KINEMATIC CONTRIBUTIONS AND SYNERGIES IN OPTIMAL SWING PERFORMANCE IN GOLF

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Executive Summary

The golf swing is a highly complex motor task that involves the coordination of a large number of joint motions to achieve the ultimate goal of hitting a ball with optimal distance and direction. It has been recently suggested that an understanding of swing mechanics should include the potentially functional role of intra-individual variability. Specifically, inter-swing variability throughout the kinematic chain may act in a compensatory manner, assisting skilled golfers to achieve an accurate and consistent swing outcome.

The purpose of coordinating each individual joint motion optimally in the swing is to influence the kinematics of the club-head at ball impact. While many anecdotal assertions exist with respect to the influence of specific impact club-head kinematics on subsequent ball flight parameters, such assertions need to be quantitatively validated before they can be accepted and implemented by coaches and/or sport scientists.

Prior to any analysis involving the determination of club-ball impact kinematics it is important to validate the methods used to collect data around the time of the ball/club collision (lasting around 0.5ms). A range of methods (such as interpolations, extrapolations and filtering) have been previously employed to determine data ‘at impact’ despite a lack of evidence validating the accuracy of any specific methods.

The aims of this thesis were to (i) validate methods for determining golfer and club kinematics ‘at impact’, (ii) identify the relationships between specific impact club-head kinematics and subsequent ball flight parameters, (iii) identify the presence of compensatory relationships between the individual joint kinematics involved in the swing and, (iv) assess the role of individual joint motions and their compensatory behaviour during the swing.

In the first study participants were asked to hit at a regular golf ball as well as a target with negligible mass (paper target). No difference was observed in the golfers’ pre impact swing kinematics between the two target conditions. However, the average post impact club-head velocity after hitting a golf ball (41.3ms\(^{-1}\) ±2.4) was significantly lower than after hitting a paper target (44.6ms\(^{-1}\) ±3.1), highlighting the potential inaccuracies of previous methodologies that have extrapolated impact kinematics from
post impact data. The lack of club-ball collision artefact in the paper target condition allowed for the evaluation of previously published methodologies in determining club-head impact kinematics. It was found that a method involving extrapolating pre impact data was the most accurate method to determine all impact club-head kinematics other than resultant velocity.

In study 2, club-head kinematics and early ball flight characteristics were captured from 21 male golfers, hitting the ball with their own driver. Using regression analyses, club-head kinematics at impact (velocity, orientation, path and centredness) were used to explain the variability in five dependent variables of early ball flight characteristics (resultant velocity, launch angle, side angle, back spin and side spin). Club-head kinematics at impact explained a significant proportion of early ball flight characteristics (adjusted $r^2 = 0.71-0.82$), even when generalised across individual clubs. Specifically, resultant velocity, vertical velocity, lateral velocity, loft angle and rotation angle of the club-head, as well as the centredness of impact, all significantly contributed to at least one initial ball flight characteristic.

The impact club-head kinematics identified as important in study 2 were used as Variables of Interest (VI) for the last two studies. In study 3, a random sensitivity analysis based on empirical data from 10 skilled male golfers, revealed the presence of compensatory relationships between the individual joint motions involved in executing the swing. This compensatory behaviour appears to play a functional role in enabling skilled golfers to achieve precise and consistent execution of key club-head kinematics.

Additional surrogate analyses in study 4 revealed that the compensatory behaviour in the swing was primarily dictated by a small number (2 to 5) of ‘key’ individual joint motions for each participant in the consistent coordination of specific VI’s. Some of these ‘key’ joint motions were common across the sample. In particular, right wrist flexion, elbow extension, elbow pronation and shoulder internal rotation were found to commonly contribute to compensatory behaviour influencing distance and/or accuracy in the swing. However, the majority of the joint motions that played a key role in compensatory relationships were unique to specific individuals supporting an individual approach to understanding the mechanics influencing performance.
This thesis provides an understanding of the validity of varying methodologies for the determination of impact kinematics of the golfer and club during the swing. Additionally, the roles of specific impact club-head kinematics on subsequent ball flight characteristics are quantitatively outlined. Finally, the existence of compensatory relationships and the identification of ‘key’ joint motions offer theoretical and applied insight into the ability of skilled golfers to consistently coordinate optimal club-head kinematics during the drive.
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Those people close to me understand that getting this thesis completed has been a long and arduous journey. I would like thank all those who have helped me along the way, especially when it looked like that journey might never end. Firstly, I would like to thank my supervisors; Professor Bruce Elliott, Dr Peter Mills and Dr Jacqueline Alderson for their guidance, advice and mentorship during this process. There are many traits from the three of you that I will continue to model myself on as a researcher.

As the process of completing this thesis was complicated by a mixture of technical setbacks and ‘life’ it was the support/patience of my family and friends who really made completing possible. To that end, my beautiful wife Aditi should receive a great deal of praise. Your amazing support in the dual roles of wife and ‘unofficial fourth supervisor’ helped me survive this period... as well as allow the occasional sentence of mine to make sense.

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Finally, I would like to dedicate this thesis to my daughter, Tiya. You came into this world while I was working on this research and my life was irrevocably changed. I live for your smile and I hope that my greatest achievement is to prepare you in some way for the joyful and testing times ahead. I am already proud of you in more ways than you could imagine but maybe one day my completion of this cob-web destined document will provide you with a little pride in your ‘silly Daddy’ too.
# Table of Contents

Executive Summary .................................................................................................................. ii

Acknowledgments .................................................................................................................... v

Table of Contents ................................................................................................................... vi

List of Tables ........................................................................................................................ x

List of Figures ........................................................................................................................ xi

Thesis Declaration Form ......................................................................................................... xiii

## Chapter 1: The Problem .................................................................................................... 1

1.1 INTRODUCTION .............................................................................................................. 1

1.2 STATEMENT OF PROBLEM ......................................................................................... 4

1.3 SIGNIFICANCE OF STUDY ........................................................................................... 5

1.4 AIMS & HYPOTHESES ................................................................................................. 5

1.5 LIMITATIONS/DELIMITATIONS .................................................................................. 8

## Chapter 2: Literature Review .............................................................................................. 9

2.1 THE IMPORTANCE OF BIOMECHANICS IN GOLF .................................................. 9

2.2 BIOMECHANICAL CHARACTERISTICS OF THE GOLF SWING ......................... 10

2.2.1 Temporal Definitions of the Swing .......................................................................... 10

2.2.2 Measures of Performance in the Golf Swing .......................................................... 11

2.3 EMPIRICAL RESEARCH INTO THE GOLF SWING ................................................. 13

2.3.1 Kinematics and Kinetics of the Foot-Ground Interaction ....................................... 13

2.3.1.1 Ground Reaction Force .................................................................................... 13

2.3.1.2 Centre of Pressure ........................................................................................... 14

2.3.2 Kinematics and Kinetics of the Lower Limbs .......................................................... 16

2.3.3 Kinematics and kinetics of the pelvis and trunk ....................................................... 18

2.3.4 Kinematics and kinetics of the upper limbs ............................................................. 22

2.3.5 Kinematics and kinetics of the club ......................................................................... 24

2.3.6 Variability in the golf swing ..................................................................................... 26

2.3.7 Summary of Empirical Research ............................................................................ 29

2.3.8 Limitations of Empirical Research ......................................................................... 29
Chapter 5: Identifying compensatory joint kinematics in the golf drive .......... 85

5.1 INTRODUCTION .............................................................................. 85

5.2 METHODS ......................................................................................... 87

5.2.1 Participants .................................................................................... 87

5.2.2 Procedures ..................................................................................... 87

5.2.3 Data acquisition model ................................................................. 88

5.2.4 Forward Kinematic Model (FKM) .................................................. 90

5.2.5 Random Sensitivity Analysis ....................................................... 92

5.2.6 Statistical Analysis ....................................................................... 92

5.3 RESULTS ......................................................................................... 93

5.3.1 FKM Validity ............................................................................... 93

5.3.2 Random Sensitivity Analysis ....................................................... 95

5.4 DISCUSSION .................................................................................... 95

5.4.1 Validity of the Forward Kinematic Model (FKM) ......................... 96

5.4.2 Strength of Compensatory Behaviours ........................................ 97

5.4.3 Applied Relevance ....................................................................... 98

5.4.4 Future Recommendations ............................................................ 99

5.5 CONCLUSION ................................................................................ 100

Chapter 6: Identifying the role of individual joint kinematics in the golf drive ... 101

6.1 INTRODUCTION .............................................................................. 101

6.2 METHODS ....................................................................................... 102
List of Tables

Table 3.1  RMS error of club-head kinematics calculated at the last frame pre impact, at three different frequencies (400 Hz, 200 Hz and 100 Hz), from swings at a paper target..................................................................................................................................................61

Table 3.2  RMS error of impact kinematics using 2nd order polynomial extrapolations, based on varying magnitudes of preceding data......................................................62

Table 3.3  RMS error of extrapolation method (2nd order polynomial using 12.5 ms of preceding data) and club-head kinematics calculated at the last frame pre impact at 400Hz........................................................................................................................................62

Table 4.1  Mean (± standard deviations) of all variables included in the analyses, across participants in part1 (n=21) and part 2 (n=8). Golf ball variables are all calculated at peak resultant velocity and club-head variables are all calculated at ‘virtual impact’........................................................................................................................................77

Table 4.2  Results of five stepwise regressions using club-head kinematics, at impact, to predict ball flight kinematics.............................................................................................78
List of Figures

Figure 3.1  Golf swing marker set for golf swing trials:  A) Anterior view B) Posterior view C) Club-head markers

Figure 3.2  A) Reflective markers on club-head B) Four key points on club-face identified in the calibration procedure to identify club-head coordinate system.

Figure 3.3  Driver at address, preparing to swing at a regulation golf ball (A), and paper target (B).  The red line in B) is for clarity in the diagram only.

Figure 3.4  Five discrete time points during the swing that were used to statistically compare the two treatment conditions.

Figure 3.5  Representative resultant club-head velocity for the golf ball and paper target conditions, from one participant (Time = 0 corresponds to impact between club-face and ball/virtual ball).  To provide a visual representation of the influence of post impact data, club-head velocity is also presented from the golf ball condition where the raw data was first treated with a 2nd order Butterworth filter.

Figure 3.6  Average resultant velocity of selected anatomical landmarks around impact, for both golf ball condition (solid line) and paper target condition (dotted line).

Figure 4.1  Golf ball variables measured:  A) Golf ball resultant velocity (m/s), B) Golf ball launch angle (°), C) Golf ball side angle (°), D) Golf ball back spin (rev/s), and E) Golf ball side spin (rev/s).

Figure 4.2  A) Golf ball covered in reflective tape as used in part 1.  B) Golf ball with two marks as used in part 2.

Figure 4.3  A) Reflective markers on club-head B) Four key points on club-face identified in the calibration procedure to identify club-head coordinate system.

Figure 4.4  Club-head variables measured:  A) Club-head resultant velocity (m/s), B) Club-head vertical velocity (m/s), C) Club-head lateral velocity (m/s), D) Club-head loft angle (°), E) Club-head rotation angle (°), and F) Centredness of impact (mm).

Figure 4.5  Scatter plots of the three strongest relationships between club-head variables and subsequent ball flight characteristics.  These relationships are between A) club-head resultant velocity and golf ball resultant velocity, B) club-head vertical velocity and golf ball launch angle, C) club-head rotation angle and golf ball side angle.

Figure 4.6  Variables involved in the five stepwise regressions used to explain early golf ball flight characteristics.

Figure 5.1  Variables of Interest (VI) associated with performance from Sweeney et al. (2013).  A) Club-head resultant velocity (m/s), B) Club-head vertical velocity (m/s),
C) Club-head lateral velocity (m/s), D) Club-head loft angle (°), E) Club-head rotation angle (°), and F) Centredness of impact (mm). .................................................................88

**Figure 5.2** Variables of interest (VI) and their influence on performance in the swing. Based on findings from Sweeney et al. (2013). .................................................................89

**Figure 5.3** Illustration of segments involved in the Forward Kinematic Model (FKM)..............................................................................................................................................92

**Figure 5.4** Bland-Altman plots, mean differences and level of agreements between empirical and FKM measures of A) club-head resultant velocity, B) club-head vertical velocity, C) club-head lateral velocity, D) centredness of impact, E) club-head loft angle and F) club-head rotation angle at impact...........................................................................92

**Figure 5.5** The average increase in the variance (%) for the surrogate data when compared with the empirical data, across each variable of interest. Error bars indicate ± standard deviation. ................................................................................................................................95

**Figure 6.1** Club-head kinematic variance (σ²) for a representative participant across E, S and each I. A) resultant club-head velocity B) centredness of impact C) vertical club-head velocity D) club-head loft angle E) lateral club-head velocity F) club-head rotation angle................................................................................................................................103/104

**Figure 6.2** Number of participants for which individual degrees of freedom were identified as playing a ‘key’ role in specific VI compensatory synergies. A) VI’s which influence distance in the golf drive B) VI’s which influence direction in the golf drive..................................................................................................................................................105/106
Thesis Declaration Form

DECLARATION FOR THESES CONTAINING PUBLISHED WORK AND/OR WORK PREPARED FOR PUBLICATION

Please sign one of the statements below.

3. This thesis contains published work and/or work prepared for publication, some of which has been co-authored. The bibliographical details of the work and where it appears in the thesis are outlined below. The student must attach to this declaration a statement for each publication that clarifies the contribution of the student to the work. This may be in the form of a description of the precise contributions of the student to the published work and/or a statement of percent contribution by the student. This statement must be signed by all authors. If signatures from all the authors cannot be obtained, the statement detailing the student’s contribution to the published work must be signed by the coordinating supervisor.

- Sweeney, M., Mills, P., Alderson, J., Elliott, B. (In review) Treatment of kinematic data at impact during the golf drive. Journal of Sports Sciences. [Chapter 3]

The four studies in this thesis were researched, developed, analysed and interpreted by Matthew Sweeney. Professor Elliott, Dr. Mills and Dr. Alderson all assisted with conceptual issues and Dr. Mills provided assistance with the FKM development. At present Study 4 is published with the Sports Biomechanics journal and chapter 3 is in review with the Journal of Sports Sciences.

Student Signature ……………………………………………………………………………………………………….

Coordinating Supervisor Signature …………………………………………………………………………………
Chapter 1
The Problem

1.1 INTRODUCTION

Golf is one of the world’s most popular sports with an estimated 55 million people competing at the start of the 21st century (Farrally, Cochran, Crews, Hurdzan, Price, Snow & Thomas, 2003). This popularity is also reflected in Australia where golf is the largest participation sport with 1.3 million players (Australian Bureau of Statistics, 2000). The aim of each hole of golf is to move the ball from the tee to the cup in the least number of strokes possible. This is achieved by hitting the ball with optimal distance and accuracy (Adlington, 1996). All strokes that the golfer may employ in the pursuit of moving the ball toward the cup can be classified into one of two principle motions: the swing and putt (Hume, Keogh & Reid, 2005). Of these, the swing is the more complex and most commonly performed.

It is logical to assert that the trajectory of the golf ball following impact is largely determined by the kinematics of the golfer and golf club at the time of impact. Consequently, a thorough understanding of the influence of golfer and club swing kinematics on subsequent ball flight may significantly benefit social, competitive and professional golfers alike.

Although numerous studies have used motion analysis to investigate the kinematics of the golf swing, questions remain concerning optimal acquisition and processing parameters for swing kinematics output. More specifically, a number of investigators who have reported club-head kinematics ‘at impact’ have either filtered/interpolated data through impact (Fradkin, Sherman & Finch, 2004; Coleman & Rankin, 2005; Worobets & Stefanyshyn, 2007), reported data at the frame prior to impact (Myers et al., 2008; Egret, Nicolle, Dujardin, Weber, & Chollet, 2006), or provided little or no detail outlining how the impact point was determined (Neal & Wilson, 1985; McLaughlin & Best, 1994; Mason, McGann & Herbert, 1995; Zheng, Barrentine, Fleisig & Andrews, 2008). Such limitations warrant serious consideration, as for example it has been suggested that filtering through impact may lead to artefact,
including the underestimation of velocities at impact (Knudson & Bahamonde, 2001; Tabuchi, Matsuo & Hashizume, 2007). Additionally, a golf drive impact phase is reported to last approximately 0.5 ms (Hocknell, Jones & Rothberg, 1996; Roberts, Jones & Rothberg, 2001), while the majority of researchers have sampled data at a rate of every 5 ms or higher (≤200 Hz). Subsequently, reporting data at the frame prior to impact may not accurately represent impact phase kinematics and kinetics.

The most common mechanical measure of performance in the golf swing literature thus far has been the velocity of the club-head at impact (Sprigings & Neal, 2000; Fradkin et al., 2004; Gordon, Moir, Davis, Witmer & Cummings, 2009; Keogh et al., 2009). Its popularity as a performance measure can be attributed largely to its suggested role as a major determinant of drive distance (Hay, 1993; Hume et al., 2005). Despite this suggestion, the exact role of club-head velocity on drive distance remains inadequately quantified. Additionally, limited research has focused on identifying the possible kinematic influences on ball flight direction and spin. Understanding the kinematics which influence ball direction could be of great importance, as it has been anecdotally suggested that direction can play an even greater role than distance in dictating whether the outcome of a shot is successful (Addlington, 1996).

Much biomechanical research to date has focused on identifying average kinematics of the club and body segments that are achieved by golfers of varying skill levels at discrete time points in the swing (Egret, Dujardin, Weber & Chollet, 2004; Cole & Grimshaw, 2009; Chu, Sell & Lephart, 2010; Okuda, Gribble & Armstrong, 2010). However, it has been suggested that the variability of movement, rather than average kinematics at discrete time points may shed the greatest light on the determinants of mechanical success for a particular task (Bartlett, Wheat & Robins, 2007; Bradshaw et al., 2009; Langdown, Bridge & Li, 2012). In golf, it is clear that skilled players exhibit a high level of consistency in performance variables, such as impact club-head kinematics (Bradshaw et al., 2009; Betzler, Monk, Wallace & Otto, 2012), but it is not well understood how this is coordinated within a movement task that involves such a large number of individual joint motions (Dillman & Lange, 1994).

A recent study by Horan, Evans and Kavanagh (2011) indicated that skilled golfers tended to exhibit significantly higher movement variability than outcome variability, where movement variability refers to within individual joint motions in the kinematic
chain and outcome variability refers to the resulting outcome of a task (often represented by the club-head kinematics at impact). Horan and associates (2011) suggested that this dichotomy in variability may indicate compensatory patterns in the distal segments of the swing. Specifically, motion in the more distal segments (such as the upper limbs) may compensate for the variability in earlier more proximal segment motion to allow for a consistent execution of club-head kinematics at impact.

Compensatory relationships between individual joint motions within a kinematic chain (similar to which Horan et al. suggested is likely present in the golf swing) has been identified in other tasks (Bernstein, 1967; Arutyunyan, Gurfinke & MirskiiLatash, 1969; Latash, 1998; Cusumano & Cesari, 2006; Bartlett et al., 2007). Indeed, it has been suggested that the ability of skilled performers to organise their individual joint motions into compensatory synergies could be one of the most important components of achieving consistent and precise performance (Latash, 1998; Bartlett et al., 2007; Langdown et al., 2012). To date, no research has investigated the potential presence of compensatory behaviour in the golf swing however, there have been recent calls to make this a priority for future analysis (Glazier, 2011; Langdown et al., 2012).

One method to provide more definitive answers regarding the presence of compensatory patterns in the kinematics of the swing is to perform a ‘randomised sensitivity analysis’ (RSA) (Kudo et al., 2000; Mills, Barrett, Morrison & Simeoni, 2003; Muller & Sternad, 2004; Mills, 2007) on empirically collected kinematics of the golfer and club. An RSA approach initially involves the creation of a forward kinematic model (FKM) representing empirical data from each of the individual movements which dictate the outcome of the task. A large number of simulated trials (forming a surrogate data set) are then created from inter-trial permutations performed at the individual joint motion level. Importantly, this surrogate data set is free from any compensatory relationships that may exist between individual joint kinematics. Therefore, clear evidence of compensatory relationships in the task would exist if the outcome variability produced across the surrogate data set is significantly higher than that exhibited empirically. Conversely, no difference between the empirical and surrogate data set outcome variability would indicate that individual joint variability is merely a product of random sensory noise (Muller & Sternad, 2003; Mills, 2007).
If compensatory relationships are present in the execution of the golf swing one of the most pertinent question from a coaching perspective would be which specific individual joint motions contribute to these compensatory relationships. One approach, employed by a previous researcher to investigate compensatory relationships in coordinating minimum toe clearance in gait (Mills, 2007), has the potential to assess the role of each individual joint motion toward the role of any compensatory relationships present in a task. Mills (2007) referred to this approach as an ‘individual surrogate analysis’ and after employing it reported that some individual joint motions contributed heavily to the compensatory relationships influencing toe clearance in gait, while other individual joint motions appeared to play a negligible role. If compensatory behaviour exists in the execution of the skilled golf swing a similar approach could allow for the identification of key individual joint motions which skilled golfers use to consistently produce optimal distance and accuracy.

1.2 STATEMENT OF PROBLEM

There is limited scientific knowledge concerning the influence of golfer and club kinematics on successful performance of the golf drive. First, the effect of filtering or interpolating kinematic data through impact, and the applicability of assuming impact kinematics is well represented by pre impact data, is poorly understood. Such an understanding is imperative if scientists and coaches are to have confidence in research findings based upon analyses that include club-head impact kinematics. Secondly, the club-head impact kinematics and subsequent ball flight parameter relationship has yet to be quantitatively defined, which is necessary to establish the importance of the role of impact club-head kinematic variables such as velocity, path and orientation, on subsequent ball distance and/or accuracy. Thirdly, there is currently a limited understanding of the role movement variability plays in allowing skilled performers to achieve desired club-head kinematics. While many coaches assume that any variability is detrimental to performance, it is possible that some movement variability is a critical aspect of skilled performance in the golf swing and should be an important consideration when coaching swing technique. Finally, to date the role of specific joint motions in coordinating consistent execution of the golf swing is poorly understood. A lack of understanding about the role of individual mechanical motion throughout the
swing phase means that a large proportion of the mechanical advice coaches pass on to players is anecdotal, which has the potential to be conflicting, misleading or at worse, incorrect.

1.3 SIGNIFICANCE OF STUDY

There are potentially a number of theoretical and practical implications stemming from this research that provide a significant contribution to golf scientific literature. Such contribution includes an improved understanding of the influence of variable sampling frequencies and differing filtering techniques on the validity of impact phase club-head kinematics. Additionally, the role of impact club-head kinematics in creating ball distance and/or accuracy in the drive is examined. The presence of compensatory relationships amongst the individual joint kinematics of the skilled golf swing is also assessed. Finally, some insight will be garnered regarding the process by which skilled golfers coordinate individual joint degrees of freedom to consistently execute optimal club-head kinematics (outcome).

From a practical perspective, a better understanding of the validity of data treatment methods, such as filtering and sampling frequency on club-head kinematics, will act as an important guide for commercial manufacturers, who develop and market devices purported to measure impact kinematics for coaching and/or club-fitting purposes. Additionally, this research will contribute to a greater knowledge surrounding the potential role of movement variability and compensatory behaviour in facilitating optimal swing performance. Understanding whether or not movement variability in the swing has an important functional role has the potential to change the way golf coaches think about the mechanics of the swing and how skilled performance is achieved.

1.4 AIMS & HYPOTHESES

Study 1:

The aims of study 1 can be broken into two parts. The primary aim of the study is to ascertain the most accurate data treatment method for estimating the kinematics of a
golf club at impact. In order to undertake this evaluation, a condition needs to be created where participants will recreate the kinematics of hitting a golf ball, but removes the effect of ball-club collision on the club-head. The secondary aim is therefore to assess whether a group of skilled golfers achieve the same pre impact kinematics, but different post impact kinematics, when swinging at a target with negligible mass versus when swinging at a normal golf ball.

The hypotheses of study 1 are:

1. When selected kinematics of golfer and club are compared between hitting a golf ball and a target of negligible mass, no significant differences will exist at three pre impact discrete time points (25 ms pre impact, 10 ms pre impact and 1 frame pre impact), however, significant differences will exist at two post impact discrete time points (1 frame post impact and 10 ms post impact).
2. A method involving extrapolating pre impact data through the impact phase will be significantly more accurate in replicating club-head impact kinematics when compared with data calculated from the frame prior to impact (at all capture frequencies ≤ 400 Hz).

Study 2:

The aim of the study 2 is to quantify the relationships between club-head kinematics and early ball flight characteristics, across a group of sub 10 handicap golfers using their preferred drivers.

The hypotheses of study 2 are:

1. Impact club-head resultant velocity and centredness of impact will account for over 75% of the variance in resultant ball velocity.
2. Impact club-head vertical velocity, club-head loft and vertical centredness of impact will account for over 75% of the variance in subsequent ball launch angle.
3. Impact club-head lateral velocity, club-head rotation and lateral centredness of impact will account for over 75% of the variance in subsequent ball side angle.
4. The offset created between impact vertical path and loft of the club-head at impact will account for over 75% of the variance in subsequent ball back spin.
5. The offset created between impact lateral path and rotation of the club-head at impact will account for over 75% of the variance in subsequent ball side spin.

**Study 3:**

The aim of study 3 is to identify whether the movement variability within the swings of skilled golfers can be attributed to random noise or whether this movement variability at individual joints contributes to some type of compensatory pattern of coordination. Specifically the study will focus on identifying compensatory relationships in contributing to the impact velocity, path and orientation of the club-head, as well as the centredness of ball impact on the club-face.

The hypotheses of study 3 are:

1. For each participant, a full surrogate data set will produce significantly greater variance in all club-head variables of interest (VI) when compared with the FKM data. This will confirm the presence of compensatory behaviour amongst individual joint motions in the golf swing.

**Study 4:**

The aim of study 4 is to assess the role of individual joint kinematics in the compensatory relationships previously identified in the skilled golf drive. If only specific degrees of freedom contribute to the compensatory behaviour in the golf swing, a secondary aim of the study will be to identify these movements while also determining if these results are stable across a sample of skilled golfers.

