Is Movement Variability Relevant for the Elite Golfer? A Biomechanical and Modelling Perspective

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I dedicate this thesis to my parents. Everything positive I’ve ever achieved has been due to your unconditional love and support. You have been the best supporters and mentors I could ever have asked for. I know I am very lucky to have you both.

Thank you
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ABSTRACT

Movement variability, while being a topic discussed extensively throughout the movement sciences, is still not understood. The effect of movement variability on outcome has not been ascertained. In particular, there has been a dearth of research investigating movement variability in the golf swing. The objective of this thesis was to investigate the effect of movement variability on outcome and outcome variability. Using experimental methods, the initial aim of this thesis was to quantify movement variability of sixteen participants and investigate the relationship between the quantified movement variability and outcome variability in the golf swing. The results indicated no statistically significant relationship between movement variability and outcome variability either in the backswing or downswing phase of the swing. Following this, modelling methods were used in the investigation of movement variability on outcome in the golf swing. Firstly, a computer model of a participant’s golf swing was created and validated. Then a method to apply movement variability at single anatomical points to the computer model was developed. Subsequently, different levels of movement variability were applied to single anatomical points in the computer model. The results revealed there was no practical effect on outcome. In order to investigate movement variability of measures more complex than single anatomical points, the final stage of this thesis investigated the movement variability of a multi-segment measure, torso-pelvic separation angle. Torso–pelvic separation angle was quantified for all sixteen participants. The results revealed no significant relationship between movement variability in this measure and outcome variability. Applied movement variability in this measure to the validated computer model created previously, revealed no practical effect on outcome. Collectively, the results of this thesis indicate that movement variability has no effect on outcome beyond the natural variation range of the participant at the elite level of performance. These findings have implications for coaching the golf swing in that it is important for golf coaches to understand the effect of variability relative to shot outcome for each individual. At the elite level, advocating an invariant swing may not lead to a more consistent shot outcome.
AUTHOR’S DECLARATION

I hereby declare that the work contained within this thesis is my own work, and was completed without collaboration or assistance from others, apart from the counsel received from my supervisors, Dr Ross Anderson and Dr Ian Kenny of the Physical Education and Sport Sciences Department, University of Limerick. This work also has not been submitted to any other University or higher education institution, or for any other academic award within the University.

________________  __________________  __________________
Catherine Tucker  Dr Ross Anderson  Dr Ian C Kenny
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GLOSSARY OF TERMS AND ACRONYMS

Movement variability is the variation in kinematic measures over repeated performance of a motor skill.

Outcome variability is the variation in performance outcome measures.

**DST** – Dynamical systems theory

**SD** – Standard deviation

**CV** – Coefficient of Variation

**SSC** – Stretch Shortening Cycle

**ADD** – Address

**TOB** – Top of the backswing

**IMP** – Impact

**DOF** – Degrees of freedom

**FT** – Follow through

**SS** – Spanning Set

**VC** – Vector Coding
1.0 THESIS INTRODUCTION

In analysing and measuring the performance of a motor skill, it is instructive to break the observation of the skill into two levels of performance; performance production measures and performance outcome measures. Performance production measures refer to a group of motor skill performance measures that provide an indication of the performance of aspects of the motor control system while performing an action (e.g., kinematic patterns, kinetic patterns, force production etc.) whilst performance outcome measures refer to a group of motor skill performance measures that provide an indication of motor skill outcome or result (e.g., distance travelled by golf ball, deviation from target line of a golf shot) (Magill 2007). The determination of the most influential performance production measures on performance outcome is important in order to inform coaching techniques. For the purposes of this thesis, movement variability refers to variation in performance production measures (i.e. limb kinematics). Outcome variability refers to variation in performance outcome measures (i.e. ball velocity).

Human movement is inherently variable and there has been much research directed at this concept (Hamill et al. 1999, Wilson et al. 2008). Movement variability is a term that refers to variations in performance production measures across multiple repetitions of a task (James et al. 2000). Previously, this variability of movement has been interpreted as detrimental to performance outcome and linked to dysfunctional aspects of human performance and pathology (Hausdorff et al. 1997, Crowther et al. 2008a, Crowther et al. 2008b) and therefore something that needs to be minimised (Slifkin and Newell 1998). With increasing research into this facet of human movement, this perspective has changed and it has been postulated to be beneficial to human movement (Davids et al. 2003) and injury risk reduction (Pollard et al. 2005). The advent of dynamical systems theory has changed this perspective where variability of movement is seen as a necessary mechanism to allow the system to have a variety of movement responses. Thus, this allows the system the ability to adapt to changing environmental constraints (Davids et al. 2003).

When the numerous constraints, such as environmental, morphological and task constraints (Higgins 1977) that interact on the human system are considered, a completely invariant movement pattern within an individual is not likely. Further, a common optimal movement pattern between individuals is not likely either given the individual-specific nature of these constraints. This is not to say all variability of
movement is beneficial, but as Hamill et al. stated in 2006 (p.154), ‘the actual role of variability in movement is currently a significant question being addressed in the movement sciences’.

To be successful in a sport such as golf requires that the player produces consistent performance outcome. To have this consistent outcome requires that the club head dynamics at ball impact are as invariant as possible. It is not known how movement variability during the swing and outcome variability are related due to a lack of research in this area. If it is unknown whether movement variability is beneficial or detrimental to outcome (e.g. shot accuracy in golf), then it can be difficult for a coach or clinician to advise a client on how to improve an incorrect movement pattern. Consequently, movement variability has been targeted as an important area to research in the golf swing (Williams and Sih 2002). Therefore, it is necessary to address the topic of movement variability in more detail.

1.1 THESIS AIMS

The main aim of this thesis was to investigate the relationship between movement variability and movement outcome in the golf swing. From the literature review presented in Chapter 2, it is evident that there is a limited amount of research investigating movement variability in the golf swing.

Initial investigations were focused on using a typical group-based experimental approach to quantify and examine movement variability in the full golf swing across a group of category one (handicap ≤ 5) participants. The relationship between movement and outcome variability was examined.

The majority of research in the area of movement variability has been conducted through analysing the movement patterns of “real” subjects. A limitation of this technique is that the amount and type of variability within a movement pattern cannot be controlled due to the inherent variability within human subjects. This prevents the ability to establish a deterministic relationship between movement variability quantified and movement outcome. Thus, it is proposed to explore the use of computer modelling to create ‘virtual’ subjects in conjunction with traditional experimental methods in order to investigate movement variability in the golf swing. Modelling offers the ability to impose artificially controlled amounts of variability on a specific data stream and assess
the outcome. Through application of this technique along with the movement variability quantified in experimentation, the aim is to identify the parameters that when varied, have the most influence on the outcome of the golf swing (e.g. club head velocity/orientation). The advantages and limitations of modelling and simulation are presented in Chapter 2.

Following this experimental approach, the modelling approach was pursued focusing on an individual analysis based on the results of the experimental approach. As the models are driven by positional data, the initial investigation into variability was directed at movement variability of positional data. Subsequently, the next step was to investigate movement variability of a multi-segment coordinative measure relevant to golf swing performance.

The relationship between movement variability and movement outcome is not understood. More specifically, movement variability in the golf swing is less understood. To the author’s knowledge, there exists little previous research that used modelling and simulation methods to examine movement variability and in particular movement variability of the golf swing. These factors provided the impetus behind this thesis.

1.2 THESIS STRUCTURE AND OUTLINE

This thesis consists of a general literature review, one methodological study, three sequential studies, a model development and validation chapter, two calculation technique development chapters, and an overview of the future work planned as part of this project. Each study is presented in manuscript format; each containing its own individual introduction, methods, results, discussion and conclusions. A number of the studies also appear in shorter form as publications in Appendix A1.

Figure 1.1 illustrates the inter-connectivity of the four core thesis sections along with the flow of information. A brief description of each section and their objectives follows.

- **Section One**: This section provides a detailed review of relevant literature related to movement and outcome variability, current understandings of the golf swing and computer modelling and simulation methods. This section also
incorporates the examination of a number of methodological issues pertinent to the studies of subsequent sections.

