years and having a registered golfing handicap ≤ 5. All participants were informed of the research procedures and informed consent was given by all participants prior to testing. Permission to conduct the study was provided by the Institutional Human Research Ethics Committee. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

This study utilised a repeated-measures design. Each participant hit six shots with each of two drivers (i.e. 12 shots) that were fitted with interchangeable shafts of the same broad stiffness grading ("stiff") but with differing kick point locations. While professional golfers may have the kick point location customised for their clubs (Cheong et al., 2006; Huntley et al., 2006), in this study it was not feasible to change kick point location without also modifying the shaft mass. A 56 g "stiff" shaft, termed the shaft with a low kick point, and a 78 g "stiff" shaft, termed the shaft with a high kick point, were utilised in this study. The drivers had identical grips, heads and club length, and were typically used by elite-level male golfers. The static kick point was defined as the point of maximum deflection along the shaft from a vector-line created between the end of the grip and the tip of the shaft, when a 2.3 kg load was suspended from the tip. The static kick point of both shafts had been located using an opto-electronic motion analysis as described elsewhere (Joyce et al., 2013).

A professional club-fitter performed the relevant testing methods to obtain the other properties of the two shafts (Table 5.1). Shaft stiffness was measured using a shaft frequency analyser which measured the oscillations in cycles per minute when a perturbation was applied. Torsional stiffness was determined by measuring the angular displacement of the shaft while a known torque was applied. The shaft was clamped at the butt end during these first two procedures. Next, the swingweight of each driver was measured with the shaft balanced at a fulcrum point at a known distance from the butt end. The required swingweight to achieve balance was added, with the heavier shaft showing a higher swing-weight. Finally, the moment of inertia about the centre of mass was determined using the Auditor MoI speed match system (Technorama, Taiwan) which measures the amount of resistance to motion about a fixed axis on the shaft.

Table 5.1 Properties of the drivers fitted with shafts containing the high and low kick points. A M ± SD value is provided for the static kick point value only.

	High Kick Point Driver	**Low Kick Point Driver**
Static Kick Point (% of length from club tip)	58.4 ± 1.5	55.3 ± 1.5
Shaft Mass (kg)	0.078	0.056
Shaft Stiffness (cpm)	238.0	241.0
Torsional Stiffness (°)	4.0	3.0
Centre of Mass (m from butt)	0.858	0.834
Shaft-Weighting (category)	D3	D1
Moment of Inertia about CoM (kg.m^2)	0.039	0.036
Club Length - grip, shaft and clubhead (m)	1.19	1.19
Clubhead mass (kg)	0.200	0.200
Clubhead face loft (°)	10.5	10.5

After a standardised warm up which included five familiarisation swings with each driver, each participant hit their 12 shots from an artificial turf surface into a net positioned 5 m in front of them. Participants were instructed to hit the golf ball as straight as possible using their full, normal swing. To eliminate potential bias, shot order was block-randomised (i.e. all shots were hit with either driver in a blocked format) and participants were blinded to the drivers they were using. This was done by covering any visual markings on each shaft. Selected swing parameters and their related launch conditions were measured using a real-time launch monitor. To confirm that the kick points evaluated in a static manner would still be considered as high (78 g shaft) and low (56 g shaft) when determined from dynamic evaluation (i.e. during the golf swing), the opto-electronic motion analysis system was used to determine the location of the dynamic kick point. Three of the six shots from each driver were utilised for further analysis. The trials selected for analysis were those displaying the highest clubhead speed and showing no obvious differences in the ball velocity/clubhead speed ratio as measured by the launch monitor. The selected trials were also required to have minimal marker drop out during motion analysis data collection.

5.3.2 Data Collection and Analysis

In this study, a 10 camera opto-electronic MX-F20 Vicon-Peak Motion Analysis system (Oxford Metrics, Oxford, UK), operating at 500 Hz was used. The system's accuracy was confirmed by determining the average of three static trials for the distance between two markers of three known lengths of 300.6 (± 0.006 mm), 200.3 (± 0.003 mm), and 100.6 (± 0.005 mm).

5.3.2.1 Flexural Rigidity (EI) Testing

To determine whether stiffness of the two shafts used in this study was actually similar, the EI profiles of the two shafts were determined. This was done by using a slight variation on a previously published approach (Brouillette, 2002). The above mentioned motion analysis system was used to measure deflection distances under a constant load applied to each shaft. In this protocol, the butt end of the shaft was clamped to a bench and a retro-reflective marker was positioned at the base of this clamp. A second retro-reflective marker was positioned at the same level on a stand-alone surface to provide a horizontal reference line, A third marker was then placed at the tip of the shaft. Deflection distance was considered as the vertical distance between the third marker and the line defining the horizontal. All deflection distances were measured with reference to the deflection distance under the shaft's own weight.

For the first trial of each EI profiling process, a weight of 15.5 N was hung from the tip of each shaft while the base of the grip was positioned level with the end of the bench. For all subsequent trials the same weight was hung from the shaft's tip and the cantilever distance was decreased by 5 cm. Three trials were recorded for each cantilever distance and an average deflection distance was calculated. Excellent reliability was found for deflection distance (Intraclass Correlation Coefficient = 0.999, relative Standard Error of Measurement = 2.9 %), for both shafts. The following formula was used to determine the EI value at each cantilever length *n*,

$$EI_n = \frac{\frac{1}{3}\,F[l_n^3 - l_{n-1}^3]}{w(l_n) - \frac{1}{3}\,\frac{M_{n-1} l_{n-1}^3}{\overline{\overline{EI}}_{n-1}}}$$

where F was the force produced by the weight suspended from the tip of the shaft while l_n and $w(l_n)$ were the cantilever length and the deflection distance sampled at each point, respectively. Further, M_n was the bending moment of each point sampled as determined by $F(l_n - l_{n-1})$ and EI_{n-1} was considered to be $Fl_{n-1}^3 / 3w(l_{n-1})$.

5.3.2.2 Swing Parameters and Related Launch Conditions

A real-time launch monitor (Zelocity PureLaunch™, Arizona, USA) positioned 4-5 m directly behind the hitting area and aimed down a target line, was used to measure two swing parameters (attack angle, clubhead speed at ball impact) and three launch conditions (ball velocity, launch angle and spin rate). Negative attack angle values (Figure 5.1) indicated that the clubhead was descending, in relation to the ground, at the point of ball impact (Tuxen, 2008). The device's software predicted whether the ball would have landed within a 37 m wide fairway; shots landing outside were disregarded.

Figure 5.1 Defining positive (left) and negative (right) attack angle (clubhead) and effect on launch angle (ball).

To determine the validity of all five variables measured by the launch monitor in this study, except ball spin, eight high level amateur golfers (age = 23.5 years; handicap 2.2 ± 1.4) were recruited independently of the main study. Four variables were measured concurrently by the launch monitor and the above mentioned motion analysis system. A static calibration trial was obtained with three retro-reflective markers positioned in a triangular arrangement on top of the driver's clubhead, and four markers positioned at each corner of the clubface. A piece of retro-reflective tape was attached to the ball to act as a single marker. During the dynamic trials, the four clubface markers were removed and reconstructed as virtual markers. Clubhead speed at impact was calculated as change in displacement over time of the virtual central clubhead marker, as was ball velocity (Sweeney et al., 2009). Launch angle was calculated from the coordinates of the ball marker from the equation:

$$Launch\ angle\ \theta = tan\theta = (Zc - Zi)/(Xc - Xi)$$

where Xc and Xi were the current and initial positions of the ball in the horizontal direction respectively and Zc and Zi were the current and initial positions of the ball in the vertical direction (Sweeney et al., 2009). Attack angle was calculated in a similar manner using the horizontal coordinates of the central clubface marker referenced from a virtual global coordinate system (Betzler et al., 2012b). Each participant hit six shots but three trials where maximal ball velocity was measured were chosen for analysis. All coordinate data were smoothed using a Woltring filter with a mean square error of 20 mm^2 (Woltring, 1986). All three-dimensional modelling was undertaken using Vicon BodyBuilder V3.6.1. Pearson's product moment correlations were calculated for the four variables using STATA V9.1 (Stat Corp. Texas, USA). Results from this validation study revealed excellent correlations for the four variables (0.927-0.972) which indicated the launch monitor produces valid estimates for these variables.

5.3.2.3 Dynamic Kick Point Location and Amount of Shaft Bend

The same motion analysis system was used to determine the dynamic kick point location and the amount of shaft bend in the downswing. Eleven lightweight retro-reflective markers (1.4 cm in diameter) were positioned approximately in-line along each of the shafts using double-sided adhesive tape, the first at the bottom of the grip and the rest equi-spaced down the shaft (7 cm apart). The most distal marker was positioned over the tip of the shaft. All coordinate data were smoothed as previously described.

To determine the dynamic kick point (quantified as the percentage of shaft length from the tip to the base of grip) with sub-marker precision, the shape of the shaft during the downswing was approximated. This involved using cubic spline interpolation from the top of the backswing – 0 % (the frame in which the clubhead markers were shown to begin to move in the opposite direction, to commence the downswing) to the frame before ball impact – 100 % (the frame prior to which the reflective tape on the ball was shown to move). The dynamic kick point was considered as the point on the shaft where the perpendicular distance, from a vector connecting the most proximal and distal markers on the club, was maximised. The amount of shaft bend occurring in the principal bending plane was also determined for each trial. Specifically, the Euclidian distance (the perpendicular distance as described above) was also quantified. The amount of shaft bend was determined at regular points in the downswing (0 %, 20 %, 40 %, 60 %, 80 % and 100 %).

The validity and reliability of the method for determining the dynamic kick point's location during the golf swing have been demonstrated (Joyce et al., 2013). When compared to measures taken by the club-fitter in a static sense, the motion-analysis method has shown excellent agreement (95 % limits of agreement = -0.8 ± 3.1 % of shaft length). High levels of between-trial reliability were recorded for dynamic kick point's location at maximum bending (Intra-class Correlation Coefficient = 0.936-0.957, relative Standard Error of Measurement = 0.4-1.1 %).

5.3.3 Statistical Analysis

All data were initially screened and assumptions relating to parametric tests were met. To determine whether differences in the five swing parameters and related launch conditions existed between the drivers fitted with the shafts containing the high and low kick point, a repeated measures linear mixed model, using data from all trials, was used. The random factors were the swing parameters and related launch conditions, while the fixed factors were the two drivers with differing kick point location. Bonferroni corrections were applied for the coefficients of the mixed model with the alpha level set at 0.01.

To detect any significant associations between the five swing parameters and related launch conditions for each driver, Pearson's product moment correlations and the related 95 % confidence intervals were calculated. The calculations were undertaken for both shafts. Repeated measures data should not be assumed as independent in a correlational analysis (Bland & Altman, 1994). However, as the number of observations was the same for each participant, the means of the three observations were taken and the correlation values calculated on n = 12 observations (Bland & Altman, 1995). Correlation coefficient values between 0.2 and 0.4 were considered as weak associations, values between 0.4 and 0.7 were considered as moderate and values above 0.7 as strong (Johnson, 2000).

Finally, to determine whether differences in the amount of shaft bend were evident between-drivers, a repeated measures linear mixed model was again used with all trials considered. The downswing (0-100 % at 20 % intervals) was entered as the repeated random factor and the two kick point drivers were entered as the fixed factor. While clubhead speed was initially included as a covariate for this analysis, it was not influential. Therefore, the repeated measures linear mixed model was re-run without clubhead speed. All statistical analyses were undertaken using STATA V9.1 (Stata Corp. Texas, USA).

5.4 Results

The locations of the dynamic kick point for the drivers fitted with the high and low kick point shafts (determined statically) were 58.7 ± 3.2 % and 62.1 ± 2.0 % respectively. Therefore, the relative positioning of the low and high static kick points from dynamic evaluation was confirmed. Comparison of the EI profiles of the two shafts (Figure 5.2) revealed that the shaft containing the high kick point had greater stiffness when compared to the shaft containing the lower kick point at i) from the tip to 0.2 m of shaft length and ii) from 0.6 m from the tip to the butt. The EI values between 0.25 m – 0.55 m from the tip were very similar.