The hypotheses of study 4 are:

1. An individual surrogate analysis will reveal that for each outcome variable of each golfer, specific joint motions will contribute to compensatory relationships while other will not.

2. The individual joint motions which will contribute to compensatory relationships in the swing will be consistent amongst the skilled participants.
1.5 LIMITATIONS/DELIMITATIONS

Limitations of the studies are:

- Noise may be introduced into the marker movement signal during the swing, as a product of soft tissue artefact and/or from poor marker placement to represent specific anatomical locations. However, in order to ensure this noise remains at a minimum, a calibrated anatomical systems technique (CAST) approach (Cappozzo, Catani, Croce & Leardini, 1995) was employed. This ensured that the markers used to define joint centres were held away from soft tissue areas and joint centres known to introduce high levels of soft tissue artefact (skin, muscle, adipose), and held relative to associated segment technical coordinate systems throughout the swing.

Delimitations of the studies are:

- Only golfers deemed proficient (handicap of less than 10) in performing the swing participated in the research, narrowing the population of whom the findings can be applied.

- Golf swings were performed in laboratory conditions and not a natural course environment, limiting the ecological validity of the results. Although the swing was in no way impeded by the testing environment.

- The forward kinematic model is based upon the following assumptions:
  - The dimensions of a segment remain constant over the course of the movement recorded.
  - Each joint has a single point about which, the three axes of the two adjoining segments rotate.

- Golfers used their own driver in order to increase external validity.
Chapter 2
Literature Review

2.1 THE IMPORTANCE OF BIOMECHANICS IN GOLF

Golf has one of the highest participation rates of any sport in the world. Farrally et al. (2003) reported that approximately 55 million people take part in the sport each year on approximately 30,000 courses worldwide. In fact, over 20 percent of the adult population in many countries play golf, either as a competitive sport or as a leisure activity (Thériault & Lachance, 1998). With such a high participation rate it is important to address swing technique, as success is one of the reasons behind people continuing to play and enjoy the game.

A golfer’s feeling of self-competence and enjoyment in the game has been shown to be strongly linked to their performance; measured both relative to others, as well as their own previous performances (Dewar & Kavussanu, 2011). It stands to reason therefore that in golf, enabling any player to improve their performance will ultimately lead to greater participation and a benefit from the well documented health benefits that are associated with regular golfing activity (Parkkari et al., 2000; Farahmand, Broman, De Faire, Vågerö & Ahlbom, 2008; Dear, Porter, & Ready, 2010).

Understanding factors affecting performance is particularly important at the top level of the game. Achieving optimal performance at this level can not only lead to personal satisfaction but substantial financial benefit. For example, the top ranked golfer in the world has generally earned over $10 million in official annual prize money in the last seven seasons (www.pgatour.com). On top of this, successful players often receive lucrative endorsements, business opportunities and appearance money.

When breaking down performance in golf, it is considered that success is a product of requiring the least amount of strokes to get the ball from the tee and into the hole (Wiren, 1990). Integral to each one of these strokes is the movement of the club through impact with the ball, which is ultimately a product of the golfer’s swing (Wiren, 1990; Hay, 1993). A clear understanding of the mechanics of the golf swing, therefore,
allows players, coaches and scientists to both make sense of performance and explore new ways of optimising swing mechanics.

While biomechanics of the swing has attracted considerable research, the motion itself is one of the most difficult and complex performed in sport (Dillman & Lange, 1994). Perhaps as a consequence of this, a comprehensive understanding of how the mechanics of the swing interacts with performance is far from being achieved (Farrelly et al., 2003; Osis & Stefanyshyn, 2010). The sections below will discuss what knowledge thus far has been provided by biomechanical investigation into the swing, as well as the areas where our understanding is limited.

2.2 BIOMECHANICAL CHARACTERISTICS OF THE GOLF SWING

2.2.1 Temporal Definitions of the Swing

From a temporal perspective, the golf swing is typically broken up somewhere between three and five phases. When broken into three phases, the swing consists of the ‘backswing’, ‘downswing’ and ‘follow-through’. The ‘backswing’ describes the phase during which the club is moving away from the ball with the purpose of placing the club in the optimal position to start the downswing (Hay, 1993). Subsequently, the ‘downswing’ is the period between the top of the backswing to the time of impact (Burden, Grimshaw & Wallace, 1998; Hume et al., 2005). Finally, the ‘follow-through’ describes the period post impact, where the body and club movements gradually slow before coming to rest (Hay, 1993).

Instead of defining the start of downswing from movement of the club-head, some authors have defined it from the change in direction of other segments in the body. As the club-head is rarely the first segment in the system to start the forward movement (Burden et al., 1998; Nozawa & Kaneko, 2003; Cole & Grimshaw, 2009) this alternative definition leaves time between where the downswing starts and the club-head starts its forward movement. This has been referred to as the ‘transition phase’ (Fleisig, 1994).

In addition to the phases mentioned, authors will often refer to both ‘early downswing’ and ‘late downswing’. This is due to the considerable differences in kinematics and
kinetics that typically occur during these different sections of the downswing. While some researchers have arbitrarily referred to these ‘sub-phases’ without any specific definition as to where they occur, others have used identifiable events in the swing, such as when the club-shaft is parallel to the ground (McLaughlin & Best, 1994) as worthy of consideration.

2.2.2 Measures of Performance in the Golf Swing

One key to meaningful research, irrespective of the research design, is the validity of one’s dependant variables (Baumgartner & Hensley, 2012). With this in mind, it is clear that any golf research with the intent of drawing performance related conclusions must rely on a valid measure of performance.

From an applied perspective, the most direct measure of performance for a golf stroke would be the displacement between the resting place of the ball and the intended target. While this measure is popular in research investigating the putting stroke (Gwyn & Patch, 1993; Taylor & Shaw, 2002; Karlsen, Smith & Nilsson, 2008), only a handful of scientific papers have employed such a direct measure of performance during the full swing (Abernathy, Neal, Moran & Parker, 1990; Neal, Abernathy, Moran & Parker, 1990; Kanwar & Chowgule, 1994, Kenny, Wallace & Otto, 2008a). Perhaps the most obvious reason for the scarcity of this measure is due to its impracticality. Specifically, much of the necessary research equipment is difficult to operate in a setting such as a golf course or driving range, where measuring the final position of the shot would be possible. Another reason is likely due to the possible threat to internal validity. That is, confounding variables such as the wind, air temperature and condition of the ground upon landing are difficult to control in an outdoor setting.

In lieu of the final position of the ball, a performance measure for some investigators has been the initial launch conditions of the ball (Wallace, Otto & Nevill, 2007; Myers et al., 2008; Kenny et al., 2008a). This refers to kinematic variables such as the initial velocity, trajectory and spin of the ball, which are typically measured using specifically designed radars or launch monitors. While the launch conditions of the ball are not a direct measure of performance, it can be considered an accurate summary of the golfer’s contribution to the outcome of the stroke. That is, any variable with potential to
influence the final resting place of the ball beyond this time is not in the control of the golfer and, therefore, it is only to this point in the shot that the golfer has influence over the outcome.

Even more indirect than the launch conditions of the ball is the most common performance measure across the golfing scientific literature, which is the velocity of the club-head at, or near, impact with the ball (McLaughlin & Best, 1994; Mason et al., 1995; Neal & Wilson, 1985; Fradkin et al., 2004; Coleman & Rankin, 2005; Myers et al., 2008; Egret et al., 2006; Worobets & Stefanyshyn, 2007; Zheng et al., 2008; Ellis, Roberts & Sanghera, 2010). The rationale for this measure as a performance indicator is based around its proposed importance in determining the initial velocity of the ball post impact and, therefore, the eventual displacement of the stroke (Hume et al., 2005). While few would question that club-head velocity plays an important role in achieving distance in the golf swing, there is a paucity of evidence with respect to the exact quantification of this role. Specifically, little research has focused on how velocity interacts with other club-head mechanics that could influence ball velocity, such as centredness of impact. Furthermore, other performance variables that may be important in achieving distance and/or accuracy in the golf swing remain poorly understood, as well as having been largely ignored in scientific research.

Variables overlooked in the literature include those relating to the initial direction and spin of the ball. It is suggested that the vertical component of these variables would be dictated largely by the orientation and path of the club-head at impact in the sagittal plane (Wiren, 1990), which would likely play an important role in the distance achieved from any swing. In the same way, the lateral component of the ball’s trajectory and spin is suggested to be dictated by the orientation and path of the club-head in the transverse plane, ultimately dictating the accuracy of the stroke (Hay, 1993). However, despite these biomechanically logical suggestions, there is a paucity of quantitative evidence outlining the specific relationships between impact club-head kinematics and the subsequent ball flight characteristics.
2.3 EMPIRICAL RESEARCH INTO THE GOLF SWING

2.3.1 Kinematics and Kinetics of the Foot-Ground Interaction

During the swing, the golfer remains in contact with the ground and is therefore able to use the reaction forces applied back to the body to perform the movements that will ultimately allow them to hit the ball (Williams & Cavanagh, 1983). The importance of generating movement during the swing has resulted in the foot-ground interaction being a popular topic of investigation among scientists.

2.3.1.1 Ground Reaction Force

Early research focused on the ground reaction forces in the golf swing established the general pattern of forces experience by skilled golfers. The start of the backswing was associated with an anterior shear force applied by the right foot (to simplify terminology all golfers will be considered right handed in this thesis) and a posterior shear force applied by the left foot (Carlsoo, 1967; Williams & Cavanagh, 1983; Barrentine, Fleisig & Johnson, 1994). The subsequent coupling effect between the left and right foot was reported to produce a general torque that transferred up the body, aiding in the axial rotation of the pelvis away from the target. A similar pattern of opposing shear forces is evident in the downswing, but in the opposite direction. That is, golfers tended to produce a posterior sheer force at the right foot and an anterior sheer force at the left foot. Again, this has been suggested as critical in the creation of torque that allows the core of the golfer to turn towards the target (Williams & Cavanagh, 1983; Barrentine et al., 1994).

In addition to an anterior/posterior coupling pattern, Barrentine et al. (1994) reported a medial/lateral coupling of shear forces between the golfer and ground. The authors concluded that this effect would further add to the rotational torque during both backswing and downswing, aiding the rotation of the golfer’s lower trunk. A further interesting observation from the work of Barrentine et al., (1994) is a spike in transverse plane torsional forces between the left foot and ground shortly after impact. This was attributed to the potential of role of the left leg in slowing the rotation of the body into the follow through. This, in addition to the findings with respect to force coupling would suggest that an interface between the golfer and the ground could be important in accelerating and decelerating the rotations of the body.
2.3.1.2 Centre of Pressure

Although analysis of linear ground reaction forces, torques and moments provide a valuable insight in the interaction between golfer and the ground, a more common concept considered important by coaches is ‘weight transfer’ (Wright & Toms, 2003; Breed & Midland, 2008; De La Torre, 2008). How coaches conceptualise weight transfer can be somewhat varied but from a quantitative perspective, researchers have represented it through the movement of a point where the average of all the pressures or vertical ground reaction forces act between the golfer and the ground. Commonly referred to as centre of pressure (COP), researchers have analysed both the COP of the individual feet, as well as the resultant COP between the two feet.

One of the key findings of early golf research was that skilled golfers tend to have a COP position more toward the heel and medial aspect of each foot for the duration of the swing (Richards, Farrell, Kent & Kraft, 1985; Koenig, Tamres & Mann, 1993). A proposed explanation was that such a pressure distribution allows better players to achieve stability through the swing, whilst rotating with great force. Koenig et al. (1993) additionally reported that better players tend to have less overall shoe movement and a more circular migration of their COP.

Another finding that seems consistent across the COP literature is that skilled players transfer their COP away from the target early in backswing and then start to transfer forward around the transition between backswing and downswing (Cooper, Bates, Bedi & Scheuchenzuber, 1974; Richards et al., 1985; Burden et al., 1998). Cooper et al. (1974) reported that the golfers’ weight continued to move toward the target during the downswing, resulting in an average COP position at impact of 75% toward the front foot. However, Burden et al. (1998) reported that all of their participants moved their weight slightly backwards just before impact. Further, early research has also suggested a high level of inter-subject variability in the COP movement during the swing, especially amongst players of modest skill (Richards et al., 1985; Wallace, Grimshaw & Ashford, 1994).

Ball and Best (2007a) suggested that a limitation of some of the previous scientific literature examining COP patterns in golf may be a lack of identification of different swing styles or movement strategies. They warned that if groups of players employed
distinctly different strategies in the swing, their COP patterns would likely group together, forming ‘clusters’. Subsequent failure to recognise such clusters in the data would expose any statistical analysis to the risk of both type I and type II errors.

In their subsequent investigation, Ball and Best (2007b) performed a cluster analysis on the COP movement of sixty golfers with abilities ranging from professional to high handicappers. Their analysis confirmed two distinct COP styles existed within their sample; these were referred to as the “Front Foot” and “Reverse” styles. In line with previous research, both styles consisted of a COP movement toward the back foot during the backswing and back toward the front foot in the early downswing. Where participants differed, however, was through impact, where golfers with the Front Foot style continued to transfer their weight onto the front foot whereas the Reverse group transferred their weight towards the back foot. Interestingly, no performance differences were evident between the groups and, therefore, it was concluded that either of these styles was a valid way of transferring weight in the golf swing for a given individual.

In their second study, Ball & Best (2007b) performed correlational and regression analyses to assess the influence of COP movement on performance, within the two styles. For the Front Foot group, the analyses revealed that greater impact club-head velocity was associated with a larger range of COP movement and a more rapid COP movement in the downswing. For the Reverse group, positioning the COP more toward mid-stance late in the backswing along with transferring the COP more rapidly towards the back foot at impact, was associated with greater impact club-head velocity. Therefore, while the direction may be different, for both of these groups it would seem that transferring the COP over a greater distance and at a greater speed has some relationship with club-head velocity.

A more recent study by Ball and Best (2011) has indicated that the same distinct COP styles exist irrespective of the club being swung. Specifically, golfers of varying skill levels performed swings using a driver, 3-iron and 7-iron, with subsequent cluster analyses confirming the presence of “Front Foot” and “Reverse” styles in all three conditions. Further, 96% of the golfers analysed used the same swing style for all three clubs.
The research by Ball and Best (2007a; 2007b; 2011) is important in placing the analysis of the golf swing into perspective. That is, by identifying clusters in the way golfers move their COP through the swing they have shown that it may inappropriate to assume that all golfers swing with one strategy or ‘swing style’. Whilst their findings most directly clarify some of the literature regarding COP movement, the analysis they employed should also act as a guide to analysing other variables in the golf swing in the future.

2.3.2 Kinematics and Kinetics of the Lower Limbs

While few would suggest that movement of lower limbs solely determine the amount of power and accuracy in the golf swing, coaches and scientists generally agree that effective leg movement, as well as weight transfer, are the basis for a successful swing (Adlington, 1996). A common perception among coaches and some scientists is that the role of the lower limbs in the swing is to provide a stable base for the arms and club to rotate (Adlington, 1996). Although the ground reaction forces and COP of golfers has attracted a substantial amount of research, this is not the case for the kinematics or kinetics specific to the lower limbs during the swing. Much of the understanding of lower limb movement, therefore, still relies on anecdotal evidence.

For example, prior to the start of a golfer’s backswing, a popular coaching recommendation is to have both knees slightly flexed (Leadbetter & Huggin, 1990; Alpenfels, 1994; Adlington, 1996). Quantitatively this was supported to some extent by Egret et al., (2004), who reported average knee flexion angles at ‘address’ of approximately 18° and 17° for a group of expert golfers in the right and left knees respectively. Interestingly, the same study reported a greater flexion at the both knees, for a group of lesser skilled players.

As mentioned earlier, the torque provided to the body via the ground reaction forces is suggested to transfer through the lower limbs to allow the pelvis to rotate away from the target in the backswing and back toward the target to initiate the downswing (Williams & Cavanagh, 1983; Barrentine et al., 1994). To initiate this torque at the start of the downswing, it has been anecdotally suggested that the right foot and ankle supinate and drive the right knee forward (Leadbetter & Huggin, 1990).
Whilst the right hip, knee and ankle remain in a stable flexion throughout the downswing, it has been suggested that the left knee extends to ‘brace’ against the forward rotation of the body in the moments prior to impact (Shauger, 2004). The work of Egret et al. (2004) supports this assertion, reporting that both skilled and unskilled players flexed their left knee slightly through the backswing but returned to a more extended position at impact. This ‘bracing’ of the left leg is possibly related to the high abduction loading seen in the left leg (Gatt, Pavol, Parker & Grabiner, 1998; Lynne & Nofall, 2010), as well as the spike in transverse plane torsional forces between the left foot and ground previously mentioned from the work of Barrentine et al. (1994).

Bechler, Jobe, Pink, Perry, and Ruwe (1995) provided some insight with respect to muscle activation of the lower limbs during the golf swing. The investigation revealed that the hamstrings of the left leg had a maintained activation throughout the downswing. It was suggested to be responsible for the stable knee flexion observed and, therefore, supported the claim that the role of the lower limbs in the golf swing is to provide a stable base for pelvis rotation.

In a study investigating the effect of shoe type and skill on knee joint loading, Gatt et al. (1998) reported that neither of these had a significant influence on the pattern of loading. However, their research did indicate an inconsistency of loading patterns between players and the left and right knee. In contrast, Lynne & Nofall (2010) found there to be a somewhat consistent pattern of knee loading among a group of low handicappers. In both studies, the magnitude of knee loading was reported as being at its highest during the downswing phase. In an effort to contextualise the loading of the knees experienced during the golf swing, Lynne and Nofall (2010) demonstrated that these loads were higher than experienced in walking and ascending stairs, similar to that during a drop landing but lower than when performing a typical side stepping manoeuvre.

Robinson (1994) attempted to shed some more light on the influence of the lower limb on the golf swing, by including some selected kinematics of the region into a regression analysis explaining the variance in club-head velocity in the swing. Amongst a number of other kinematic and kinetic variables throughout the body, the linear velocity of the left knee was reported to have a significant relationship with the club-head velocity at impact. However, the reasons why knee velocity might exert an influence on club-head
velocity were poorly explained in the article. Additionally, the research suffered from a lack of detailed methodology, whilst also violating a number of statistical issues. Specifically, the study had a high number of independent variables (>80) but a relatively small sample size (N = 30), putting it at great risk of type 1 error (Vincent & Weir, 2012). Further, the regression method chosen for the analysis assumes a linear relationship between variables, which is unlikely to be the case in such a complex movement as the golf swing (Craig, 1989). As a result, this paper, unfortunately, shed little quantitative insight into the lower limb kinematics involved in a successful swing.

2.3.3 Kinematics and kinetics of the pelvis and trunk

Due to its mass and size, the core of the body has the potential to transfer a great deal of angular momentum. Consequently, optimal rotation of this part of the body has been suggested as one of the key factors in achieving a powerful golf swing (Leadbetter & Huggin, 1990; Hay, 1993). As a result, many empirical studies have focused over the last 20 years on the movement of the pelvis and trunk in the swing.

Important to understanding the scientific literature on the core of the body during the swing is recognising the different methods investigators have used to define this movement (Wheat, Vernon & Milner, 2007). Some investigators have represented upper body rotation with a vector passing though the markers placed on the left and right acromion processes, projected onto a global transverse plane (Burden et al., 1998; Grimshaw & Burden, 2000; Mitchell, Banks, Morgan & Sugaya, 2003; Egret et al., 2006; Myers et al., 2008; Zheng et al., 2008; Cole & Grimshaw, 2009). Similarly, some researchers have represented the pelvis with a vector running between two markers placed over the hip joints (Burden et al., 1998; Zheng et al., 2008; Cole & Grimshaw, 2009). However, an alternative method to track the movement of pelvis and trunk has been to collect data from gyroscopes and potentiometers directly affixed to the golfer (McTeigue, Lamb, Mottram & Pirozzolo, 1994; Cheetham, Martin, Mottram & St Laurent, 2001; Lindsay, Horton & Paley, 2002). It is apparent that these different measurement techniques would represent the movement of slightly different systems. Specifically, tracking a device that is affixed to the spine would logically represent the movement of the thorax alone, whereas tracking an inter-acromion vector relative to the pelvis is likely to represent the movement of both the trunk and scapular.
Wheat et al. (2007) carried out an investigation on the effect of different methods of upper body measurement in the golf swing, arguing that an inter-acromion method could lead to misrepresentative data of the ‘spine alignment’. The investigators affixed markers to the thorax as well as the acromion process of 10 participants during the golf drive and tracked them using a three dimensional motion capture system. To calculate position of the upper body in the transverse plane, an inter-acromion vector, thorax vector and cardan angle approach were used. The results of the study indicated little difference between the methods when the golfer addressed the ball. However, a significant divergence of angles at both the ‘top of backswing’ and ‘impact’ led the authors to conclude that the inter-acromion method may misrepresent pure ‘thorax’ alignment. The results of recent research has further confirmed the differences among commonly employed methods for calculating trunk motion, leading to calls for consistency among the future research (Kwon, Han, Como, Lee & Singhal, 2013; Brown, Selbie & Wallace, 2013).

Also important to define in the understanding the kinematic literature on the trunk and pelvis motion during the golf swing is the measure referred to as the ‘X-factor’. This measure has been prevalent in the scientific and popular golfing literature in describing the rotation of the ‘shoulders’ relative to the ‘hips’ (McLean, 1996, Cheetham et al., 2001; Cole & Grimshaw 2009). Typically, this is described with respect to rotation on the transverse plane and is similar to the pelvic-shoulder ‘separation angle’ commonly described in the cricket and tennis literature (Burnett, Elliott & Marshall, 1995; Elliott, Fleisig, Nicholls & Escamilla, 2003).

Definition issues aside, studies using the aforementioned techniques have revealed important information with respect to the kinematics of the trunk and pelvis employed by skilled golfers during the golf swing. At ‘address’, research has indicated that skilled golfers tend to adopt a trunk position that is slightly open, laterally tilted to the right and flexed forward around 30º (McTeigue et al., 1994; Lindsay et al., 2002; Zheng et al., 2008). This position is similar to the common coaching recommendations regarding the proper alignment of the upper body as the golfer addresses the ball (Leadbetter & Huggin, 1990; Adlington, 1996). With respect to performance however, it is interesting to note that research by McLaughlin and Best (1994) revealed that skilled players have a significantly more upright trunk during setup than players of lesser skill. Additionally,
Okuda et al. (2010) reported that skilled players had a slightly more open pelvis position at address.

From the position at’ address’, skilled golfers tend to initiate the backswing by a rotation of the upper torso, followed immediately by some degree of pelvic rotation (Hogan & Wind, 1957; McTeigue, Lamb, Mottram & Pirozzolo, 1994). The rotation of the pelvis and trunk continues until late backswing, where a common coaching recommendation is to achieve a maximum ‘shoulder turn’ of around 90 degrees (Schempp & Mattsson, 2005; Alpenfels, 1994). This ‘shoulder turn’ described amongst coaches generally corresponds to a measure of the inter-acromion vector in a transverse plane. When using this method, investigators have reported peak rotation of between 100º and 106º for skilled players (Grimshaw & Burden, 2000; Egret et al., 2004; Myers et al., 2008; Cole & Grimshaw, 2009). However, as discussed, the inter-acromion measure may not accurately represent the rotation of the thorax alone. Instead, it is likely to include the rotation of both the trunk and scapular segments (Wheat et al., 2007). When using a method that tracks the alignment of the thorax alone, McTeigue et al. (1994) found a group of professional players that had an axial rotation of 87º (±12º) at the top of backswing.

There has been some conflicting evidence to date as to whether achieving a greater upper body axial rotation prior to the downswing is, in fact, beneficial to performance in the drive. The results of some empirical investigations would suggest that peak rotation of the body’s pelvis and trunk has no significant influence on the performance of the swing (McTeigue et al., 1994; Bulbian, Ball & Seaman, 2001; Joyce, Burnett & Ball, 2013; Kwon et al., 2013). However, a number of empirical investigations have also concluded that players of a higher skill level generally achieve a greater peak axial rotation of the upper body (Cheetham et al., 2001; Mitchell et al., 2003; Egret et al., 2004; Myers et al., 2008; Cole & Grimshaw, 2009). In particular, this greater rotation of the trunk in skilled players appears to be achieved both relative to the global coordinate system (Egret et al., 2004; Myers et al., 2008) and the pelvis (Cheetham et al., 2001; Myers et al., 2008; Cole & Grimshaw, 2009). As mentioned, the latter is as often referred to as the ‘X-factor’.

Skilled players generally initiate the forward axial rotation of the pelvis, then trunk, prior to the start of the forward swing (Burden et al., 1998; Nozawa & Kaneko, 2003;
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mark, Hellström, Halvorsen and Thorstensson (2010) also reported that peak velocities of the pelvis and trunk segments occur sequentially with an incremental increase in magnitude. This sequential movement of the pelvis then trunk utilised by skilled golfers has been suggested to be important by both placing the muscles of the trunk under greater stretch during the ‘transition phase’ of the swing (Hume et al., 2005), as well as conforming to the ‘summation of speed’ principle, originally described by Bunn (1972). Golfers who are less skilled are less likely to have such sequential order of rotations at the start of their downswing and can often initiate the forward rotation of the pelvis and trunk at the same time as the first forward movement of the club (Nozawa & Kaneko, 2003).

At impact, the trunk is more upright, axially rotated into an open position and laterally flexed to the right than at ball ‘address’ (Burden et al., 1998; McTeigue et al., 1994; Zheng et al., 2008). The trunk being more upright at impact is contrary to some popular golfing literature, which has suggested that the trunk should maintain a steady level of flexion from setup through to past impact (Els & Newell, 1999). A further look at the scientific literature provides further evidence against this coaching recommendation, with a number of studies reporting a lack of trunk forward flexion angle through any part of the swing (McTeigue et al., 1994; Derksen, Van Riel & Snijders, 1996; Lindsay et al., 2002; Zheng et al., 2008). Whilst it might be a useful teaching cue to instruct players to maintain only small fluctuations of trunk flexion through the swing, it is important to note that this is not actually observed in skilled players.