- **Section Two:** In this section movement variability is examined in a cohort of highly skilled participants. This section incorporates the development of a method to quantify movement variability and subsequently examines whether there is a relationship between the movement variability quantified and shot outcome variability.

- **Section Three:** Following on from section two, an individual-based analysis is undertaken using alternative methods to the experimental approach. This section details the application of movement variability, quantified in section two, to a validated computer model of the golf swing of one participant and the associated effect on shot outcome in order to ascertain what parameters, if any, affect shot outcome for that individual.

- **Section Four:** This section combines both the experimental work of section two and the modelling work of section three by investigating the movement variability of a coordinative measure and the effect of variability in this coordinative measure on shot outcome.
The brief thesis outline, by chapter, is as follows:

- Chapter 2 provides a thorough, critical review of current scientific literature relating to movement variability, past and current theoretical understandings of movement variability, current understandings of the full golf swing, computer modelling and simulation methods and their application to golf swing research.
- Chapter 3 details certain methodological issues that were considered necessary to investigate prior to undertaking subsequent studies. This covered the validation of the motion capture system and the launch monitor device used.
- Chapter 4 details the development of a calculation technique to quantify movement variability of marker trajectories in the golf swing.
- Chapter 5 utilises the method developed in Chapter 4 to quantify movement variability of marker trajectories in different phases of the swing and subsequently examine the relationship, if any, between the movement variability quantified and outcome variability.
- Chapter 6 involves the creation and validation of a computer model of an elite female performing a golf swing. Within the chapter, a detailed account of the process involved in model construction, validation and simulation is provided and discussed.
- Chapter 7 provides a detailed account of the process involved in developing a technique to create data sets based on the natural movement variability at specific anatomical landmarks of a participant to the computer model created in Chapter 6.
- Chapter 8 details the application of movement variability at specific anatomical points of the computer model developed in Chapter 6 in order to determine the effect on a shot outcome measure.
- Chapter 9 reports on the analysis of movement variability of a multi-segment measure (torso-pelvic separation angle) in the golf swing and its relationship with outcome variability. It also details an individual-based analysis involving the application of movement variability to the torso-angle separation angle of the participant.
- Chapter 10 provides general thesis conclusions, implications and recommendations for future analysis and research in this area.

### 1.3 REFERENCES


2.0 ABSTRACT

The purpose of this chapter is to provide a critical review of the literature relating to movement variability, current understandings of the golf swing and computer modelling and simulation methods. A detailed review of movement variability literature is provided, highlighting the different perceptions of movement variability from various motor control theories and the change in how movement variability is viewed currently. The golf swing is the motor skill on which the assessment of the effect of movement variability is focused. Therefore, a review of current understandings of the golf swing is presented with particular emphasis on movement variability and understandings of single-subject analysis. The advantages offered by computer modelling and simulation are highlighted in terms of how movement variability can be examined. An extensive review of computer modelling approaches with particular emphasis on modelling of the golf swing is presented. This review was undertaken to inform and underpin future decisions in the thesis with regard to the type of modelling approach to undertake to allow investigation of the research question and to best represent the golf swing.

2.1 SCOPE AND STRUCTURE

The literature review is divided into four major parts. The first part details movement variability, its definition and considerations of the role of movement variability. Research pertaining to movement variability in the clinical and sports setting is presented and critically analysed. The second part details golf swing analysis, the main focus of kinematic research in the golf swing and movement variability research in the golf swing. The third part introduces the concept of computer modelling and simulation, its advantages and limitations and different modelling approaches are described. The development of modelling and simulation research of the golf swing is also detailed. The fourth and final part summarises the main conclusions from the literature review and the direction for research in this thesis.

A thorough literature search was performed by searching the following databases (PubMed, Science Direct, Sports Discus, Medline and Google Scholar) with the key words “movement variability”, “outcome variability”, “sport”, “golf swing” “clinical” “pathology” “biomechanical modelling” “simulation”, “biomechanics” in various combinations. Additionally, citations were followed up when they appeared to be relevant to the topic of movement variability and the golf swing. Further sources of
information were the “Science and Golf”, “The Engineering of Sport” and “The International Society of Biomechanics in Sport” conference proceedings.

2.2 MOVEMENT VARIABILITY

2.2.1 What is Movement Variability?

In statistical terms, movement variability can be defined as the variance of the data about the mean and is typically quantified in terms of the square root of the variance, i.e. the standard deviation (Riley and Turvey 2002). In more general terms, it can be described as variations in motor performance across multiple performances of a task (James et al. 2000).

2.2.2 Considerations of Movement Variability in Motor Control Theory

2.2.2.1 Movement Variability as Detrimental

Traditionally, movement variability has been viewed as error or a property of movement to be minimised or completely eradicated from a movement pattern in order to achieve a more consistent outcome (Glazier et al. 2006). This perspective arose from the application of motor control theories which were heavily influenced by engineering and computer sciences. The main theory was that of the existence of a “motor programme” that contained all the information necessary for the execution of a particular movement pattern. From a speed-accuracy trade-off information processing model, three sources of impulse variability (or error) were suggested by Schmidt et al. (1979) with the three proposed sources being:

i. Selection of an incorrect motor programme for the given task (this being a central command error)

ii. Incorrect scaling of the parameters responsible for executing the programme (this is a central or peripheral error or both)

iii. The presence of random noise in the system during programme execution (this is a peripheral error)
Thus, this information processing perspective views a performer as some form of human communications channel whereby the input signals and output of the system have a relationship that is linear and deterministic (Button et al. 2006). From this theoretical viewpoint of signal processing, variability is viewed as a problem of system control (Silfkin and Newell 1998) or as producing movement inaccuracy (Schmidt et al. 1979). Variability in the signal that produces the outcome is therefore viewed as noise and erroneous. Through this view of a human performer, this noise can be eliminated through experience of the task and practice of the task in question.

It was assumed that high variability in outcome measures of a skill was accompanied by high level of movement variability that produced the outcome measures (Glazier et al. 2006). Since the most skilled performers typically exhibit low variability in the outcome (task criterion), it was thought that this was associated with invariance in the movement pattern that produced the outcome. Thus, variability is viewed as detrimental to normal function.

2.2.2.2 A Changing Perspective on Movement Variability

The previous section details the interpretation of movement variability with respect to certain motor control theories. As can be seen, these theories are influenced by engineering and control concepts. They propose a one-to-one mapping between motor commands and the following motor output and as such, variability in the movement is viewed as noise in the system which is random. There was a distinct dearth of literature up until this point (prior to 1967) that measured and documented variability in human movement. Thus, the aforementioned theories had not been fully substantiated through experimental findings.

It was the work of Bernstein (1967) that was one of the earliest pieces of research that quantified movement variability in the context of a hammering task. Through studying the trajectory of the hammer, Bernstein (1967) found that there was large trial-trial variability present in the trajectory of the hammer despite the end point being invariant at the point of impact. From this work, it was suggested that the same motor solution, in this case, the end point of the hammer, could be produced from variable trajectories. In order to lend some explanation to these findings in his work, Bernstein speculated that it may be through the many degrees of freedom (DOF), which are of course inherent in biological systems (Newell and Corcos 1993), that this observed movement variability
arises. Indeed Bernstein believed that there could not possibly be any unambiguous, straightforward relationship between the nervous impulses and movement produced due to the fact that initial postural conditions, inertia and reactive forces combine with active muscles forces to produce any movement (Turvey 1990). Thus, Bernstein dismissed previous theories that advocated a one-one mapping of motor commands and the associated motor output. Bernstein coined the phrase, “the degrees of freedom problem” to describe the coordination conundrum that the human system has to solve to satisfy the movement outcome. The problem is that there are so many degrees of freedom available that the system has to reduce the number of independent variables to be controlled. Coordination is defined as the patterning of limb and body motions relative to that of events and environmental objects (Magill 2007).