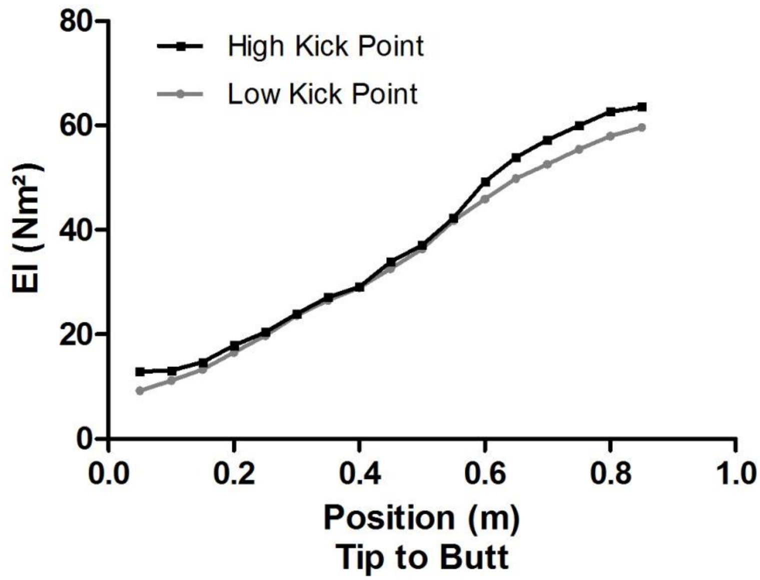


Figure 5.2 Flexural rigidity (EI) profiles for the two shafts used in this study. Higher EI values indicate higher stiffness.

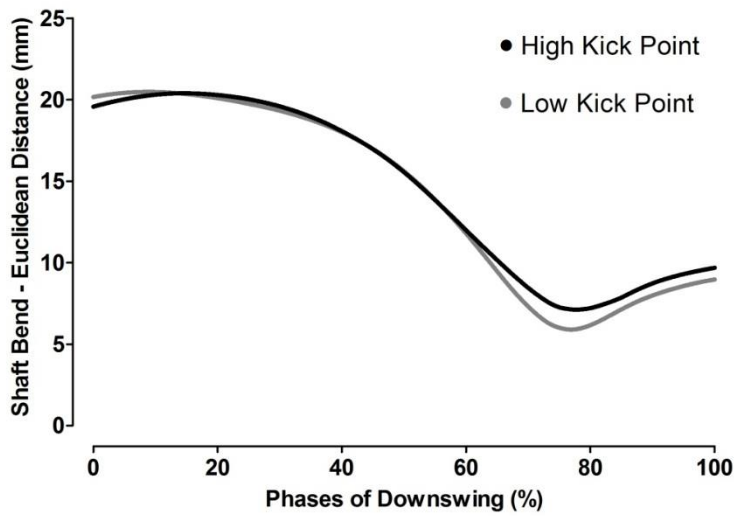
The linear mixed model showed significant ($p < 0.01$) differences, between the drivers containing differing kick point location, for three of the five swing parameters and related launch conditions (Table 5.2). Specifically, the driver fitted with the shaft containing the high kick point produced; higher values for ball spin rate, a more negative angle of attack, and a lower launch angle. The correlation analysis revealed a strong, positive association between clubhead speed and ball velocity for both drivers (Table 5.3). There was also a strong and negative relationship between launch angle and ball spin for the high kick point driver. Further, a moderate, positive association was found between the angle of attack and launch angle for the driver fitted with the high kick point shaft. Examination of the 95 % confidence intervals for the four significant correlation values showed that none of these crossed zero.

Table 5.2 M ± SD swing parameters and related launch conditions for drivers fitted with shafts containing high and low kick points (n = 36 for each shaft).

	High Kick Point M ± SD	**Low Kick Point M ± SD**
Clubhead Speed (m/s)	48 ± 2	48 ± 2
Ball Velocity (m/s)	67 ± 2	66 ± 3
Launch Angle (°)*	8 ± 2	10 ± 2
Attack Angle (°)*	-3 ± 1	-1 ± 2
Spin Rate (rpm)*	4168 ± 495	3614 ± 531

* - indicates a significant difference ($p \leq 0.01$) between-shaft.

As revealed by ensemble averages of the three trials, the maximum amount of shaft bending for the driver fitted with the low kick point shaft occurred at 8.9 ± 4.0 % into the downswing while the corresponding point for the high kick point shaft happened at 14.7 ± 3.5 % (see Figure 5.3a). From the linear mixed model analysis, there was significantly more shaft bending at 0 %, 20 % and 40 % of the downswing when compared to 60 %, 80 %, and 100 % of the downswing (Figure 5.3b). While there was no significant difference ($p > 0.05$) in the amount of shaft bending between the drivers with differing kick point locations, there was a significant difference ($p < 0.05$) between the drivers at 80 % and 100 % of the downswing. Specifically, the driver containing the high kick point shaft showed more shaft bending when compared to the driver fitted with the low kick point shaft.



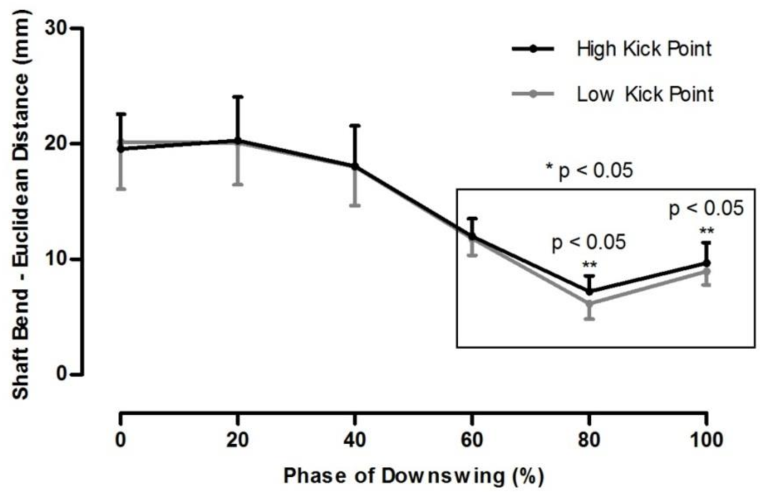


Figure 5.3 Amount of shaft bend from Top of Backswing (0 %) to Ball Impact (100 %) for the drivers fitted with the high and low kick point shafts. Data are presented as a) an ensemble average of the continuous data (top) and b) at a series of discrete data points (bottom). From the main effects analysis, the conditions bound by the box (60 %, 80 % and 100 %) were all significantly different (* $p < 0.05$) to 0 %, 20 %, and 40 %. From the simple effects analysis there were between-driver differences (** $p < 0.05$) evident at 80 % and 100 % of the downswing.

Table 5.3 Correlation coefficient values between the swing parameters and related launch conditions (n = 12). These values were calculated separately for the drivers fitted with the shafts containing the high (top value) and low (bottom value) kick points. The 95 % confidence intervals are also reported in brackets.

	Clubhead Speed	**Ball Velocity**	**Launch Angle**	**Attack Angle**	**Spin Rate**
Clubhead Speed					
Ball Velocity	0.735 (0.54 : 0.86)** 0.701 (0.48 : 0.84)*				
Launch Angle	0.243 (-0.09 : 0.53) 0.409 (0.09 : 0.65)	0.428 (0.12 : 0.66) 0.042 (-0.29 : 0.37)			
Attack Angle	0.047 (-0.29 : 0.37) 0.184 (-0.15 : 0.48)	0.331 (0.00 : 0.59) 0.242 (-0.09 : 0.53)	0.576 (0.31 : 0.76)* 0.305 (-0.03 : 0.58)		
Spin Rate	-0.327 (-0.59 : 0.00) -0.410 (-0.65 : -0.09)	-0.531 (-0.73 : -0.25) 0.094 (-0.24 : 0.41)	-0.905 (-0.95 : -0.82)** -0.543 (-0.74 : -0.26)	-0.384 (-0.63 : -0.06) -0.475 (-0.70 : -0.17)	

* Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

5.5 Discussion

While researchers have examined the effect of differences in shaft properties such as; mass, stiffness, length and swingweight on swing parameters and related launch conditions (Harper et al., 2005; Wallace et al., 2007; MacKenzie & Sprigings, 2009b; Betzler et al., 2012; Haeufle et al., 2012), we are unaware of any previous experimental research that has investigated the effect of kick point location on these variables. Consistent with previous anecdotal reports (Chou & Roberts, 1994; Mather et al., 2000; Jackson, 2001; Cheong et al., 2006), the driver fitted with the shaft containing the high kick point shaft displayed a more negative attack angle as well as a lower launch angle and greater spin rate. In stating these findings the difficulties in isolating the kick point variable should be highlighted. Firstly, the shafts used in this study had differing mass and this may have influenced the swingweights of the drivers. Therefore, as experienced by previous researchers who have investigated the effect of shaft mass and swingweight on swing parameters and related launch conditions (Harper et al., 2005; Wallace et al., 2007; Haeufle et al., 2012), isolating the effect of a single club parameter is challenging. While isolating the effect of kick point location from shaft mass and swingweight in this study was not possible, it is worth noting that swingweight has previously been shown to have no effect on swing parameters and related launch conditions such as; clubhead speed (Haeufle et al., 2012), ball velocity, launch angle and ball spin (Wallace & Hubbell, 2001; Harper et al., 2005). In this study there was no effect of kick point location on clubhead speed. Although other simulation studies had predicted an increased clubhead speed for lighter shafts, the experimental evidence suggests elite golfers do not respond to changes in shaft mass in a mechanically predictable way (Lee & Kim, 2004; Harper et al., 2005; Haeufle et al., 2012).

While we tested two “stiff” shafts in this study, the actual stiffness along the length of the shaft was quantified using EI profiles (Brouillette, 2002). From this analysis, it was found that the tip and butt sections of the two shafts differed slightly with respect to their EI values. This is an important consideration as there is anecdotal evidence that tip stiffness may influence launch angle (Wishon, 2011). The current study found that the driver fitted with the shaft containing the low kick point had a lower stiffness at the tip of the shaft and this may have contributed to the higher launch angle recorded with this driver.

Unsurprisingly, the correlation analyses between the swing parameters and related launch conditions revealed a strong and positive relationship between clubhead speed and ball velocity for both drivers (Wallace et al., 2007). Of more interest however, was the examination of relationships between the three variables that differed between the drivers. Preliminary evidence from others (Tuxen, 2008; MacKenzie & Sprigings, 2009b) has led to the belief that a more negative angle of attack may result in an increased spin rate on the ball and a lower launch angle. Indeed there was moderate and positive association between attack angle and launch angle for the driver fitted with the shaft containing the high kick point which indicated that participants who hit down on the ball more had lower launch angles. However, this significant association was not evident for the driver containing the low kick point shaft. The strong, negative relationship between launch angle and spin rate for the driver fitted with the shaft containing the high kick point. There was also a similar negative moderate, but non-significant correlation for the driver containing the low kick point. Increased spin imparted on the ball was associated with lower launch angles and this finding supports previous research (Penner, 2003; Tuxen, 2008) where elite golfers who aim to maximise clubhead speed off the tee lowered their launch angles and imparted greater spin on the ball when attempting to maximise driving distance.

As mentioned above, the driver fitted with the shaft containing the high kick point displayed a more negative angle of attack. This difference is probably due to the lag created by the significant between-driver difference in kick point location, which is thought to affect the presentation of the clubface to the ball at impact (Tuxen, 2008; MacKenzie & Sprigings, 2009a). As clubhead presentation can be determined by bending of the shaft (Wallace & Hubbell, 2001; Joyce et al., 2013), an examination of shaft bending during the downswing was also undertaken in this study. As shown in Figure 5.3a and 5.3b there was a general trend for the amount of shaft bending to decrease throughout the downswing. Whilst no significant between-driver differences were found in the amount of shaft bending early in the downswing, differences were seen at 80 % of the downswing and one frame before impact (100 %). The full story of lagging of the shaft cannot be elucidated by this study as only bending in the principal plane was measured. Hence, the amount of lag/lead and toe-up/toe-down could not be quantified. It is known from experimental (Betzler et al., 2012) and simulation (MacKenzie & Sprigings, 2009a) studies that the greatest amount of shaft bending occurs at the top of the backswing and this takes the form of predominantly toe-up bending. However, at around 60 % of the downswing, lagging of the shaft increases more rapidly while toe-up bending begins to transition into toe-down bending. Therefore, it is possible that the differences found at 80 % of the downswing in the current study are due to shaft lag. However, this needs to be confirmed in future work. It is also worth noting that while the changes in the angle of attack may have been due to altered shaft dynamics, the swing path, which was not measured in the study, and the difference in the EI profiles of the two shafts, cannot be discounted (MacKenzie & Sprigings, 2009a).