While the sequential movement of the pelvis and trunk segments is well established, a recent study by Horan and Kavanagh (2012) focused on the control of these two segments through the swing. The descriptive results clearly reflected the differences in the timing and magnitude of the pelvis/trunk rotations throughout the downswing. However, a subsequent cross correlational analysis indicated a strong coupling relationship between the pelvis and trunk, identifying a potential method for simplifying motor control strategies and ensuring more consistent motor patterns.Interestingly, the movement of the head did not appear to exhibit the same coupled relationship with either the movement of the trunk or the pelvis.
2.3.4 Kinematics and kinetics of the upper limbs

Similar to a number of hitting sports, the upper limbs have been shown to be integral in the delivery of power in the golf swing (Neal & Wilson, 1985; McLaughlin & Best, 1994; Chu et al., 2010). Based on the characterisations of the golf swing by Cochran and Stobbs (1968), much of the early upper limb research into the golf swing focused on the movement of a single theoretical ‘arm’ segment in conjunction with the club moving through a two dimensional ‘swing plane’. The angle formed between the arm and club segments in this plane is commonly referred to as ‘wrist-cock’ (Jorgensen & Adair, 1994; Adlington, 1996). With respect to this measure, the literature has been consistent in showing that better players tend to create a smaller angle between club and arm during early downswing, as well as maintain this angle later into the downswing (Milburn 1982; Koenig et al., 1993; McLaughlin & Best, 1994; Robinson, 1994; Chu et al., 2010). Additionally, the planar empirical research has demonstrated that the deceleration of the hands late in the downswing allows a large positive force to be transferred across the wrist joint, aiding in the achievement of peak linear club-head velocity at impact (Vaughan, 1981; Neal & Wilson, 1985; Chu et al., 2010).

Despite the insight of the above findings, using a two dimensional ‘wrist-cock’ measure is limited in its ability to accurately represent the complex movement of the wrists and upper limbs throughout the swing (Coleman & Rankin, 2005). The first reason for this is due to the clear evidence that the swing does not operate in a single two dimensional plane (Neal & Wilson, 1985; Vaughan, 1981; Cooper & Mather, 1993; Koenig et al., 1993; Coleman & Rankin, 2005; Coleman & Anderson, 2007). Secondly, the ‘wrist-cock’ measure only accounts for the movement of one rigid upper limb in conjunction with the club. The evidence is clear though, that the upper limb contribution to the golf swing is much more complex than can be explained by just one joint from one limb (Jobe, Perry & Pink, 1989; Morgan, Banks & Bow, 1999; Mitchell et al., 2003; Hume et al., 2005).

While sparse, the three dimensional empirical research that has focused on the upper limbs has revealed some important normative data. It has been observed that during the backswing, the left arm continues the initial motion of the pelvis and trunk by adducting laterally, flexing upwards and internally rotating (Fleisig, 1994; Hume et al., 2005). Simultaneously, the right upper arm is vertically elevated and externally rotated, whilst
the right elbow undergoes flexion (Hume et al., 2005). Finally, radial deviation at both the left and right wrist occurs later during the backswing to create the ‘cocking’ seen from a two dimensional perspective (Neal & Wilson, 1985; Cooper & Mather 1993).

At the top of the backswing, descriptive research has indicated that skilled players typically have their left arm horizontally adducted across the chest by around 125°, vertically elevated by 110° and internally rotated (Mitchell et al., 2003). The right arm, in general, is minimally laterally adducted, vertically elevated around 75-90° and externally rotated to approximately 85° (Mitchell et al., 2003, Hume et al., 2005). The right elbow is flexed around 90°, whilst the left elbow is almost completely extended (Hume et al., 2005).

From this point, the left arm undergoes horizontal abduction, vertical adduction and external rotation, while the right arm is horizontally adducted and internally rotated during early downswing (Hume et al., 2005; Teu, Kim, Fuss & Tan, 2006). The right elbow also undergoes rapid extension. Later in the downswing both wrists act together to perform the final rotation of the club through a mixture of flexion and ulnar deviation (Teu et al., 2006; Sweeney, Mills, Mankad, Elliott & Alderson, 2012). The research to date has also indicated the highest angular velocities in the downswing are achieved by internal/external rotation of the upper arm (9.6 rad/s), supination of the forearm (8.2 rad/s) and flexion at the left and right wrist (11.1 rad/s & 26.7 rad/s respectively) (Teu et al., 2006; Sweeney et al., 2012). These findings are interesting as little research has focused on the potential influence of the internal/external rotation of the upper arms or the supination/pronation of the forearms on developing power in the golf swing.

The general pattern of movement with respect to the upper limbs during downswing is often considered mirrored to that of the backswing, but in a more sequential order. The three dimensional analysis by Neal, Burko, Sprigings and Landeo, (1999) confirmed that skilled players experience large rotational torques in a proximal to distal sequence through the upper limbs. Moreover, Okuda, Armstrong, Tsunezumi and Yoshiike (2002) noted a sequential muscular activation from the trunk through the upper limb of an elite golfer. This sequential rotation of segments is common across a number of sporting tasks and is likely to be valuable in achieving the high club-head velocities noted at impact during the swing (Putnam, 1993).
2.3.5 Kinematics and kinetics of the club

The movement of the golfer described in the previous sections are ultimately to dictate
the kinematics of the club-head as it makes impact with the ball. It is important,
therefore, to understand the kinematics and kinetics the club itself throughout the swing.

Important to understanding the pattern of club-head kinematics throughout the swing is
how it is influenced by the club shaft. Research into the movement of the shaft has
focussed largely on its stiffness and length. With respect to the former, early empirical
investigations indicated that stiffness of shaft had little effect on performance (Milne
1992; Van Gheluwe, Deporte & Ballegeer, 1990; Knight, Leonard, Wicks & Blough,
1997). However, the results of some more recent investigations have suggested
otherwise. In particular, Worobets and Stefanyshyn (2007) asked a small group of
golfers to drive the golf ball using five different shafts, each with a different level of
stiffness. The subsequent statistical analyses revealed that there was a significant
within-participant effect using different shaft stiffness’s with respect to the club-head
velocity at impact. Importantly, however, it was noted that the shaft that allowed the
highest club-head velocity to be achieved was not the same across participants. That is,
there was no single club that allowed a greater club-head velocity to be achieved by all
of the golfers involved.

To address the limitation of their previous work, Osis and Stefanyshyn (2010) more
recently suggested that there may be an unconscious adaptation effect by golfers when
playing with different shaft flexes, which may have influenced some of the previous
research. In an attempt to investigate this, the authors analysed the club kinematics of
golfers hitting with drivers of varying shaft stiffness whilst a vibration rig was attached
to selected muscles of the arm. The purpose of the rig was to interfere with the
proprioceptive feedback of the golfer and therefore render them blind to the stiffness of
the shaft. Their results indicated that of the 24 participants, 11 achieved significantly
higher club-head velocity at impact with a more flexible shaft.

Empirical research has also focused on the length of the golf club and its influence on
performance. Wallace et al. (2007) assessed the launch conditions of a group of skilled
golfers when using four drivers of different lengths. While there was some evidence
that using a longer driver would allow for greater ball velocity at launch, the benefits
gained were somewhat minimal. Additionally, the overall launch conditions were not deemed to be improved by hitting with a longer club, as this also was linked to decreased launch angle.

A year later, the results of Kenny et al. (2008a) suggested a more definitive influence of shaft length on ball velocity. A greater club-head velocity and no decreased launch angle was observed through allowing players to hit with a longer than regulation club length. More than just measuring the launch conditions though, they were also able to directly calculate the ball carry of the shot by tracking it on a custom built practice hole. Using this, they noted that the increased initial ball velocity when hitting with a longer driver translated into a greater carry distance but this failed to reach significance. Interestingly, there did not seem to be any accuracy detriment when using the longer club, leading researchers to suggest that skilled golfer are likely to gain some advantage by using a longer driver.

With respect to the club-head itself, the general pattern of displacement has often been reported in the scientific literature, although seldom directly. In one study, Nozawa and Kaneko (2003) compared the club-head velocity throughout the downswing between amateur and professional female golfers. Contrary to what could have been expected, it was the amateur players that achieved a higher club-head velocity for the majority of the downswing. However, late in the downswing the professional players accelerated the club-head at such a rate that they achieve a velocity 25% greater that the amateurs at impact. This suggests that it is not simply the average club-head velocity through the swing that is important, but the timing of this velocity and specifically how great it is at impact.

At impact, researchers have reported club-head velocities ranging from 32m/s to 51m/s (Nagao & Sawada, 1977; Watanabe, Kuroki, Hokari & Nishizawa, 1998; Worobets & Stefanyshyn, 2007; Zheng et al., 2008). The methods used to collect data around this time may be contentious, as data treatment around the time of a collision has been brought into question in different sporting tasks (Knudson & Bahamonde, 2001; Nunome, Lake, Georgakis & Stergioulas, 2006; Tabuchi et al., 2007). In particular, it has been suggested that interpolating through time of impact may cause a misrepresentation of the data. This is quite relevant to the golf swing research, as a number of investigators have interpolated club-head data directly through impact to
ascertain values of club-head velocity (Neal & Wilson, 1985; McLaughlin & Best, 1994; Mason et al., 1995; Fradkin et al., 2004; Coleman & Rankin, 2005; Worobets & Stefanyshyn, 2007; Zheng et al., 2008). This is despite evidence suggesting the club-ball collision can have a dramatic effect on club-head kinematics (Williams & Sih, 2002; Ellis et al., 2010).

Further investigation is needed to assess the effects of the different methods of data treatment around impact in the swing in order to ensure that the most accurate method is used by researcher moving forward. Similarly, future research is necessary to establish a “gold standard” in collecting data and calculating valid and repeatable kinematics at impact.

2.3.6 Variability in the golf swing

The above sections have outlined the empirical research into the golf swing, which has focussed almost solely on the ‘typical’ or ‘average’ mechanics golfers demonstrate swing after swing. Recently though it has been suggested that a focus on average mechanics alone limits our potential understanding of what enables golfers to achieve skilled performance in golf (Bartlett et al., 2007; Glazier, 2011; Langdown et al., 2012). Instead, a greater emphasis on understanding the role of the inter-swing fluctuations, which occur in the mechanics of the swing, is likely to provide the most meaningful insight into how skilled performance is achieved (Glazier, 2011; Langdown et al., 2012).

Inter-trial variability in any form has traditionally been viewed by sport biomechanists as unwanted noise which should be reduced as much as possible in order to achieve a consistent outcome. This view appears to have merit when considering that a common hallmark of skilled performance is the ability to achieve very little variability in the outcome of a task (Bartlett et al., 2007; Fleisig, Chu, Weber & Andrews et al., 2009; Betzler et al., 2012). However, the notion that all variability is detrimental to performance fails to consider the concept of motor equivalence (Stelmach & Digglies, 1982) or motor abundance (Gelfand & Latash, 1998). That is, in a redundant system there are multiple ways that the biomechanical degrees of freedom can be configured to achieve the same outcome. Indeed recent evidence suggests that variability within the individual motions that ultimately influence a task (to be referred to as ‘movement
variability’ in the thesis) may is an intrinsic aspect of skilled performance, which plays a key functional role in skilled performers achieving consistency and accuracy in a task outcome (Bartlett et al., 2007, Langdown et al., 2012, Preatoni et al., 2013).

Over the past 40 years a large body of evidence has accumulated demonstrating that variability can play an important functional role in achieving success in a given task (Arutyuyan et al., 1969; Newell & Slifkin, 1998; Van Emmerick & Van Wegen, 2000). An often cited example of the functional role of variability was reported by Arutyunyan and colleagues (1969) in an investigation into elite and amateur pistol shooting. They found expert shooters exhibited greater variability at the wrist and shoulder but less variability in the displacement of the task-relevant endpoint (ie. the pistol tip). These results demonstrate that in a redundant system (multiple ways to achieve the same outcome), movement variability may act in a coordinated way to maximise the precision and consistency of the outcome. The results of Arutyuyan et al. (1969) also highlight the important distinction between outcome variability and movement variability, which is often overlooked by coaches and biomechanists.

As mentioned, one of the key traits of skilled performance in the golf swing is the ability to achieve low outcome variability (Kite & Dennis, 1994; Bartlett et al., 2007; Betzler et al., 2012). Scientific and anecdotal evidence suggests that skilled golfers achieve a high level of consistency in both the distance and direction of the golf drive, as well as the club-head kinematics at impact (Suttie, 2006; Breed & Midland, 2008; Betzler et al., 2012). Therefore it seems reasonable to assume that outcome variability in the swing can be represented either by the inter-swing fluctuations in the final position of the ball or the individual club-head kinematics that directly dictate the ball flight.

An early attempt to investigate movement variability in the swing (Bradshaw et al., 2009) focused on the variability of specific joint motions among golfers of differing skill levels. Bradshaw et al. (2009) reported that more skilled performers exhibited less movement variability, as measured by specific joint motions during the swing. While it was suggested that these results may be in support of the assertion that absolute movement invariance is favourable, it is important to consider that skilled golfers in this study still exhibited some level of movement variability in the joint motions analysed. It is also important to consider that subsequent papers (Glazier, 2011; Langdown et al., 2012, 2013).
2012) have questioned the methodology of Bradshaw et al. (2009) in assessing movement variability.

A recent investigation by Tucker, Anderson and Kenny (2013) found no relationship to exist between outcome variability and the movement variability (represented by movement of markers, placed over anatomical landmarks). The finding of Tucker et al. (2013) that movement variability exists independent of outcome variability, is consistent with similar research investigating variability in the execution of other sporting tasks (Bartlett et al., 2007; Pretoni et al., 2013).

Horan et al. (2011) attempted to shed further light on the issue of variability in the golf swing by investigating the relative movement variability of proximal and distal segments in the kinematic chain. Interestingly they found that throughout downswing, skilled golfers’ exhibit significantly greater movement variability in the motion of their pelvis/trunk compared with that of their hands and the club-head. Such a decrease in movement variability more distally in the kinematic chain likely indicates some sort of compensatory role by the segments in between the trunk and hands. As with the example of Arutyunyan et al. (1969) discussed above, compensatory type patterns similar to those suggested to exists by Horan et al. (2011) have been previously been identified in the coordination of other a range of different tasks, such as reaching, throwing and gait (Jaric & Latash, 1999; Kudo, Tsutsui, Ishikura, Ito & Yamamoto, 2000; Adamovich et al., 2001; Muller & Sternad, 2004; Mills, 2007). While researchers to yet to definitively identify compensatory type patterns in the golf swing, doing so would provide strong support for the assertion that movement variability within the swing has a functional role in allowing low outcome variability to be achieved.

The results of the few studies to date which have focussed on the role of variability in the swing indicate that a greater understanding of the role of movement variability in the swing may provide important insight into how the golf swing is executed successfully, on a consistent basis by skilled golfers. It is clear though, that there is a great deal more research required in order to allow scientists, and those in the applied arena, to understand the complete role of variability in the swing.
2.3.7 Summary of Empirical Research

From this review it is clear that the empirical research has acted to both provide an overview of the kinematics/kinetics typically achieved by golfers, as well as highlight the relationship between particular body segment movements and performance. With respect to the former, a paucity of evidence still exists around the kinematics/kinetics produced by golfers at both the upper and lower limbs. In particular, few researchers have reported three dimensional data at the ankle, knee, hip, shoulder, elbow or wrist through the swing. Further information is needed on the pattern of these movements over the entire swing.

With respect to the highlighted relationships between specific degrees of freedom and performance, research to date has tended to focused on a small number of variables. These include COP motion, trunk rotation (or X-factor/X-factor stretch) and wrist-cock. Each of these has been linked to performance with differences shown between skilled and unskilled players. However, empirical research has yet to provide an understanding of these relationships that is able to considerably aid golfers and coaches in the applied setting. Additionally, there are a large number of other degrees of freedom, whose potential relationship with performance has yet to be explored.

Finally the early empirical research into the role of variability in the swing suggests that a functional role might exist to the movement variability exhibited by skilled golfers (Horan et al., 2011; Glazier, 2011; Langdown et al., 2012; Tucker et al., 2013). In conjunction with the growing body of research around movement variability in other motor tasks it is clear that a greater research focus is required on variability in the swing rather than solely on the typical kinematics exhibited by golfers at discrete points of time.

2.3.8 Limitations of Empirical Research

As previously described, much of the scientific investigation into the mechanics of the golf swing has been empirical in nature, often appearing in the form of descriptive, correlational or comparative research. Each of these research types can provide coaches and players with an important resource in describing how elite players are able to perform their swing, as well as highlighting some key mechanical differences between skill levels. Indeed, some of the mechanical differences highlighted between skill levels
presented above almost certainly play key roles in the development of efficient
technique, thus allowing a golfer to hit the ball further, straighter and perhaps more
consistently. However, the statistical measures that are necessary in these empirical
studies, unfortunately, suffer from certain limitations. One of these is the assumption
that relationships between the analysed variables are linear in nature. This is unlikely
the case in movements that are highly complex, such as the golf swing (Craig, 1989).

A second common assumption of empirical research is that of causality. In particular, it
is common in the golf literature to suggest that a specific variable has a possible
influence on performance because it is found to be executed differently between skill
levels, or it is found to be statistically related to performance. However, there are well
documented problems associated with drawing causality from either statistical
relationships or differences when possible confounding variables exist (Brodie,
Williams & Owens, 1994; Baumgartner & Hensley, 2012). Unfortunately, these
confounding factors are almost impossible to eliminate when performing empirical
research on a movement as complicated as the golf swing.

Both of these limitations should be considered when interpreting the results of any
empirical study on the golf swing. Future empirical investigations should also
acknowledge these limitations, as well as attempt to lessen their impact on the research.

2.4 SIMULATION MODELLING OF THE GOLF SWING

Simulating the golf swing mathematically to investigate the influence of different
parameters is a method that does not inherently suffer from the same limitations
associated with the statistical analyses identified in purely empirical research. With
respect to the golf swing, simulation modelling has been employed in its simplest form
since the late 1960’s, although significant advances have occurred in recent years.

The models themselves have varied with respect to whether they are driven by: kinetics
or kinematics of the swing, the direction of modelling, number of segments represented,
and dimensionality of the data. For the purposes of this review they will be categorised
based on the type of biomechanical data that drives the calculations, as well as the
number of segments that are represented.
2.4.1 Kinetic Modelling

2.4.1.1 Two Segment Planar Models

When Cochran and Stobbs (1968) first introduced the simplified double pendulum model of the swing they also created a set of mathematical equations to simulate how such a model could operate without the use of active torque around the wrist joint. The model consisted of two segments representing the club and left arm of the golfer. Both of these segments were assumed to be completely rigid and to operate in a single two dimensional plane. With torques being applied to the proximal end of each segment, representing the effect of gravity and centrifugal force, the subsequent kinematics of the segments were calculated. The results confirmed that when representing downswing with a simplified model, an arm and club segment can be coordinated to allow a ‘natural’ acceleration of the club, driven only by centrifugal force and gravity. Similar two segment models were subsequently used by a number of researchers to investigate the influence of different temporal, kinetic and club design characteristics on the golf swing.

Budney and Bellow (1979) employed an inverse dynamics approach to investigate the effect of different swing weights on the forces applied to the golfer during the swing. Empirical kinematics were calculated using data captured from a single video camera set up perpendicular to the theoretical swing plane of a golfer. This data acted as the basis of the model, as well as established the criterion value to be met in the subsequent simulations. These simulations were carried out with modified parameters, such introducing the effect of ‘drag’ and manipulating the swing weight of the club. It was concluded that there was little effect of ‘drag’ or introducing different club swing weights on the meeting the criteria set by the empirical data. However, a driver with a graphite shaft was reported as requiring less effort to swing by the golfer than one of steel construction.

While the inverse dynamics approach by Budney and Bellow (1979) revealed some interesting insight into the effects of the club on the golfer, all other two segment simulation studies have applied a forward dynamic approach to their investigations. Jorgensen (1970) developed a forward dynamic two segment model of the swing to further investigate the effect of different kinetic timings during the swing. Similar to
Cochran & Stobbs (1968), toques were applied to the proximal end of each segment throughout the simulated downswing with the effect on the endpoint kinematics assessed. However, the original contribution of this investigation was the simulating temporal effects on the wrist torque applied during the downswing. It was revealed that an onset of muscular wrist torque too early in the downswing would lead to a restriction of peak club-head velocity. Conversely a delay in this toque until late in the downswing (0.07s prior to impact) was shown to marginally increase club-head velocity at impact.

A further model comprising of two rigid segments operating in a single plane was used by Pickering and Vickers (1999) to validate a criterion method of defining impact in the modelled swing. Previous forward dynamic research had defined impact as occurring when the club segment was aligned vertically during the downswing. This criterion method was compared with a new approach, where impact was determined by the point at which the horizontal club-head velocity was at its maximum. It was concluded that the latter was the more appropriate definition of impact and resulted in higher resultant club and wrist velocities at impact than had previously been reported. Using this criterion method to simulate temporal effects on the application of torques during the swing, they found similar results to Budney & Bellow (1979). In particular that a delayed release of the ‘wrist-cock’ angle results in an increased club-head velocity.

In another investigation using a two segment, forward kinetic model, Miura (2002) set out to investigate the anecdotal assertion that skilled players had a tendency to pull the club towards the axis of rotation just prior to impact. To allow this movement to be included in the modelling of the swing the researcher included an additional translation actuator into the two segment model. He subsequently concluded that an increase in club-head velocity could indeed be achieved through a purposeful pulling of the club upwards near impact.

Continuing the work of Pickering and Vickers (1999), Chen, Inoue & Shibara, (2007) used a two segment model to address the topic of the positioning of impact, with the possible influence of differing wrist kinetics. Using a Lagrangian approach they applied different wrist torque profiles to a double pendulum model, assessing the effect on peak horizontal club velocity as well as velocity when the shaft was vertical to the ground. The conditions applied in the simulations consisted of the following types of wrist release: natural (N), passive (PW), active (AW) and passive/active (PAW). In N, no
torque was applied to the wrist joints, in PW the wrist was allowed to release through gravity alone after reaching a set negative value, in AW active torques were applied to the wrist magnitudes consistent with the empirical measures of Neal et al. (1999). Finally, the PAW condition consisted of a mixture of the previous two approaches.

Chen et al. (2007) (similar to Pickering & Vickers earlier) concluded that the optimal position for which the ball-club impact should occur is the point at which the horizontal club-head velocity was at its peak. It was found that the PAW condition produced the highest club-head velocity both at this time, as well as the point where the shaft was aligned vertically to the ground. Additionally, the point at which peak horizontal club-head velocity occurred was found to be sensitive to the different wrist conditions imposed. Irrespective of the type of wrist torque applied though, optimal impact position was always further forward in the stance (towards the target) than the midpoint between the feet.

White (2006) attempted to re-examine the principles of efficiency in the golf swing using a double pendulum model that was similar to Cochran and Stobbs (1968), in that it was driven only by torques provided by inertia. He reported that the arm and club segments represented in the model could coordinate themselves to hit the ball without any active contribution at the wrist joint, as had previously been reported by Cochran and Stubbs (1968). The results of this study also highlighted that a smaller minimum angle between arm and club through early downswing would increase the efficiency in a passive swing.

With respect to the influence of club parameters, White’s (2006) simulations indicated that more distance and efficiency could be achieved with a longer club shaft. While this influence was linear in nature, the author noted that it would eventually be limited by the laws of the game and the ability of the golfer to overcome the greater inertia at the top of backswing. Specifically, he reported that the efficiency of the stroke would seem to plateau at a certain club length.

White (2006) also carried out simulations to assess the effect of manipulating the club-head mass on the impact club-head velocity. The results suggested that an optimal mass of the club would be somewhere close to 200g. This optimal mass was suggested to be
only a rough guide though, as other confounding variables, such as the muscle properties were not accounted for in the model.

It is clear that using only two segments to model the swing has been popular in the research, likely due to its simplicity. As would be expected from a model that only features one joint, much of the research has centred on the importance of optimal kinetics across the wrist. Specifically, a number of studies seem to support the assertion that the swing can be performed without any active muscle torque. However, it is also consistently reported in the double pendulum simulation research that a strategy which creates a larger wrist cock angle, holds this angle until late in the downswing and produces an active torque to ‘uncock’ the wrist leading up to impact will allow for the greatest club-head velocity to be achieved.

2.4.1.2 Three Segment Planar Models

As a real golf swing is the product of coordinating a large number of segments, representing more of these in simulation models is likely to better represent the real motion of the golfer and club. Even in the early work of Cochran and Stobbs (1968) it was suggested that adding a third segment to the model may increase the possible club-head velocity achieved in the calculations. They did not include this in their modelling suggesting that introducing another moving segment would provide too complex a coordination pattern for their algorithms. However, more recent simulation investigations have regularly included a third segment. The additional segment in these models has been to represent the motion of the trunk/torso during the swing.

Whilst most of the three segment planar modelling research of the swing has been forward dynamic in nature, Tsujiuchi, Koizumi and Tomii (2002) used an inverse dynamics approach. They collected empirical data from the swings of three players and simplified the 3D kinematics onto a projected 2D ‘swing plane’. In a similar approach to Budney & Bellow (1979), these researchers used inverse dynamics to simulate the kinetics that were being applied throughout the swing. However, unlike Budney & Below they introduced a third segment at the proximal end of their model to simulate movement at the trunk. Additionally, the shaft was modelled as a flexible segment to better represent the movement of a real club. Unfortunately the mathematical specifics of this modelling were poorly outlined in the paper. With respect to their results, the
authors reported that all players underwent a negative wrist torque just before impact, possibly allowing a transfer of angular momentum into the bending shaft. However, it is important to appreciate that conclusions drawn from a planar model do not take into account off centre rotations of the wrist and club.

Campbell and Reid (1985) were the first to incorporate three segments into a forward dynamics approach. As a part of their study, optimisations were run to meet two criteria. The first criteria involved optimising club-head velocity at impact, whilst not exceeding predefined joint torques. The second criterion involved achieving a defined club-head velocity at impact, whilst minimising the work performed by the golfer. Simulations ran to meet the second criterion indicated that a hallmark of an efficient swing was the sequential order of peak torques. They also showed that a large reduction in the work performed by the golfer during the swing did not necessarily translate into a large reduction in impact velocity of the club-head. Combined, these results would suggest that golfers can conserve effort in the swing and still achieve high club-head velocity at impact by employing a sequential pattern of forces applied through the downswing.