Work by Arutyunyan (1968, 1969) examined aiming accuracy in pistol shooting in expert and novice marksmen. These studies found that the experts had low variability in the spatial orientation of the barrel of the gun compared to the non-experts. However what was interesting was that these expert performers had increased variability in their arm movements, specifically at the shoulders and elbows but not at the wrists. This increased variability at these joints was not apparent in the non-experts. This provided some evidence that demonstrated the existence of compensatory movements by experts in their efforts to stabilise the position of the gun barrel. This study was welcome in that it began to examine both movement variability and outcome variability in an effort to examine the link between them. Collectively these studies by Arutyunyan (1968, 1969) and Bernstein (1967) were extremely important in the context of understanding movement variability and the link to movement outcome. They cast doubt on the previous view from motor programme theory of movement variability as detrimental to the outcome of a movement pattern.

Motor equivalence refers to an end result that can be produced by a variety of joint revolutions and specific muscular contractions (Sporns and Edelman 1993). The findings by Bernstein (1967) and Arutyunyan (1968, 1969) displayed evidence of a motor equivalent effect, in that the end point variability remained low despite variable movements being produced.

Both the work of Arutyunyan (1968, 1969) and Bernstein (1967) were excellent in terms of allowing a more thorough understanding of variability in human movement. Both authors examined the movement variability present and the outcome variability (end-
point variance). It is important that not just the movement variability or outcome variability are quantified and examined in isolation, but they are considered simultaneously in order to examine the relationship, if any, between them.

2.2.2.3 The Application of Dynamical Systems Theory to Movement Analysis

The findings of Bernstein (1967) and Arutyunyan (1968, 1969) provided evidence that previous motor control theories did not account effectively for variability present in a movement pattern. The movement variability observed in these studies did not appear to lead to more variable outcome. Thus it is possible that this movement variability is functional and beneficial as it was possible for a variable movement pattern to produce a consistent outcome. The narrow viewpoint of the theories didn’t allow movement variability to be any way beneficial to a movement outcome and as such is considered erroneous.

Dynamical systems theory (DST) is the study of systems that change over time (Walter et al. 1993). More specifically it is a theory that encompasses numerous areas such as mathematics, physiology, biology, chemistry and psychology to describe systems that are constantly evolving and changing (Williams et al. 1999). In complex dynamical systems, their different organisational states change in response to internal and external pressures (Williams et al. 1999). Thus considering the human system as a complex dynamical system means that the generation of movement patterns involves many factors. Movement patterns are then the result of individual neural pathways and muscles working collectively in what are termed coordinative structures. These coordinative structures are functionally specific collectives of joints and muscles that the neural system constrains to act in a cooperative fashion to produce an action (Magill 2007). DST proposes that movement pattern variations are attributable to the systems response to local and global perturbations (Kurz and Stergiou 2004). The application of nonlinear analyses, specifically that of DST, to analyse human movement has allowed a better understanding of variability in human movement. Indeed, DST considers variability to be a theoretical issue that is deserving of further study in its own right (Davids et al. 2003). This theory proposes that movement patterns self-organise and emerge from numerous interactions of a dynamical nature between many task, environmental and organismic constraints imposed upon the system. Higgins (1977) defined the constraints imposed upon the system as biomechanical, morphological and environmental. Operating above these constraints is the task constraint, which is the
most influential constraint of movement that one attempts to optimise. These are interdependent constraints which also interact with previous experiences to produce the future movement pattern. Newell (1986) cited in Davids et al. (2003), schematically illustrated the interactive nature of the constraints on the system as can be seen in Figure 2.1. In this illustration, the interaction of how the task, environmental and organismic constraints interact to produce a movement pattern is highlighted.

Figure 2.1 – Newell’s Model of Interacting Constraints. Taken From Davids et al. (2003).

2.2.3 Movement Variability Research

The goal of sports biomechanics is to reduce injury and improve performance (Bartlett 1999) and as such movement variability has been examined in the literature from both these perspectives. Further, from the clinical biomechanics perspective movement variability has been also researched with respect to pathology.

2.2.3.1 Injury Research and Movement Variability

Considering the nonlinear approach to studying movement variability, much research has been directed at the concept of injury. Indeed, an injury-variability hypothesis has been suggested in that variability may be beneficial. The hypothetical benefit of increased variability is that may allow a broader distribution of stresses across the tissue and so reduce the risk of chronic damage to the musculoskeletal structures (James 2004).

James et al. (2000) examined the injury-variability hypothesis discussed previously by conducting a study which compared the variability of a number of joint moment characteristics of healthy (n=10) and injury prone (n=10) subjects in a controlled vertical landing activity. The study measured variability in the initial landing phase of
the moment peak, time to peak and impulse values of the ankle, knee and hip joints across ten trials for each subject. The subjects performed ten landings from a platform set at three different heights (50, 100 and 200% of their respective maximum vertical jump (MVJ)). Differences between the groups were observed when a multivariate analysis of variance (MANOVA) statistical test was carried out on the results; however the direction of the differences between the groups were inconsistent. The results were not absolutely consistent with the variability-injury hypothesis, that the injury prone group would be less variable than the healthy group. Variability of the peak ankle joint moment for the 100% MVJ was greater for the injury prone group compared to that of the healthy group thus contradicting the injury-variability hypothesis. Conversely, the variability in time to peak ankle joint magnitude was greater for the healthy group compared to the injury prone group at 50% MVJ which supports the injury-variability hypothesis. When all heights were considered collectively, variability in a linear combination of the variables indicated group differences using the MANOVA. However follow-up analysis of this failed to detect any differences for individual joint moment variables or indeed the direction of the differences. Taking the results collectively, the hypothesis could not be supported nor refuted. Whilst this was a novel approach to validate the injury-variability hypothesis, it may be that the analysis of discrete measures, e.g. peak ankle moment, did not capture the entire movement pattern. Perhaps the analysis of a continuous measure of variability such as those used by Hamill et al. (1999) might have been more insightful as variability over the whole movement pattern would have been quantified.

Hamill et al. (1999) used a dynamical systems theory (DST) approach to examine movement variability as quantified using the Continuous Relative Phase (CRP) of various lower-extremity couplings. This study compared the movement variability of healthy, non-injured subjects and injured subjects who suffered from patellofemoral (PFP) pain while running on a treadmill at three different speeds, 2.5, 3.0 and 3.5 m.s⁻¹. Variability of the normalised CRP ensemble curves was calculated using the standard deviation (SD) of each point on the curve and quantified using the average SD over the complete movement; being either the support phase of the movement or the complete movement cycle. The main finding of this particular study was that asymptomatic healthy individuals consistently displayed more variability than symptomatic PFP individuals. The phase of the stride which displayed the greatest difference in CRP variability was the swing phase in which the PFP subjects had lower variability for all four couplings examined as can be seen in Figure 2.2. The findings of this study
demonstrated that the application of a DST approach can extract interesting findings which challenge previous thoughts on variability and injury. In this case, if one took the traditional viewpoint of higher movement variability being indicative of the pathological condition, one would expect the PFP subjects to display greater variability than their non-injured counterparts. It could be speculated the lower variability in the PFP patients could have an inflexible pattern of movement that could in theory be producing the pathological condition in this group or indeed it may simply be an adaptation to the pain caused by the condition.

Figure 2.2 – Comparison of CRP variability for 4 different lower limb couplings between a healthy and PFP subject highlighting the increased variability for the healthy subject in the couplings analysed. Taken from Hamill et al. (1999).