Some limitations of the study should be acknowledged. Firstly, as stated above the kick point variable was not completely isolated in this study as there were differences between-driver for shaft mass, swing weighting and EI profiles. Secondly, this investigation only examined a small cohort of participants which included a mixture of high level amateur and elite golfers who swung drivers fitted with “stiff” shafts. Thirdly, swing parameters and related launch conditions, such as clubhead orientation, and impact location, were not examined in this study. The exclusion of impact location in this study meant that clubhead speed was the most suitable outcome available for measuring ball distance (Lephart et al., 2007; Myers et al., 2008; Keogh et al., 2009). Future investigations may wish to assess ball velocity instead if impact location is considered. Fourthly, as the principal bending plane of the shaft was examined in this study, it is unclear as to which component of bending (toe up / down, and lead / lag) was occurring and if this was known, a better understanding of the between-driver differences could be achieved. The use of strain gauges attached to the shafts would clearly identify not only the dominant bending plane, but also the interaction between the two planes, throughout the downswing. Finally, this study was conducted indoors and involved a short familiarisation period, therefore, participants did not have long to be able to visually perceive shot outcome and consequently adapt to the different clubs provided. It should also be mentioned that there may be an effect of player-ability with respect to this consideration.

In conclusion, this study revealed that a driver fitted with a shaft containing a high kick point displayed a more negative attack angle, a lower launch angle and a greater rate of ball spin when compared to a driver fitted with a low kick point shaft. It is possible that the difference found in the attack angle may have resulted, in part, from the differences found for launch angle and ball spin. The correlation analysis between these variables resulted in some support for this hypothesis but further investigation of these relationships may be worthwhile. It is possible the attack angle differed between the drivers, due to the greater amount of shaft bending found in the late downswing (80 % and just before impact) for the driver containing the higher kick point. The amount of shaft bending may have also been influenced by the differing EI profiles. Measurement of shaft lag in future studies is also recommended. The findings of this study may benefit golf teaching professionals, club-fitters, and biomechanists seeking to optimise a golfer’s swing parameters and related launch conditions.

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CHAPTER 6

STUDY V

In this Chapter a culmination of the technique (trunk and wrist kinematics) and equipment (drivers fitted with shafts of different mass and kick point location) factors were analysed to see if driver clubhead speed produced by high level male amateur golfers was associated with similar or different technique variables. With previous research (Suzuki et al., 2009; Osis & Stefanyshyn, 2012; Sweeney et al., 2012) highlighting the importance of wrist kinematics in producing clubhead speed, the addition of a wrist segment to the existing trunk model (Study I & II) was deemed important with the aim of explaining more variance in clubhead speed for the driver model from Study II. Recent experimental research into the interaction between golfers who hit with drivers fitted with shafts of differing stiffness (Betzler, 2010; Osis & Stefanyshyn, 2012) have suggested further investigation is needed to understand how golfers modify their swing kinematics to optimise the performance of the shaft in the downswing. It is unknown what effect changing modifiable shaft properties will have on swing kinematics, and their association with clubhead speed.

Therefore, the aims of the final study were to determine whether trunk and wrist kinematics differed when using drivers fitted with shafts of differing properties. The second aim was to determine what trunk and wrist variables were most strongly associated with clubhead speed for each driver.

A preliminary investigation of trunk and wrist kinematics when using drivers with different shaft properties

This Chapter is presented in the pre-publication format adapted from:

Joyce, C., Burnett, A., Cochrane, J., & Reyes, A. A preliminary investigation of trunk and wrist kinematics when using drivers with different shaft properties (2014). (In Review – International Journal of Sports Science & Coaching).

6.1 Abstract

The first aim of the study was to determine whether trunk and wrist kinematics differed when using drivers fitted with shafts of differing properties, i.e. kick point location (low and high) and mass (56 g and 78 g). The second aim was to determine if trunk and wrist kinematics were associated with clubhead speed for each driver. Twenty high level amateur male golfers (Mean ± SD: handicap = 1.9 ± 1.9 score) had their three-dimensional trunk and wrist kinematics collected for both driver trials. Swing parameters and related launch conditions were collected using a real-time launch monitor. A two-way repeated measures ANOVA revealed significant ($p \leq 0.003$) between-driver differences; specifically, faster trunk axial rotation velocity and an early wrist release for the driver fitted with the low kick point shaft. Regression models for both drivers explained a significant amount of variance in clubhead speed. Wrist kinematics were shown to be the most associated with clubhead speed indicating the importance of this segment in producing clubhead speed, regardless of hitting with drivers of differing properties.

6.2 Introduction

A golfer who is able to generate faster clubhead speeds can increase hitting distance off the tee (Fletcher & Hartwell, 2004) and this may help reduce the number of shots per round if driving accuracy can be maintained (Wiseman & Chatterjee, 2006). Factors relating to an individual's technique as well as equipment factors (the club they hit with) can be modified in an attempt to improve driving distance. This in turn, can be done by optimising swing parameters and related launch conditions of the ball (Harper et al., 2005; Wallace et al., 2007; Tuxen, 2008; Betzler et al., 2011; Haeufle et al., 2012; Lacy et al., 2012). In an attempt to understand driving outcome measures of the ball, previous investigations have modified properties of the driver's shaft such as, shaft length (Lacy et al., 2012), shaft mass (Harper et al., 2005; Haeufle et al., 2012) and shaft stiffness (Betzler, 2010).

Experimental investigations have demonstrated that altering shaft stiffness may change the dynamic bending profile during the downswing, which in turn may affect the swing kinematics of highly skilled golfers (Betzler, 2010; Betzler et al., 2011). However, no differences in swing kinematics have been found in highly skilled golfers when using drivers of varying stiffness (Betzler, 2010). Shaft stiffness has typically been graded using a qualitative rating such as ladies, regular, stiff and extra-stiff (Betzler, 2010). However, shaft stiffness can be more precisely defined using flexural rigidity (EI) testing. This approach gives a quantitative grading of stiffness by examining the 'bending stiffness' at multiple locations along the shaft, rather than its general shape of the shaft under static load (Figure 4.1) (Brouillette, 2002; Huntley et al., 2006; Swanek & Carey, 2007). This gives a more precise estimate of a shaft's complete bending profile.

Another modifiable shaft property, the kick point, is usually determined in a static manner and is considered to be the maximum bend point from a line joining the two ends of a loaded shaft (Jackson, 2001). A shaft with a high kick point will have a maximum bend point closer to the grip, while a shaft with a low kick point will have its point of maximum bend closer to the clubhead. Recent research has found that kick point location can affect swing parameters and related launch conditions (Joyce et al., 2014), specifically, with a high kick point shaft providing a lower launch angle of the ball and more spin than a low kick point shaft (Mather et al., 2000; Cheong et al., 2006; Joyce et al., 2013b; Joyce et al., 2014).

It is unknown whether highly skilled golfers will modify the kinematics of their body when using drivers containing a different kick point location. Research undertaken to understand how highly skilled golfers influence swing parameters and related launch conditions such as clubhead speed, and the effect this has on shaft performance has largely been inconclusive. However, it is thought to be related to manipulations of upper body kinematics (Milne & Davis, 1992; Stanbridge et al., 2004; Cheong et al., 2006; White, 2006; Worobets & Stefanyshyn, 2007; Suzuki et al., 2009; MacKenzie & Sprigings, 2009; Betzler, 2010). Previous experimental studies have examined trunk kinematics of low handicap golfers and their effect on clubhead speed (Lephart et al., 2007; Chu et al., 2010; Horan et al., 2010; Joyce et al., 2013a). Maximising angular displacement between the pelvis and shoulders at the top of the backswing (X-factor), and the associated countermovement of the pelvis at the start of the downswing (X-factor stretch) for example, has been shown to contribute to greater clubhead speed by creating a summation of speed that results in greater force being applied by the club to the ball at impact (Cheetham et al., 2001; Myers et al., 2008; Chu et al., 2010).

The X-factor has been shown not to be significantly associated with clubhead speed in homogenous cohorts due to a reduced amount of varied swing styles that influence X-factor (Kwon et al., 2013). However, recent three-dimensional methods used to analyse X-factor have allowed the trunk to be modelled as multiple segments rather than shoulders relative to pelvis only (Joyce et al., 2010). These methods have found significant associations between the lower trunk relative to pelvis angular displacement with clubhead speed in homogenous cohorts (Joyce et al., 2013a). This is possibly linked to the importance of X-factor stretch (countermovement of the pelvis) not being as varied as complex swing styles which influence X-factor as mentioned previously, and its association with clubhead speed (Joyce et al., 2013a). Although previous research has identified between-club differences in body kinematics, and their association with fast clubhead speeds, this has yet to be examined when using the same club (driver) fitted with shafts of differing kick point locations.

In addition to the trunk kinematics, the involvement of the 'leading' arm (i.e. the left arm for right handed golfers) has also been shown to be an important factor in influencing clubhead speed (Sprigings & Neal., 2000; Teu et al., 2006; Chu et al., 2010). Highly skilled golfers are known to exhibit a relatively late release of the wrists (i.e. a more delayed movement of the wrists from a radially deviated wrist position) in an attempt to maximise clubhead speed at ball impact (Sprigings & Neal, 2000; Teu et al., 2006; Betzler, 2010; Chu et al., 2010). In fact a delayed wrist release may result in increases in clubhead speed of between 9-46% (Milburn, 1982; Sprigings & Neal, 2000). Given that different shaft properties (including kick point) would change the 'feel' when swinging two different golf clubs, it is plausible that the kinematics of the upper body and arms could be affected (Betzler, 2010). Given the importance of wrist kinematics in contributing to the generation of high clubhead speeds, it would be of value to golfers and golf coaches to investigate upper body kinematics when using drivers with differing kick points. Of particular focus should be the trunk and wrist kinematics as they have both been demonstrated to be important and through our understanding of kinetic chain and transfer momentum through the golf swing the trunk movement will impact the wrist movement with the goal of maximising clubhead speed (Tinmark et al., 2010; Horan & Kavanagh, 2012).

The first aim of the study was to determine whether trunk and wrist kinematics differed when using drivers fitted with shafts of differing properties, i.e. kick point location (low and high) and mass (56 g and 78 g). The second aim was to determine if trunk and wrist kinematics were associated with clubhead speed for each of these drivers.

6.3 Methods

6.3.1 Participants

Participants recruited for this study included 20 right-handed, high level amateur male golfers (Mean ± SD: age = 24.6 ± 5.6 years, registered golfing handicap = 1.9 ± 1.9 score). At the time of testing, participants had a registered golfing handicap of 5 or lower, were aged between 18 and 35 years, and had no back pain in the previous 12 months prior to testing (as assessed by a modified Nordic Low Back Pain questionnaire). Ethical approval to conduct the study was provided by the Institutional Human Research Ethics Committee.

6.3.2 Experimental Protocol

A repeated-measures design was utilised for this study, with each participant hitting five shots each with two drivers (i.e. 10 shots). The two drivers were fitted with shafts with differing kick point location. A 56 g “stiff” shaft known to have a low kick point, and a 78 g “stiff” shaft known to have a high kick point (Joyce et al., 2013b) were used in this study. Isolating the effect of a single club parameter can have its difficulties in golf research (Harper et al., 2005; Haeufle et al., 2012) and in this study it was not feasible to change kick point location without having the shaft mass also modified, from shafts that are available on the market. The driver lengths, grips and clubheads were identical. The decision of what driver clubhead and shaft selection was made in consultation with an AAA Australian PGA teaching professional, who determined which drivers were typically used by elite-level male golfers. The properties of each driver are shown in Table 6.1, with the flexural rigidity (quantitative stiffness) of each driver shown in Figure 5.2. The procedures relating to the collation of these driver properties are reported elsewhere (Joyce et al., 2014). All properties in Table 6.1 were considered when explaining the between-club differences in golf swing kinematics and regression equations in the discussion.

Table 6.1 Properties of the two drivers fitted with the high and low kick point shafts.

	High Kick Point Driver M ± SD	**Low Kick Point Driver M ± SD**
Static Kick Point (% of length from club tip)	58.4 ± 1.5	55.3 ± 1.5
Shaft Mass (kg)	0.078	0.056
Shaft Stiffness (Hz)	4.0	4.0
Torsional Stiffness (°)	4.0	3.0
Centre of Mass (m from butt)	0.858	0.834
Shaft-Weighting (category)	D3	D1
Moment of Inertia about CoM (kg.m2)	0.039	0.036
Club Length - grip, shaft and club-head (m)	1.19	1.19
Club head mass (kg)	0.200	0.200
Club head face loft (°)	10.5	10.5

Testing for each participant was conducted on two days with players using a different driver on each day. The order of testing for each driver was randomised and the two sessions were separated by 24-48 hours. It has been suggested that experienced golfers need time to familiarise themselves with a new club (Kenny et al., 2008). Therefore, prior to testing on each day, participants completed two familiarisation sessions, they being; an outdoor session and then an indoor session prior to the actual laboratory testing session. These sessions were always completed in this order and they were conducted within one hour of each other. The outdoor session was conducted at a driving range located at a golf course located nearby to the Biomechanics laboratory where testing took place. This session was performed first so each participant had the opportunity to receive visual feedback via the ball's trajectory and its final landing position. Participants then completed the indoor familiarisation session at the laboratory prior to data collection. The familiarisation protocol was the same for each session with all participants hitting 10-20 shots each time. The exact number of shots was determined by the participant deciding when they felt sufficiently familiar with the driver. Total time required for the indoor familiarisation and testing was approximately 90 minutes on each day.