Turner and Hills (1998) used a three segment model driven by forward dynamics to assess whether the kinematics of the swing could be better replicated than when using a traditional two segment approach. Motion of the model was driven by constant torques applied across the origin of the torso segment, as well as across the shoulder and wrist joints during the downswing. Temporal manipulations were then made to these torques with their simulated effect on the kinematics of the club-head assessed. The authors reported that the kinetics were similar to those described in previous empirical simulation research involving two segments. A series of further discrete observations were also made, most of which supported the findings of previous literature. For example, they reported that a simulated later release of ‘wrist-cock’ resulted in an increased club-head velocity as had been reported by Jorgensen (1970). Novel to this study though, was the conclusion that the golfer can avoid unnecessary effort by keeping the arm as close as possible to the trunk until late into the downswing.

Kaneko and Sato (2000) used a similar approach to Jorgensen (1970) to further investigate the optimal control used by players during the golf swing. These authors reported that the use of a minimum power criterion provided the most accurate
reflection of real torques used through the swing. Further simulations were also carried out from the same study in order to better understand the influence of length and inertial properties of the club on swing performance. These revealed that when the club was longer, less work was required for the swing to achieve the same club-head velocity.

Sprigings and Neal (2000) further used a three segment model to expand upon the existing literature with respect to the importance of the wrist kinetics in swing performance. Similar to previous models, the segments included in the model were rigid in nature and assumed to rotate primarily in a single plane. However, in contrast to previous research the torque generators applied to the proximal end of each segment were constrained to the force-velocity properties of human muscle. Also, body segment lengths and parameters were based on data for a representative golfer with a standing height of 1.83m and mass of 80kg (De Leva 1996), using a standard driver (43.5 in). As with previous models the effect of gravity was included through its influence on the moment of inertia for both the club and arm segments in the model. However, the plane of rotation for this study was offset at 60° to horizontal, therefore changing the gravitational effects of these segments.

The subsequent simulations of Sprigings and Neal (2000) assessed temporal influences of wrist un-cocking, as well as the effect of active versus passive activation of torque across the wrist joint late in downswing. It was shown that an active application of force to the wrist joint late in the downswing increased the club-head velocity by 9% compared with a ‘natural release’ where gravity was the primary factor allowing the club segment to rotate forward relative to the arm. Analogous to previous research, optimal club-head velocity was seen to be produced when torques generators were commenced in a sequential order.

Sprigings and McKenzie (2002) further developed the model of Sprigings and Neal (2000) to analyse the nature of the torques applied to the torso, shoulder and wrist throughout the entire downswing. From a validation standpoint the results suggested that the three segment model produced more accurate torques at the shoulder than that of previously used two segment models. From a performance perspective, the application of an active torque at the wrist, late in the downswing, was again reported as being advantageous. However, the authors reported less of an increase in club-head velocity as a result of this torque application than previous research (Jorgensen, 1970;
Pickering & Vickers, 1999). The reason for this was suggested to be because the onset of muscle torques during their model was more gradual, to reflect the properties of muscles, and not instantaneous as employed in previous models.

Another important finding of Sprigings and McKenzie (2002) was that approximately 24% of the kinetic energy that is supplied to the club comes directly from the torque generated at the wrist. This was contrary to previous suggestions that the main source of power in the swing could be attributed to the large muscles of the leg and torso (Cochran & Stobbs, 1968).

Aicardi (2007) explored a new method to optimizing the club-head velocity at impact using a three segment model. To avoid some of the complications of previous optimisation techniques, a simplified approach was used restricting the number of inputs per joint to three. To ascertain optimal joint trajectories, a number of assumptions were made about the kinematics, kinetics and temporal nature of the downswing. These included, a monotonic change in joint angles throughout the downswing, zero active torque at both the top of backswing and impact, total time of downswing being constant irrespective of the manipulations and impact occurring at a predefined position in the global coordinate system. The authors concluded that a change in any joint trajectory or initial position of segments was able to cause a marked change in optimal club-head velocity.

While the technique introduced by Aicardi (2007) may possess some advantageous over those used by other researchers, some of the aforementioned assumptions could bring into question the immediate conclusions of the study. In particular empirical research has indicated that downswing is seldom initiated by any two segments together (Burden et al., 1998; Okuda et al., 2002; Nozawa & Kaneko, 2003; Cole & Grimshaw, 2009) and therefore it seems unlikely that there would be any point that could be defined as the start of the ‘downswing’ where there is zero torque being applied across any joint of the upper body. Additionally, if the club-head velocity were to be optimised through the downswing it would seem logical that the total time of the downswing would be reduced and therefore not be constant.

Despite the addition of another degree of freedom, the above simulations of the golf swing have mostly acted to highlight the importance of kinetics and kinematics across
the wrist over those across the shoulder or rotation of the torso. Specifically, the timing and magnitude of torque applied across the wrist has consistently been reported to be important in planar simulations irrespective of whether two or three segments are represented. Also an analogue between the two and three segment approaches is that a sequential order of energy being flowed from the torso, down the upper limbs seems crucial in allowing optimal wrist torque to be achieved.

2.4.1.3 Four Segment Planar Models

A hallmark of the two and three segment planar models used to simulate the golf swing is the assumption that a single theoretical ‘upper arm’ segment remains completely rigid throughout the swing. Whilst this is anecdotally supported by coaches, recent empirical research has indicated that this may not be the case (Teu et al., 2006). By introducing two arm segments a four segment model has the ability to account for the kinetics and kinematics produced at the elbows.

Iwatsubo, Kawamura, Furuichi and Yamaguchi (2002) used an inverse dynamics approach to compare the joint histories and torques of a two models of different complexities, both driven by empirical data. The first was a two segment model similar to that of previous studies (Cochran & Stobbs, 1968; Budney & Below, 1979), while the second was a four segment model that was similar to that of Tsujiiuchi et al. (2002) where the single ‘arm’ segment was divided into an ‘upper arm’ and ‘forearm’. The paper reported little differences between the models with respect to kinetics at the wrist joint. However, when comparing shoulder kinetics between varying level participants, differences were no longer evident using the two segment model. This led to the authors concluding that the four segment model was more accurate in representing the swings of golfers with different skill levels.

A further study Tang and Abraham (2003) compared the outputs achieved between a three and four segment model. Unlike Iwatsubo et al. (2002) the models were driven by a forward dynamics approach, which was carried out in specialised software package (Autolev). Validation of both models was performed via correlating the resulting kinetics and kinematics with data measured empirically from elite collegiate and professional golfers. It was deemed that the kinematics of both the three and four segment model correlated highly with empirical data, with the latter considered more
accurate, as it allowed for a representation of the elbow joint degree of freedom. This was important as the golfers measured underwent an elbow range of motion of 11.5° - 28.6° throughout the downswing.

Important to note with respect to the assessment of validity in the Tang and Abraham, (2003) study, is the strength of the correlations, which were reported to be ‘strong’ between modelled and empirical data. Although some discrete correlations coefficients were as high as 0.99, others were as low as 0.44 between empirical kinematics and the three segment model. However, the kinetics of both models had weak to no correlation with empirical data. In response to this the authors pointed out that each joint torque was a good fit prior to its peak, with correlations in this phase being between 0.814 and 0.917. However, the peak joint torques occurred well before impact, indicating inaccuracies at the most critical phase for the club-head during the swing.

Although the findings of Tang & Abraham (2003) may be considered cautiously, when paired with that of Iwatsubo et al. (2002), it seems likely that a four segment model of the swing has more validity in representing the kinetics and kinematics of the swing than a model only consisting of two or three segment. However, to date there has been no four segment simulation study into the swing that has gone further than validation and investigated the potential influences on performance.

2.4.1.4 Simplified Three Dimensional Models

In recognition of the limitations and assumptions that are inherent in the planar approach which will be discussed later in this review, some researchers have used a three dimensional approach to analyse the mechanics of the golf swing.

Vaughan (1981) used a three dimensional approach to investigate the forces and torques imposed on the golfer from the club. Empirical data was collected from two professional golfers using two orthogonally positioned cameras. Kinematics calculated from this collection along with the inertial parameters of the club allowed the use of inverse dynamics to calculate kinetics at a proposed single point where the hands contact the club. By using a simplified single point that acted as the connection between club and golfer, the author acknowledged that information about wrist cocking/uncocking was not able to be extrapolated. Despite the simplifications, a number of discrete conclusions were drawn from the investigation. One was that the
downswing was initiated by the pulling on the club along the line of the shaft. Secondly, torques throughout the downswing acted to both change the plane which the club moved, as well as rotating the club-head to achieve a ‘square’ alignment at impact. Finally a net negative torque was observed to be applied by the golfer to the club late in the downswing, which acts to decrease hand speed whilst simultaneously increasing club-head speed.

A few years later Neal & Wilson (1985) used a similar method to analyse the kinetics applied to the golfer during the swing. In addition to the single club segment modelled in Vaughan (1981), kinetics was also flowed up a single theoretical arm segment in accordance to the ‘double pendulum’ model of Cochran and Stobbs (1968). Despite the extra segment, the conclusions drawn were similar to those of Vaughan (1981). Specifically that the club did not operate in a single plane for any significant period of time and that a large negative torque late in the downswing appeared to slow down the hands whilst increasing the speed of the club-head.

In 2004, Tsunoda and colleagues published a study centred on validating a more complex model which employed a rigid representation of the upper arm and forearm segments whilst modelling the club as a flexible segment. Similar to previous three dimensional models, the authors used an inverse dynamics approach with inputs based on empirical data collected previously. Specifically, the empirical data was captured using a ten camera motion capture system operating at 250Hz, with 19 markers placed over the golfer and club. Whilst the outputs from the model based on the upper arm segments correlated well with the empirical data, the shaft strain measured did not. Specifically the model was shown to over-predict shaft strain in the phase just prior to impact. Consequently, the model presented by Tsunoda et al. (2004) will require more development prior to its acceptance as a research tool.

While the three dimensional investigations discussed so far used an inverse dynamics approach, a handful of simplified three dimensional studies have used a forward dynamic approach to assess the influence of different swing parameters. The first of these was Jones et al. (2002) who used a typical two segment model. The wrist joint was modelled as a spherical connection with movement possible in all three degrees of freedom. The shoulder joint was fixed in space with movement possible around two axes. Manipulations performed centred on the orientation of the club at the top of
backswing as well as the inertial properties of the club itself. The simulated effect of these manipulations highlighted how sensitive both club-head accuracy and velocity are to small changes in the club properties. However, little was reported with respect to the influence of technique on performance or the possible interaction with club properties.

This interaction between technique and golf club design was a major focus of a more recent investigation into the swing (Suzuki, Haake & Heller, 2005). This study utilised a simplified double pendulum model of the swing with the allowance for arm rotation. While this allowed the model to be defined as ‘three dimensional’, it should be kept in mind that this was only the case for one degree of freedom. Subsequent forward dynamical simulations revealed that the optimal timing of ‘wrist uncocking’ during the downswing can be influenced by the oscillating characteristics of the club shaft. The modelling of the club as a flexible element though, introduced similar errors to that of Tsunoda et al. (2004).

McKenzie (2005) performed a more thorough investigation of the effect of shaft stiffness through the use of a three dimensional model of the club (itself broken into three segments) and the arms. The three segments of the club were joined by flexible links that were designed to replicate the bending and dampening properties of the shaft. He reported that for the same torque across the wrist, there was no particular level of shaft stiffness that would be optimal for generation of club-head velocity. This conflicts to some degree with some of the recent empirical research with respect to shaft stiffness (Worobets & Stefanyszyn, 2007; Osis & Stefanyszyn, 2010).

Similar to the planar simulation investigations to date, the three dimensional approaches discussed so far still suffer from the simplifications of focusing on a limited number of segments. However, they have served to highlight both the complexity of the swing, as well as the potential influence of club properties on swing mechanics.

**2.4.1.5 Full Body Three Dimensional Models**

Whilst previously not practically possible, there has recently been a focus on modelling the full body during the golf swing in the empirical research (Zheng et al., 2008; Chu et al., 2010). This has also been reflected in the simulation research with the ultimate goal to create a model that represents all the degrees of freedom that are in motion during the swing.
Nesbit, Cole, Hartzell, Oglesby and Radich (1994) presented a three dimensional simulation model of the swing that included 15 body segments. In this investigation the motion of only five of the 15 segments were validated against data collected empirically. Additionally, methods of this validation were poorly outlined. Later Nesbit published a further two papers (Nesbit 2005; Nesbit & Serrano 2005) that used a full body model of the swing incorporating a forward simulation approach. Empirical data from 85 golfers was collected and incorporated into a limited analysis (Nesbit, 2005), with data from four of these participants used for a more detailed investigation of the mechanics involved with alteration of club properties (Nesbit, 2005; Nesbit & Serrano 2005).

This empirical data supplied the original joint coordinate data, which together with the ground reaction forces were used to drive the model. The full investigation consisted of four sub models; the android (golfer) model, flexible club model, impact model and ground surface model. All 15 segments of the android were modelled as rigid components with inertial properties being based on those that of a humanoid database available as part of the ADAMS software package. The club was modelled as a flexible component with its deformation properties being ascertained by the analytical methods outlined in Friswell and Mottershead (1998). All joints were either modelled as perfect ball and socket or hinge joints and the loading between the two hands adjoined to the club were assumed to be equal. The modelled joints were not constrained to the properties of muscles or tendons with no strain energy able to be stored.

The subsequent modelling solutions were performed using ADAMS software with the kinetics driven by torque and ground reaction force data from previous studies. With respect to validation, the inverse dynamics solution was compared with manually-calculated joint torques, results from other studies, and ground reaction force data. These all showed reasonable agreement. Subsequent forward simulations were performed to verify the derived joint torques. These appeared to be successful when only one degree of freedom was driven by derived torques and the remainder were driven by empirical kinematics. However, where all the degrees of freedom were driven by the derived toques the forward simulation failed, leading to unpredictable results. Consequently, the effects of manipulations were not able to be assessed from a kinematic perspective.
An important finding from the inverse dynamics component of the Nesbit investigations was that players appeared to employ a coordinated timing pattern to allow for a late release of the wrist without the use of negative torques in the upper limb. While this is in some agreement with previous research, where the importance of sequential timing is emphasised, it is in contrast to data showing negative torques are common in the downswing to allow an efficient transfer of momentum across segments (Vaughan 1981; Neal & Wilson, 1985).

Kenny, McCloy, Wallace, and Otto (2008b) presented a full body model of the swing with the potential of forward dynamic solutions. The aim of their investigation was to validate a forward dynamic model simulating the swing of a single golfer using three different club lengths (46, 48 & 50 inches). One participant was asked to hit eight drives using each club length, the subsequent kinematics being captured by a five camera motion analysis system. The model created was further scaled from 54 anthropometric measurements taken from the participant and in total consisted of 19 segments and 42 degrees of freedom.

To achieve study’s goal of model validation, kinematic outputs predicted using the model were correlated against those collected empirically. To ensure the validation process was not compromised the empirical markers included in these correlations were supplementary to those used to generate the model. A validation of the kinetics of the model was carried out via comparison to grip force measurements reported in previous investigations. The subsequent agreement was high and the validation of the model was deemed successful. Whilst the model had the potential for forward kinetic solutions only findings with respect to validation and inverse dynamic solutions were presented. Using this inverse dynamics approach, it was revealed that certain muscles would be required to produce a significantly greater force if swinging with longer driver lengths to maintain the same club-head velocity.

To date there remains a paucity of full body, three dimensional, forward simulation investigations into the golf swing. Some researchers have advanced this methodology and Kenny et al. (2008b) specifically revealed some important information with respect to the influence of driver length. However, so far this has not translated into applied information for coaches and players with respect to mechanical influences on performance and injury. Betzler, Monk, Wallace, Otto and Shan (2008) wrote about the
great potential of this approach as a tool in the future to investigate the effects of equipment on the swing. Further than this though, the development of an accurate and valid method to investigate the influence of each degree of freedom involved in the swing has perhaps the greatest potential to provide meaningful knowledge on the mechanics of the swing.

2.4.1.6 Limitations of Previous Simulation Models

Of the simulation models used to date there are a number of limitations that exist which are likely to influence both their internal and external validity. Some of these which have the greatest ability to effect conclusions with respect to performance will be discussed.

As is clear from the previous sections of this review that the vast majority of the simulation modelling of the golf swing has been carried out using a planar approach. This approach assumes that for the most part the swing operates in a single, two dimensional plane. While these planar models of the golf swing have provided some important insight into the mechanics of the golf swing there are clear limitations to this approach. Perhaps most importantly, it has been demonstrated repeatedly that the swing does not operate in a single plane (Neal & Wilson, 1985; Vaughan, 1981; Koenig et al., 1993; Coleman & Anderson, 2007). While one recent study reported that some golfers maintain a steady club-head plane from mid-downswing to mid-follow through (Shin, Casebolt, Lambert, Kim & Kwon, 2008) this was not case for the entire downswing. Further, no other segments of the golfer have been found to operate in any steady plane for any period of the swing (Neal & Wilson, 1985; Vaughan, 1981) nor do they appear to operate at a steady offset from each other (Coleman & Rankin, 2005).

An additional limitation of many planar investigations is the assumption that the swing has a fixed pivot point or ‘hub’ about which the segments of the upper limb rotate to create an efficient swing. This assumption can be traced back to the original work of Cochran & Stobbs (1968) where this ‘steady hub’ concept was important in their assertion that a successful swing was designed to be as simple as possible. Recently though, three dimensional evidence has revealed that the swing does not, in fact, operate around a single fixed hub. In particular, empirical evidence has indicated that irrespective of how this hub of rotation is defined, it does not remain stable for any
period during the swing (Sanders & Owens, 1992; Nesbit & McGinnis, 2009). The investigation of McTiegue et al. (1994) also demonstrated that the spine angle, which would be critical to a stable hub, also undergoes constant change throughout the different stages of the swing. However, of more importance than just an incorrect assumption, some simulation investigations have indicated that the movement of a theoretical ‘pivot point’ during the downswing would have a significant influence on performance. Specifically, in a revised model from his previous research Jorgensen & Adair (1994) showed that a model incorporating a moving pivot point was not only more realistic to empirical data but club-head velocities were increased by about 17%. Additionally, Jorgensen and Adair speculated that skilled golfers lifted their central axis of rotation shortly prior to impact to allow for an increase in club-head velocity impact. This was subsequently observed by Tsunoda et al. (2004) and shown to be an advantage in the generation of club-head velocity (Miura, 2002). The evidence against this fixed hub of rotation therefore is substantial and should be considered when reviewing investigations that are based on this assumption.

The final limitation of note with respect to the planar approach to modelling the swing is the inability of the simulations to assess accuracy. Due to the very two dimensional nature of the modelling the endpoint lacks a three dimensional path or orientation, which are the likely kinematics to dictate the subsequent path of the ball. This has meant that despite the relatively large number of simulation studies of the golf swing none to date have added any considerable knowledge, either basic or applied, with respect to the mechanical influences on accuracy in the swing.

Aside from the planar simplifications discussed, almost all simulations to date have only represented a very limited number of segments. Specifically, the majority of simulation models have been limited to two or three segments. These have typically corresponded to the movement of a trunk, left upper limb (or a ‘single’ upper limb) and club segment. While the movement of these segments are undoubtedly important, empirical studies have indicated that the other degrees of freedom involved in the swing are also influential to performance (Mitchell et al., 2003; Zheng et al., 2008; Okuda et al., 2010). Further supporting the evidence that limited segments may not reveal the entire picture is the common finding across simulation studies that models representing a greater
number of segments better represent the kinematics measured from real swings (Iwatsubo et al., 2002; Sprigings & McKenzie (2002; Tang & Abraham, 2003).

It is of particular concern that the right upper limb has not been represented thus far in the simulation research. Anecdotally the right arm is suggested to supply the power, whereas the left arm is commonly seen as the one that ‘guides’ the swing (Hume et al., 2005). Empirical research has also highlighted the importance of the right side with Jobe et al. (1989) reporting skilled players had high muscle activations of the internal rotators of the right humerus during the downswing. Additionally, Morgan et al. (1999) revealed that younger and more skilled players tend to achieve a significantly greater internal/external rotation range of motion for the right upper arm. With this in mind it would seem prudent that future simulation modelling of the golf swing take into account the right upper limb.

Another notable limitation of the previous simulation research is concerned with the use of kinetics to drive the models. The major difficulty associated with this approach is that current analysis techniques render direct measurement of kinetics at human joints impossible. Some investigators have therefore based the kinetics used to drive the model on those inferred through inverse dynamic calculations performed on empirical data (Budney & Bellow 1979; Kaneko & Sato 2000; Tang & Abraham, 2003; Kenny et al., 2008b). Unfortunately as this is an indirect measure the accuracy of the model diminishes as the degrees of freedoms increase. Adding to this inaccuracy is that the original coordinate data must be twice differentiated, as a part of the inverse dynamic calculations needed to infer kinetics. Consequently, kinetically driven, multi-dimensional models of the golf swing based on inverse dynamic calculations are sensitive to small errors in empirical data collection.

Investigators that have not used indirectly measured kinetics to drive their simulation models instead have used kinetics that make assumptions with respect to the shape and nature of torque patterns during the swing (Turner & Hills, 1998; Pickering & Vickers, 1999; White, 2006; Chen et al., 2007). Two common assumptions from this research are that the shoulder torque remains constant throughout the downswing and that wrist torque is simply activated or deactivated at specific points. Betzler et al. (2008) recently suggested that both of these assumptions do not reflect the true nature of the torques able to be produced by a golfer during the swing. Some investigators have attempted to
take into account the parameters at which muscles operate (Sprigings & Neal 2000; Sprigings & McKenzie 2002) but this sort of approach has yet to be validated against the torques of real golfers of differing standards.

2.4.2 Forward Kinematic Modelling

Forward simulation modelling of the golf swing to date has exclusively used kinetics to drive the kinematic motion of all degrees of freedom contained in the model. However, a technique used recently to better understand the compensatory coordination of specific tasks (Kudo et al., 2000; Mills et al., 2003; Muller & Sternad, 2003; Muller & Sternad, 2004; Mills, 2007) has raised the potential of another approach to modelling of the golf swing. This technique is known as a randomised sensitivity analysis (RSA). It involves the creation of a forward kinematic model which ultimately predicts a variable of interest based on a set of individual degrees of freedom. The time history of each degree of freedom is normalised and subjected to an intra-degree of freedom, intra-trial permutation to generate a surrogate data set. This process simulates the removal of any compensatory relationships between degrees of freedom. Therefore if compensatory synergies exist a significantly higher variability in the variable of interest would be expected in the surrogate data set when compared to the empirical data set. Alternatively, a lack of difference in the variable of interest variance between the empirical and surrogate data sets would suggest the movement variability across individual kinematics can be attributed to random sensory noise.

This approach has been used in to investigate compensatory synergies between ball release variables in throwing (Kudo et al., 2000), a virtual skittles task (Muller & Sternad, 2004) and for a reaching task (Muller & Sternad, 2003). Of most interest for this review though is the research into the compensatory synergies involved in minimum toe clearance during the gait of young and elderly men (Mills et al., 2003; Mills, 2007). Further than just identifying if general compensatory synergies exist, these investigations highlighted that the RSA approach can be used to assess the influence of individual degrees of freedom on outcome variance. The forward kinematic model of Mills (2007) was based on the concept that at any point in time, the position and orientation of a system’s endpoint is a product of the orientation and dimensions of all the previous segments in the kinematic chain. With this in mind the position and orientation of the system endpoint can be predicted, at any time point,
based on kinematic information with respect to each of the preceding segments. Subsequent differentiation would also allow for the prediction velocity and path of the system endpoint. Specifically in the model created by Mills (2007), the system endpoint was the toe of the swing foot and the variable of interest was the minimum vertical distance between this point and the ground. This endpoint was dictated by a chain of segments that started at the stance foot, with forward kinematics being flowed up the stance leg, across the pelvis and down the swing leg.

Using this approach Mills (2007) was not only able to identify that compensatory synergies exist in the coordination of minimum toe clearance the gait of both young and elderly men but was able to provide insight into the relative contributions of specific degrees of freedom. Interestingly the degrees of freedom which minimum toe clearance would be thought to be the most sensitive were not necessarily the ones which were identified in the analysis as contributing most to the movement synergies through the movement. For instance it would be expected that stance hip abduction/adduction would have a large influence on the variation in minimum toe clearance. However, this was shown to have minimal influence, while other degrees of freedom such as stance knee flexion/extension, stance ankle plantar/dorsi-flexion and inversion/eversion all provided substantial contribution to minimum toe clearance.

This novel modelling approach certainly has potential as a research tool for assessing the contributions of individual segment motions during the golf swing. In particular, this approach could quantify the influence individual joint kinematics have on both distance and accuracy in the golf drive. Whilst this approach does not immediately bring an understanding of the forces and torques behind the swing motion it has some important advantages over previous kinetic modelling used in the golf.

One advantage of the purely kinematic approach to forward modelling of the swing is the lack of assumptions that are involved in the calculation of the each segments movement through the swing. The other major advantage of kinematic approach is its applied relevance compared with that of a kinetically driven modelling approach. While understanding the kinetics that cause the desired motions in the swing would be of some applied relevance, coaches and players more often deal with kinematics when improving or modifying technique.
2.5 SUMMARY

From a methodological view point, it is clear from reviewing the literature that a paucity exists in the validating a gold standard for calculating club-head kinematics at impact. Additionally whilst there is a great deal of anecdotal evidence on the influences of ball flight, the relationship between club-head kinematics and the subsequent launch characteristics of the ball are yet to be assessed quantitatively. Addressing both of these issues is in the future is important to ensure researchers are able to reduce the likelihood of both type I and II errors and therefore confidently provide meaningful applied information to the golfing community.

With respect to performance, both the empirical and simulation literature have identified some specific joint motions that appear to play a major role in the development of club-head velocity. For example common to many empirical and simulation research is the identification of motion at the wrist in creating greater club-head velocity during the swing. Despite this identification of a few typical kinematics common to skilled golfers, it largely remains unclear what specific recommendations a coach might suggest to increase distance and/or accuracy in the swing. It seems clear that for future research to bring us closer to a complete understanding of skilled performance is achieved in the golf swing that a greater focus should centre on the potentially functional role of movement variability in the swing.