Heiderscheit et al. (2002) also examined movement variability in PFP impaired (n=8) and non-PFP (n=8) impaired individuals running at a fixed speed (2.68 m.s⁻¹) and at their preferred speed. Similar to the study of Hamill et al. (1999), they examined coordination variability of lower-limb couplings, but using a different technique to quantify this variability due to problems with CRP when studying non-sinusoidal motion. A modification of the vector-coding (VC) technique proposed by Sparrow et al. (1987), was used to quantify the intra-limb couplings. Vector coding is a technique used to quantify coordination from variable-variable (e.g. angle-angle) plots (Glazier et al. 2003). Stride length variability was also quantified for each group. When running at
their preferred speed, the PFP group displayed more stride length variability than the non-PFP group. The authors had hypothesised that there would be no difference between groups for this particular variable but it is in keeping with the findings of the previous research into stride characteristics in people at risk of falling (Hausdorff et al. 1997) and Parkinson’s patients (Hausdorff et al. 1998). With respect to the coordination variability results for the joint couplings there were no observable differences between the groups over the entire cycle. When the entire cycle was divided into five different phases, it revealed a group difference in thigh rotation/leg rotation coupling with PFP group showing reduced variability in this coupling which was in agreement with the findings of Hamill et al. (1999). It is possible that this was a mechanism compensating for the pain prior to the heel strike event.

Pollard et al. (2005) conducted a study which examined movement variability in male and female subjects performing an unanticipated cutting manoeuvre task. As females have a much higher reported risk of non-contact Anterior Cruciate Ligament (ACL) injury than males (Ireland 1999), the coordination variability of the male (n=12) and female (n=12) joint couplings in the lower limb were calculated and compared. The authors calculated coordination variability utilising the vector-coding technique used by Heiderscheit et al. (2002) applied to the relative motion plots of the relevant couplings. The main findings of the analysis were that the female subjects had less variability in four of the six couplings in the first 40% of the stance phase. They had less coordination variability in the following couplings: 32% less thigh rotation/leg rotation variability; 40% less thigh abduction-adduction/leg abduction-adduction variability; 46% less knee flexion-extension/knee rotation variability; and 44% less knee flexion-extension/hip rotation variability. The remainder of the couplings did not highlight any significant difference between the genders although there was a trend towards reduced variability in the female group. Like Hamill et al. (1999), the reduced variability could be related to less flexible coordination patterns.

Movement variability was also investigated with respect to an injured group of participants who suffered from varying degrees of ankle instability (Brown et al. 2012). Subjects (n=88), who were divided into four groups based on their classification of ankle stability, performed ten single-leg landings from 50% maximum vertical jump height. Movement variability was quantified using coefficient of variation of the mean ensemble curves of the ankle, knee, hip and trunk motion in three planes for the ten trials. Similar the findings of Hamill et al. (1999) and Heiderscheit et al. (2002), the non-
injured group displayed significantly ($p \leq 0.05$) more variability in knee and hip joint motion than the injured group when performing a single-leg jumps.

Analysing the results of the aforementioned studies, it appears that those who are impaired by injury display less movement variability in certain joint motions and in some joint couplings compared to healthy controls. The study of James et al. (2000) failed to fully support the proposed injury-variability hypothesis. However, the findings of Hamill et al. (1999), Heiderscheit et al. (2002), Pollard et al. (2005), and Brown et al. (2012) did highlight that the injured condition is actually less variable than the healthy condition for certain traditional and coordination variability measures. Interestingly in the study of Heiderscheit et al. (2002), the injured group displayed more variability in stride length but less variability in coordination of the lower-limb couplings. Stride-length is, in essence, an outcome measure. It is interesting that the outcome measure displayed large variability despite relatively low variability in the coupling measures analysed. This highlights the complexity of the relationship between movement variability and the associated outcome. It could be that the reduced variability in movement is an adaptation of the system in response to the pain associated with their injury. It could also be hypothesised that the reduced variability in movement is a contributory factor to their injured state in that the relative invariance of their movement patterns resulted in the same tissues being repeatedly stressed. However, it is important to clarify that no cause and effect between injury and variability was concluded from these studies. The previous association of injury and high movement variability has been refuted through using both DST techniques (e.g. CRP in Hamill et al. (1999)) and traditional measures of variability (CV% as used in Brown et al. (2012)).

### 2.2.3.2 Pathology Research and Movement Variability

Traditionally, movement variability has been considered indicative of the pathological condition (Davids et al. 2003). This perspective emerged from the fact that the postural and locomotor systems of patients with different pathologies appeared to have high levels of movement variability and further, variability was believed to be negatively correlated with stability (Hamill et al. 2006). Previously, a variable centre of mass (COM) was believed to reflect postural control that was in a degenerative state (Woolacott et al. 1986) and resultanty effort was directed at the improvement of postural stability through reduction of the movement of the centre of pressure (COP) and COM. In a study of COP patterns by van Wegen et al. (2002) of young (24 - 38
years) and older subjects (55 – 69 years) in two different conditions, quiet stance and leaning, it was found that the younger subjects were able to lean further than their older counterparts. Further, it was found that the older subjects exhibited greater COP variability than the younger subjects in their maximal lean condition. The older subjects displayed less variability in the quiet stance condition. The findings of this study indicated that the younger subjects were better able to stabilise themselves in the new postural demand in that they could lean further forward relative to their base of support. As the older subjects were not able to lean as far forward and had higher variability, it indicated that this variability was likely destabilising. This is an example that the observed movement variability must be considered in the context of the task. In the case of the older subjects they could not exploit their variability as it would compromise succeeding the task (i.e. not falling over). Thus in the case of the findings of this study, it appeared that the observed variability could only be exploited if the task demand is firstly met.

Further examination of movement variability and pathology was performed in a series of studies with Peripheral Arterial Disease (PAD). Crowther et al. (2008a, 2008b) performed two studies which examined movement variability with a variety of variability quantification techniques. In their first study Crowther et al. (2008a) examined the intra-limb coordination variability of PAD patients (n=28) and age-matched controls (n=25) during normal walking. Joint angular kinematics were examined using two-dimensional (2-D) motion analysis recording at 50 Hz. Variability of the joint coordination was calculated using a normalised root-mean square (NoRMS) technique and vector-coding (VC) method. The results of the comparison revealed significantly higher levels of joint coordination variability (in the sagittal plane) in the PAD patients compared to their age-matched controls for both techniques used, NoRMS and VC. This could indicate the pathological condition induced lower levels of stability and thus are not able to adapt to perturbations, such as obstacles, when walking. Claudication pain is the pain associated PAD and as such the movement variability may be an adaptation of the system prior to the onset of this pain. In their other study of PAD patients, Crowther et al. (2008b) investigated movement variability of single joints in the lower limb in an effort to ascertain where specifically the movement variability existed. Similar to their previous study, 2-D video analysis methods were employed in their study of the gait cycle for the two populations. Coefficient of Variation (CV) of the single joint angle variability over the gait cycle was quantified. The spanning set (SS) was also used to quantify the variability of the single joints. The results of this study confirmed that there
was significantly higher variability in the PAD group compared to the controls and thus the results agree with their previous study (Crowther et al. 2008a) for the CV measures. The variability of the joint movements as calculated using the SS revealed no significant differences between the groups. The SS as used by Kurz and Stergiou (2003) has been criticised in that it may not be an appropriate measure to examine inter-trial variability. It has been found not to be a sensitive enough measure to detect differences in variability of knee kinematics during the gait cycle of over-ground running (Kong and Candelaria 2009). It was also found in a test of simulated variability data that the SS technique was heavily weighted toward variability present in the early phases of the movement (Hanlon et al. 2009). Thus, there are unresolved questions as to the suitability of the SS as a measure of the variability of human movement. Furthermore, these studies used 2-D analysis to quantify their measures of interest which is a limitation of the methods used. Two-dimensional analyses don't allow for analysis of any movements out of the sagittal plane. A more thorough understanding of the coordination of the lower-limb would have been performed through 3-D analysis in which couplings of the joint rotations about the transverse axis could have been quantified.