6.3.3 Data Collection and Analysis

6.3.3.1 Trunk and Wrist Kinematics

A 10-camera MX-F20 Vicon-Peak Motion Analysis system (Oxford Metrics, Oxford, UK) operating at 500 Hz was used to capture all three-dimensional kinematics. During testing, participants wore bicycle shorts and golf shoes only and a total of twenty one retro-reflective markers were attached to them during static trials. The six lower arm and hand "anatomical" markers were then removed for dynamic trials. A further two markers were attached to the shaft of the driver during the dynamic trials to identify top of the backswing, and a piece of retro-reflective tape was attached to the ball to identify ball impact (Table 6.2). These markers were used to provide three-dimensional golf swing kinematics of the body, create a multi-segment trunk model (Joyce et al., 2010) as well as a model of the leading arm that being; the left arm for right-handed golfers (Betzler, 2010; Sweeney et al., 2012). These models were developed using Vicon BodyBuilder V.3.6.1 and the complete model was then used in Vicon Nexus V.1.7.1 (Oxford, UK) to obtain all kinematic variables (as described below).

The multi-segment trunk model consisted of three segments: trunk, lower trunk and pelvis. Table 6.2 shows the markers which define each reference frame from which each segment was created. Cardan angles were reported for the trunk (shoulders – pelvis reference frames) and lower trunk (lower trunk – pelvis reference frames) were reported using a ZYX (lateral bending, flexion/extension and axial rotation respectively) order of rotation (Joyce et al., 2010). Positive values indicated trunk extension, right lateral bending and left axial rotation and negative values indicating trunk flexion, left lateral bending and right axial rotation.

The wrist joint was modelled using three-marker clusters placed on the forearm and the hand and these were positioned along with the six anatomical markers they being; the forearm and hand markers during the static calibration trials. The anatomical markers were removed and produced virtual anatomical markers for dynamic trials, as not to impede the natural movement of the wrist in each participant's golf swing (Cappozzo et al., 1996). Cardan angles for the wrist were also reported using a XYZ order of rotation (Betzler, 2010). With previous investigations suggesting ulnar/radial deviation at the wrist joint is important for increasing clubhead speed (Sprigings & Neal, 2000; Teu et al., 2006; Chu et al., 2010), it was the wrist movement which was of interest for this study. Positive values indicated radial deviation and negative values indicated ulnar deviation.

Table 6.2 Placements of the retro-reflective markers.

Reference Frame	Markers	Anatomical Marker Placement
Shoulders[1]	Left Shoulder	Left Acromion Process (LACRM)
	Right Shoulder	Right Acromion Process (RACRM)
	T10 vertebra	Tenth Thoracic Spinous Process (T10)
Lower Thorax[2]	Sternum	Xiphoid Process, distal end of the Sternum
	T10 vertebra	Tenth Thoracic Spinous Process (T10)
	L1 vertebra	First Lumbar Spinous Process (L1)
Pelvis[1,2]	Left Anterior Pelvis	Left Anterior Superior Illiac Spine (LASIS)
	Right Anterior Pelvis	Right Anterior Superior Illiac Spine (RASIS)
	Left Posterior Pelvis	Left Posterior Superior Illiac Spine (LPSIS)
	Right Posterior Pelvis	Right Posterior Superior Illiac Spine (RPSIS)
Forearm[3]	Medial Elbow	Medial epicondyle
	Lateral Elbow	Lateral epicondyle
	Medial Wrist	Styloid Process of the Radius
	Lateral Wrist	Styloid Process of the Ulna
Wrist[3]	Medial Wrist	Styloid Process of the Radius
	Lateral Wrist	Styloid Process of the Ulna
	Medial Hand	Distal end of the second Metacarpal
	Lateral Hand	Distal end of the fifth Metacarpal
Forearm Cluster[3]	Three markers equi-spaced triangularly	Mid-posterior forearm triangle pointing towards wrist
Wrist Cluster[3]	Three markers equi-spaced triangularly	Mid-posterior hand triangle pointing towards fingers
Golf Club		
	Upper Shaft	1/3 length of shaft from grip
	Lower Shaft	2/3 length of shaft from grip

[1] – Trunk, [2] – Lower Trunk, [3] – Wrist

6.3.3.2 Event Detection and Biomechanical Variables

Two critical events in the golf swing were used in this study they being; top of backswing and ball impact. Top of the backswing was identified as the frame where the two club markers changed direction to initiate the downswing (Lephart et al., 2007; Myers et al., 2008; Joyce et al., 2013a). Ball impact was defined as the frame immediately before when the ball (fitted with a piece of retro-reflective tape) was first seen to move after contact (Joyce et al., 2013b). Maximal trunk and lower trunk rotation was determined to be the peak value shortly after the top of the backswing. This variable (also known as ‘X-factor stretch’) was obtained due to the pelvis counter-rotating to commence the downswing while the shoulders remained relatively still which increases the separation angle (Cheetham et al., 2001). Wrist release was defined as the point where rapid ulnar deviation occurred (Teu, et al., 2006; Sweeney et al., 2012), and this has been shown in Figure 6.1. The timing of wrist release was defined as a percentage value during the downswing from top of the backswing (0 %) to ball impact (100 %). Ulnar/radial wrist deviation only was reported as this movement plane in which ‘wrist release’ occurs has shown to increase clubhead speed (Sprigings & Neal, 2000; Teu et al., 2006; Suzuki et al., 2009; Sweeney et al., 2012).

Initially, 28 variables relating to trunk and wrist kinematics were collected; however, after examination of correlation matrices, a high degree of multicollinearity was seen to exist between some of these variables. Consequently, a reduced total of 20 variables were included in the final analysis (see Table 6.4). A further five variables were quantified relating to swing parameters and related launch conditions (see Table 6.5).

From the five trials recorded for each driver, three were chosen for analysis based on maximal clubhead speed, the ball landing within a predicted 37 m wide fairway (from the launch monitor described below), and had minimal marker drop out. All trials were smoothed using a Woltring filter with a mean square error of 20mm^2 (Woltring, 1986). Ensemble averages for the trunk and lower trunk angular displacement data, as well as wrist ulnar/radial deviation between top of backswing and ball impact were created. In preparation for the ensemble average process, all data were time normalised (0-100%) using cubic spine interpolation.

6.3.3.3 Swing Parameters, Related Launch Conditions and Launch Monitor Validation

A real-time launch monitor (PureLaunch™, Zelocity, USA) was used to measure five swing parameters (clubhead speed at ball impact, attack angle of the clubface) and their related launch conditions (ball velocity, launch angle and spin rate). To independently validate the launch monitor, a comparison of four of the five variables (all except spin) with the above mentioned motion analysis system was undertaken. Eight participants (age = 23.5 years; handicap 2.2 ± 1.4) were recruited independently of the main study. A static calibration trial was obtained with three retro-reflective markers positioned in a triangular arrangement on top of the driver's clubhead, and four markers positioned at each corner of the clubface. A piece of retro-reflective tape was attached to the ball to act as a single marker. During the dynamic trials, the four clubface markers were removed and reconstructed as virtual markers. Clubhead speed at impact was calculated as change in displacement over time of the virtual central clubhead marker, as was ball velocity (Sweeney et al., 2009). Attack angle was calculated at impact from the virtual central clubface marker referenced from a virtual global coordinate system (Sweeney et al., 2009). Launch angle was calculated from the coordinates of the ball marker from the following equation (Sweeney et al., 2009).

$$Launch\ angle\ \theta = tan\theta = (Zc - Zi)/(Xc - Xi)$$

Where Xc and Xi were the current and initial positions of the ball in the horizontal direction respectively and Zc and Zi were the current and initial positions of the ball in the vertical direction (Sweeney et al., 2009). Negative attack angle values indicated that the clubhead was descending, in relation to the ground, at the point of ball impact (Tuxen, 2008). The launch monitor was positioned 4-5 m directly behind the hitting area and was aimed down a target line. Trials were voided if the launch monitor failed to record clubhead speed or ball velocity, shots resulting in inaccurate driving (balls landing outside of a predicted 37 m wide fairway) or, if the subject felt that improper contact was made with the ball. Three trials from each participant were analysed All coordinate data were smoothed using a Woltring filter with a mean square error of 20 mm^2 (Woltring, 1986). All three-dimensional modelling was undertaken using Vicon BodyBuilder V3.6.1. To quantify the validity of the launch monitor, multiple indices were obtained, these included: the 95% limits of agreement accuracy [mean bias (difference of means) + standard error of the mean (SEM)] and two measures of precision. These were the root mean square error of prediction (RMSEP) and residual error (RE), which can be defined as precision adjusted for mean bias (Robertson et al., 2013).

6.3.4 Statistical Analysis

For the first aim of the study, that being to determine whether between-driver differences existed for all trunk and wrist kinematics examined in this study, a two-way repeated measures ANOVA using data from all three trials per driver was used. The random factors were the trunk and wrist kinematics, while the fixed factors were the two drivers containing different kick points. The assumptions relating to these procedures namely; normality, linearity, homeoscedasticity and independence of residuals were met for each driver model. For the trunk and wrist kinematic variables there were 20 between-club comparisons conducted so a Bonferroni adjustment of the p-value ($p \leq 0.003$) was made to correct the family wise error rate. For the five swing parameters and their related launch conditions, the critical p-value value was adjusted to $p \leq 0.01$. With regards to the launch monitor validation, the 95% limits of agreement were obtained using MedCalc V12.1.4 (MedCalc Software, Mariakerke, Belgium) while mean bias, RMSEP and RE were calculated using Microsoft Excel™.

Relating to the second aim of the study, stepwise linear regression models were generated for each driver, in which swing kinematics were the independent variables, and the clubhead speed of each driver was the dependent variable. All three trials per driver were used in each of these models. As there were 20 participants, and as the sample size should be at least five times the number of independent variables (Norman & Streiner, 2003) a maximum of four variables were included in the final regression models. The final model reported for each driver was that with the highest amount of variance explained while attempting to achieve the lowest p-value possible. The assumptions for these procedures were checked by normal P-P plot distribution, and random scatter-plots showing independent errors, with casewise diagnostics showing low standardised residuals. To internally validate the model, five-fold cross validation was performed for the final regression model for each driver. The Root Mean Square (RMS) and pseudo R squared (R^2) were computed at each fold as goodness of fit measures. All statistical analyses were undertaken using STATA V9.1 (Stata Corp. Texas, USA).

6.4 Results

Evidence towards the validity of the four variables produced from the launch monitor can be seen in Table 6.3. Although all four variables showed a slight systematic bias towards the launch monitor, the reported mean bias of each variable was within the 95% limits of agreement, and low RMSEP and RE values were reported for each variable.

Table 6.3 Validation statistics for the launch monitor.

Variable	Mean Bias (SD)	95% Lower – Upper LoA	RMSEP	RE
Clubhead Speed (m/s)	-0.35 (± 1.17)	-2.68 – 1.98	0.01	0.12
Ball Velocity (m/s)	-0.40 (± 1.17)	-2.74 – 1.93	0.01	0.16
Launch Angle (º)	-0.08 (± 0.85)	-1.77 – 1.62	0.00	0.00
Attack Angle (º)	-0.54 (± 0.53)	-1.60 – 0.52	0.01	0.28

LoA – limits of agreement, RMSEP – root mean square error prediction, RE – residual error

Ensemble average data of the relative angular displacement and velocity of the trunk, lower trunk and wrist for the two drivers from the top of the backswing (0 %) to ball impact (100 %) are shown in Figures 6.1 and 6.2 respectively. While the descriptive data relating to trunk and wrist kinematics for both drivers are reported in Table 6.4. Results from the two-way repeated measures ANOVA revealed that there were four significant ($p \leq 0.003$) between-driver differences. With respect to the trunk, a larger amount of left lateral bending was reported at the top of the backswing, as well as there being faster axial rotation velocity being evident at ball impact for the driver fitted with the low kick point shaft. Further, the lower trunk segment showed a larger amount of maximum axial rotation for the driver fitted with the high kick point shaft. Finally, the wrists were released 4.3 % later (which translates to 0.044 s) in the downswing, for the driver fitted with the high kick point shaft when compared to the driver fitted with the low kick point shaft. Analysis of the swing parameters and their related launch conditions revealed a significantly lower launch angle for the high kick point driver (Table 6.5).