In reviewing the simulation modelling approaches employed by previous researchers it seems that one method of addressing the current paucity of understanding with respect to movement variability can be found in a recently developed forward kinematic modelling approach (Kudo et al., 2000; Mills et al., 2003; Muller & Sternad, 2003; Muller & Sternad, 2004; Mills, 2007). This approach is free from many of the assumptions of the current kinetically driven models. Additionally, when combined with a RSA approach is capable of identifying the presence of compensatory synergies in the golf swing as well as the potential role of individual joint motions within these synergies. This insight is likely to significantly contribute to our understanding of variability in the swing as well as drive future research in identifying the specific mechanical alterations which are likely to lead increased distance and accuracy in the swing.
Chapter 3

Treatment of kinematic data at impact in the golf drive


3.1 ABSTRACT

Kinematics of the club-head and golfer at impact are popular performance indicators in the scientific literature. However, it is generally difficult to capture data at the precise point of impact and due to this dilemma there is currently a lack of validation of the methods used to estimate kinematics during this discrete phase. A 12 camera opto-reflective system operating at 400Hz was used to capture the impact kinematics of nine male golfers performing drives in two conditions; 1) at a golf ball, and 2) a target of negligible mass (paper target). No differences in pre impact kinematics of the golfer and the club-head were observed between the ball and the paper target conditions. A significant difference in post impact club-head kinematics highlights the potential errors associated with the post impact data treatment approaches of previously published research. Using data from the paper target condition to validate data treatment methods it was found that an approach involving extrapolating pre impact data through impact to a virtual first point of contact was the most appropriate for estimating impact club-head kinematics.

3.2 INTRODUCTION

During a golf swing, the clubs physical characteristics, in conjunction with the club-head kinematics at ball contact, will have the ultimate influence on the initial ball flight characteristics and the resulting shot distance and accuracy. Due to the importance of kinematics at this stage of the swing, many researchers have attempted to report the kinematics of the club and the golfer at this critical time. Unfortunately, with the ball-club contact lasting around 0.5 milliseconds (Hocknell, Jones & Rothberg, 1996;
Roberts, Jones & Rothberg, 2001), and typical frame rates of motion capture systems ranging between 50Hz and 400Hz (Coleman & Rankin, 2005; Sweeney, Mills, Alderson & Elliott, 2011), the entire phase of impact regularly occurs between two captured fields. A variety of filtering and interpolation methods have been employed to calculate data which is reported as occurring “at impact”, yet there is a paucity of quantitative research comparing the merits of each particular technique.

In the process of estimating kinematics occurring “at impact” several researchers have filtered and/or interpolated empirical data collected through the time of impact, using both pre and post impact data (Neal & Wilson, 1985; McLaughlin & Best, 1994; Mason et al., 1995; Fradkin et al., 2004; Coleman & Rankin, 2005; Worobets & Stefanishyn, 2007; Zheng et al., 2008). One concern with the filtering and/or interpolation techniques used to date is the lack of detail researchers have provided regarding the approaches employed. Another concern with filtering or interpolating across impact is the use of data post impact. Research in other sports has suggested that when kinematic data undergoes a significant change as a result of the collision between ball and an implement, the inclusion of post impact data in some filtering and/or interpolation procedure likely leads to erroneous results (Knudson & Bahamonde, 2001; Nunome et al., 2006; Tabuchi et al., 2007). With a sudden and considerable change in club-head kinematics post impact previously established for the golf swing (Williams & Sih, 2002; Ellis et al., 2010), it is reasonable to assume that previous attempts to filter and/or interpolate club-head kinematics through the time of impact may have been inappropriate. In addition to its effect on the club-head kinematics, the ball-club collision could plausibly result in a significant change in the segment and joint kinematics of the golfer. This influence on the golfer’s biomechanics has yet to be explored, warranting further investigation examining the influence of the ball-club collision on post impact data in the swing.

Another method of reporting data “at impact” has been to simply report kinematics calculated from the last frame prior to impact occurring (Myers et al., 2008; Egret et al., 2006). The advantage of this approach is that it removes the influence of the impact on the resulting kinematic data. However, as the entire impact phase consistently falls in between frames at typical motion capture system frame rates, some time offset logically exists between the last frame captured prior to impact and the precise point of first
contact. This gap in time that potentially includes some portion of impact, will be dictated largely by the capture sampling rate and whilst this may be only a few milliseconds (at the highest capture frequencies used to date) there is currently little understanding of how much kinematics change over this period. Quantifying the change in kinematics over the last few milliseconds of the downswing is important in revealing the validity of reporting kinematics from the last frame prior to impact, as a representation of kinematics occurring “at impact”.

One further method of estimating swing kinematics “at impact” has been to extrapolate club-head kinematics to an estimated time of impact based on pre impact data (Williams & Sih, 2002; Betzler et al., 2012; Worobets & Stefanyszyn, 2012). This method offers the promise of more accurately representing “at impact” kinematics as it avoids the limitations of incorporating post impact data, as well as taking into consideration the changes that might occur in the last few milliseconds of the downswing. However, none of the studies employing an extrapolation approach have validated their methodology against ‘ground truth’ impact data. A thorough validation against ‘ground truth impact data’ is important for any approach to be adopted by future researchers as the most appropriate for estimating “at impact” kinematics. Any validation of an extrapolation method should include such factors that are likely to influence the accuracy of this method. One such factor is the quantity of pre impact data upon which the extrapolation equation is based.

One method of validating techniques that estimate impact kinematics is to collect data at a high enough frequency to capture the club-head kinematics occurring immediately before impact. Unfortunately for this is not possible using the motion analysis systems available. Another method of validating techniques which estimate impact kinematics lies in the novel approach employed in a recent investigation focussed on bat speed, trajectory and timing for baseball batters striking a stationary target (Tabuchi et al., 2007). To assess bat kinematics without impact artefact, Tabuchi et al. (2007) asked a sample of baseball players to hit polystyrene balls in lieu of a regulation baseball. The results indicated skilled baseball players showed no difference in pre impact kinematics whether swinging at a regular baseball or polystyrene ball. However, the significant decrease in bat velocity caused by impact when hitting a regular baseball did not occur when hitting a polystyrene ball. The use of a similar surrogate ball approach in the golf
drive may allow the replication of normal pre impact kinematics, whilst avoiding the artefact of the ball-club collision on post impact data, allowing a subsequent accurate interpolation to the precise point of initial contact. This establishment of ‘ground truth impact data’ would enable validation of different techniques for estimating impact phase kinematics and potentially provide a valuable resource in resolving the methodological uncertainty concerning the most appropriate manner in which to treat and analyse impact data during the golf swing.

The primary aim of the study was to ascertain the most accurate method for estimating the kinematics of the golfer and club at impact. This involves the validation of two methods previously employed in research; i) reporting the kinematics which occur at the last frame pre impact and ii) extrapolating pre impact data to the first point of impact. Important to pursuing the primary aim of the study is to explore factors that likely influence the accuracy of each method, such as the capture frequency used when reporting data from the last frame pre impact, and the quantity of pre impact data entered into the equation when extrapolating data to the first point of impact. Before an accurate evaluation of methods to report “at impact” data can be carried out, it is necessary to create a condition which allowed golfers to mimic the pre impact kinematics of hitting a golf ball, whilst avoiding the influence of the ball-club collision on the post impact kinematics of the golfer and club. The secondary aim of this study therefore was to assess whether a group of skilled golfers swinging at a target with negligible mass would achieve the same pre impact kinematics, but different post impact kinematics when compared with swinging at a regulation golf ball.

3.3 METHODS

3.3.1 Participants

Nine male golfers with a mean (±SD) handicap of 4 (±2.7) participated in the study. Mean (±SD) participant age, height and mass were 24 years (±6), 178.7 cm (±9.3) and 78 kg (±9.2), respectively. Ethical approval was granted from the relevant Human Research Ethics Committee, prior to participant recruitment and data collection. Written consent was provided by all participants and they were free to withdraw from the study at any time.
3.3.2 Data Acquisition - the model

Three dimensional (3D) kinematic data was recorded using a 12 camera Vicon MX system (ViconPeak, Oxford Metrics, Oxford, UK), operating at 400 Hz. Vicon’s generic procedures were used to calibrate the volume and to linearise all 12 cameras. A total of fifty one retro-reflective markers, all 16 mm in diameter, were affixed to the golf club and the golfer for subject specific static calibration trials.

Figure 3.1 Golf swing marker set for golf swing trials: A) Anterior view B) Posterior view C) Club-head markers.

Of these, forty three markers, inclusive of the eight ‘T-bar’ 3-marker clusters, remained affixed to each subject and club during each dynamic swing trial (Figure 3.1). The markers affixed for static subject calibration trials identified the position of key anatomical landmarks required for the definition of segment anatomical coordinate systems (ACSs) in accordance with the methods previously described by Besier, Surnieks, Alderson and Lloyd (2003) as well as Campbell, Lloyd, Alderson & Elliott (2009). These markers were located bilaterally on the ulnar and radial styloid processes, as well as anterior and posterior to the glenohumeral joint centre. A Calibrated Anatomical Systems Technique (CAST) was used to identify the bilateral 3D locations of the lateral and medial elbow epicondyles, outputting two virtual markers, which were referenced to an upper arm technical coordinate systems (TCSs) (Cappozzo et al., 1995; Campbell et al., 2009). This technique was adopted to minimise marker
shift related to the excessive skin movement associated with the placement of markers around joint centres (Cappozzo et al., 1995).

Due to the limitation of placing markers on the club-face, a method similar to the CAST was used to identify four key points on the club-face. These points were referenced in a TCS defined by markers affixed atop the club-head, which allowed for club-face markers and a subsequent coordinate system to be created without affixing markers directly to the club-face itself. The four key points on the face were: the bottom most point of the club-face, the centre of the middle groove on the club-face, and two points 40 mm on either side of the centre, also along the middle groove (figure 3.2).

![Figure 3.2](image)

A) Reflective markers on club-head
B) Four key points on club-face identified in the calibration procedure to identify club-head coordinate system.

3.3.3 Data Acquisition - procedures

After a standard five minute self-directed warm up, each participant was asked to perform, in a random order, two trials for both the ‘standard ball condition’ (Figure 3.3A) and the ‘paper ball condition’ using their natural technique. In the standard ball condition, participants were requested to hit a regulation golf ball (Titleist NXT Tour) off a rubber tee for maximum distance into a net approximately three metres away. In the paper ball condition, participants were asked to strike with maximum velocity, a paper target that served as a replacement for both the golf ball and the tee (Figure 3.3B). The paper target was created to act as a visual aid to create a situation where the golfers could perform their swing, without the possible change in club-head and golfer kinematics caused by the mass of the golf ball. The position of the golf ball and paper
target was defined in the laboratory coordinate system in a previous calibration trial and will be referred to as the ‘virtual ball’.

![Image of a golf ball and a paper target with a red line]

**Figure 3.3**  *Driver at address, preparing to swing at a regulation golf ball (A), and paper target (B). The red line in B) is for clarity in the diagram only.*

### 3.3.4 Data Processing

All marker trajectory data were labelled and any broken trajectories were interpolated using a cubic spline. No trials comprised broken trajectories of greater than 10 ms, nor were there any broken trajectories in the 25 ms leading to impact.

Whilst data from both golf ball and paper ball conditions were used in the comparison of pre impact kinematics, only data collected during the paper ball condition was used for the further analysis validating methods of estimating impact kinematics. For every trial from the paper ball condition, calculations of club-head kinematics at impact were ascertained by performing a 101 point, 2\textsuperscript{nd} order polynomial interpolation on the 4 frames (10ms) surrounding impact (2 before and 2 after). ‘Virtual impact’ was defined when the distance between the centre of the club-face and the edge of the virtual ball was at its minimum value in the forward direction of the laboratory (toward the target). It is recognised that an off-centre impact combined with a non-square club face may
result in errors in using this method of defining impact. However, with all impacts being calculated as falling within 35mm of the centre of the club the likelihood of such errors compromising the results was deemed negligible.

In order to identify the influence of capture frequency on the validity of reporting data from the last frame pre impact, the data originally captured at 400 Hz was also resampled at 200 Hz and 100 Hz. For the experimental extrapolation trials, all raw marker time series were cropped at the frame prior to impact and customised MatLab software (The MathWorks, Inc., Natick, Massachusetts, United States) was used to performed a 2\textsuperscript{nd}-order polynomial extrapolation estimating an additional ten frames of data (i.e. through impact). The same interpolation method used above was then employed to calculate the kinematics of the club-head at ‘virtual impact’. To explore the influence of the quantity of pre impact data used in the polynomial equation, nine extrapolations were performed; each based on a different quantity of pre impact data. The time base of pre impact data chosen for these nine extrapolations were; 5 ms, 7.5 ms, 10 ms, 12.5 ms, 15 ms, 17.5 ms, 20 ms, 22.5 ms and 25 ms.

3.3.5 Data Analysis

Statistical analyses were performed using SPSS 15.0 (SPSS, Inc., Chicago, IL, USA). Tests for skewness and kurtosis confirmed the normality of all data analysed. A two-way repeated measure ANOVA was used to compare club-head velocity across the five discrete time points selected during the swing (Figure 3.4), as well as between the golf ball and paper target conditions. In order to assess the potential influence of the ball-club collision on the kinematics of the golfer’s body, the same statistical procedure was used to compare the resultant velocities of selected body segment trajectories across the golf ball and paper target conditions. Changes to anatomical landmark marker velocities have previously been established as an indicative measure of the potential artefact arising from the collision between a ball and implement (Knudson & Bahamonde, 2001; Nunome et al., 2006; Tabuchi et al., 2007). The specific trajectories selected included the bilateral wrist, elbow and shoulder joint centres, as well as the torso segment origin (which was defined at the midpoint between the markers placed over T10 and the inferior aspect of the sternum). These body segment trajectories were selected as they represent discrete points throughout the distal portion of the kinematic
chain, likely to clearly reflect any potential influence on the body resulting from the ball-club collision.

Figure 3.4 Five discrete time points during the swing that were used to statistically compare the two treatment conditions.

Subsequent methods for determining data “at impact” were performed on the paper target trials, where ‘virtual impact’ could be used as the criterion (used to calculate RMS error) free from the influence of the ball-club collision. This criterion was compared against club-head kinematics captured at the last frame pre impact, at the original capture frequency of 400 Hz as well as the resampled frequencies of 200 Hz and 100 Hz. The same procedure was used to calculate RMS errors for the extrapolation method, across each of the nine equations (based on different times of pre impact data) and across each of the selected club-head kinematics.

The particular extrapolation chosen to have the least RMS error across the selected club-head kinematics was compared with reporting the club-head kinematics at the last frame prior to impact at 400 Hz in the final analysis. This involved an independent T-test for each club-head kinematic variable (five in total). Using a Bonferroni correction the significance level for each of the T-tests was set at $\alpha < 0.01$. 

58
3.4 RESULTS

The repeated measure ANOVA revealed a significant event-ball interaction effect. A subsequent post hoc analysis revealed no difference (p > .05) between the two conditions at any of the three time points prior to impact (25 ms pre impact, 10 ms pre impact and 1 frame pre impact) (Figure 3.5). However, a significant difference was found (p < 0.001) between the standard and paper ball conditions at the two time points measured post impact (1 frame post impact and 10 ms post impact). In the frame immediately post impact, the golf ball condition produced a club-head average velocity of 3.8 (±1.8) m/s less than that produced in the paper target condition. This difference increased to an average of 13.1 (±0.8) m/s at 5 frames (≈10 ms) post impact.

![Figure 3.5](image)

**Figure 3.5** Representative resultant club-head velocity for the golf ball and paper target conditions, from one participant (Time = 0 corresponds to impact between club-face and ball/virtual ball). To provide a visual representation of the influence of post impact data, club-head velocity is also presented from the golf ball condition where the raw data was first treated with a 2nd order low pass Butterworth filter with a cut-off frequency of 25Hz.
Figure 3.6  Average resultant velocity of selected anatomical landmarks around impact, for both golf ball condition (solid line) and paper target condition (dotted line).
No main or interaction effect (p > .05) existed between the golf ball and paper target conditions with respect to upper limb and trunk kinematics shown in Figure 3.6. Mean resultant velocities for the trunk and at selected joint centres of the upper limbs can be seen in Figure 3.6.

The analysis of reporting club-head kinematics calculated at the frame immediately prior to impact (at 400 Hz, 200 Hz and 100 Hz) revealed consistently higher RMS errors when data were resampled at lower capture frequencies (Table 3.1).

*Table 3.1*  *RMS error of club-head kinematics calculated at the last frame pre impact, at three different frequencies (400 Hz, 200 Hz and 100 Hz), from swings at a paper target.*

<table>
<thead>
<tr>
<th></th>
<th>400Hz</th>
<th>200Hz</th>
<th>100Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centredness of Impact (mm)</td>
<td>27.8</td>
<td>46.7</td>
<td>138.2</td>
</tr>
<tr>
<td>Club-Head Position (mm)</td>
<td>81.4</td>
<td>107.3</td>
<td>286</td>
</tr>
<tr>
<td>Club-Head Resultant Velocity (m/s)</td>
<td>0.3</td>
<td>0.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Club-Head Loft Angle (°)</td>
<td>2.0</td>
<td>2.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Club-Head Rotation Angle (°)</td>
<td>4.9</td>
<td>5.4</td>
<td>15.1</td>
</tr>
</tbody>
</table>

The method of extrapolating data to impact indicated that the accuracy of doing so is influenced by the quantity of pre impact data used in the polynomial equation (Table 3.2). There was no single quantity of pre impact data which gave the most accurate estimation of impact data across each of the club-head kinematics analysed. However, due to the fact that the extrapolation method where the polynomial equation included 12.5 ms of pre impact data produced relatively small errors for each club-head kinematic variable, it was subsequently chosen as the last frame prior to impact for comparison with the highest capture rate (400 Hz).
Table 3.2  RMS error of impact kinematics using 2\textsuperscript{nd} order polynomial extrapolations, based on varying magnitudes of preceeding data.

<table>
<thead>
<tr>
<th>Time base of pre-impact data input into extrapolation</th>
<th>5 ms</th>
<th>7.5 ms</th>
<th>10 ms</th>
<th>12.5 ms</th>
<th>15 ms</th>
<th>17.5 ms</th>
<th>20 ms</th>
<th>22.5 ms</th>
<th>25 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centredness of Impact (mm)</td>
<td>4.7</td>
<td>3.0</td>
<td>2.1</td>
<td>1.9\textsuperscript{L}</td>
<td>2.0</td>
<td>2.1</td>
<td>2.4</td>
<td>2.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Club-Head Position (mm)</td>
<td>7.1</td>
<td>4.0</td>
<td>2.9</td>
<td>2.4\textsuperscript{L}</td>
<td>2.7</td>
<td>3.0</td>
<td>3.4</td>
<td>3.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Club-Head Resultant Velocity (m/s)</td>
<td>0.3\textsuperscript{L}</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Club-Head Loft Angle (°)</td>
<td>0.7</td>
<td>1.1</td>
<td>0.9</td>
<td>1.5</td>
<td>0.7\textsuperscript{L}</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Club-Head Rotation Angle (°)</td>
<td>0.7</td>
<td>1.3</td>
<td>0.6</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2\textsuperscript{L}</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{L} = lowest RMS for particular dependent variable

Table 3.3  RMS error of extrapolation method (2\textsuperscript{nd} order polynomial using 12.5 ms of preceding data) and club-head kinematics calculated at the last frame pre impact at 400Hz.

<table>
<thead>
<tr>
<th>Pre-impact frame at 400Hz</th>
<th>Extrapolation based on 12.5 ms of previous data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centredness of Impact (mm)</td>
<td>27.8</td>
</tr>
<tr>
<td>Club-head position (mm)</td>
<td>81.4</td>
</tr>
<tr>
<td>Club-head resultant velocity (m/s)</td>
<td>0.3</td>
</tr>
<tr>
<td>Club-head Loft Angle (°)</td>
<td>2.0</td>
</tr>
<tr>
<td>Club-head Rotation Angle (°)</td>
<td>4.9</td>
</tr>
</tbody>
</table>

\textsuperscript{*}Sig \textit{p} < .01

The final comparison of methods to represent club-head kinematics ‘at impact’ revealed that the extrapolation method (involving 12.5 ms of preceding data) had the least RMS error for four out of the five club-head kinematic variables (centredness of impact, club-head position, club-head loft angle, club-head rotation angle) (Table 3.3). Conversely, when representing club-head velocity at impact, no significant difference existed between the extrapolation method and reporting club-head kinematics at the frame prior to impact (at 400 Hz).
3.5 DISCUSSION

The primary aim of this study was to ascertain the most accurate method for estimating the kinematics of the golfer and club at impact. The results indicated that extrapolating pre impact data to the time of first contact between ball and club provides the best estimate of impact club-head position and orientation. However, when estimating impact club-head velocity there is no difference between the extrapolation techniques employed in this study and merely reporting the velocity calculated from the last frame pre impact. The secondary aim of this study was to create a condition which allowed participants to replicate pre impact kinematics of swinging at a normal golf ball with the impact artefact removed on post impact data. The lack of difference in pre impact kinematics between the paper target and regular ball conditions confirmed the replication of normal pre impact kinematics in the paper target trial. Additionally, the significant decrease in velocity occurring at the club-head post contact with a regular golf ball was not observed in the paper target condition. It could therefore be concluded that the paper target enabled golfers to achieve similar pre impact kinematics to that observed when swinging at a regular golf ball. Importantly though, swinging at the paper target did not appear to produce any of the ball-club collision artefact evident when the club collides with a normal golf ball.

The influence of the ball-club collision on post impact club-head kinematics observed in this study supports the findings of previous research (Williams & Sih, 2002; Ellis et al., 2010). This effect is so pronounced that on average the club-head lost 31% of its resultant velocity in the 10 ms post impact. During the same time period in the paper target condition, the club-head lost only 1% its resultant velocity. Of additional note is that the club-head velocity, post collision with a regular golf ball, never approximated the post impact club-head velocity observed when swinging at a paper target. This pattern is in contrast to the influence of impact in other sporting actions such as the tennis serve, where although the effect of impact on the racquet is considerable, it is reported to be only temporary in nature (Reid, 2007). The rapid and ongoing changes to post impact club-head kinematics observed in this study serve to draw attention to the likely inaccuracies of any technique that estimates impact club-head kinematics from filtering and/or interpolation techniques that include post impact data.
Some researchers have filtered and/or interpolated the kinematics of joint/segments kinematics of the golfer across the impact phase in order to estimate “at impact” values (Neal & Wilson, 1985; Coleman & Rankin, 2005). With the ball-club collision having such a substantial effect on post impact club-head kinematics, it is plausible that segment and joint kinematics may also be affected. However, in the current study, there were no significant differences in the selected post impact anatomical velocities whether hitting at a golf ball or paper target, indicating a lack of influence from the ball-club collision in the current dataset. It can be concluded that in estimating impact kinematics of selected key locations of a golfer’s body, it may be appropriate to include post impact data in a filtering and/or interpolation data treatment approach. It would be prudent however, to treat all data captured around the time of an impact with care, as vibrations from impact may result in marker shift (Nunome et al., 2006). Specifically the authors would recommend that all data collected from the golf swing is checked for any unexpected perturbations around the time of impact, prior to performing any form of data manipulation.

With an accurate interpolation to the first point of contact able to be made for the club-head kinematics in the paper target condition, two techniques previously employed by researchers to ascertain club-head kinematics “at impact” were subsequently validated. The first method to be validated was that of reporting club-head kinematics calculated at the last frame pre impact (Myers et al., 2008; Egret et al., 2006). In validating this approach, it is useful to consider the RMS errors in Table 3.1 (calculated via comparing virtual impact data with that from the last frame pre impact) as representing the club-head kinematic changes that occur in the last few milliseconds prior to ball contact. It was clear from the analyses that capture rate had a large influence on the accuracy of this method. However, even at the highest capture rate (400 Hz), the position of the club-head returned an RMS of 81.4 mm and the rotation angle an RMS of 4.9° respectively. This indicates a considerable change occurring in the position and orientation of the club-head in the last few milliseconds prior to ball contact, suggesting that it is inappropriate to represent the “at impact” position or orientation of the club-head as representative of data from the last frame pre impact.

In contrast to the rapid change in position and orientation of the club-head in the last few milliseconds pre impact, club-head velocity did not appear to change dramatically.
When comparing the data at the last frame pre impact, to the interpolated values at impact, there was an average difference in club-head velocity of 0.3 m/s. The current findings would suggest that club-head velocity calculated up to 5 ms prior to impact may be an appropriate reflection of the club-head velocity achieved at impact. To consistently capture data within 5 ms of impact however, a capture frequency of at least 200 Hz is required.

The second validation technique of calculating “at impact” club-head kinematics was that of extrapolating data to virtual impact based on pre impact data (Williams & Sih, 2002; Betzler et al., 2012; Worobets & Stefanyszyn, 2012). One of the important aspects of this technique explored by the current study was the influence of the quantity of pre impact data from which the polynomial equation was based. This quantity of pre impact data was found to significantly influence the accuracy of the extrapolation technique output, although there was no clear trend across dependant variables as to whether more or less pre impact data provided a more accurate result (as determined by smallest RMS). In lieu of a specific quantity of pre impact data being consistently accurate across all dependent variables, 12.5 ms of pre impact data was chosen as a potential compromise, as it produced relatively small errors for each dependent variable. A polynomial extrapolation based on approximately 12.5 ms of data immediately pre impact was subsequently compared with the method of reporting kinematics from the last frame pre impact at 400 Hz.

The final comparison revealed that extrapolating to virtual impact (using 12.5 ms of pre impact data) was significantly more accurate for representing the impact position and orientation of the club-head compared with reporting data from the last frame prior to impact. It would be a recommendation of this study, that future investigations estimating impact club-head kinematics use a similar extrapolation approach to that included in the final comparison. However, as there was no difference between the two methods when estimating the club-head velocity at impact, reporting data from the last frame pre impact may be suitable for any investigation where velocity alone is the club-head variable of interest (assuming the sampling frequency is equal to or greater than 200 Hz). Future investigations have the potential to reduce erroneous results in their data reported “at impact” by implementing either of these approaches.
With respect to estimating impact kinematics in the golf swing, the current study provides important insight into the accuracy of varying filtering and extrapolation approaches. However, further work is required for a comprehensive understanding of the most accurate method to treat data around this time. For example, while the current study focused on a 2nd order polynomial extrapolation technique, other orders of polynomial equations (or even linear extrapolations) should be explored. In the pursuit of more comprehensive analysis of data treatment around impact, it would also be valuable if future investigations were able employ a capture frequency sufficiently capable to reliably and consistently capture the club-head at the initial point of impact. Such an investigation would facilitate validation attempts of data treatment methods without the use of a paper target condition.