Myers et al. (2009, 2011) also investigated gait variability with PAD patients (n=19) and healthy matched (n=17) controls. Using a different measure of variability than Crowther et al. (2008a, 2008b), the Lyapunov exponent, variability of ankle, knee and hip joint angles were assessed through the aforementioned Lyapunov exponent\(^1\) and the standard deviation (SD) and CV. In the first study, Myers et al. (2009) compared the variability of the lower limb angles using the listed measures between the impaired individuals and healthy controls. Their results indicated that the symptomatic PAD patients displayed significantly \((p < 0.05)\) higher variability than healthy controls even in the absence and presence of claudication pain using the largest Lyapunov exponent value. Results using CV also highlighted significantly \((p < 0.05)\) higher variability in the PAD group to the healthy group. Taking the results collectively, it appears higher variability in the lower limb angles measured here are indicative of the pathological condition. In their follow-up study, Myers et al. (2011) examined joint kinematic variability in the PAD patients before and after the onset of claudication pain. Using the same measures as previously (Myers et al. 2009), no differences in variability apart from the largest Lyapunov exponent of the ankle were found before and after the onset of pain.

\(^1\) Lyapunov exponents measure the degree of convergence of patterns in state space where the magnitude of the exponent provides an indication of the stability of the system (Hamill et al. 2006).
From examination of research looking at movement variability in the pathological condition, it appears that high movement variability in lower limb measures is observed in the symptomatic group (PAD patients) compared to the asymptomatic group. This finding appears to be consistent throughout the literature as movement variability has been quantified in 2-D and 3-D analyses with many variability quantification techniques. This observed higher variability may be an adaptation of the system to the onset of claudication pain in that it is allowing pain-free movement or an indication of a loss of stability of the system as a result of the PAD. Once again, it is highlighted that no deterministic relationship has been determined between movement variability and the pathological condition.

2.2.3.3 Sports Biomechanics Research, Performance Research and Movement Variability

The application of DST to examine movement variability or more specifically coordination variability has revealed some interesting findings and challenged previous perceptions of increased movement variability as being detrimental. This has led to movement variability being examined within sports biomechanics. Indeed, there have been calls from biomechanists to increase their research in this domain (Bartlett et al. 2007). Given the traditional association of increased variability and poor performance, coaches and practitioners alike may believe that a specific model or technique repeated with consistency is the key to improved performance.

DST tools have been proffered as viable methods of analyses in the investigation of a sporting movement pattern (Glazier et al. 2003). The exploration of movement variability using DST techniques in injury and pathology has prompted sports biomechanics researchers to use these techniques in an effort to improve performance. This has led to researchers examining movement variability amongst different skill levels of performer, in an effort to understand if low or high movement variability is related to improved performance. The use of the aforementioned DST techniques has been increasing in recent years in relation to sports performance research.

The use of non-linear techniques have been applied to subjects (n=7) performing race walking (Preatoni et al. 2010). A sample entropy technique was applied to examine fluctuations in lower limb angles and ground reaction forces from twenty trials. The results indicated that the variability did not just contain random noise; it also contained
information about the inherent property of the neuro-musculoskeletal system, i.e. its flexibility to external perturbations and health. The study also highlighted that variable patterns exist even in the movement patterns of elite subjects.

Button et al. (2003) and Robins et al. (2008) examined the movement variability of basketball players performing basketball shooting. Evidence of compensatory variability was uncovered in both studies. In the study of Button et al. (2003), it was found that the elite performers were more successful in outcome (i.e. number of free-throws scored) but there were subtle compensations in the angular motions of the wrist and elbow joints in these experienced players. No significant differences in levels of movement variability were ascertained between the differing levels of performer although the elite performers had lower outcome variability. There was evidence of compensatory variability in this study in that there was an observed increase in the variability (standard deviation) of joint angle at release from the elbow to the wrist joint. This interaction of the joints along the kinematic chain has been suggested to minimise the variability of the release parameters and thus reduce outcome variability. Robins et al. (2008) changed the task in their study in that they examined shooting performance in basketball at three different distances for three different levels of performer. Their study suggested that with developing task expertise, compensatory control develops and remains with changing shooting distance (task constraint).

In studies examining the effect of skill level on movement variability (Button et al. 2003, Anderson et al. 2008, Robins et al. 2008, Fleisig et al. 2009), some significant differences between skill levels were found. The study of Fleisig et al. (2009) in examining levels of variability amongst varying levels of baseball pitchers (n=93) did observe overall decreases in kinematic variability across all skill levels. It was also notable that all performers exhibited intra-individual variability for all measures. The notion of the capability of a performer to execute an invariant pattern repeatedly has been dismissed through all aforementioned studies. Movement variability as quantified using measures of coordination, or discrete single measures over repeated trials highlighted that variability exists at all levels of performer for different movements, weightlifting (Anderson et al. 2008), basketball shooting (Button et al. 2003, Robins et al. 2008) and baseball pitching (Fleisig et al. 2009). Wilson et al. (2008) examined coordination variability of three intralimb couplings for five expert triple jumpers in a descriptive study using the same vector-coding (VC) technique as used in Heiderscheit et al. (2002). The results indicated a U-shaped curve best represented the results of
the coordination variability and outcome. Some of their results supported traditional motor learning perspectives in the least skilled performer displaying the highest level of coordination variability. Overall, considering the previously mentioned studies, there appears to be no distinct differences in movement variability in skill level that might lead one to believe that experts display the most invariant coordination and movement patterns. It appears that the more elite performers might be better able to explore their variability more effectively throughout the movement in order to produce a consistent outcome, e.g. consistent release parameters of the wrist in the basketball free throw (Button et al. 2003). In a further attempt to associate movement variability and performance, Mullineaux and Uhl (2010) examined coordination variability in successful and unsuccessful free throws in basketball. Interestingly, using the coordination variability results, the authors were able to distinguish between successful and unsuccessful free throws. A statistically significant difference ($p < 0.05$) between the VC quantification of variability between the wrist and elbow at the time of release was detected between successful and unsuccessful shots. It is worth noting that the VC technique utilised by the authors in this case (Mullineaux and Uhl 2010), followed the specific technique developed by Tepavac and Field-Fote (2001). This was different to that used by others (Heiderscheit et al. 2002, Wilson et al. 2008), who used a modification of the method of Sparrow et al. (1987). It is important that the techniques used in this research are consistent between studies in order to allow effective comparison between different sets of data. It is also imperative from an applied perspective that the techniques undertaken are easily understood by practitioners and coaches. A potential criticism of some of the techniques used (VC, NoRMS, Sample Entropy) here is that while they might be complex enough to extract important facts about the non-linearity of processes within the neuromuscular system, they potentially are not easily understood and implemented by coaches and those who work closely with athletes in an effort to improve performance. These methods require a thorough understanding of and the ability to perform the mathematical calculations involved.

Bradshaw et al. (2007) attempted to develop a method to quantify biological movement variability (BMV%) in a study of expert sprinters ($n=10$) performing four sprint starts. In order to produce a measure that is solely BMV%, the authors attempted to remove any methodological error (as measured by the standard error of the mean (SEM%)) that may have been inflating the CV% measure when analysing the sprint start. BMV% (CV% - SEM%) was calculated for the trunk angle and the push-off angle of the foot in takeoff at the instant of block push-off and the instant of toe-off for the first two strides.
It was concluded that the generation of a consistent high horizontal speed from the starting blocks was associated with consistent, faster strides at the start and thus better performance. The authors also used this technique in the quantification of BMV% with respect to the golf swing (Bradshaw et al. 2009). However, this quantification technique does not appear to adequately deal with the problematic issue of inflation of CV% calculation by methodological error. The calculation of the SEM% was done over repeated performance trials but this is likely to contain movement variability. In order to calculate the true SEM%, the calculation needs to be done over repeated measurements of the same trial (Glazier 2011). Therefore the issue of removal of systematic/technological error that may interfere with the calculation of true movement variability is still an unresolved issue. Both studies (Bradshaw et al. 2007, Bradshaw et al. 2009) were welcome in their examination of movement variability in sporting movements. There was an attempt to link their quantified movement variability to the outcome (accuracy and club head velocity with BMV% in the golf swing study (2009)) and in their attempt to deal with the aforementioned issue of quantifying true BMV%. However, the studies were potentially limited in its analyses of the variability of just discrete variables. Discrete variables, while informative, do not allow a thorough understanding of the entire movement pattern performed over time and thus continuous methods may be more advantageous (James 2004). Continuous methods such as angle-angle plots and time-series graphs represent movement variability as a function of time or other parameter.