The results from the regression analyses are shown in Table 6.5. The regression models for each driver were able to explain a significant amount of variance in clubhead speed. Specifically, 60% of variance was explained for the driver fitted with the shaft containing the low kick point and 67% of variance was explained for the driver fitted with the shaft containing the high kick point. For each model, the two variables most strongly associated with clubhead speed were related to the wrist. For the driver with the high kick point shaft wrist release point in the downswing (β=0.415) and radial deviation of the wrist at the top of the backswing (β=0.380) were two variables most associated with clubhead speed. The two other variables included in this model were slower lower trunk axial rotation velocity at ball impact (β=-0.249) and radial deviation of the wrist at ball impact (β=0.176). For the low kick point shaft, radial deviation of the wrist at the top of the backswing (β=0.775) and radial deviation of the wrist at ball impact (β=0.568) were the two variables most associated with clubhead speed. The other two variables in the model were, a reduced amount of trunk lateral bending at ball impact (β=-0.486) and greater lower trunk maximum axial rotation (β=-0.438).

The results relating to the five-fold cross validation are outlined in Table 6.7 and these revealed a RMS range of 2.12-2.59 and R^2 range of 0.44-0.64 for the driver fitted with the low kick point shaft. For the driver fitted with high kick point shaft, the RMS range was 2.09-2.86 and the R^2 range was 0.49-0.81.These results tend to suggest the regression equations were valid.

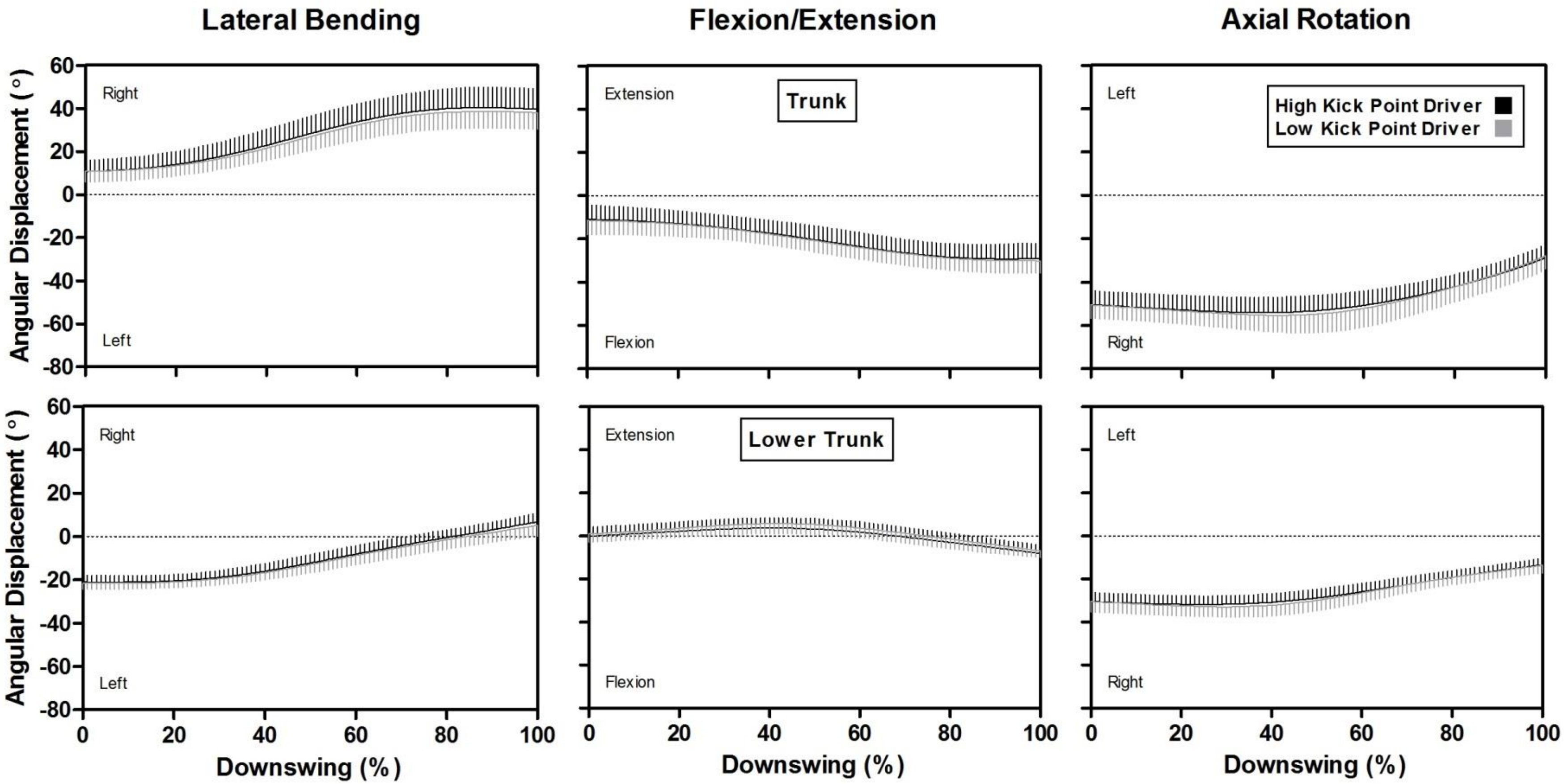

Figure 6.1a Ensemble averages of lateral bending, flexion/extension and axial rotation angular displacement data. The ensemble averages are shown for the trunk and lower trunk segments from the top of the backswing (0 %) to ball impact (100 %) for both the high kick point and low kick point drivers. Shaded areas represent one standard deviation from the mean.

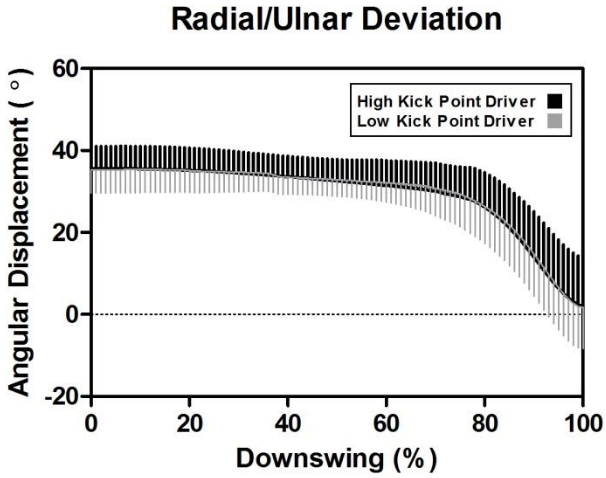

Figure 6.1b Ensemble averages of wrist radial / ulnar deviation angular displacement data. The ensemble averages are shown from the top of the backswing (0 %) to ball impact (100 %) for both the high kick point and low kick point drivers. Shaded areas represent one standard deviation from the mean.

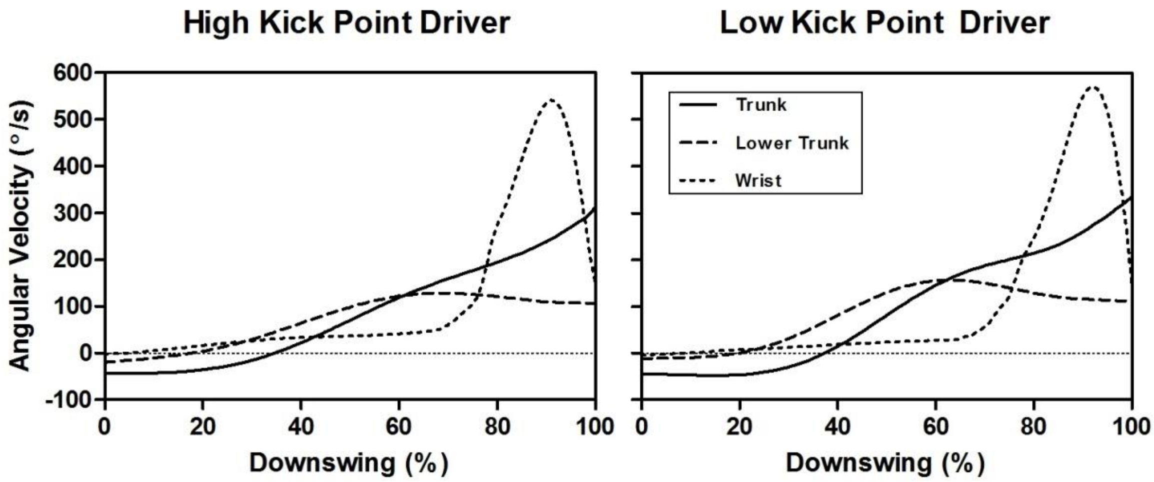

Figure 6.2 Ensemble averages of relative trunk, lower trunk and wrist angular velocity data. The ensemble averages are shown from the top of the backswing (0 %) to ball impact (100 %) for both the high kick point and low kick point drivers.

Table 6.4 Summary of the segment swing kinematics (M ± SD).

		High Kick Point Driver	Low Kick Point Driver	p-value
Lateral bending (°)				
TOB	**Trunk**	10.7 (± 6.8)	11.5 (± 7.3)	<0.001*
	Lower Trunk	-20.8 (± 3.6)	-21.0 (± 3.7)	0.544
BI	**Trunk**	30.7 (± 5.3)	31.1 (± 6.1)	0.259
	Lower Trunk	6.3 (± 3.8)	6.3 (± 3.8)	0.859
Flexion / extension (°)				
TOB	**Trunk**	-10.5 (± 7.1)	-10.9 (± 6.9)	0.032
	Lower Trunk	-0.5 (± 5.2)	-0.7 (± 5.7)	0.363
BI	**Trunk**	-39.0 (± 8.0)	-38.9 (± 8.1)	0.863
	Lower Trunk	-8.1 (± 5.7)	-6.9 (± 7.7)	0.190
Axial rotation (°)				
TOB	**Trunk**	-50.8 (± 6.8)	-50.7 (± 6.7)	0.706
	Lower Trunk	-30.7 (± 5.1)	-30.6 (± 5.1)	0.507
BI	**Trunk**	-28.4 (± 5.9)	-27.5 (± 6.1)	0.014
	Lower Trunk	-13.5 (± 3.1)	-13.1 (± 3.4)	0.094
Maximum axial rotation (°)				
BI	**Trunk**	-57.3 (± 6.7)	-57.0 (± 6.9)	0.258
	Lower Trunk	-34.8 (± 4.5)	-34.1 (± 4.7)	0.001*
Trunk axial rotation velocity at ball impact (°/s)		314.3 (± 31.9)	336.3 (± 37.2)	<0.001*
Lower trunk axial rotation velocity at ball impact (°/s)		109.9 (± 23.7)	113.8 (± 23.5)	0.098
Wrist radial / ulnar deviation (°)				
TOB		34.7 (± 8.7)	34.5 (± 6.8)	0.763
BI		1.9 (± 12.7)	1.2 (± 12.0)	0.353
Wrist release (% downswing)		76.3 (± 10.7)	72.0 (± 9.0)	<0.001*
Wrist velocity at ball impact (°/s)		148.0 (± 96.3)	137.4 (± 119.0)	0.536

* - indicates a significant difference ($p \leq 0.003$) exists between driver.
Abbreviations: Top of Backswing (TOB) and Ball Impact (BI).

Table 6.5 Swing and launch parameters for the drivers fitted with the high and low kick point shafts (M ± SD).

	High Kick Point Driver	Low Kick Point Driver	p-value
Clubhead speed (m/s)	49 (± 4)	48 (± 3)	0.091
Ball velocity (m/s)	68 (± 5)	67 (± 4)	0.897
Launch angle (°)	7 (± 2)	9 (± 2)	0.005*
Spin rate (r/min)	4078 (± 619)	3865 (± 656)	0.034
Attack angle (°)	-3 (± 2)	-2 (± 2)	0.057

* - indicates a significant difference ($p \leq 0.01$) exists between driver.

6.5 Discussion

There were two aims of this study: (a) determine whether trunk and wrist kinematics, and swing parameters and related launch conditions would differ when using drivers fitted with shafts of different kick point location; and (b) determine what trunk and wrist kinematics were most strongly associated with clubhead speed for each of the drivers. While four between-driver differences in swing kinematics were found (Table 6.4), it could be reasonably argued that only two of these four variables (trunk axial rotation velocity at ball impact and the point of wrist release in the downswing) would seem to be meaningful in a practical sense. This is due to the small magnitude of differences being evident between-drivers for the other two variables. A discussion of the two findings with practical application follows.

Table 6.6 Linear regression models explaining clubhead speed for the drivers fitted with the high and low kick point shafts.