While the current research has important ramifications for future research focussed on the golf swing, it is important to bear in mind that methodological issues involved in data treatment around a collision are not unique to the biomechanics of the golf swing. For example, similar methodological issues are faced when reporting “at impact” data from a range of sporting actions which involve some type of high velocity collision between a ball and implement/body part. Consequently, the approach of the current study to create data free from the artefact of the normal collision with the ball, has the potential to provide guidance in the approach taken to determine kinematics at the point of impact in sports such as; tennis, football, baseball, handball, hockey and volleyball. Additionally, the recommendations from this study are also useful to the applied golf sport science setting. Specifically, an increasing number of people are now involved in the collection of golf swing kinematics and include club fitters and coaches, who use the data in an attempt to help golfers across all skill levels improve their game. Highlighting techniques to reduce possible errors in estimating impact club-head kinematics could prove to be just as important to this applied arena.

3.6 CONCLUSION

The current study describes a novel method of assessing the accuracy of different techniques to calculate kinematics “at impact” during the golf swing. It was apparent from the results that the collision between club and ball had a dramatic and ongoing
effect on the club-head kinematics but not on the kinematics of the golfer’s body. As a result any attempt to represent the club-head kinematics at the time of impact should avoid the use of club kinematic data collected post impact. As most current motion analysis systems are not able to capture club-head kinematics immediately pre impact, an extrapolation/interpolation method based on 12.5 ms of pre impact data is an accurate alternative to predict club-head kinematics “at impact”.
Chapter 4

The influence of club-head kinematics on early ball flight characteristics in the golf drive


4.1 ABSTRACT

Despite many coaching and biomechanical texts describing how the kinematics of the club-head at impact contributes to ball flight distance and accuracy, there is limited quantitative evidence to support such assertions. The purpose of this study was to quantify the relationship between club-head kinematics and subsequent early ball flight characteristics during the golf drive. An opto-reflective system operating at 400Hz was used to capture the swing of 21 male golfers using their personal drivers. Three-dimensional displacement data permitted the determination of club-head kinematics at impact, as well as initial ball flight characteristics. Regression analyses revealed that impact club-head kinematics (velocity, orientation, path and centredness) explained the variance in five dependent variables of early ball flight characteristics (resultant velocity, launch angle, side angle, back spin and side spin). The results of this study indicate that club-head kinematics at impact explained a significant proportion of early ball flight characteristics (adjusted $r^2 = 0.71-0.82$) and that this trend can be generalised across individual club types.

4.2 INTRODUCTION

A number of authors have attempted to explain the determinants of ball flight in the golf swing (Daish, 1972; Hay, 1993; Miura, 2002; Wiren, 1990). These observations have been based on a combination of different physical laws relating to collisions and
projectile motion. While these laws are unquestionably applicable to the golf swing there has been little empirical research that has investigated how these principles interact to influence distance and accuracy in the drive.

It is popularly held that a high club-head velocity is the critical performance variable in the golf drive (Fradkin et al., 2004; Gordon et al., 2009; Keogh et al., 2009; Sprigings & Neal, 2000). This view holds that velocity of the club-head at impact is the most influential factor in dictating initial ball velocity and, therefore, projected distance of the ball (Hay, 1993). While it is reasonable that club-head velocity should indeed play a large part in generating ball velocity, it has also been suggested that the location of impact relative to the centre of the clubface will also affect ball velocity (Hocknell, 2002; Wiren, 1990). Researchers have quantitatively established that the location of impact on the club-face has a significant effect on club-head orientation, path and velocity following impact (Ellis et al., 2010; Williams & Sih, 2002). However, there is currently a lack of understanding of the relative contribution of both club-head velocity and impact location on resultant ball velocity.

There is some suggestion that key characteristics of ball flight aside from velocity are also determined by more than one kinematic variable of the club-head at impact (Hay, 1993; Wiren, 1990). For example, the initial direction of the ball in flight is suggested to be the result of both the direction of the club-head velocity vector, and its orientation at impact (Hay, 1993; Wiren, 1990). However, what is unclear is which of these is more important as well as if other kinematic factors, such as centredness of impact, play an additional role. For instance, the direction of the velocity vector of the club-head at impact may be more important than club-head orientation in determining the direction of the ball in early ball flight and subsequently, may be a better predictor of stroke outcome. Determining the relative importance of club-head variables is important for both scientists and coaches alike. From a scientific perspective, key performance indicators from the club-head can act as meaningful dependent variables for comparative investigations, as well as training or intervention research designs. From an applied perspective, identifying the contributions of individual club-head kinematics has the potential to shape teaching and coaching methodologies, as well as influence the fitting of clubs to an individual’s swing pattern.
The aim of the current study was to quantify the relationships between club-head kinematics and early ball flight characteristics across a group of individuals using their own drivers. It was hypothesised that a combination of club-head velocity, orientation, path and centredness of impact would account for a significant proportion of the variance in each of the early ball flight characteristics.

4.3 METHODS

4.3.1 Participants

Twenty-one male golfers volunteered to participate in the study. Participants mean (±SD) age, height, mass and handicap were 24.2 (±5.7) years, 181.2 (±8.0) centimetres, 79.0 (±7.9) kilograms and 5.7 (±4.2, ranging between 1 - 14) respectively. The protocol used in this study was approved by the University of Western Australia’s human research ethics committee.

4.3.2 Procedures

A standardised 5-minute warm up that involved hitting balls at increasingly higher intensities with sequentially longer clubs was undertaken by all participants. The collection procedure was then divided into two parts to facilitate accurate collection of early ball flight characteristics. In part 1, golf ball resultant velocity, side angle (direction of velocity vector in the transverse plane) and launch angle (direction of the velocity vector in the sagittal plane) (Figure 4.1A-C) were tracked using a 12 camera Vicon MX opto-reflective motion analysis system (ViconPeak, Oxford Metrics, Oxford, UK), operating at 400 Hz. In part 2, back spin and side spin of the ball (Figure 1D & E) were tracked using a launch monitor (Vector Pro 2; Accusport, Winston-Salem, USA). Both parts of the research involved participants using their own driver to perform 10 drives off a rubber tee into a net situated four metres in front of the contact position. Participants were instructed to adopt a normal swing pattern to hit the ball straight for maximum distance. All drivers had a club-head volume of 460 cc and comparable club-face sizes.
Figure 4.1  Golf ball variables measured:  A) Golf ball resultant velocity (m/s), B) Golf ball launch angle (°), C) Golf ball side angle (°), D) Golf ball back spin (rev/s), and E) Golf ball side spin (rev/s).

In part 1, Titleist NXT golf balls were covered in reflective tape (Figure 4.2A). While this is accepted as a limitation, any effect of covering the ball in tape was considered to be minimal as key early ball flight characteristics, such as velocity and launch angle, were similar to that noted in previous research (e.g., Nagao & Sawada, 1998; Wallace et al., 2007). Subjectively, players reported feeling no difference around the time of impact.

At the completion of part 1 the first eight participants were asked to carry out part 2 of the study. For these trials the Vector Pro 2 captured two sequential still images of the ball immediately following impact using cameras mounted on the device, triggered by the sound of impact being detected via an inbuilt microphone in the device. By tracking two circular marks drawn on the ball (in accordance with the Vector Pro 2 manufacturer recommendations - Figure 4.2B) initial back spin and side spin of the ball were able to be calculated by the software provided by the manufacturer. The Vector Pro 2 has been shown to be accurate and reliable when measuring the initial velocity and direction of the ball (Sweeney, Alderson, Mills & Elliott, 2009a). The manufacturer also reports that the system can accurately measure back spin and side spin to within 150 rpm.
For both parts of the study, the opto-reflective motion analysis system was used to track club-head kinematics. Three retro-reflective markers, all of which were 16 mm in diameter, were affixed to the top of the club-head as shown in Figure 4.3A. These markers created a technical coordinate system, which was used to reference four virtual points on the club-face (Figure 4.3B). These four points were originally marked with pen and corresponded to the mid-point on the centre-most groove on the club-face, two points 4 cm to each side of the mid-point along the same groove, and the most inferior part of the club-face perpendicular to a line created by the first three points. Using a spherical pointer method, similar to that used by Capozzo (1995) these four points created the club-head technical coordinate system. This technical coordinate system was then transferred to the laboratory-based coordinate system to enable global club-head kinematics to be defined. All calculated club-head and early ball flight characteristics are displayed in Figures 4.1 and 4.4.
4.3.3 Treatment of Data

Marker trajectory data were labelled and any broken trajectories were interpolated using a cubic spline. No trials comprised broken trajectories of greater than 10 ms, nor were
there any broken trajectories in the 25 ms leading to impact. To remove the influence of
the club-ball collision, an extrapolation/interpolation approach (based on 12.5 ms of pre
impact data) was employed in accordance with the recommendation of the previous
chapter. Specifically, all raw data collected after the frame immediately pre impact was
ignored. Instead, a 2nd-order polynomial based on five data points prior to impact was
used to create marker coordinates for the following 10 frames, representing a period of
0.0225 s. To ascertain readings precise to the first point of ‘virtual impact’ impact, a
further 101-point interpolation was carried out on the four frames where the club-face
and virtual ball were closest to each other. ‘Virtual impact’ was defined as the point
within the interpolated data where the centre of the club-face was closest to the ball in
the forward direction of the laboratory (toward the target).

4.3.4 Variables

In part 1, raw coordinate data for the golf ball was used to calculate the resultant
velocity, side angle and launch angle during early ball flight (Figure 4.1). Seven
kinematic variables of interest were also calculated from raw coordinate data of the
club-head at ‘virtual impact’ (Figure 4.4). The use of raw coordinates as well as
calculation of club-head kinematics at ‘virtual impact’ was carried out in accordance to
the recommendations in Chapter 3. Resultant club-head velocity was derived from the
resultant velocity of the centre of the club-face. Both the vertical and lateral velocity
vectors were calculated and used to represent the path of the club-head (Williams & Sih,
2002). Club-head ‘loft’ and ‘rotation’ angles represented the orientation of the club-
face with respect to the global coordinate system. Specifically, club-head loft
corresponded to a backward tilt (relative to the direction of the swing) in the sagittal
plane, whereas club-head rotation corresponded to longitudinal axis rotation of the club-
face in the transverse plane. Finally, the vertical and horizontal distance between the
ball impact position on the club-face and the centre of the club-face was calculated to
represent the centredness of impact.

For part 2, two kinematic variables (side spin and back spin – Figure 4.1) were
calculated from the raw coordinate data of the golf ball. An additional two kinematic
variables were also calculated from the raw coordinates of the club-head at ‘virtual
impact’. One was calculated from the offset between the direction of the vertical
velocity vector and the loft angle of the club-head. The second was calculated from the
offset between the direction of the horizontal velocity vector and the rotation angle of the club-head.

4.3.5 Data Analysis

A statistical program (SPSS, v14) was used to average 10 trials for each participant for both parts of the study and subsequent analysis of the skewness and kurtosis of all variables confirmed a normal distribution of each. Five separate forward stepwise regressions were performed to assess the ability of club-head kinematics to predict resultant ball velocity, ball side angle, ball launch angle, ball side spin and ball back spin. Prior to performing these regression analyses all assumptions were taken into account (Vincent & Weir, 2012). It is accepted that the regression analysis used exposes the study to possible inaccuracies from the heterogeneity of the sample, as well as a potential misidentification of non-linear relationships. Caution was taken to avoid these during the analyses, with individual relationships qualitatively assessed for linearity, as well as the possible effect of sample heterogeneity. As an example, Figure 4.5 shows the strongest relationships of the study, all of which show clear linearity and appear to be without influence from sample heterogeneity. The dependent and independent variables involved in each regression are displayed in Figure 4.6. For each stepwise regression, the level of significance was $\alpha < 0.01$. 
Figure 4.5  Scatter plots of the three strongest relationships between club-head variables and subsequent ball flight characteristics. These relationships are between A) club-head resultant velocity and golf ball resultant velocity, B) club-head vertical velocity and golf ball launch angle, C) club-head rotation angle and golf ball side angle.
Figure 4.6  Variables involved in the five stepwise regressions used to explain early golf ball flight characteristics.

4.4 RESULTS

Means and standard deviations for all club-head and early ball flight characteristics are presented in Table 4.1. A number of club-head variables contributed significantly to the prediction of early ball flight characteristics (Table 4.2). These included centredness of impact in addition to the resultant velocity, loft, rotation and vertical velocity of the club-head.
Table 4.1: Mean (± standard deviations) of all variables included in the analyses, across participants in part 1 (n=21) and part 2 (n=8). Golf ball variables are all calculated at peak resultant velocity and club-head variables are all calculated at ‘virtual impact’.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Ball Resultant Velocity (m/s)</td>
<td>65.6 (±5.1)</td>
</tr>
<tr>
<td>Ball Launch Angle (deg)</td>
<td>10.1 (±2.5)</td>
</tr>
<tr>
<td>Ball Side Angle (deg)</td>
<td>1.2 (±3.2)</td>
</tr>
<tr>
<td>Ball Back spin (revs/s)</td>
<td>2383 (±663)</td>
</tr>
<tr>
<td>Ball Side spin (revs/s)</td>
<td>-148 (±123)</td>
</tr>
<tr>
<td>Club-Head Resultant Velocity (m/s)</td>
<td>45.4 (±3.6)</td>
</tr>
<tr>
<td>Total Off-Centredness of Impact (mm)</td>
<td>14.1 (±4.5)</td>
</tr>
<tr>
<td>Club-Head Loft Angle (deg)</td>
<td>8.8 (±4.0)</td>
</tr>
<tr>
<td>Club-Head Rotation Angle (deg)</td>
<td>-1.0 (±4.3)</td>
</tr>
<tr>
<td>Club-Head Lateral Velocity (m/s)</td>
<td>1.6 (±2.7)</td>
</tr>
<tr>
<td>Club-Head Vertical Velocity (m/s)</td>
<td>-1.2 (±2.4)</td>
</tr>
</tbody>
</table>
Table 4.2  Results of five stepwise regressions using club-head kinematics, at impact, to predict ball flight kinematics.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Independent Variables</th>
<th>Adjusted R Square</th>
<th>Direction of Relationship</th>
<th>df</th>
<th>F</th>
<th>Significance</th>
<th>Std Error of Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Velocity</td>
<td>Club-head Velocity</td>
<td>0.75*</td>
<td>positive</td>
<td>1.19</td>
<td>62.3</td>
<td>0.000</td>
<td>1.97 m/s</td>
</tr>
<tr>
<td></td>
<td>+ Centeredness of Impact</td>
<td>0.82*</td>
<td>negative</td>
<td>2.18</td>
<td>44.8</td>
<td>0.000</td>
<td>1.71 m/s</td>
</tr>
<tr>
<td>Ball Launch Angle</td>
<td>Club-head Vertical Velocity</td>
<td>0.68*</td>
<td>positive</td>
<td>1.19</td>
<td>43.1</td>
<td>0.000</td>
<td>1.4º</td>
</tr>
<tr>
<td></td>
<td>+ Club-head Loft Angle</td>
<td>0.74*</td>
<td>positive</td>
<td>2.18</td>
<td>29.6</td>
<td>0.000</td>
<td>1.3º</td>
</tr>
<tr>
<td></td>
<td>+ Vertical Centeredness of Impact</td>
<td>0.81*</td>
<td>negative</td>
<td>3.17</td>
<td>28.5</td>
<td>0.000</td>
<td>1.1º</td>
</tr>
<tr>
<td>Ball Side Angle</td>
<td>Club-head Rotation</td>
<td>0.82*</td>
<td>positive</td>
<td>1.19</td>
<td>90.2</td>
<td>0.000</td>
<td>1.4º</td>
</tr>
<tr>
<td></td>
<td>+ Club-head Lateral Velocity</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Horizontal Centeredness of Impact</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ball Back Spin</td>
<td>Offset between Club-head Loft &amp; Vertical Path</td>
<td>0.73*</td>
<td>positive</td>
<td>1.7</td>
<td>20.4</td>
<td>0.004</td>
<td>341 revs/s</td>
</tr>
<tr>
<td>Ball Side Spin</td>
<td>Offset between Club-head Rotation &amp; Lateral Path</td>
<td>0.82*</td>
<td>positive</td>
<td>1.6</td>
<td>33.8</td>
<td>0.001</td>
<td>52 revs/s</td>
</tr>
</tbody>
</table>
The first stepwise regression analysis from part 1 revealed that together, resultant club-head velocity at impact and centredness of impact accounted for 82\% (f = 44.8) of the variance in peak resultant ball velocity across all participants. Additionally, step 1 of the analysis revealed resultant club-head velocity alone explained 75\% (f = 62.3) of the variance in peak resultant golf ball velocity.

With respect to direction of the ball, the three independent variables (club-head velocity vector, orientation and centredness of impact) all significantly contributed to explaining the variance in launch angle of the ball in part 1. Together, vertical velocity of the club-head, loft of the club-head and the vertical centredness of impact on the club-face accounted for 81\% (f=28.5) of the variance in golf ball launch angle. The only independent variable that significantly explained the variance in side angle was the club-head rotation in the transverse plane, which explained 82\% (f = 90.2) of the variance.

The variance in both back spin and side spin of the golf ball was able to be significantly explained by the offset between the direction of the velocity vector and orientation of the club. This offset explained 73\% (f = 20.4) of the variance in back spin and 82\% (f = 33.8) of the variance in side spin.

\textbf{4.5 DISCUSSION AND IMPLICATIONS}

The primary aim of this study was to explain the variance in golf ball launch kinematics based on club-head kinematics at impact. As hypothesised, for each dependent variable, a large degree of the variance in early ball flight characteristics could be explained by one or more club-head kinematic variables at impact. While there is unquestionably some interaction between individual club specifications and some of the measures calculated in the current study, the results suggest that the relationships between club-head kinematics and the subsequent early ball flight characteristics are consistent across both a selection of different drivers and across individuals.

\textbf{4.5.1 Golf Ball Resultant Velocity}

Club-head velocity is perhaps the most commonly reported kinematic variable in the golfing scientific literature. It is often used as the sole measure of performance, under
the assumption that a higher club-head velocity will produce a higher initial ball velocity and therefore, greater distance (Gordon et al., 2009; Keogh et al., 2009; Sprigings & Neal, 2000). The results from this study support the notion that club-head velocity is a strong predictor of resultant ball velocity.

Although club-head velocity explained the majority of variance in ball velocity, centredness of impact also contributed significantly. Unlike club-head velocity, the influence of centredness of impact has at times, been overlooked in the scientific literature. However, its inclusion as a significant factor in explaining the variance in ball velocity in the present study attests to its importance in allowing players to achieve a maximal driving distance. It appears that in addition to club-head velocity, future investigations of the swing should also take into account centredness of impact.

4.5.2 Golf Ball Launch Angle

In the golf swing, the horizontal displacement of the ball is influenced directly by its initial launch angle (Hay, 1993). However, the launch angle of the golf ball is a kinematic variable that has received limited attention in the scientific literature. Our findings indicate that launch angle of the ball is influenced by both the path and orientation of the club-head at impact, in addition to the location of impact on the club-face. The teaching model of Wiren (1990), which is popular among many professional coaches, highlights the importance of the vertical path of the club-head at impact to the resulting vertical trajectory of the ball. That is, the angle formed by the ascending or descending arc of the club-head relative to the slope of the ground will influence the trajectory and distance of the ball. This effect is strongly supported by the results of the current study, with vertical velocity of the club-head explaining the majority of the variance (68%) in the initial launch angle of the ball. However, the results from this research highlight other important contributors to the launch angle of the golf ball during the drive.

Another variable found to play a role in significantly predicting the launch angle of the ball was the loft of the club-face at impact. This kinematic measure is a result of both the orientation of the club-head at impact and the degree of loft with which the face of the club sits relative to the club-head. Interestingly, the former of these relationships is almost entirely influenced by the kinematics of the golfer in each swing, whereas the
latter can only be manipulated through the design of the club. Therefore, for skilled players who possess club kinematics with low outcome variability (Dowlan, Brown, Ball, Best & Wrigley, 2001; Jobe et al., 1989; Betzler et al., 2012) the results of the current study highlight the importance of correct club fitting in allowing maximal driving distance to be achieved. For example, a skilled player not achieving an optimal ball launch angle may be attributed to the loft angle of the club being used being inappropriate for the player’s swing characteristics.

4.5.3 Golf Ball Side Angle

The accuracy of any shot in golf is the result of the ball’s initial direction and spin (Miura, 2002). Initial lateral direction is especially important in the drive, where a small error in side angle can cause a large error in lateral position of the ball relative to the target. For example, discounting the effect of air resistance, a 280 m drive miss-hit by 2˚ will land 9.77 m offline, while a 120 m wedge shot miss-hit by 2˚ will land 4.19 m offline. Hay (1993) suggested that both the orientation of the club at impact and the path along which it is moving play a key role in the direction travelled by the ball. The current data supports Miura’s (2002) suggestion that the orientation of the club-head at impact is the most important factor in determining the initial lateral direction of the ball. In fact, club-head rotation alone explained 82% of the variance in golf ball side angle and was the only independent variable to achieve significance in the regression analysis. While it would be difficult to argue that the path of the club-head at impact and centredness of impact have no influence on the lateral direction of the ball during flight, it would appear that these did not play an important enough role to achieve statistical significance.

4.5.4 Golf Ball Spin

As well as the initial direction of the ball, the spin imparted on the golf ball will largely dictate both distance and accuracy achieved in the drive (Hay, 1993). Miura (2002) reported that a shot resulting in a ‘hook’ or a ‘slice’ is caused by excessive spin about the vertical axis, resulting from misalignment between the position of the club-face and the path of the club at impact. That is, if the club-face is not aligned perpendicular to the direction that the club-head is travelling at impact, rotation of the ball will occur during flight due to an off-centre impact. This appears to be quantitatively supported
by the analyses performed in the present study. The variance in both side spin and back spin produced in the drive appears to be best explained by the alignment between club-head orientation and path. This also supports the popular coaching recommendation of keeping the club-head ‘square’ at impact to reduce the possibility of a hook or a slice.

4.5.5 Further Implications

For the purpose of this investigation, the variables associated with early ball flight characteristics were treated independently. However, what should not be ignored is the interaction of these variables and their possible combined influence on stroke outcome. For example, a number of articles in the popular golfing literature have focused on the potential benefit of using a club with an increased loft angle (Johnson, 2006; Masters, 2010; Statchura & Wilson, 2003). This increased loft angle has been suggested to aid golfers in producing an increased launch angle of the ball, which in turn may contribute to a greater flight distance of the ball (Chou, 2004). While results from the present study suggest that loft angle may well increase ball launch angle, it also suggests that a disparity between the loft of the club and the vertical path of the club may result in greater back spin. This increased back spin will effectively reduce ball distance and therefore negate any potential benefit achieved by increasing the ball launch angle. It is evident that while the results of this study provide a better understanding of the influence of impact club-head kinematics on specific launch kinematics of the ball, researchers and coaches should be mindful of the interaction effect between such variables.

While the current study attempted to facilitate a high level of external validity by allowing golfers to use their own driver, it is likely that design differences across clubs would have had some effect on early ball flight characteristics. Although this serves as a limitation of the present study, early ball flight characteristics were still significantly explained by the club-head kinematics at impact across golfers regardless of club design differences. A further limitation of the current study was the use of linear regression analyses. Despite the caution taken, the possibility of error deriving from sample heterogeneity and non-linearity of statistical relationships should be considered when interpreting the current results.
Future research could take into account the influence of specific design differences, such as the size of the ‘sweet spot’, club-face composition and shaft specifications and their effect on performance. Research in this vein would allow valuable insight into the influence of club design and specifications on the interaction between the variables explored in the current study.

4.6 CONCLUSION

This study has identified strong relationships between club-head kinematics at impact and subsequent ball flight characteristics. Each component of initial ball flight (resultant velocity, launch angle, side angle, back spin and side spin) was well explained by the kinematics of the club-head at impact. In summary, resultant ball velocity seemed to be largely determined by the velocity of the club-head at impact, as well as the centredness of this impact on the club-face (82% of the variance in ball velocity explained by these two variables). While the launch angle of the ball during early flight was explained by the orientation, path and centredness of the club-head at impact (81% of variance explained), only the orientation of the club-head significantly explained the variance in side angle (82% of variance explained). Finally, it was evident that the majority of variance in both back spin and side spin can be explained by the misalignment between the orientation and the path of the club-head at impact (73% and 82% of the variance in back spin and side spin explained respectively). These results allow both researchers and coaches to have a better understanding of the key club-head kinematics that are required to produce optimal early ball flight characteristics.

Acknowledgment

The authors of this paper would like to sincerely thank Titleist for the use of the launch monitor and assistance in technical difficulties throughout the research.
Chapter 5

Identifying compensatory joint kinematics in the golf drive

5.1 INTRODUCTION

The golf swing is a complex task involving the coordination of a large number of body segments in the pursuit of generating club-head kinematics to produce ball distance and accuracy. Despite the complexity of the golf swing, skilled golfers are able to consistently execute necessary club-head kinematics required for high performance (Watanabe et al., 1998; Betzler et al., 2012). While there have been detailed descriptions of the segment and joint kinematics throughout the golf swing, there is limited understanding of how skilled golfers coordinate segment and/or joint kinematics to achieve consistent endpoint kinematics. In expanding knowledge of skilled performance a research priority is to further the understanding of the role intra-individual swing variability in consistently achieving precise club-head kinematics at impact with the ball (Bartlett et al., 2007; Glazier, 2011; Langdown et al., 2012).