2.2.4 Movement Variability Summary

It can be deduced from the studies cited that the traditional notion of movement variability as only detrimental to movement outcome is no longer tenable. Variability is a ubiquitous, unavoidable feature of human movement that is present even in the most expert performers. Through the analysis of variability with DST techniques, it appears that in certain circumstances that it is a beneficial adaptive mechanism (Hamill et al. 2006). The use of continuous measures appears to more fruitful in this regard of examining the entire movement (James 2004). Therefore, for the purposes of this PhD, continuous measures will be used in the investigation of movement variability. It appears more of an emphasis needs to be placed on examining the movement variability quantified and the outcome of the movement in an effort to understand the cause and effect of movement variability. One cannot conclude from the previously discussed studies that variability is beneficial or detrimental to movement. The
relationship between movement variability and movement outcome is still not fully understood.

2.3 THE GOLF SWING

Golf is a game that is hugely popular throughout the world across all ages and socioeconomic groups, with approximately 27 million participants in the United States according to the U.S. Census Bureau (2004) and 4.39 million in Europe (KPMG 2011). However, it is a game that has the potential to be infinitely frustrating for those who partake in it. For the seemingly simple task of hitting a ball with the club, the golf swing is an extremely complex multi-segmental movement, where the player has to constrain and coordinate many degrees of freedom in order to achieve the goal of hitting the ball with both accuracy and consistency. The following sections detail the main teaching model in golf, the main swing kinematic variables that have been researched and the consideration of movement variability in golf swing research.

2.3.1 Current Teachings and Understandings of the Golf Swing

The coaching of the golf swing is most influenced by the teachings of Wiren (1990) (Hume et al. 2005). This teaching model focuses on mechanical definitions and laws of ball flight. The laws are club head speed, centeredness of contact, club head path, angle of approach and clubface position. The factors listed in Figure 2.3 are the biomechanical features that combine to influence the flight final ball displacement after being struck by a golf club.
Figure 2.3 – Deterministic model of the factors that contribute to distance travelled for a golf shot. Taken from Hume et al. (2005)

It would appear from analysing the numerous golf coaching manuals and golf coaching articles that are published in golf magazines, that certain coaches believe in an optimal swing that we should all attain. This is evidenced by coaches advocating players attain certain movements with absolute invariance at key sections of the golf swing; for example at the top of the backswing or another discrete measure. Frequently in golf magazines, coaches write articles describing a feature of the golf swing they “should attain” in order to improve their swing performance, e.g. (Kaspriske 2011). These articles are typically accompanied by 2-D photos of a swing sequence of a professional golfer who possess the swing feature the coach is describing. The focus of these articles appears to be a feature of the swing that the coach believes is an important feature of performing the swing. Thus, it is based on personal opinion and not in consultation with the scientific literature (Bradshaw et al. 2009). There have been attempts to bridge the gap between the scientific literature and teaching, as evidenced by the work of Mann and Griffin (1998) discussed in Section 2.3.3.2.
2.3.2 Biomechanical Research on the Kinematics of the Golf Swing

2.3.2.1 Introduction

The first major attempt to scientifically analyse the swing was by Cochran and Stobbs (1968). In their "search for the perfect golf swing", they modelled the golfer as a double pendulum based on high speed videos of the swings of several professionals. The authors advocated certain parameters of the swing that golfers should focus on attaining in their swing such as maintaining the stillness of the hub and concentrating on the correct timing of wrist release. This piece of work mainly focused on the physics involved in the golf swings that they analysed using their model and not specifically on how the players can take advantage of this knowledge of the important physical factors involved in the successful swings of the experts analysed. It has been commented that there has not been a significant advancement on this piece of work since (Farrally et al. 2003). In an effort to examine the factors that influence outcome the most, researchers have begun to quantify the effect certain kinematic and kinetic variables have on the outcome of the swing. This section focuses on the kinematic research of the golf swing.

As there is a positive association between ball displacement and club head velocity at impact (Hume et al. 2005) (see Figure 2.3), the attainment of high club head velocity has been highlighted as desirable for improved performance (Burden et al. 1998). Therefore, club head (Egret et al. 2003, Egret et al. 2006, Meister et al. 2011) and ball velocity have been generally used as the shot outcome measure in kinematic studies (Myers et al. 2008, Chu et al. 2010). Club head velocity has received support from the literature as the study of Fradkin et al. (2004) found a strong negative correlation (r=0.95) between handicap and the club head velocity of the subjects (n=45). Thus, club head speed is a valid indicator of performance level.

Examples of kinematic measures that have been examined in the golf swing are, wrist flexion-extension angle (Zheng et al. 2008b), elbow angle, hip rotation angle (Egret et al. 2006), shoulder motion (Mitchell et al. 2003), trunk flexion-extension (Lindsay and Paley 2002), arm-trunk angle, segmental sequencing of specific segments (Anderson et al. 2006). A measure that has received increased attention in comparison to other variables is that of torso-pelvic separation angle as evidenced by these studies that have examined this parameter (McLean 1992, McTeigue et al. 1994, Burden et al. 1998, Cheetham et al. 2000, Myers et al. 2008, Cole and Grimshaw 2009, Chu et al. 2010, Healy et al. 2011, Meister et al. 2011) and has also been identified in a review of
golf biomechanics literature as an important factor in maximising distance (Hume et al. 2005).

2.3.2.2 Torso-Pelvic Separation Angle in the Golf Swing

A substantial amount of golf kinematic research in the last number of years has focused on the area of absolute and relative torso and pelvic rotation and its link to improved club head or ball velocity at impact. Therefore, this section provides a review of this research. The term torso-pelvic separation angle (also referred to as the X-Factor angle) relates to the amount of relative separation between the torso and pelvis (Meister et al. 2011). The X-Factor Stretch refers to the magnitude of the relative separation between the torso and pelvis in the downswing where the separation appears to be maximised due to the counter-rotation of the pelvis before the torso (Cheetham et al. 2000).