Model	Independent Variables	Beta Coefficient	Standardised Error	p-value	Variance Explained (%)
High Kick Point Driver	Wrist release point in the downswing	0.415	0.033		
	Wrist radial / ulnar deviation (TOB)	0.380	0.036		
	Lower trunk axial rotation velocity (BI)	-0.249	0.014		
	Wrist radial / ulnar deviation (BI)	0.176	0.028	<0.001*	67 %
Low Kick Point Driver	Wrist radial / ulnar deviation (TOB)	0.775	0.057		
	Wrist radial / ulnar deviation (BI)	0.568	0.026		
	Trunk lateral bending (BI)	-0.486	0.070		
	Lower trunk maximum axial rotation	-0.438	0.099	<0.001*	60 %

* - indicates a significant amount of variance explained ($p \leq 0.05$).
Abbreviations: Top of Backswing (TOB) and Ball Impact (BI).

Table 6.7 Results of the five-fold cross validation for each driver.

	Root Mean Square Error (RMS)	Pseudo R Square (R^2)
High Kick Point Driver		
Fold		
1	2.43	0.53
2	2.12	0.66
3	2.09	0.49
4	2.86	0.81
5	2.85	0.49
Low Kick Point Driver		
Fold		
1	2.59	0.60
2	2.12	0.59
3	2.14	0.64
4	2.24	0.44
5	2.44	0.64

Slower trunk axial rotation velocity at ball impact was reported for the driver fitted with the high kick point shaft. This may be related to the fact that the high kick point shaft condition in this study was created by using a heavier (78 g) shaft when compared to the low kick point shaft condition (56 g). No differences in clubhead speed and ball velocity were observed in the two drivers. The experimental findings of Haeufle et al. (2012) also revealed no differences in clubhead speed for two drivers with the same 22 g difference in shaft mass and they speculated that the increase in shaft mass may cause muscles related to the trunk to contract more slowly. The second between-driver difference of a later wrist release for the driver fitted with the high kick point shaft may be related to the slower trunk axial rotation velocity. Wrist release was shown to have occurred 4.3 % later in the downswing. A delayed wrist release has been shown to increase clubhead speed (Sprigings & Neal, 2000; Teu et al., 2006; White, 2006; Chu et al., 2010). As no between-driver difference in clubhead speed was seen, it could be assumed that clubhead speed was generated by more involvement of the wrist than the trunk for the driver fitted with the high kick point shaft. Alternatively, the early wrist release for the driver fitted with the low kick point shaft may explain that the faster trunk axial rotation velocity helped to achieve a similar clubhead speed to the driver fitted with the high kick point shaft.

The delayed wrist release for the driver fitted with the high kick point shaft may be explained by the interaction of the wrist and the heavier, high kick point shaft. White et al., (2006) explained that wrist release elicits changes in the performance of the shaft during the downswing. It was reported that shaft properties such as moment of inertia are affected by wrist release. A higher moment of inertia, increased tip stiffness (Figure 5.2), as well as an increased amount of bending in the latter stages of the downswing have been previously reported for the high kick point shaft when compared to the low kick point shaft (Joyce et al., 2014). The between-driver difference in wrist release may be due to participants attempting to optimise the un-loading of the shaft through these properties in the downswing for optimal swing and related launch parameters. One such difference in launch parameters seen in this study was that of a lower launch angle for the driver fitted with the high kick point shaft (Table 6.5). As implied above, clubhead presentation may be influenced by the bending of the shaft in the downswing, as well as stiffer shafts (Figure 5.2) being less lofted at ball impact (Butler & Winfield, 1994; Horwood, 1994; Mather et al., 2000; Wishon, 2011; Haeufle et al., 2012; Joyce et al., 2013b).

The regression models generated for each driver resulted in similar (and high) amounts of variance being explained in clubhead speed (Table 6.6). Importantly, the most strongly associated variables with clubhead speed for both models were variables related with the wrist, which is consistent with previous research (Milburn, 1982; Sprigings & Neal, 2000; Osis & Stefanynshyn, 2012). These variables were specifically; the release point of the wrists in the downswing, as well as the radial / ulnar deviation of the wrist at the top of the backswing and at ball impact. Firstly, participants who displayed greater radial deviation of the wrist joint (or wrist cocking) at the top of backswing had greater clubhead speed and this has been supported in previous research (Chu et al., 2010). Previous studies have shown an increased wrist cock angle at the top of the swing is essential for accelerating the club in the early stages of the downswing (Robinson, 1994; Sprigings & Neal, 2000; White, 2006; Chu et al., 2010). Shortly after the point of wrist release, wrist velocity rapidly decreases at approximately 90% of downswing (see Figure 6.1). It has been suggested that wrist torque increases at this point (reducing wrist velocity), so that the club can release through ball impact and maximise clubhead speed (Kaneo & Sato, 2000; Osis & Stefanyshyn, 2012). The finding of a small amount of wrist cock maintained at ball impact being related to increased clubhead speed is in agreement with previous studies (Pickering & Vickers, 1999; Chu et al., 2010).

Variables of lower associations with clubhead speed (Table 6.6), firstly for the driver fitted with the high kick point shaft, were lower trunk axial rotational velocity at ball impact. This finding was previously discussed when a more delayed wrist release was seen for the driver fitted with the high kick point shaft, as well as slower trunk rotational velocity at ball impact. From what also can be seen in the regression model for the driver fitted with the high kick point shaft, the delayed release of the wrists was most likely the cause of clubhead speed, and involvement of the trunk and lower trunk not as important. Secondly, for the driver fitted with the low kick point shaft, lower associations with clubhead were seen by reduced right lateral bending and increased lower trunk maximum axial rotation. Previous recommendations report increasing right lateral bending of the trunk to facilitate higher launch angles (McHardy et al., 2006; Gluck et al., 2007) so it is unclear why this was reported for this study. Increasing lower trunk maximum axial rotation has been previously reported as being highly associated with clubhead speed (Joyce et al., 2013a). However, for both regression models, wrist segment variables were the most highly associated with clubhead speed which conforms to other investigations into the importance of the wrist at producing clubhead speed (Sprigings & Neal, 2000; Teu et al., 2006; White, 2006; Sweeney et al., 2012).

There were some limitations of this study. Firstly, isolating the single shaft modification of kick point was not permitted without other observed differences in mass, swing weighting and flexural rigidity (Joyce et al., 2014). Although this suggests that other shaft factors may have influenced differences in swing parameters and related launch conditions than kick point alone, it has previously been shown that modifying swingweight has no effect on swing and launch conditions (Wallace & Hubbell, 2001; Wallace et al., 2007; Haeufle et al., 2012). Secondly, there may have been more practically applicable differences in swing kinematics observed and possibly different associations with clubhead speed if participants were able to perceive shot outcome during indoor testing as in the outdoor familiarisation. In staging these limitations however, the bending, and flexural rigidity profiles of each shaft were known (Joyce et al., 2014). This type of detail has not been described in previous research examining wrist release and shaft stiffness (Betzler, 2010; Osis & Stefanyshyn, 2012).

In conclusion, slower trunk axial rotation velocity and a greater delayed release of the wrist were seen when using the driver fitted with the high kick point shaft, indicating the importance of the wrist in generating clubhead speed. Whereas greater trunk axial rotation velocity at BI was observed in the low kick point driver, indicating the trunk is important for generation of velocity in this driver. A similar amount of variance was explained for both drivers and similar variables were shown to be associated with clubhead speed. The results from this study may assist teaching professionals and club fitters in understanding the interaction between the golfer, and the club that they are hitting with to maximise golfing performance. Future research which examines shaft bending profiles during the downswing and player interaction for modifiable driver properties will also be important for biomechanists and teaching professionals.

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CHAPTER 7

DISCUSSION AND CONCLUSIONS

7.1 Introduction

This doctoral investigation has contributed towards an increased understanding of technique and equipment factors that influence swing parameters, such as clubhead speed and attack angle, as well as related launch conditions such as launch angle, spin rate and ball velocity in the sport of golf. This has been achieved by developing and then using, a variety of three-dimensional biomechanical analysis methods.

Technique factors have previously been investigated with a particular focus on the trunk. An increased separation of the shoulder-pelvis alignment when viewed in the transverse plane or 'X-factor' during the golf swing has been linked to increased clubhead speed (Burden et al., 1998; Cheetham et al, 2001; Myers et al., 2008). Although research has been conducted on the trunk during the golf swing the trunk has been considered as containing one, or a limited number of segments (Hsu et al., 2008; Brown et al., 2013; Kwon et al., 2013), whereas a multiple segment three-dimensional analysis is needed to interpret the golf swing in an anatomically meaningful way. As described in Section 1.3.3, the numerous studies that have quantified the X-factor through three-dimensional modelling of the segments involved, have actually utilised methods that could be considered as dissimilar (Brown et al., 2013; Kwon et al., 2013). As reported in Table 1.1, Horan et al. (2010) and Kwon et al. (2013)

used modern Cardan angle methods to determine X-factor. Both authors reported no correlation between X-factor and clubhead speed. This thesis used a multi-segment trunk model and three-dimensional Cardan methods to provide a better representation of trunk kinematics of which these authors reported, using modern methods to report X-factor.

Recent experimental research has also quantified wrist movement in the golf swing (Sweeney et al., 2011; Osis & Stefanyshyn, 2012; Sweeney et al., 2012). However, there seems to have been no research that has investigated the role of the wrists, as well as the segments of the trunk and their association with clubhead speed. Further, this thesis investigated the differences in swing kinematics when hitting with different clubs (driver and five-iron), as well as the same club (driver) with differing shaft properties (i.e. the kick point location).

With regard to equipment factors, previous authors (Brouillette, 2002; Harper et al., 2005; Cheong et al., 2006; Tuxen, 2008; Wishon, 2011; Betzler et al., 2011) have suggested there are many modifiable properties, such as stiffness, mass and length of golf shafts that can alter the swing parameters and related launch conditions. Experimental research is limited on the dynamic performance of the golf shaft in the downswing and it is unclear how these modifiable properties influence swing parameters as well as the related launch conditions at ball impact (Mather et al., 2000; Summitt, 2000; Wishon, 2011). This thesis conducted a dynamic evaluation of how modifiable shaft properties influence swing parameters and related launch conditions at ball impact when hitting with a driver. This was undertaken by analysing the bending profile of each shaft (with low and high kick point location) in the downswing. This provided further understanding as to how high level amateur male golfers may modify their swing kinematics when hitting with these drivers. Although recent anecdotal evidence suggests that players of high ability will delay their wrist release point in the downswing based on stiffness differences in the tip of the shaft (Wishon, 2011), previous research has failed to find differences in swing kinematics when hitting with drivers of different stiffness (Betzler, 2010). It is also unknown through regression modelling, if the same, or different kinematic variables are responsible for producing clubhead speed when hitting with the same club (driver) fitted with shafts of varying properties. This thesis investigated if hitting with drivers fitted with shafts containing different modifiable properties resulted in a difference in swing kinematics, and the variables that are associated with clubhead speed.

Research using a variety of methods to quantify golf swing kinematics and their relationships to clubhead speed have recruited heterogeneous cohorts (Chu et al., 2010; Myers et al., 2008). There has been a lack of research examining homogenous cohorts (such as high level amateurs) to assess clubhead speed using different clubs, and how modifying driver properties (shaft stiffness, kick point) can induce different swing kinematics and different swing parameters and their related launch conditions. The use of a homogenous cohort is important, as these players may be more likely to modify their swing kinematics based on shaft modification (Wallace & Hubbell, 2001; Osis & Stefanyshyn, 2012). Further, they may have low variability in shot outcomes (Langdown et al., 2012), particularly when hitting with clubs the player is familiar with (Kenny et al., 2008). These gaps in the related research inspired the direction of this doctoral thesis.

7. 2 Summary and Conclusions

Due to the related gaps in knowledge, the overall aim of this thesis was to determine the technique (trunk and wrist kinematics) and equipment (modifiable shaft properties) factors that influenced swing parameters and related launch conditions. The main factors investigated were the swing kinematics of the high level amateur male golfer, and whether between-club (driver vs. five-iron) and within-club (drivers fitted with different shafts) differences were evident. Also, it was of interest to know what variables were important in achieving clubhead speed. This thesis consisted of five individual studies and the aims and a summary of the key findings from each of these studies are summarised below.

Study I – Methodological considerations for the three-dimensional measurement of the X-factor and lower trunk movement in golf

The aim of the first study of the thesis was to develop a new multi-segment trunk model by which to examine the X-factor and lower trunk movement during the golf swing. The model developed in this study used a Cardan sequence of rotations to define magnitudes of trunk and lower trunk rotation in flexion/extension, lateral bending and axial rotation. An initial validation was undertaken by means of comparing data generated from a three-dimensional motion analysis system to that obtained by a 'gold-standard' 3-Space Fastrak™ electromagnetic tracking system and visual estimates of quasi-static and dynamic (golf swing) movements. Further, validity of the model was tested for the quasi-static and dynamic trials.