To understand how variability might affect swing performance it is important first to clarify the distinction between movement variability and outcome variability (Glazier, 2011; Langdown et al., 2012). In a motor task, such as the golf swing, ‘movement variability’ can be defined as the inter-swing fluctuations in the individual joint motions throughout the kinematic chain. Whereas ‘outcome variability’ is the swing to swing variations in the outcome of a task, such as club-head kinematics at impact (Glazier, 2011). With respect to swing outcome variability it is clear that skilled golfers are able to achieve highly consistent club-head kinematics at impact (Watanabe et al., 1998; Betzler et al., 2012). In order to accomplish this consistency in club-head kinematics it is plausible that skilled golfer may possess a similar negligible level of inter-swing movement variability. However, research has clearly indicated this is not the case with golfers of all skill levels shown to exhibit some level of inter-swing movement variability (Bradshaw et al., 2009; Tucker et al., 2013). In fact, recent research has
indicated that the movement variability exhibited by skilled golfers is significantly
greater than their outcome variability (Horan et al., 2011).

A dichotomy between outcome and movement variability has been found to exist in
other motor tasks (Arutyunyan, Gurfinkel & MirskiiLatash, 1969; Bernstein,
1967;Latash, 1998; Cusumano & Cesari, 2006; Bartlett et al., 2007) and can be
explained through the concept of motor equivalence. Motor equivalence applies to a
motor task where multiple ways that the individual joint kinematics of the body can be
coordinated to achieve the same performance related outcomes (i.e. redundancy exists
within the system). Investigations focussed on other motor tasks have revealed that
kinematic redundancy is exploited by the motor control system through the organisation
of compensatory relationships between individual kinematics in the system (Kudo et al.,
2000; Muller & Sternad, 2004; Cusumano & Cesari, 2006; Mills, 2007). For example,
studies by Arutyunyan and colleagues (1968; 1969) revealed that variations present in
the body and pistol angles during a shooting task compensate for each other enabling a
steady pointing position. It has been suggested that the organisation of such
‘compensatory synergies’ within kinematics of motor tasks may play a functional role in
allowing for environmental adaptations, reducing injury risk and facilitating changes in
coordination patterns, all whilst maintaining the precision required for task outcome
(Bartlett et al., 2007). Some authors have recently called for investigations focussing on
identifying such patterns in the golf swing, enhancing our insight into the mechanical
coordination of skilled performance in golf (Glazier, 2011; Langdown et al., 2012).

To investigate potential compensatory synergies in tasks such as; throwing (Kudo et al.,
2000), gait (Mills et al., 2003; Mills, 2007), a virtual skittles task (Muller & Sternad,
2004) and a reaching task (Muller & Sternad, 2003), an approach termed Random
Sensitivity Analysis (RSA) has been developed. For a task involving an open kinematic
chain, the RSA approach initially involves some form of forward kinematic model
(FKM) that includes each of the degrees of freedom involved in the task. For the
purposes of this study a ‘degree of freedom’ will refer to any specific joint motion
through a single anatomical plane (e.g. flexion/extension at the wrist joint is one degree
of freedom, whilst elbow pronation/supination is another). The time history of each
degree of freedom, collected over multiple trials, are normalised and subjected to an
intra-degree of freedom, inter-trial permutation to generate a surrogate data set. The
surrogate data set is entered into the FKM and the kinematics of task relevant outcome variable(s) are calculated and compared with that recorded in the original empirical data set.

In conducting the RSA, permutations conducted to create the surrogate data set act to remove any compensatory relationships that may exist between individual joint kinematics. Consequently, if intra-individual movement variability occurs as a result of random sensorimotor noise, little difference would be expected between surrogate and empirical data sets with respect to the outcome variability produced. Alternatively, if the surrogate data set produced a greater outcome variability compared with the empirical data, the existence of compensatory synergies (acting in the empirical data to minimise outcome variability) would be signified.

The aim of this study was to identify whether skilled golfers exhibit compensatory relationships between individual joint kinematics that act to minimise variability of club-head kinematics at the time of impact. Specifically the study will focus on identifying compensatory relationships in contributing to the velocity, and orientation of the club-head at impact and centredness of ball impact on the club-face.

5.2 METHODS

5.2.1 Participants

Ten male participants with a mean (±SD) handicap of 3.4 (±2.4) were recruited for the study. The average age, height and mass of the participants were 23.2 (±6.2) years, 1.82 (±0.09) metres and 79 (±8.4) kilograms respectively. Ethics approval was granted from the relevant committee prior to participant recruitment and data collection. All participants provided informed written consent to participate in the study.

5.2.2 Procedures

Each participant performed a 5-minute warm-up which involved hitting golf balls with incrementally increasing intensity. Participants then performed 10 drives using their personal driver, into a net situated four metres in front of them. Participants were
instructed to hit each shot as if it were a drive that they would hit on a straight par 5 hole.

5.2.3 Data acquisition model

Seventy-seven retro reflective markers of 16 mm diameter were affixed to the participant and club during the calibration procedure (Figure 5.1). Twenty eight of these markers identified key anatomical landmarks required for the definition of segment anatomical coordinate systems (ACSs). The remaining markers, inclusive of 12 semi-rigid ‘T-bar’ clusters, were used to define technical coordinate systems (TCSs) that represented the movement of each segment. The ‘calibrated anatomical systems technique’ (CAST) method (Cappozzo et al., 1995) was used to identify the bilateral three dimensional (3D) position of the lateral and medial elbow epicondyles, as well as the knee lateral and medial femoral condyles. The locations of these landmarks were defined in the associated segment TCSs of the upper arm and thigh respectively. A similar protocol was utilised to define critical club-face virtual markers with respect to a TCS created from three markers affixed to the top of the club-head (Sweeney, Mills, Alderson & Elliott, 2013). Three-dimensional marker trajectories from each swing were sampled at 400 Hz using a 12 camera Vicon MX opto-reflective motion analysis system (ViconPeak, Oxford Metrics, Oxford, UK).

All marker trajectory data was labelled and any broken trajectories were interpolated using a cubic spline. No trials comprised broken trajectories of greater than 10 ms, nor were there any broken trajectories in the 25 ms leading to impact. To remove the influence of the club-ball collision on the club-head kinematics, methods recommended from the findings of Chapter 3 were employed. Specifically, 2nd order polynomials were was fitted to the club-head marker trajectories for the five data points prior to impact, and then extrapolated for the subsequent 10 frames (representing a period of 0.0225 s). All marker data was then subjected to a low-pass 2nd order Butterworth filter with marker specific cut-off frequencies being defined via the residual analysis approach outlined in Winter (1990).

To ascertain readings precise to the first point of ‘virtual impact’ impact, a further 101-point interpolation was carried out on the four frames where the club-face and virtual ball were closest to each other (two frames prior to impact + two frames post impact).
‘Virtual impact’ was defined as the point where the centre of the club-face was closest to the ball in the forward direction of the laboratory (toward the target). The time of impact was determined from this method and used to define the end of the downswing phase. The start of the downswing phase was defined as the point at which the club-head reached its lowest vertical position during the transition phase between backswing and downswing.

Three-dimensional segment and joint kinematics were calculated in BodyBuilder software (ViconPeak, Oxford Metrics, Oxford, UK) using the UWA model (Lloyd, Alderson & Elliott, 2000; Besier et al., 2003; Campbell et al., 2009), which is consistent with ISB recommendations for defining anatomical motions (Wu et al., 2002; Wu et al., 2005). Empirical kinematics of the golfer and club during the downswing phase of each trial were temporally normalised to 101 points; this data set will be referred to as the empirical data set (E). For each trial from E, a value was obtained at impact for each variable of interest (VI). These VI’s were chosen from those found to influence early ball flight characteristics in Sweeney et al. (2013) and are displayed in Figure 5.1 with their theoretical influence on performance outlined in Figure 5.2. The subsequent variance in VI data at impact was calculated across E for each participant, and is subsequently referred to as \(\sigma^2_{VI_E}\).

**Figure 5.1** Variables of Interest (VI) associated with performance from Sweeney et al. (2013). A) Club-head resultant velocity (m/s), B) Club-head vertical velocity (m/s), C) Club-head lateral velocity (m/s), D) Club-head loft angle (°), E) Club-head rotation angle (°), and F) Centredness of impact (mm).
5.2.4 Forward Kinematic Model (FKM)

The FKM developed for this investigation was adapted from the equations used by Mills (2007), and represented the golfer as a 12-link kinematic chain with the left foot acting as the initial segment and the centre of the club-face acting as the terminal point (Figure 5.3). This simplification was necessary as including two upper and/or lower limbs in the model would not allow endpoint solutions based on modifications at a single degree of freedom. The left leg was selected for inclusion in the model due to its role as a base around which body rotates during the swing (Bechler et al., 1995). The right arm was selected for inclusion in the model due to its suggested role in creating...
power in the swing (Cochran & Stobbs, 1968; Hume et al., 2005; Sweeney et al., 2012).
The FKM model can be described through the equation:

$$G_P^C = G_P^I + \sum_{i=1}^{N} iP_i \cdot G_i^G_{R_{xyz}}(\alpha, \beta, \chi)$$  
Eq. 5.1

Where $G_P^C$ was the position of the centre of the club-face in the global coordinate system {G}, $G_P^I$ was the position of the left foot (initial segment) defined in {G}, $iP_i$ was the position of the endpoint of segment i defined within segment i’s anatomical coordinate system {A} and $G_i^G_{R_{xyz}}(\alpha, \beta, \chi)$ was the rotation matrix defining the orientation of segment i, which was composed via sequential rotations about the z-, x- and y-axes of segment i by the angles $\alpha, \beta, \chi$ (corresponding to the medio-lateral, anterior-posterior and vertical axis). $\alpha, \beta$, and $\chi$ were explicitly defined for the left foot; for the remaining segments $\alpha, \beta$, and $\chi$ were defined through

$$G_i^G_{R_{xyz}}(\alpha, \beta, \chi) = i^{-1}Q_i^G_{R_{xyz}}(\alpha, \beta, \chi) \cdot i^{-1}R_i^G_{xyz}(\alpha, \beta, \chi)$$  
Eq. 5.2

Where $i^{-1}Q_i^G_{xyz} (\alpha, \beta, \chi)$ was the rotation matrix composed from the joint angles describing the orientation of segment i with respect to segment i-1, which was composed via sequential rotations about the z-, x- and y-axes of segment i by the angles $\alpha, \beta$, and $\chi$ (corresponding to rotations about the medial-lateral, anterior-posterior and vertical axes). Position and orientation data calculated at each time point during the downswing from equations 5.1 and 5.2 enabled calculation of linear and angular displacement, which were differentiated with respect to time to calculate linear and angular velocity respectively.
5.2.5 Random Sensitivity Analysis

For each participant, a surrogate data set \( (S) \) consisting of 1000 trials was created by performing random intra-degree of freedom, inter-trial permutations of joint angle data from \( E \). Specifically, all individual joint kinematics for each trials in \( S \) were randomly assigned from those empirically achieved by the participant throughout the 10 empirical trials. For example, a single trial from \( S \) may have had the wrist flexion profile empirically achieved by that participant in trial 10, the wrist ulnar deviation profile empirically achieved in trial 2, elbow flexion profile from trial 7, and so on. Every trial in \( S \) was therefore a composite of individual joint kinematics which were achieved across different trials by that participant. For each trial from \( S \), a value was obtained at impact for each VI. Variance of each VI at impact was calculated across \( S \), which is represented as \( \sigma^2_{VI_s} \).

5.2.6 Statistical Analysis

Agreement between VI kinematics measured empirically and those predicted by the FKM was assessed using the Limits of Agreement (LOA) approach (Bland & Altman, 1986).
If no compensatory synergies existed in a golfer’s swing, one would expect $\sigma^2 \text{VI}_S \approx \sigma^2 \text{VI}_E$. Conversely, if compensatory synergies did exist in a golfer’s swing then it would be expected that $\sigma^2 \text{VI}_S > \sigma^2 \text{VI}_E$. The existence of compensatory synergies was therefore assessed by comparing $\sigma^2 \text{VI}_S$ with $\sigma^2 \text{VI}_E$ using a Wilcoxon Rank-Sum test. All analyses were performed in PASW Statistics (18.0.1) with statistical significance set at $\alpha < 0.05$.

5.3 RESULTS

For the empirical trials ($n=10$), the 10 participants displayed an impact club-head resultant velocity of 49.7 m/s ($\pm 3.7$), vertical velocity of 3.2 m/s ($\pm 1.7$), rotation angle of 3.1 ° closed ($\pm 3.2$), loft angle of 9.3 ° ($\pm 5.8$) and centredness of impact of 13.6 mm ($\pm 1.8$).

5.3.1 FKM Validity

The LOA assessments of VI’s measured empirically versus those predicted by the FKM are displayed in Figure 5.4. All mean differences and limit of agreements were deemed negligible (mean difference for club-head resultant velocity = 0.05 m/s, vertical velocity = 0.02 m/s, lateral velocity = 0.02 m/s, loft angle = 0.002 deg, rotation angle = 0.007 deg, centredness of impact = 0.03 mm)
Figure 5.4 Bland-Altman plots, mean differences and level of agreements between empirical and FKM measures of A) club-head resultant velocity, B) club-head vertical velocity, C) club-head lateral velocity, D) centredness of impact, E) club-head loft angle and F) club-head rotation angle at impact.
5.3.2 Random Sensitivity Analysis

The Wilcoxon rank sum tests revealed that $\sigma^2 \text{VI}_S$ were significantly greater than $\sigma^2 \text{VI}_E$ ($p < 0.01$) for every participant, across each VI. This increase was greatest for centredness of impact where the average $\sigma^2 \text{VI}_S$ (2101.2 ±1146.9 mm) was 28 fold higher than the average $\sigma^2 \text{VI}_E$ (74.4 ±40.4 mm). The smallest increase was observed for club-head loft angle where the average on average $\sigma^2 \text{VI}_S$ (1.7 ±102.2 °) was 8 fold higher than the average $\sigma^2 \text{VI}_E$ (0.2 ±12.5 °) (Figure 5.5).

![Figure 5.5](image)

**Figure 5.5** The average increase in the variance (%) for the surrogate data when compared with the empirical data, across each variable of interest. Error bars indicate ± standard deviation.

5.4 DISCUSSION

The primary purpose of this study was to identify whether skilled golfers exhibit compensatory relationships between individual joint kinematics that act to minimise variability of club-head kinematics at the time of impact. The results indicate that the inter-trial fluctuations seen in the individual joint kinematics of the skilled golf swing are not random, but in fact work together in a compensatory pattern. Furthermore, these compensatory behaviours appear to act to dramatically reduce the outcome variability in the swing, highlighting the functional role of movement variability in ensuring skilled golfers can achieve consistent and precise club-head kinematics at impact. This
functional role of movement variability should not be ignored when considering the contributors to biomechanical success in the swing.

5.4.1 Validity of the Forward Kinematic Model (FKM)

In pursuing the primary aim of this study a FKM was created where club-head kinematics were almost identical to that empirically measured. The strong agreement found between the FKM outputs and those calculated empirically (mean differences and LOA all near zero) are similar to those reported previously by Mills (2007). However, the level of agreement with empirical data is considerably greater than previous investigations which have modelled the golf swing (Budney & Bellow 1979; Turner & Hills 1998; Pickering & Vickers 1999; Kaneko & Sato 2000; Tang & Abraham, 2003; White, 2006; Chen et al., 2007; Kenny et al., 2008b). It is reasonable to assume that the accuracy of the FKM can be largely attributed to the kinematics that drive the model, in contrast to previous biomechanical models of the swing which have been driven by kinetics. The kinetics used by previous researchers has been based on data that has been indirectly measured from empirical kinematics (typically from inverse dynamic calculations) which introduces assumptions and therefore some error into the calculations. Adding to the limitations of the kinetic approach is that the original coordinate data must be twice differentiated as a part of the inverse dynamic calculations needed to infer kinetics. Consequently, kinetically driven, multi-dimensional models of the golf swing based on indirect calculations are sensitive to small errors.

While the current kinematic approach to modelling the swing has greater accuracy than a kinetically driven model of comparable complexity there is an important limitation to consider. Specifically a forward kinematic approach to modelling the swing is limited in that it ignores the potential influence on changing kinetic factors (such each segment’s moment of inertia as it rotates) that occur during the action. It is accepted that this limitation has some influence on the ability of model to produce data that could be replicated empirically. However, it is important to note that all individual joint kinematics used to drive the surrogate data sets (during the RSA) were achieved empirically by the participant in one of their swings. This along with the strong
agreement between the FKM and empirical data would support the validity of the current model.

5.4.2 Strength of Compensatory Behaviours

The results from the current study clearly indicate that the outcome variability of skilled golfers is significantly increased when simulating the removal of compensatory relationships amongst individual joint motions. Previous investigations using an RSA approach similarly reported significant increases in outcome variability when the influence of any inter degree of freedom relationships were removed (Kudo et al., 2000; Mills, 2007). However, the magnitude of the increased outcome variability observed in the surrogate data (8 to 28 fold increase) from this investigation is greater than those reported previously. Kudo and colleagues investigated whether intra-trial relationships between release parameters enhanced accuracy in a throwing task. Participants performed 150 throwing trials and the first and last block of 30 trials were analysed. Removal of any compensatory coordination in the surrogate data set resulted in a modest increase in performance variability, ranging from 6% to 12% in the first and last block of trials respectively. In a later study focussed on the coordination of minimum toe clearance in gait, Mills (2007) observed a fivefold increase in outcome variability after removing the influence of any potential compensatory relationships. Mills (2007) proposed that some of the higher compensatory behaviour observed in his study, when compared with Kudo et al. (2000), could be attributed to the larger number of degrees of freedom and an FKM representing the kinematic chain (as opposed to just endpoint kinematics in the study of Kudo and colleagues). The findings of the current study for the golf swing are consistent with the notion of a positive relationship between the magnitude of compensatory behaviour and the number of degrees of freedom within the kinematic chain.

Unlike previous research the current study employed an RSA approach to investigate the presence of compensatory behaviours towards not one, but multiple outcome variables in the same task. Compensatory relationships between individual degrees of freedom were found to minimise variance in all of the key club-head kinematic VI. Whilst compensatory relationships were signified across all outcome variables measured, the different magnitudes to which each of these outcome variables were influenced is also noteworthy. For example of the six club-head kinematic variables
assessed, centredness of impact stood out as having the greatest relative increase in variance when the influences of compensatory relationships between degrees of freedom were removed. In fact the variability increase observed for centredness of impact was 28-fold compared to an 18-fold increase in club-head velocity variability, which was the next highest observed. The demand for precision and consistency in centredness of impact is likely higher than other impact club-head kinematics, as a few centimetres off-centre could result in a significant decrement to the outcome of the swing (Betzler et al., 2012). The greater relative strength of compensatory behaviours influencing centredness of impact observed in the current study might then be attributed to the high demand for precision in golf, to ensure the ball consistently collides within the desired area of the club-face.

5.4.3 Applied Relevance

As well as contributing toward the theoretical understanding of performance in the golf swing the current findings also provide important insights for coaches and golfers. For instance, in the pursuit of performance consistency and accuracy many golf coaches advocate relative invariance within specific joint motions. In contrast, the findings from this study suggest that inter-swing fluctuations of individual joint motions are both an inherent aspect of the swing and potentially play a critical role in the ability to achieve a successful outcome. While it is unlikely all movement variability is beneficial to performance, based on the current evidence it is clear that coaches would be ill advised to strive for invariance in the individual joint motions of their pupils.

Of further applied relevance is the support the current results provide toward the assertions of dynamical systems theorists, and in particular how they might relate to the golf swing. Dynamical systems theory suggests that there is a functional role for movement variability in expressing the range of possible transitions between patterns of movement that a system can accomplish. In reflecting on how the dynamical systems theory might apply to the golf swing Glazier & Davids (2005) suggested that one of the most pertinent implications for golfers was to the nature their practice. Specifically, if movement variability plays a functional role in the swing then large amounts or repetitive practice of the golf swing, under similar constraints, may not be an optimal strategy to improve performance in the golf drive (Glazier & Davids, 2005). Conversely, practice involving the systematic manipulation of key constraints may
prevent the golf swing from becoming too rigid and promote what Bernstein (1967, p. 134) described as “repetition without repetition” (i.e., the development of a stable but flexible golf swing). The findings of the current study are consistent with a functional role of variability within the golf swing and therefore provide support for the recommendations of Glazier and Davids (2005) and should be considered by coaches and golfers when designing their practice plans.

5.4.4 Future Recommendations

With compensatory relationships identified within the kinematic chain of the skilled golf swing, an immediate question likely to be proposed by coaches and players would be how individual joint kinematics contribute to these relationships. In particular, it is not clear whether each of the specific joint motions in the kinematic chain contributes equally to the compensatory behaviour observed or whether outcome variability is influenced primarily by a few ‘key’ individual joint motions. If ‘key’ individual joint motions do exist then their identification (within individuals, as well as across participants) would provide valuable applied and theoretical insights into how skilled performance is achieved in the golf swing.

Further investigation is also warranted into the potential differences in compensatory behaviour across expertise, gender and swings with different clubs (e.g., driver vs. pitching wedge). With respect to expertise, Kudo et al. (2000) found that a small amount of practice both improved performance and increased the compensatory behaviour in a novel throwing task, indicating that proficiency may have a significant influence on the strength of compensatory behaviour. Future research uncovering key differences (and/or similarities) in the swings of novice and skilled golfers has the potential to provide meaningful theoretical insight of swing mechanics, thus assisting coaches’ recommendations for skill development. Similarly future research focussed on identifying differences in the compensatory behaviours between genders and across different clubs has the potential to greatly expand our knowledge of the nature of biomechanical success in the golf swing

The current study focused specifically on compensatory relationships that exist within a kinematic chain in the golf swing starting at the left lower limb, passing through the right upper limb and finally to the golf club. This necessary simplification of the
kinematic chain enabled an effective FKM to be created and has provided a clear identification of compensatory behaviours in the golf swing. However, future investigations have the potential to provide a more complete understanding of compensatory relationships within the swing by also focussing on the right lower limb and left upper limb.

5.5 CONCLUSION

The current study presented a method to identify the presence of compensatory relationships within the individual joint motions of the swing. The FKM approach was found to produce club-head kinematics in excellent agreement to those produced empirically, and a subsequent RSA approach allowed the simulated removal of any compensatory relationships between individual joint motions in the swing. When the influence of compensatory relationships were removed the intra-individual variance in club-head resultant velocity, vertical velocity, lateral velocity, loft angle, rotation angle and centredness of impact increased by an average of between 8 and 28 fold. Based on these results it is evident that movement variability within the individual joint motions of the swing acts in a compensatory manner to minimise the inter-swing variability of the club-head kinematics at impact. Although to different magnitudes, these compensatory relationships were apparent in the swings of each skilled golfer tested and appear to play a critical role in the ability of skilled golfers to deliver the golf club to the ball in a precise and consistent manner. The current study provides insight into the role of movement variability in the swing and with it, the potential to change how scientists and coaches view the role of variability in the swing.
Chapter 6

Identifying the role of individual joint kinematics in the golf drive

6.1 INTRODUCTION

The golf drive is a highly complex movement that requires the coordination of many individual degrees of freedom at various joints of the body. Previous research has revealed that skilled golfers achieve consistency in the golf drive via attaining precise and consistent club-head kinematics, such as club-head velocity, path and orientation, as well as the centredness of where the ball impacts on the club-face (Hay, 1993; Miura, 2002; Betzler et al., 2012; Sweeney et al., 2013). At the kinematic level of analysis, the golf drive is highly redundant. That is, for a given set of environmental conditions the number of individual joint motions within the kinematic chain exceeds the number of joint motions required to achieve optimal club-head kinematics. In understanding how skilled golfers achieve such consistently in impact club-head kinematics authors have suggested a key research focus lies in quantifying the role of intra-individual variability within the swing (Bartlett et al., 2007; Glazier, 2011; Langdown et al., 2012).

Despite the relative invariance in final club-head kinematics achieved by skilled golfers there does not appear to be any such invariance in the individual joint motions that make up the kinematic chain during the swing (Bradshaw et al., 2009; Horan et al., 2011; Tucker et al., 2013). In fact, for skilled golfers the inter-trial variability in individual joint motions (movement variability) is significantly greater than the variability observed in the club-head kinematics directly influencing performance (outcome variability) (Horan et al., 2011). The previous chapter has indicated that this dichotomy between movement variability and outcome variability is a result of compensatory relationships, which are manifested in the individual joint motions. Identification of the presence of such compensatory relationships in the previous chapter was important in enhancing our understanding of swing mechanics. However, what is unclear from the previous chapter is how each individual joint motion involved in the golf swing contributes to the observed compensatory relationships.
An ‘individual surrogate analysis’ has previously been employed to identify the individual joint motions which contribute to compensatory synergies in gait (Mills, 2007). This analysis is a continuation of the Random Sensitivity Analysis (RSA) approach (employed in the previous chapter) but creates multiple surrogate data sets, effectively simulating the systematic removal of each individual degree of freedom’s contribution (in isolation) to any compensatory relationships present. After using this approach in analysing gait, Mills (2007) reported that some individual joint motions contributed heavily to the compensatory relationships influencing toe clearance, while other individual joint motions appeared to play a negligible role.

It is plausible that in the golf swing all individual joint motions in the kinematic chain contribute equally to the compensatory relationships within the swing. Alternatively, it may be that selected joint movements play a more significant role in performance than others, in a similar manner as occurs in foot clearance in gait (Mills, 2007). An individual surrogate analysis has the potential to identify whether each individual joint motion contributes equally to compensatory behaviours, or alternatively to demonstrate which individual joint motions are most important in reducing outcome variability. Identifying the specific contribution (or lack of contribution) of each individual joint motion toward compensatory behaviours, may provide valuable insight for scientists and coaches seeking an understanding how mechanical success is achieved in the golf swing.

The aim of this study is to assess the role of individual joint kinematics in the compensatory relationships which act to minimise outcome variability in the skilled golf drive. If specific degrees of freedom are identified, that contribute to the compensatory behaviour in producing club-head kinematics, then a secondary aim is to identify these movements while also determining if these results are stable across a sample of skilled golfers.