The investigation of torso-pelvic separation angle (also referred to as X-Factor) and maximum torso-pelvic separation angle (also referred to as X-Factor Stretch) at the beginning of the downswing has a physiological basis. The performance benefits (i.e. increased power which leads to increased ball displacement) associated with increased torso-pelvic separation angle have been attributed to the Stretch Shortening Cycle (SSC). When golfers are completing their backswing and transitioning to the downswing, the pelvis begins to slow down and changes its rotational direction, to rotate towards the target as the upper body is still completing the backswing and rotating backwards. As the pelvis has begun rotating before the torso, it will have a greater rotational velocity early in the downswing. Due to this increased velocity, there is a greater separation between the pelvis and torso. This sequence of movement results in increased eccentric stretching or lengthening of the muscles of the upper-extremity, hips and trunk before these muscles contract in a concentric manner at the top of the downswing. This action of lengthening of muscles prior to an immediate concentric contraction is referred to as the Stretch Shortening Cycle (SSC). Theoretically, this SSC leads to the muscles being able to perform more powerfully than in a concentric contraction alone (Enoka 1994). This effect has been reported other movement studies that analysed vertical jumping where subjects jumped higher in the counter-movement jump (where there is a pre-stretch prior to concentric contraction) compared to a squat jump (concentric contraction alone) (Moran and Wallace 2007).
Torso-pelvic separation in golf has been associated with an increased ball velocity in a number of studies. It was first referred to in a magazine article by McLean (1992) where the results of work that was done using a device called the Swing Motion Trainer to measure the rotation of the hips and shoulders were presented. The results indicated that this torso-pelvic separation value correlated positively with the player’s position in the driving distance statistics (i.e. those who drove the ball farthest had a greater torso-pelvic separation). McTeigue et al. (1994), with whom McLean had collaborated with for his magazine article, produced more extensive results. Using the same device as McLean had employed, they examined the torso-pelvic separation in 51 professionals, 46 senior professionals (>50 years) and 34 amateurs. The results indicated that there was no clear correlation between the specific torso position and driving ability. The authors suggested that the quantified torso-pelvic separation at the top of the backswing may have contributed to increased driving distance. However, they also stated that it may be due to the torso-pelvic separation angle at the beginning of the downswing (the X-Factor Stretch) as they had discovered 70% of the professionals rotate their hips first in the downswing. Despite this observation, the authors did not examine this parameter in their work. Following on from this, Cheetham et al. (2000) examined the torso-pelvic separation angle at the beginning of the downswing in highly-skilled (n=10) and less-skilled (n=9) golfers hitting ten shots with a 5-iron. There were no statistically significant results between the skill levels with respect to torso pelvic separation angle at top of the backswing. When torso pelvic separation angle at the beginning of the downswing was analysed, the highly-skilled golfers demonstrated significantly greater stretch ($p < 0.001$) in their torso-pelvic separation angle (19%) compared to the less-skilled (13%). This observed increase in torso-pelvic separation angle was a result of the counter-rotation of the hips towards the target before the shoulders had completed their rotation. This is known in golf coaching as “leading with the hips”. The authors highlighted that this (torso-pelvic separation angle at the beginning of the downswing) was a more pertinent performance variable than mere torso-pelvic separation at the top of the backswing as this increased stretch facilitates greater club head velocity at impact through increased force production. Burden et al. (1998) in their study of sub 10-handicap golfers and their respective hip and shoulder motion found that three-quarters of their subjects displayed this counter-rotation of the hips back towards the target near the completion of the backswing.
Increased torso-pelvic separation has been found to be a discriminating factor between skill levels. Myers et al. (2008) found a significant difference ($p < 0.0001$) in torso-pelvic separation (see Figure 2.4 for their torso-pelvic separation angle definition) between the high velocity ball group ($n=14$) and the low ($n=21$) and medium ball velocity group ($n=65$) at the top of the backswing in shots performed with their driver. The authors surmised that increased torso-pelvic separation at the top of the backswing and its maximum value at the beginning of the downswing contribute to increased torso rotation and torso-pelvic separation velocity in the downswing which ultimately culminates in increased ball velocity. Zheng et al. (2008b) calculated torso rotation relative to the pelvis in an attempt to quantify differences between four different levels of golfers; professional, low handicap, medium handicap and high handicap. There was a significantly ($p < 0.05$) higher trunk rotation relative to the pelvis between the professionals ($60 \pm 7^\circ$) and the high handicap group ($49 \pm 12^\circ$) at top of the backswing. Chu et al. (2010) also examined a number of variables such as leading hip flexion, leading knee flexion, torso-pelvic separation and torso-pelvic separation angle changing rate, and their relationship to increased ball velocity. The subjects ($n=308$) performed ten shots, of which the shots with the five highest ball velocities were analysed. The variables were analysed, using stepwise linear regression, at four points of the golf swing; top of the backswing, acceleration phase of the downswing, and the last 40 ms prior to impact. The torso-pelvic separation angle and pelvis superior shift velocity and trunk lateral bending were the most influential predictors of ball velocity at
the top of the backswing. In a study by Brown et al. (2011) of elite female golfers (n=16), it further emphasised a link between increased club head speed and increased torso-pelvic separation angle. In a different study of professional (n=10) and amateurs (n=5) hitting three different types of shots (easy, medium and hard) with their 5-iron, Meister et al. (2011) found torso-pelvic separation angle at impact and the peak torso-pelvic separation angle to be strongly correlated with club head velocity thus providing further experimental support for this variable and its positive relationship with club head and ball velocity. A study by Healy et al. (2011) of male participants (n=30) executing 5-iron shots for maximum distance found that torso-pelvic separation was significantly greater (p ≤ 0.01) in their high ball velocity group compared to their low ball launch velocity group at four events of the downswing; early downswing, mid downswing, ball contact and club horizontal follow-through, yet there was no significant difference between the two groups at the top of the backswing for torso-pelvic separation angle. This lends support to the change in focus of research from torso-pelvic separation at the top of the backswing to peak torso-pelvic separation angle during the downswing.

Interestingly, the analyses of the golf swing described previously have described the X-Factor at discrete points of the swing (i.e. torso-pelvic separation angle at top of the backswing, peak torso-pelvic separation angle in the downswing being the maximum value at a point in time in the downswing). However, it may be advantageous to analyse this feature of coordination between the pelvis and torso across the entire swing in order to understand how this variable changes over time.

### 2.3.3 Considerations of Movement Variability in the Golf Swing

Movement variability, as described previously, is an ever-present feature of human movement patterns. As it is unclear whether this is beneficial or detrimental to motor skill performance, researchers have begun examining this aspect of human performance in relation to the golf swing. It has been targeted as an important future research direction (Williams and Sih 2002, Farrally et al. 2003, Glazier 2011) in order to improve teaching methods and understandings of the determinants of a successful golf swing. The objective of the golf swing is to translate the head of the golf club through the point of ball contact in a path in line with the target and a club face that is either perpendicular to this path or oriented to produce the intended trajectory. It is clear that at the point of contact that invariance should be sought in order to produce a consistent outcome. Beyond that however, it is unknown as to whether variability of the movement
pattern is beneficial or detrimental to golf swing performance. Using the traditional approach of variability as detrimental to outcome, coaches would teach a consistent movement pattern. However, as has been highlighted previously, this may be erroneous. Knight (2004) advocated a DST approach to understanding the golf swing. In the coaching of the golf swing, there has been apparent drive towards a “one-size fits all” approach in the search for the perfect swing. In golf, no two shots are identical due to the effect of the environment, different flag position and changing weather constraints. This view is also perpetuated from within the scientific literature as can be evidenced by the work of Mann and Griffin (1998) as discussed in Section 2.3.3.2 and Cochran and Stobbs (1968) discussed in Section 2.3.2.1. However, from a DST perspective this “perfect” or “optimal” swing cannot exist owing to the intra-individual constraints that are constantly interacting and evolving over time, that produce a movement pattern. There certainly may be commonalities between players at the top level in terms of their coordination but no two players will display the same swing. This variation between and within players is something that needs to be considered in more detail in golf swing research.

2.3.3.1 Research on Movement Variability in the Golf Swing

There has been limited research on movement variability in the golf swing. To highlight the paucity of research in this area, the results of the literature review revealed an extremely low number of studies that examined movement variability in the golf swing, namely two peer-reviewed journal articles (Bradshaw et al. 2009, Horan et al. 2011), a small number of peer-reviewed conference proceedings, (e.g., Fitzpatrick and Anderson (2004), Keogh et al. (2007)) and a book chapter (Kenny et al. 2008b).

Fitzpatrick and Anderson (2004) conducted an analysis of 22 golfers (handicap 7.5 ± 0.7) performing 120 metres shots where the angular kinematic parameters of; trail and lead knee angles, the angle between shoulders and hips, and trail and lead elbow angle, were quantified. Shot outcome was analysed in the form of landing location variability (an ellipsoid was quantified from the landing location variability). The results reported only focused on a case study of one participant. No conclusions were drawn as a result of this analysis. Unfortunately no further analysis of these results was presented in the literature.
A study was conducted by Bradshaw et al. (2009), investigating the effect of movement variability on golf swing performance, with a 5-iron being struck towards a target by high- (n=10) and mid-handicapped (n=10) golfers where variability of kinematic measures, such as club head velocity, lead wrist angle, trunk angle, trail forearm angle and many more from “key technical positions” were calculated using 2-D video images. In this study, the authors attempted to calculate “true biological movement variability” using a technique developed previously (Bradshaw et al. 2007) (see Section 2.2.3.3). As expected, the skilled golfers (handicap 1 or less) had the most accurate shots (least variability in the outcome). Bradshaw et al. (2009) concluded that invariance in the key technical positions at address, mid backswing and top of backswing was the more favourable technique for the skilled golfers. This study was welcome in terms of examining variability of the golf swing and its effect on shot outcome; however, it was limited in a number of ways; the golf swing was examined with 2-D video operating at 50 Hz and looked only at discrete measures. Given that the golf swing occurs in three-dimensions, a more detailed picture of the movement can be acquired through 3-D motion analysis. Further, it is questionable whether a sampling frequency of 50 Hz is sufficient to capture enough kinematic information given the high velocity particularly of the arms and club during the golf swing. Discrete variables, while informative, do not allow a thorough understanding of the entire movement pattern performed over time and thus continuous methods may be more advantageous (Hamill et al. 2000). Continuous methods such as angle-angle plots and time-series graphs represent movement variability as a function of time or other parameter. The previously cited conference proceeding of Keogh et al. (2007) appears to be the same study of Bradshaw et al. (2009) but presented in an abbreviated format.