The study identified that a lateral bending / flexion-extension / axial rotation (ZYX) order of rotation was deemed the most suitable Cardanic sequence when analysing shoulder-pelvic separation and lower trunk movement in the golf swing. Further, the model was shown to be highly valid when compared to multiple quasi-static and dynamic trials, reporting a coefficient of multiple correlation of 0.998, and a mean absolute variability of 0.6°. Importantly, this study showed that although the lower trunk segment mirrored the range of motion of the trunk segment during the downswing, an observed difference in the magnitude of the range of motion was found. This was to be expected based on the trunk having a larger maximum range of motion (i.e. axial rotation), and demonstrates that the trunk should not be modelled as a rigid segment (Hsu et al., 2008; Brown et al., 2013; Kwon et al., 2013). This also provides the methodological basis for examining issues related to analysing characteristics of the golf swing, such as the summation of segments of specific cohorts (i.e. of various handicap) and also when hitting with different clubs.

Study II – Three-dimensional trunk kinematics in golf: between-club differences and relationships to clubhead speed

This study used the model developed in Study I to analyse the difference in trunk kinematics of 15 high level amateur male golfers hitting a driver and five-iron, as well as what technique variables were associated with clubhead speed for each club. A total of nine between-club significant differences in swing kinematics were reported for 15 high level amateur male golfers who displayed a modern swing. Differences in trunk and lower trunk flexion/extension would have been related to reduced shaft length of the five-iron. There was no between-club difference reported for the X-factor, although lower trunk axial rotation at the top of the backswing, and lower trunk maximum axial rotation were larger for the driver. The regression models generated for each club did not explain a significant amount of variance for the driver (33.7 %), although the five-iron model was able to explain a significant (66.7 %) amount of variance in clubhead speed, with trunk and lower trunk variables associated with clubhead speed. Neither anthropometric (height), nor physiological (medicine ball release velocity) variables were reported in either regression model as being associated with clubhead speed. Lower trunk maximum axial rotation was reported as the most significant variable associated with clubhead speed for the five-iron, and supported the use of the validated model developed in Study I to be used at examining trunk movement in the golf swing.

Study III – A new method to identify the location of the kick point during the golf swing

The low variance in clubhead speed reported for the driver in Study II warranted further investigation into other factors that may be associated with clubhead speed. There are probably more readily modifiable equipment factors for a driver than there might be for irons. These factors include; shaft stiffness, maximum bend point, mass, clubhead face angle, and these may have influenced different swing kinematics of participants aiming to maximise clubhead speed when using their own drivers in the previous study (Jackson, 2001; Hocknell, 2002; Wallace & Hubbell, 2001; Cheong et al., 2006). This study aimed to develop a new motion-analysis based method of analysing the bending profile of golf shafts during the downswing. This was examined using two shafts of known different kick point location

The algorithm-based motion analysis method to locate the kick point during the golf swing was shown to be valid and reliable. Two shafts of different mass (56 g and 78 g) were both shown to have a different kick point location under dynamic conditions than under static conditions. It was also reported that when using the newly developed dynamic method the kick point location moved further down the shaft from top of backswing to ball impact for both shafts, showing that the shaft performs differently to static conditions which may influence clubhead presentation at ball impact (although this was not measured).

Study IV – A dynamic evaluation of how kick location influences swing parameters and related launch conditions

The algorithm-based motion analysis method developed in Study III was used to analyse the bending profile of two shafts of differing kick points (low and high) during the downswing. This was done to determine whether differences existed in swing (clubhead speed, attack angle) and launch (ball velocity, launch angle, spin rate) parameters.

The driver fitted with the high kick point shaft reported a more negative attack angle (steeper presentation of the clubface at ball impact), a lower launch, and increased spin rate than the driver containing the low kick point shaft. Further investigation into the flexural rigidity (EI profile) of each shaft revealed differences in the stiffness profiles of each shaft, which influenced the bending profile of each shaft in the downswing and their respective swing parameters and related launch conditions. The high kick point shaft was shown to have a stiffer tip and butt section when compared to the low kick point shaft. By measuring the EI profiles of each shaft, it confirmed anecdotal claims (Wishon, 2011) that stiffer tip shafts produce lower launch angles. Also, comparing the bending profile (amount of deflection) of each shaft in the downswing, it was revealed that the high kick point shaft had greater amount of deflection at 80 % and 100 % (ball impact) in the downswing. This finding of extra “lag” of the clubhead of the driver fitted with the high kick point shaft also helped to verify anecdotal claims (Wishon, 2011) of how swing parameters and their related launch conditions can be altered. All properties (Table 6.1) were considered when explaining the between-club differences in swing parameters and related launch conditions.

Study V – Trunk and wrist kinematics when maximising clubhead speed: Effect of changing the kick point

In the final study a combination of the technique (i.e. trunk, lower trunk and wrist kinematics), equipment (i.e. drivers fitted shafts of different modifiable properties) variables, and swing parameters and related launch conditions outlined in earlier Chapters in this thesis were examined. The inclusion of a wrist segment was deemed necessary, with previous investigations reporting the importance the wrist segment has in producing clubhead speed (Milburn, 1982; Sprigings & Neal, 2000; White, 2006; Sweeney et al., 2011; Osis & Stefanyshyn, 2012). The first aim of the study was to determine whether trunk and wrist kinematics differed when using drivers fitted with shafts of differing properties, i.e. kick point location (low and high) and mass (56 g and 78 g). The second aim was to determine what technique variables related to the trunk and wrist are most strongly associated with clubhead speed for each driver.

The results of the study found four differences in golf swing kinematics. Two of these differences may have practical application. These were a slower trunk axial rotation velocity and a later release of the wrist for the driver fitted with the high kick point shaft. Analysis of the stiffness profile (EI) of each shaft also helped to explain these differences, as well as the difference reported for the launch parameter; launch angle (Wishon, 2011). Importantly, the inclusion of the wrist segment helped to explain a significant amount of variance in clubhead speed for each driver model, which was not achieved in Study II. Variables related to the wrist segment were reported as the two largest variables associated with clubhead speed for each driver model, radial deviation at the top of the backswing for the driver fitted with the low kick point shaft and wrist release point in the downswing for the driver fitted with the high kick point shaft. As with the second study, the lower trunk was also seen as a variable associated with clubhead speed, underlining the importance of the three-dimensional models developed in studies two and five to analyse golf swing kinematics.

7.3 Practical Implications of the Research

There are several practical implications of this doctoral thesis and these could be applied to both golf coaching and golf education perspectives. These implications are broadly based around two areas, i) the swing kinematics of high level amateur male golfers when using the same club (driver) when fitted with shafts of different modifiable properties, as well as different clubs (driver vs. five-iron), and ii) the performance of golf shafts in the downswing (i.e. a dynamic perspective) and how swing parameters and their related launch conditions are affected when modifying shaft properties of a driver.

7.3.1 Between and Within-Club Kinematics

The use of a multi-segment (more than two segments) trunk model used in Studies II and V provided a greater understanding of how each segment helps to maximise clubhead speed at ball impact. In Study II, maximal lower trunk axial rotation was shown to be a key variable associated with clubhead speed for the five-iron, and in Study V it was again a key variable associated with clubhead speed for the driver fitted with the low kick point shaft. The increased amount of lower trunk axial rotation observed was representative of what is seen in the modern golf swing for the trunk ('X-factor'). This has been reported in previous investigations examining clubhead speed in the golf swing (Gluck et al., 2007; Lephart et al., 2007; McHardy et al., 2006; Myers et al., 2008; Chu et al., 2010). By limiting pelvis movement throughout the backswing, the 'coiling' effect of having an increased separation angle created between the pelvis and lower thorax (Joyce et al., 2010) helps to increase clubhead speed (Gluck et al., 2007). Without the addition of a lower trunk segment to analyse golf swing kinematics, the key results from Studies II and V would not have been found.

When comparing the driver and five-iron in Study II, it was not surprising that the number of between-club differences that would be considered as practically significant was greater. This was specifically the case for trunk flexion variables where hitting with shorter clubs (irons) would logically result in a greater amount of trunk flexion (Egret et al., 2003). The second important difference again involved the lower trunk segment. Larger values of lower trunk maximum axial rotation were seen for the driver than that for the five-iron. An increase in trunk axial rotation (related with lower trunk axial rotation) is associated with faster clubhead speeds, particularly with the driver which is used to maximise hitting distance off the tee (Cheetham et al., 2001; Myers et al., 2008).

The addition of the wrist segment in the biomechanical analyses conducted in Study V was also important and necessary as previous research had shown the contribution of the wrist segment in generating clubhead speed (Teu et al., 2006; Sweeney et al., 2011; Sweeney et al., 2012). Wrist-related variables from Study V were found to be three of the four key variables associated with clubhead speed for the driver fitted with the high kick point shaft, and two of the four variables for the driver fitted with the low kick point shaft. Practically speaking, the wrist was shown to be in a radially deviated position at the top of the backswing. This helps to increase the "wrist cock angle" at the top of the backswing (Sweeney et al., 2011) although, the results at ball impact (shown for both drivers) indicated that participants who maintained a small amount radial deviation at ball impact were able to produce faster clubhead speeds. Anecdotal evidence (Wishon, 2011) suggests that golfers of high ability will delay their wrist release when using shafts of increased tip stiffness (as reported for the high kick point shaft in Study V). Increased tip stiffness prevents excessively high launch angles of the ball.

The two practical differences in golf swing kinematics seen in Study V when comparing the drivers with varying kick point location were small. Wrist release was shown to have occurred 4.3 % later in the downswing. A delayed wrist release has been shown to increase clubhead speed (Sprigings & Neal, 2000; Teu et al., 2006; White, 2006; Chu et al., 2010). As no between-driver difference in clubhead speed was seen, it could be assumed that clubhead speed was generated by more involvement of the wrist than the trunk for the driver fitted with the high kick point shaft. Alternatively, the early wrist release for the driver fitted with the low kick point shaft may explain that the second between-driver difference, faster trunk axial rotation velocity, helped to achieve a similar clubhead speed to the driver fitted with the high kick point shaft.

7.3.2 Dynamic performance of golf shafts and effect on swing parameters and their related launch conditions

The methods developed in Study III allowed the bending profiles of two drivers fitted with shafts of differing kick point location to be analysed under dynamic conditions. From Study III and IV, it was seen that a difference in kick point location was also evident under dynamic conditions (i.e. in the downswing). The variables that were associated with firstly, the different kick point location and the secondly, deflection (mm) of the shaft during the downswing, proved to be important in helping to explain the swing parameters; attack angle, and their related launch conditions; launch angle and spin rate.

No significant differences were reported for clubhead speed for the two drivers fitted with different kick point shafts in Study V although, launch angle was shown to be different. Golfers of high ability generally prefer to use heavier shafts due to their preference to have increased proprioceptive feedback (i.e. increased "feel") during the swing (Betzler, 2010; Osis & Stefanyshyn, 2102). The differences in golf swing kinematics reported in Study V may help teaching professionals to understand the relationship between the golfer, and the club that they are hitting with in a bid to obtain specific swing parameters and related launch conditions. The results may be explained by previous research examining how high ability golfers are able to control swing parameters and related launch conditions at ball impact by modifying their wrist kinematics (MacKenzie & Sprigings, 2009; Wishon, 2011). This allows the teaching professional to again match the correct golf club for a particular golfer.

The introduction of flexural rigidity testing (Brouillette, 2002) has provided a better understanding of shaft stiffness than just a stiffness grading alone (i.e. amateur, stiff, etc). This was evident in Study IV where EI testing assisted in the explanation of anecdotal evidence that suggested shafts with a stiffer tip are associated with lower launch angles of the ball. This may be the case as they prevent the clubhead from kicking forward and presenting a more lofted clubface at impact (Wishon, 2011). Together with the bending profiles reported in Study IV, flexural rigidity results of each shaft confirmed the lower launch angles reported for the driver fitted with the high kick point shaft (i.e. the shaft containing the stiffer tip).

From a golf coaching perspective, applying a more scientific approach to the idea of matching the clubs to the golfer's swing kinematics will be important at improving golfing performance (Osis & Stefanyshyn, 2012). It is important to understand how golfers will modify their swing kinematics (as seen in Study V), when hitting with drivers fitted with different shafts (i.e. kick point) as these are considered to alter the swing parameters and the related launch conditions of the ball (Cheong et al., 2006).