6.2 METHODS

The participants, data collection, data processing and initial modelling procedures are identical to those described in 5.2.1 through to 5.2.5.
6.2.1 Random Sensitivity Analysis

As in described in section 5.2.5, a surrogate data set (S) consisting of 1000 trials was created by performing random intra-degree of freedom, inter-trial permutations of joint angle data from E. For each trial from S, a value was obtained at impact for each VI. The subsequent variability of this impact data for each VI was calculated across S, which was represented as $\sigma^2_{VI_S}$.

In order to assess the role of individual degrees of freedom in the compensatory synergies an additional data set I was generated by sequentially combining individual degrees of freedom from S with the remaining degrees of freedom from E. Specifically, for each trial in I, individual joint kinematics were consistent with a single trial from E, with the exception of the single degree of freedom in focus. The downswing kinematics at this one degree of freedom was randomly replaced with those achieved in one of the other 9 empirical trials performed. A discrete I data set was created for all individual joint motions allowing the assessment of each one’s role towards the compensatory relationships identified in the last chapter. For all trials from every I, a value was obtained at impact for each VI. The subsequent variability of this impact data for each degree of freedom in contributing to each VI was calculated across I, which was represented as $\sigma^2_{VI_I}$.

6.2.2 Statistical Analysis

If a particular degree of freedom significantly contributed towards the compensatory behaviours for a particular VI it would be expected that $\sigma^2_{VI_I} > \sigma^2_{VI_E}$. Whether a particular degree of freedom contributed towards any compensatory behaviour was therefore assessed by comparing $\sigma^2_{VI_I}$ and $\sigma^2_{VI_E}$, for each VI, across each participant using a Wilcoxon Rank-Sum test. All analyses were performed in PASW Statistics (18.0.1) with statistical significance set at $\alpha < 0.05$. 

103
6.3 RESULTS

6.3.1 Random Sensitivity Analysis

The individual surrogate analysis revealed that a small number of degrees of freedom contributed to compensatory relationships for each player, across each VI (Figure 6.1). For example, in Figure 6.1A it can be seen the $\sigma^2_{VI}$ resulting from removing the influence of the right shoulder internal rotation and wrist flexion from compensatory synergies, were the only two that were significantly greater than $\sigma^2_{VI}$ ($p < 0.05$).
Figure 6.1  Club-head kinematic variance ($\sigma^2$) for a representative participant across E, S and each I. A) resultant club-head velocity B) centredness of impact C) vertical club-head velocity D) club-head loft angle E) lateral club-head velocity F) club-head rotation angle.

The number of different ‘key’ individual degrees of freedom identified across the sample varied for each VI (Figure 6.2). For example, only four different individual joint movements were identified as ‘key’ compensatory behaviours influencing club-head resultant velocity at impact across the sample, while 13 different individual joint movements were identified as ‘key’ for club-head vertical velocity (Figure 6.2A).
Figure 6.2  Number of participants for which individual degrees of freedom were identified as playing a ‘key’ role in specific VI compensatory synergies. A) VI’s which influence distance in the golf drive B) VI’s which influence direction in the golf drive.

6.4 DISCUSSION

The aim of the current study was to identify and characterise the individual joint kinematics involved in compensatory relationships that act to reduce variability of club-head kinematics during the golf drive. The individual surrogate analyses acted to remove the contribution of each individual joint motion in isolation in order to assess the role each variable plays in the compensatory behaviour identified in chapter 5. These analyses indicated that the compensatory behaviour influencing each outcome
variable, for each golfer’s swing, appears to be the result of the interactions of two to five individual joint motions. It may be reasonable to consider these individual joint motions as ‘key’ to the ability of a skilled participant in achieving consistent and precise club-head kinematics in the swing. Aside from these few key joint motions it was clear most of the individual joint motions in the kinematic chain do not contribute significantly to the compensatory synergies in the swing.

Similar to the current study, Mills (2007) previously sought to quantify the role of individual degrees of freedom within compensatory synergies in a complex task. Specifically, Mills used an individual surrogate analysis focussing on the individual joint motions involved in coordinating minimum toe clearance in gait. Similar to the current study, the individual surrogate analysis indicated that not all joint degrees of freedom involved in the movement contributed to the compensatory behaviour. However, unlike the few ‘key’ individual joint motions identified in the current study, Mills (2007) found that around half of the individual joint motions involved in the kinematic chain contributed to the compensatory synergies responsible for minimising outcome variability. While it is unclear as to why there were fewer contributing individual joint motions identified in the golf swing, one possible explanation may lie in the complexity of the golf swing. It has been suggested that synergies exist in the organisation of multi-joint motor tasks primarily to reduce the neuromuscular demand by proving a finite number of solutions which will achieve a desired outcome (Shumway-Cook & Woollacott, 2007). It is plausible to suggest that in such a highly complex skill such as the golf swing (Dillman & Lange, 1994), which is practiced less than gait, compensatory synergies require a more simple control, organised by fewer degrees of freedom.

When identifying which individual joint motions were ‘key’ contributors to compensatory relationships within the swing it was apparent that there was a large degree of heterogeneity among the participants tested. For instance, 19 individual joint motions identified as ‘key’ were unique a single participant in contributing to a specific VI. Additionally, a number of individual joint motions appeared to play key roles in the compensatory relationships of less than half of the 10 skilled participants sampled. This individuality within the joint motions involved in compensatory behaviour may be a function of specificity of individual coordination patterns that are formed during initial
motor learning of the swing. This supports previous research that has indicated that there is no single mechanical pattern for expert golfers (Ball & Best, 2007). Considering the evidence against the existence of a single ‘ideal golf swing’ it appears that an individual-based approach would be more appropriate in understanding how optimal performance is achieved by specific golfers. From an applied perspective the results suggest that coaches be cautious when adopting a ‘one size fits all’ approach to mechanical adjustments.

Despite the individuality observed in contributors to compensatory relationships, there were some individual joint motions which appeared as ‘key’ contributors to compensatory relationships across the majority of the sample. Section 6.4.1 will further discuss the individual surrogate analysis, focusing on common 3D movements identified as key to performance.

6.4.1 Common Contributors to Compensatory Synergies in the Swing

A golfer’s ability to influence distance in the golf drive is a consequence of the resultant club-head velocity, centredness of impact, vertical club-head velocity and club-head loft angle at impact (Miura, 2002; Sweeney et al., 2013). In contributing to the compensatory relationships which influence these club-head kinematics, three individual joint motions appeared to play a key role for most of the skilled golfers tested. These individual joint motions were right wrist flexion/extension, right elbow flexion/extension and right shoulder internal/external rotation.

Right wrist flexion/extension specifically was a key to the compensatory relationships influencing resultant club-head velocity at impact. The identification of wrist motion as a critical feature of the golf swing supports the previous golfing literature, which has repeatedly highlighted wrist kinematics as playing an important role in performance. Empirical research has found differences in the timing, magnitude and peak velocity of the ‘wrist-cock’ angle, between golfers of different skill levels (Milburn 1982; Koenig et al., 1993; McLaughlin & Best, 1994; Chu et al., 2010). Additionally, investigations using a simulation approach have indicated that manipulations to ‘wrist-cock’ kinetics and kinematics influence club-head velocity, throughout the downswing (Pickering & Vickers, 1999; Sprigings & McKenzie, 2002; White, 2006). However, the current research is more specific than previous investigations as it shows right wrist
flexion/extension is more important than ulnar/radial deviation in regulating club-head velocity.

Another individual joint motion identified as being critical to the compensatory relationships which influence resultant club-head velocity at impact was right shoulder internal/external rotation. While the identification of right shoulder internal/external rotation as a key variable in the regulation of club-head velocity is novel in the context of the golf literature, it has been shown to be an important contributor to the endpoint velocity in other throwing and hitting tasks (Elliott, Marshall & Noffal, 1995; Elliott, Marshall & Noffal, 1996; Marshall & Elliott, 2000; Van Den Tillaar & Ettema, 2004; Tanabe & Ito, 2007). With respect to golf, some coaches advocate a vigorous ‘turning the wrist close to impact’ to increase the distance in a drive (Hammond, 2010). While this is sometimes referred to as ‘wrist pronation’ by coaches, it could more logically be achieved via internal rotation of the upper arm at the shoulder joint.

Right elbow flexion/extension did not appear to contribute to the compensatory behaviour influencing club-head velocity for many of the participants. However, it was identified as commonly contributing to the compensatory synergies influencing centredness of impact and club-head loft angle at impact. Both of these variables have previously been shown to have an indirect influence on drive distance (Miura, 2002; Sweeney et al., 2013). Traditionally, coaches have recommended that the right elbow is flexed to approximately 90° at the top of backswing and subsequently extended throughout its range in the downswing (Hume et al., 2005; Teu et al., 2006). This potentially large range of movement at the right elbow may explain its influence on the coordination of club-head position and orientation at impact.

The club-head rotation angle at impact can be seen as the greatest influence a golfer can have on the accuracy in the golf stroke (Miura, 2002; Sweeney et al., 2013). This is due to its influence on the lateral direction of the ball, as well as the indirect role it plays in the side-spin imparted on the ball (Sweeney et al., 2013). Pronation/supination at the right elbow was the only individual joint motion which was identified as a critical parameter for more than 50% of the current sample in contributing to club-head rotation angle at impact. This common contribution of elbow pronation/supination to performance is both interesting and novel in the golf literature. The role of elbow pronation has been a focus of tennis researchers (Gordon & Dapena, 2006; King, Glynn
interested in the accuracy and performance. In the golf swing the pronation/supination at the right elbow could work in conjunction with shoulder internal rotation in contributing to the ‘turning the wrist close to impact’ previously mentioned. As no researchers (to the best of our knowledge) have investigated the potential influence of right elbow pronation/supination, the results of the current study suggests that further investigation is warranted concerning the influence of this motion.

With respect to the few common ‘key’ individual joint motions identified above, it is interesting to note their position in the kinematic chain. Specifically, it appeared from the current analysis that the individual motions which were more often identified as ‘key’ tended to be closer to the distal end of the kinematic chain. This fits well with the research of Horan et al. (2011), who reported that substantially greater inter-trial variability of the pelvis and trunk kinematics than that of the kinematics of the hand and club-head during the golf swing. A possible explanation for the location of these common contributors to compensatory behaviour could be that it is during the late period in the swing where most of club motion occurs (Koenig et al., 1993; Nozawa & Kaneko, 2003). With the distal joints in the swing undergoing the greatest movement in the last few milliseconds leading up to ball impact, compensatory adjustments would likely have greater influence on ensuring precision at the club-head kinematics at impact.

6.4.2 Future research directions

The current study has identified the specific joint motions which are responsible for the compensatory relationships influencing performance in the golf swing. A number of the joint motions identified as ‘key’ to compensatory relationships appear to be unique to individual golfers, while others are common across the sample of skilled golfers. While the identification of these key joint motions is important from an applied perspective, further investigation is required into how specific alterations of these motions may influence performance. For example, if the right wrist flexion is identified as a key motion for a particular golfer, it may be that any mechanical improvements suggested by a coach should be based on this individual joint movement. Conversely it may also be harmful to alter the mechanics at this ‘key’ movement as doing so may decrease the efficiency of existing compensatory relationships.
As mentioned in the previous chapter the current research has focused on the compensatory relationships which occur through the left lower limb, pelvis, trunk and right upper limb. Including the right upper limb in this methodological simplification was due to its suggested role in creating power during the swing (Cochran and Stobbs, 1968; Hume et al., 2005), as well as the large magnitude of muscular activation in the right upper limb during the downswing (Jobe et al., 1989; Morgan et al., 1999; Mitchell et al., 2003). Further investigations using similar approaches may consider investigating the role of the left upper limb and potentially provide a more complete understanding of the important kinematics involved in successful golf swing.

Outside of the scope of focus for the current research were the neuromuscular and kinetic drivers behind the coordination of the compensatory behaviour observed in the kinematic chain. The development and application of a kinetic-driven biomechanical model (with joint moments used as inputs) has the potential to provide further insight into the kinetic contributions of individual joints in minimising club-head kinematic variability during the swing. In doing so, such a forward kinetic modelling approach would facilitate a more complete characterisation of compensatory relationships acting to influence performance in the golf swing.

6.5 CONCLUSION

The current study presented a novel method to identify the role of individual joint motions in the compensatory relationships identified within kinematic chain of the golf swing. An individual surrogate analysis revealed that that the majority of the compensatory behaviour contributing to each club-head kinematic variable can be attributed to a small number of individual joint motions (between two and five). These specific ‘key’ joint motions identified as playing dominant roles in contributing to the compensatory relationships, were generally unique across the specific outcome variable of interest, as well as across individuals. However, a small number appeared to be consistently important in the coordination of specific club-head kinematics across the sample. Specifically, for the skilled golfers in the sample right wrist flexion-extension, elbow flexion/extension and shoulder internal/external rotation were all identified as ‘key’ motions in the compensatory relationships affecting distance in the drive.
Additionally, for the majority of participants, right elbow pronation/supination was identified as a critical contributor to the compensatory relationships affecting accuracy in the drive. With the potential importance that compensatory relationships play in the swing, the identification of ‘key’ joint motions, which are the primary contributors to these relationships provides important insight into how skilled golfers repeatedly achieve success in such a complex task.
Chapter 7

General Summary

7.1 SUMMARY

The overriding theme of this thesis has been aimed at identifying biomechanical factors that influence performance in the golf swing. Before this could be accomplished, it was necessary to address the methodological issues associated with collection, processing and interpretation of kinematic data, at and around the time of club-head-ball impact. This was achieved in the first study through comparing the kinematics produced when swinging at a golf ball compared with swinging at a target of negligible mass. The results of study 1 demonstrated that impact between the club-head and golf ball had a sudden and dramatic effect on club-head kinematics, whereas the kinematics of the golfer were not significantly altered. As the pre impact kinematics in both conditions showed no difference, a subsequent validation of methods for the estimation of impact kinematics was carried out. The results showed that an extrapolation/interpolation method based on 12.5 ms of pre impact data was the most accurate of those tested for estimation of club-head kinematics at impact.

Incorporating the methodological protocols examined in study 1, study 2 aimed to quantitatively define the influence of individual club-head kinematics on subsequent ball flight characteristics. Quantifying these relationships is of theoretical and applied importance, as the club-head is the most distal segment in the golfer-golf club kinematic chain and therefore represents the summation of performance directly controlled by the golfer. Each initial ball flight characteristic analysed in study 2 (resultant velocity, launch angle, side angle, back spin and side spin) was well explained by the kinematics of the club-head at impact (adjusted $r^2 = 0.71-0.82$). With respect to club-head kinematics; the resultant velocity, vertical velocity, lateral velocity, loft angle, rotation angle, as well as the centredness of impact, all played a significant role in dictating at least one initial ball flight characteristic.

In study 3 the role of movement variability during the swing was explored as it was related to club-head kinematics identified in study 2 as being linked to skilled
performance. To achieve this, a Forward Kinematic Model (FKM) was created, driven by empirical data, which allowed Random Sensitivity Analysis (RSA) and individual surrogate analyses to be carried out. The simulated removal of any compensatory relationships within the individual joint kinematics of the swing resulted in significantly greater variability in each of the club-head variables analysed. These results suggest that movement variability within the kinematic chain of skilled golfers, acts in a compensatory manner which allows low levels of outcome variability to be achieved. This identification of compensatory behaviour in the swing supports the assertions made by other researchers in the field, that movement variability plays an important role in allowing skilled golfers to achieve consistently high performance.

In order to investigate the role specific individual joint kinematics play in compensatory behaviours (identified in study 3) an ‘individual surrogate’ approach was employed in study 4. This analysis is a continuation of the RSA approach and effectively assessed the contribution of each specific joint motion, in isolation, towards the compensatory relationships found in study 3. It was apparent from the results that not all individual joint motions in the kinematic chain significantly contribute to the compensatory relationships influencing performance in the skilled golf swing. In fact, the number of individual joint motions that were found to contribute compensatory relationships for each club-head variable was between two and five. Some of these specific joint motions contributing to each compensatory relationship appeared to be common across the sample of skilled golfers. In particular, right wrist flexion/extension, elbow flexion/extension and shoulder internal rotation were all found to play a ‘key’ role in minimising variability in the club-head kinematics associated with distance in the drive across the players tested. Additionally, right elbow pronation/supination was identified as a common contributor toward compensatory behaviour influencing club-head kinematics associated with accuracy in the drive. However, despite identifying some common ‘key’ joint motions, it was apparent that the specific joint motions contributing to compensatory behaviours in the swing were largely individual to each golfer. This individuality suggests that many of the specific mechanical factors, that are critical in achieving consistent success in the swing, may be unique to each golfer.
7.2 APPLIED IMPLICATIONS

There are a large number of practical implications from the findings presented in this thesis. In study 1 it was demonstrated that the impact between the club-head and the ball results in a rapid and substantial change in club-head kinematics. While this finding is important from a methodological perspective, it also provides valuable background to the current general research discussion on the timing of peak endpoint velocity in hitting tasks. In particular, a contentious issue has been the disparity between the coaching point of ‘accelerating through impact’ (common to many hitting tasks) and the assertion of previous researchers that the club-head decelerates in the lead up to impact (Plagenhoef, 1971; Welch, Banks, Cook & Draovitch, 1995; Williams & Sih, 2002). In addressing this disparity, some authors have suggested that the pre impact deceleration observed by previous researchers is a symptom of smoothing data through the impact event (Levanon & Dapena, 1998; Nunome, Asai, Ikegami & Sakurai, 2002; Tabuchi et al., 2007). In particular, inappropriate smoothing through a period where there is a dramatic perturbation is likely to lead to artefact such as a pre impact decrease in velocity that does not occur empirically (Knudson & Bahamonde, 2001; Nunome, Lake, Georgakis & Stergioulas; 2006). The results from the current research, in conjunction with the findings of Sweeney, Alderson, Mills and Elliott (2009b), suggest that skilled golfers continue to increase velocity up until contact with the ball. It is important to note that ‘acceleration’ through impact does not occur due to the effect of the club-ball collision. However, as the coaching recommendation of ‘accelerating through impact’ is intended to avoid players reducing in their efforts prior to impact, it may have merit in ensuring maximal velocity is achieved at the moment of the club-ball collision.

An understanding of how of the club-head parameters at the time of impact influence ball flight kinematics is of major importance to the golfing fraternity. While some anecdotal reports have previously attempted to outline the influence of specific club-head kinematics on subsequent ball flight parameters (Wiren, 1990; Hay, 1993; Miura, 2002), an important role of the current research was to quantify these relationships. The results of study 2 support many previous anecdotal claims as well as providing some valuable clarifications from an applied perspective. For example, the analysis performed in study 2 highlighted the significant role centredness of impact plays in
determining resultant ball velocity. In particular, a more centred impact on the club-face was related to a higher subsequent ball velocity. This is important as the centredness of impact is sometimes overlooked by coaches as an important determinant of drive distance.

Another important focus of study 2 was to quantify the club-head kinematics that determine the lateral path of the ball in flight. Hay (1993) had suggested that the lateral direction of the ball was determined by both the orientation and path of the club at impact. However, Miura (2002) proposed that the orientation of the club-head at impact was the primary factor in determining the initial lateral direction of the ball. The results from the current studies support these claims, in that club-head orientation was the primary predictor of the lateral ball path. While it may not be advisable to exclude the potential role of the club-head path, it is important for coaches and players to note that the rotation angle of the club-head at impact appears to play the principal role in dictating shot accuracy.

A major finding of study 3 was the non-random nature of the movement variability within golfers’ joint kinematics when performing the swing. Specifically, it is clear that skilled golfers have the ability to compensate at specific degrees of freedom for the kinematic variability occurring in other joints. These compensations allow players to maintain a consistently high performance at the endpoint of the system, whilst permitting some variability at the individual joint level. This seemingly important functional role of movement variability is likely to be novel to coaches, as it is common practice to either ignore the role of variability entirely, or strive for invariance within the individual mechanics of the swing. Providing golf coaches with a greater understating of the role variability plays in the swing may be critical in allowing them to make more informed mechanical recommendations to golfers.

Evident from the final study of this thesis was that of numerous joint motions involved in execution of the golf swing, a small number of these appear to consistently play the primary role in dictating inter-swing consistency in club-head kinematics. Some specific joint motions found to contribute to compensatory behaviour, were common across the skilled golfers sampled, though most were individual to specific golfers. With respect to common individual joint kinematics, right wrist flexion/extension, elbow flexion/extension and shoulder internal/external rotation were found to
commonly contribute to compensatory behaviour influencing ball drive distance. Right elbow pronation/supination was the individual joint motion shown to contribute most commonly to the compensatory behaviour influencing drive accuracy. The identification of these few common key joint motions may be helpful for coaches, assisting them to distinguish which aspects of the golf swing are likely to play a critical role in efficient swing execution.

Aside from the few common joint kinematics mentioned above, the individuality evident in the compensatory behaviours of each participant provides further evidence against the existence of one ‘ideal’ or ‘perfect’ swing motion. This individuality in key joint kinematics also highlights the potential importance of identifying specific joint motions which are critical for each golfer’s performance. For example, if right elbow pronation/supination is a key joint rotation for a specific golfer, a coach may wish to focus their attention on how this movement differs between successful and unsuccessful swings, as well as how elbow pronation/supination appears to interact with (or compensate for) other joint motions in the swing.

### 7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

A common and important by-product of research is to facilitate and shape future directions of enquiry. The current thesis has answered a number of critical methodological questions and acts as an important resource for future investigators. Additionally, the current group of studies highlights specific aspects of the swing which require future investigation in the pursuit of a more complete understanding golf swing mechanics and its influence on performance.

From a methodological perspective, this research has established that certain methods for estimating club-head data at impact (e.g. filtering data across the time of impact) may result in significant inaccuracies in data estimated to occur at impact. Of particular concern is that such inaccuracies are not likely to be random in nature. For example, any club-head kinematic calculated as a product of filtering data through impact, would likely be confounded by the centredness of impact, as this is known to have a large influence on club-head kinematics post impact (Williams & Sih, 2002; Ellis et al., 2010). For future researchers, it is recommended that an extrapolation/interpolation
technique using approximately 12.5 m/s of pre impact data, be employed to calculate club-head kinematics at impact. In contrast to data at the club-head, it kinematics of the golfer’s body are not significantly affected by impact. Therefore raw motion data collected from the golfer’s body is able to be filtered around impact without the same concerns as when dealing with club-head data.

With the link between club-ball impact parameters and golf drive performance being quantitatively established in study 2, future researchers are able to focus on the factors that might affect important club-head variables. Also, while the results of study 2 support the previous use of club-head velocity as a major performance indicator (Fradkin et al., 2004; Gordon et al., 2009; Keogh et al., 2009), they also highlight the role of other club-head kinematic variables in both creating distance and accuracy in the golf drive. To ensure a broader understanding of the factors affecting performance, it is recommended future researchers include a broad range of club-head kinematics in their analyses; including variables such as club-head orientation and path, as well as centredness of impact.

The FKM/surrogate approach employed in this thesis is novel to the golf swing and has provided a number of possible directions for future research. With respect to providing a more comprehensive understanding of the compensatory behaviour in the swing, it is recommended that further investigations include an analysis of the left upper limb. While the role of the left upper limb is often described as to ‘guide the swing’, it is important for future research to aim for a bilateral understanding of how distance and accuracy are created. It is also important to note that the current sample population (male golfers with a sub-10 handicap) and particular club chosen (driver) for the analyses were specific. Consequently, there is scope for future analyses to be performed across genders and skill levels, as well as different types of golf shots (e.g. irons, wedges, chipping and putting). Such analyses have the potential to develop a broader understanding of the role that individual joint rotations play in golf.

It is also recommended that future research focus on defining the specific manner in which some of the particular common ‘key’ joint motions (identified in the final study) influence performance. For example, while it is clear that right elbow flexion/extension plays an important role for most golfers in coordinating performance, the pedagogical approach to learning or modifying swing mechanics are unknown. Research able to
provide a meaningful understanding how specific mechanical alterations will influence the swing would be of perhaps the greatest theoretical and applied importance for the golfing community.

7.4 CONCLUSION

On the basis of the results obtained in this thesis it was concluded that:

- Filtering and/or interpolating through impact may be appropriate in the calculation of golfer’s joint kinematics [Study 1].
- Any attempt to represent ‘impact’ club-head kinematics should avoid the use of club kinematic data collected post impact [Study 1].
- An approach involving extrapolating approximately 12.5 ms pre impact data through the impact phase, followed by interpolating data to ‘virtual impact’ is an accurate method for estimating club-head kinematics occurring at the first point of impact [Study 1].
- Resultant ball velocity in the golf drive is largely determined by the velocity of the club-head at impact, as well as the centredness of this impact on the club-face [Study 2].
- The launch angle of the ball during early flight of the drive is determined by the orientation, path and centredness of the club-head at impact [Study 2].
- The greatest determinant of resultant side angle of the ball in the golf drive is the orientation of the club-head at impact [Study 2].
- Both back spin and side spin of the golf ball in the drive are largely determined by the misalignment between the orientation and the path of the club-head at impact [Study 2].
- Outcome variability in the skilled golf swing is minimised through compensatory relationships that exist within the individual joint motions involved in the kinematic chain [Study 3].
- The majority of the compensatory behaviour contributing to each club-head kinematic variable can be attributed to a small number of individual joint motions (between two and five) [Study 4].
Of the individual joint motions which contribute to compensatory behaviour in the swing, a small number of appeared commonly across skilled golfers (right wrist flexion/extension, elbow flexion/extension, elbow pronation/supination and shoulder internal/external rotation). However most individual joint motions ‘key’ to compensatory behaviour were individual to specific participants [Study 4].
References


135


Appendix

Participant Consent Form
Segmental influences on the performance of the golf swing

— Consent Form —

I ____________________________ have read the information provided and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason and without prejudice.

I understand that all information provided is treated as strictly confidential and will not be released by the investigator unless required to by law. I have been advised as to what data is being collected, what the purpose is, and what will be done with the data upon completion of the research.

I agree that research data gathered for the study may be published provided my name or other identifying information is not used.

________________________  _______________________
Participant                      Date

The Human Research Ethics Committee at the University of Western Australia requires that all participants are informed that, if they have any complaint regarding the manner, in which a research project is conducted, it may be given to the researcher or, alternatively to the Secretary, Human Research Ethics Committee, Registrar's Office, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009 (telephone number 6488-3703). All study participants will be provided with a copy of the Information Sheet and Consent Form for their personal records.