7.4 Limitations and Delimitations of the Doctoral Investigation

While the sample sizes used in the studies contained within this doctoral thesis were relatively small, the studies could still be considered successful at finding key kinematic variables that were associated with clubhead speed. This was the case for different clubs (driver vs. five-iron) as well as drivers with differing kick point location. Further, significant differences between (driver vs. five-iron) and within-club (low vs. high kick point driver) were found for swing kinematics, as well as swing parameters and their related launch conditions. However, these findings cannot be generalised to golfers of differing abilities (i.e. elite and amateur) and gender.

Concerning the investigations into the golf shaft properties (Studies III and IV), the most important limitation was the inability to isolate kick point location only. Further analysis of the two shafts used in these studies revealed a difference in mass (swing-weighting) and flexural rigidity (stiffness). However, the use of flexural rigidity helped to explain, in part, differences in swing parameters and related launch conditions found in Study IV. Secondly, the amount of deflection of the golf shaft during the downswing was only considered to be occurring in the principle bending plane. This did not allow for torsional movement to be examined nor the orientation of the clubface at ball impact.

The validation of the launch monitor used in this thesis was important at reporting accurate measures in clubhead speed, specifically. As the authors were aware of a single study which validated their launch monitor (Sweeney et al., 2009), it more accurately reflected the understanding of swing parameters and their related launch conditions to the between- (and within) club differences in swing kinematics and dynamic shaft performance. Despite the use of a validated Doppler radar to determine swing parameters and related launch conditions, as well as predicting shot accuracy, a limitation that was consistent throughout the thesis was the inability of participants to view shot outcome during the indoor testing sessions. However, Study V included an outdoor familiarisation session as previously recommended (Kenny et al., 2008) and this allowed participants to receive feedback via real shot outcomes. The outdoor familiarisation session was also designed to produce a golf swing in laboratory testing conditions that was similar to their swing outdoors. This may have helped contribute to the differences in swing kinematics being found. In stating these limitations however, the bending, and flexural rigidity profiles of each shaft were known (Joyce et al., 2014). This type of detail has not been described in previous research examining wrist release and shaft stiffness (Betzler, 2010; Osis & Stefanyshyn, 2012).

Finally, the cross validation of the regression models reported in Study V provided some support towards their (internal) validity. However, recruiting an independent sample would have provided a superior form of validity (external validity). Doing this would have provided more support to the generalisability of these regression models.

7.5 Future Research Directions

With the development of the three-dimensional methods used to analyse both kinematics and kinetics of the golf swing, a number of considerations for future research may be undertaken based on the findings of this doctoral investigation. This may produce a greater number of experimental studies to investigate existing anecdotal evidence and simulation based research. Further investigation using multi-segment trunk models on golfers of different abilities and gender may also provide a greater understanding of movement patterns more generally.

An area not investigated in this doctoral thesis was the potential role that kinematics and kinetics of the lower limbs in producing clubhead speed. The lower limbs have been shown to be of importance in producing clubhead speed in simulation research (Sprigings & Neal, 2000; Nesbit, 2007). Taking a full body approach to analysing the golf swing would increase the chance of explaining additional variance in clubhead speed.

Another area of research using the three-dimensional methods from this doctoral thesis would be to investigate the difference in swing kinematics of elite golfers who are able to control their swing parameters (including swing path) and related launch conditions. This relates to golfers that are able to move the golf ball from left to right (fade), or right to left (draw). These are shots required to negotiate fairway corners, or obstacles such as trees in order to reach the green within, or under the regulation amount of shots (Robertson et al., 2013). An understanding of the kinematics employed by elite players to produce shot outcomes of a higher standard would again assist with teaching and education of the golf swing, specifically for high level amateur players looking to make finer improvements to their game. This would involve investigating other swing parameters and related launch conditions such as ball side spin and importantly, clubface orientation, which has been discussed previously as a limitation in Study IV.

With regards to equipment factors, the methods used to uncover the difference kick point location in Study III could warrant further investigation. Previous studies that have analysed dynamics of the shaft during the golf swing have placed strain gauges at the static kick point location (Milne & Davis, 1992; Betzler et al., 2011). This would indicate that sub-maximal values of strain may be reported and are therefore, may not representative of the true dynamic bending profile.

In conclusion, the results from this doctoral investigation have helped to further understand technique and equipment factors that produce clubhead speed. Additionally, the methods used to analyse the stiffness and dynamic bending profile of the two drivers used in Study V have helped to explain the differences in technique variables and their interaction with equipment variables in high level amateur male golfers.

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APPENDICIES

Appendix 1 Participant information sheet

Participant Information Form

Title of Project: **The Role of the Trunk, Upper Limb and Club Shaft in Generating Clubhead Speed in Golf**

Principal Investigator: Chris JOYCE
(School of Exercise, Biomedical and Health Sciences,
Edith Cowan University, Western Australia)

Associate Investigator: Dr. Jodie COCHRANE
(School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Western Australia)

Purpose of Study

The lack of a clear relationship between club-shaft properties and club-head speed in golf may be due to the attempt to optimise club-shaft weight for a particular player based on their swing characteristics.

Low handicap golfers are believed to use different loading patterns based on the loading weights of the club-shaft to generate higher club-head speeds and maximise driving distance, although further investigation is needed to explain the effect of this. Optimal 'club-fitting' is brought into question when club-head speed is the only criteria under consideration.

With the model developed in Study 2, and the proposed addition of an upper-limb to this model, the golfer's swing kinematics can be analysed to determine which type of shaft best suits their swing kinematics, and generates the higher club-head speed.

Participants

The participants of this study will include; 20 male candidates who have a golfing handicap of zero (scratch) to five and those between 18-30 years of age.

Procedures

After subject consent, firstly, you will have your golf swing video recorded at your golf club for determination of modern swing, analysed by two independent professional golf coaches to determine if you are eligible to partake in the study. Once this is determined, if you agree to take part in this study, you will firstly be required to fill in a subject details form stating your gender, height, weight, body mass index (BMI), age, golfing handicap and right or left handed. Following this you will need to complete the following session at Joondalup driving range, then the Biomechanics Laboratory at ECU Joondalup:

1. Familiarisation

   You will be asked hit 20-30 balls at an outdoor driving range, then repeat for indoor biomechanics lab to become familiarised with the clubs in this study.

2. Range of motion testing;

   You will be asked to perform ranges of motion to obtain absolute range of motion values to be used with your relative range of motion values in your motion analysis testing.

3. Rotational power testing;

   You will be asked to perform your golf swing with a 2kg medicine ball to derive maximum release velocity.

4. Motion Analysis testing

   You will be asked to hit 10 golf balls into a safety net with a selected Driver (two drivers in total – 20 shots), whilst fitted with light reflective 3D markers on selected body landmarks.

Each session will take between 30 and 40 minutes to complete, including warm up time.

The above procedure will need to be completed over TWO separate days (one for each of the two clubs).

If incomplete data is recorded for any reason, more than the required five swings will be required which will extend the duration of the session.

Confidentiality

All recorded data will be entered into a database using your assigned subject number only, no names will be used. Access to the stored data will be restricted by a password known only by the investigators. All data collected and consent forms will be stored safely in a locked cupboard at Edith Cowan University.

The results will be reported on, but it will be impossible to identify individual subjects as no identification numbers or names will be included in report material. On completion of the study, all data will be stored in a secure and confidential location with the investigators for the duration of the study and will not be used for further studies.

Request for Further Information

You are encouraged to discuss and/or express any concerns or questions regarding this study with the investigators at any time. You should feel confident and secure about your involvement in the study.

Refusal or Withdrawal

You may refuse to participate in the study and if you do consent to participate you will be still free to withdraw from the study at any time without fear or prejudice. If you do decide to withdraw from the study please contact the investigators at the earliest possible convenience. All data will be destroyed if you do decide to withdraw. Please contact the following people if you have problems or concerns at any stage during your participation in this project:

Dr. Jodie Cochrane   j.wilkie@ecu.edu.au   +61 8 6304 5860

Christopher Joyce   c.joyce@ecu.edu.au   +61 8 6304 5073

Approval

This study has been approved by the Edith Cowan University Human Research Ethics Committee. If you have any concerns or complaints about the research project and wish to talk to an independent person, or if you require verification of approval you may contact;

Research Ethics Officer
Edith Cowan University
100 Joondalup Drive
JOONDALUP, WA, 6027
Phone: +61 8 6304 2170
Email: research.ethics@ecu.edu.au

Appendix 2 Participant Consent Form

Title of Project: **The Role of the Trunk, Upper Limb and Club Shaft in Generating Clubhead Speed in Golf**

Principal Investigator: Chris JOYCE

(School of Exercise, Biomedical and Health Sciences,

Edith Cowan University, Western Australia)

Associate Investigators: Dr. Jodie Cochrane

(School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Western Australia)

You are of your own accord making a decision whether or not to participate in this research study. Your signature verifies that you have decided to participate in the study, having read and understood all the information accessible. Your signature also officially states that you have had adequate opportunity to discuss this study with the investigators and all your questions have been answered to your satisfaction. You will be given a copy of this consent document to keep.

I, *[the undersigned]*____

of
*[PleasePRINT]*____

Postcode ____________________ **Phone______________________________**

Consent to involvement in this study and give my authorisation for any results from this study to be used in any research paper, on the understanding that confidentiality will be maintained. I understand that I may withdraw from the study at any time without discrimination. If so, I undertake to contact the respective person at the earliest opportunity:

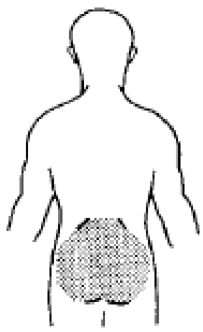
Dr. Jodie Cochrane	j.cochrane@ecu.edu.au	+61 8 6304 5860
Chris Joyce	c.joyce@ecu.edu.au	+61 8 6304 5073

Subject's Signature ______________________________ Date _______________

I have explained to the subject the procedures of the study to which the subject has consented their involvement (in writing) and have answered all questions. In my appraisal, the subject has voluntarily and intentionally given informed consent and possesses the legal capacity to give informed consent to participate in this research study.

Signature: ____________________________ Date: _______________

Appendix 3 Modified Nordic Musculoskeletal Questionnaire about Low Back Trouble



LOW BACK

In this picture you can see the approximate position of the part of the body referred to in the questionnaire. By low back trouble is meant ache, pain or discomfort in the shaded area whether or not it extends from there to one or both legs (sciatica).

Please answer by pulling a cross in the appropriate box – one cross for

1) When was the first episode of back pain? _______ day(s) / month(s) / year(s) ago

(please circle the appropriate phrase)

2) When was the most recent episode of back pain? _______ days / months / years ago

(please circle the appropriate phrase)

3) Have you ever been hospitalized because of low back trouble?

☐ No ☐ Yes

4) What is the total length of time that you have had low back trouble during the last 12 months?

☐ 0 days (jump to page 9)

☐ 1-7 days

☐ 8-30 days

☐ More than 30 days, but not every day

☐ Every day

5) Has low back trouble caused you to reduce your leisure activity during the last 12 months?

☐ No ☐ Yes

6) Have you been seen by a doctor, physiotherapist, chiropractor or other such person because of low back trouble during the last 12 months? ☐ No ☐ Yes

7) Have you had low back trouble at any time during last 7 days ☐ No ☐ Yes

8) Are you currently taking any medication for your back pain? ☐ No ☐ Yes

Appendix 4 ECU Ethics Approval

Dear Chris

Project Number: 6069 JOYCE
Project Name: The role of the trunk, upper limb and club shaft in generating clubhead speed in golf
Student Number: 2011023

The ECU Human Research Ethics Committee (HREC) has reviewed your application and has granted ethics approval for your research project. In granting approval, the HREC has determined that the research project meets the requirements of the *National Statement on Ethical Conduct in Human Research*.

The approval period is from 9 November 2011 to 31 October 2012.

The Research Assessments Team has been informed and they will issue formal notification of approval. Please note that the submission and approval of your research proposal is a separate process to obtaining ethics approval and that no recruitment of participants and/or data collection can commence until formal notification of both ethics approval and approval of your research proposal has been received.

Please note the following conditions of approval:
The HREC has a requirement that all approved projects are subject to monitoring conditions. This includes completion of an annual report (for projects longer than one year) and completion of a final report at the completion of the project. An outline of the monitoring conditions and the ethics report form are available from the ethics website:
http://www.ecu.edu.au/GPPS/ethics/human_ethics_resources.html

You will also be notified when a report is due.

Please feel free to contact me if you require any further information.

Regards
Kim

Kim Gifkins
Research Ethics Officer
Edith Cowan University
270 Joondalup Drive
JOONDALUP WA 6027
Phone: (08) 6304 2170
Fax: (08) 6304 5044
Email: research.ethics@ecu.edu.au