A recent study by Horan et al. (2011), examined segmental movement variability of the pelvis and thorax, hand trajectory variability and club head trajectory variability at 3 phases of the downswing along with inter-segmental coupling of pelvis and thorax for a cohort of 38 skilled golfers (19 male, 19 female) performing five shots with their driver. This study examined movement variability differences in the measures previously mentioned using standard deviation (SD) at the three phases of the downswing and the spanning set (SS) to provide a continuous measure of variability at the three events of the downswing (to make it a continuous measure there was information included before and after the event (+20%)). Average coefficient of correspondence was used to calculate intersegmental coupling variability. It was reported that females exhibited higher axial rotation variability at two of the phases examined in the downswing
While both genders displayed decreasing variability of hand and club head trajectory towards ball contact. This study did provide some interesting findings in relation to gender differences with respect to inter-segmental variability and variability of club head trajectories; however the relationship between the exhibited performance variability and its effect on the club ball interaction at impact were not examined thoroughly. The spanning set as highlighted in Section 2.2.3.2 does not appear to be a generally accepted measure of variability due to the concerns highlighted previously.

The study of Kenny et al. (2008b) examined the outcome variability of six elite golfers using three randomly assigned drivers using a stereoscopic launch monitor. Outcome variability was quantified in the form of club head velocity, carry, dispersion, launch angle, side angle, side spin and back spin. Even amongst these elite subjects, intra-subject variability was observed. The authors commented that the study provides support for examination of the elite golf swing through the use of single-subject analysis. This study only examined outcome variability. The examination of movement variability in conjunction with these interesting analyses of outcome could have provided a more thorough understanding of the movement strategies that these players were employing to produce the measured outcomes.
2.3.3.2 The Need for Single-Subject Analysis in the Golf Swing

Ralph Mann and renowned golf coach, Fred Griffin, combined to produce an analysis of the swings of 100 professional golfers which culminated in a computer-generated “model pro” (Mann and Griffin 1998). Although the authors did acknowledge that there were minor differences between the golfers in terms of their anthropometrics and technique, they focused the construction of their model on the commonalities between the golfers. Mann and Griffin (1998) promote their model as the optimal way to perform the swing. However, by combining so many different golfers into the one “optimal” swing, the authors failed to adequately acknowledge the many intra-individual constraints that interact to produce each professional’s own movement pattern. There is a need for improved teaching of the swing based more on consultation with the scientific literature than personal opinion however the approach of Mann and Griffin (1998) appears to be limited in their approach of combining so many swings into one model.

The majority of biomechanical research consists of a group-based analysis where groups of similar level performers are compared against a group of different level performers either in a cross-sectional or longitudinal research design. Similarly, this approach has been followed in biomechanical studies of the golf swing, where groups of low and highly skilled golfers (Zheng et al. 2008a, Okuda et al. 2010) or male and female golfers (Zheng et al. 2008b, Horan et al. 2010) were contrasted. The perceived advantage of group designs is the ability to generalise the results of a study to a population, of which a studied is group is a subset (Bates et al. 2004). However, group analysis, whilst having its advantages, can be problematic. There has been some dissatisfaction expressed regarding traditional group statistical approaches. The results of a group analysis can be somewhat misleading due to the problem of aggregation (Bates et al. 2004). Individual response patterns can be masked if the results are grouped. For example in a study of different landings of 12 subjects, the group models produced were not representative of any of the individual subjects’ performances (Dufek et al. 1995). This cancellation effect due to aggregation has also been reported in other studies (Payton 1994, Dufek and Zhang 1996). Further, when investigating elite performers, effect sizes are likely to be small (Tabachnick and Fidell 2001). Thus, in an inter-individual analysis of an elite group, important information can be overlooked due to the reduction in statistical power (Ball et al. 2003). In a study by Brown et al. (2011) examining the swing characteristics of low-handicap female golfers (n=16) using a twelve-camera 3-D motion capture system, no common optimal technique...
characteristics could be determined across all sixteen participants in the downswing in particular. Thus, the authors of the study proposed more consideration of individual swing characteristics.

Therefore, investigation of golf swing techniques at the intra-individual level of analysis is warranted, particularly at the elite level, as suggested by Kenny et al. (2008b) and Brown et al. (2011). It is not suggested here to dispense with group analysis but further investigation of group results at the individual level is required in order to prevent masking of individual strategies.

2.3.4 Golf Swing Research Summary

Ultimately, it is not known to what degree golfers vary their movement patterns. Further, due to the dearth of research examining intra-individual movement variability in the golf swing, it is not understood whether movement variability is beneficial or detrimental to the outcome of the swing. Knight (2004) even suggested that a practical solution to this is to minimise variability in the areas of the swing that have the most influence on shot outcome variability. To do this, a thorough investigation of movement variability is required to ascertain if this approach is applicable to the golf swing. It has been highlighted that there is an increasing need for single-subject analysis in the study of the golf swing at the elite level.

2.4 COMPUTER SIMULATION AND BIOMECHANICAL MODELLING

2.4.1 Introduction

In order to solve a research problem associated with a complex system, it can be necessary to reduce the system to elements that are essential, in order to simplify the effort in answering the research question. The term ‘modelling’ refers to the process of defining a representative, alternative system (Nigg and Herzog 2007). The term ‘simulation’ refers to the application of this defined ‘model’ to run many virtual experiments (Nigg and Herzog 2007). The usefulness of a model is dependent on its verifiable results and as such a purely theoretical modelling approach with no validation of its output is open to question as regards how realistic it is. Thus, the approach being adopted for the purposes of this PhD is a combination of experimental and modelling
work. The experimental data can provide validation of the model output. The following sections detail the advantages and limitations of the modelling approach, different modelling approaches and the pertinent literature relating to golf swing modelling and simulation.

### 2.4.2 Advantages and Limitations of Modelling and Simulation

There are many advantages to using a computer modelling and simulation approach as a method of approaching a research question. Firstly, the advantage of this approach is in the area of subject-safety. The subject is prevented from having to perform multiple trials of a potentially dangerous movement or experimental protocol. The validity and repeatability of the movement is maintained as the subject does not experience fatigue in the process of carrying out multiple trials. A second advantage is the saving of time for carrying out the simulations as multiple simulations can be carried out in a relatively short time period. A third possible advantage of the simulation approach is the ability to predict optimal performances of the movement using the simulation. There are some important limitations that must be taken into account when using the computer simulation approach in that it demands an advanced knowledge of computers and mathematics and validation of these computer models are difficult without experimentation (Vaughan 1984). Further, the interpretation of the simulation results can be difficult to translate into practicality. A trade-off in modelling that must always be considered is that between the simplicity and complexity of the created model. This concept is potentially limiting to the ability of a model to answer its research question if it is either too complex or simple (Betzler et al. 2008). The research question is the main determinant of how simple or complex a model should be.

The advantage of this approach for this particular research is that a model can be created based on a real-world golfer to perform multiple simulations with invariance. As has been discussed previously in Section 2.2.2.2, this is not possible with “real” subjects due to the omnipresence of movement variability. Modelling and simulation offer the ability to impose artificial variability to the system in order to ascertain its effect on movement outcome. A study that has adopted the approach of examining variability of neuromuscular control (NMC) in simulations is that of McLean et al. (2004). Subject-specific models (n=20) were created and validated for subjects performing a side-cutting task. The development and validation procedure for one subject’s model was detailed in another article (McLean et al. 2003). A 3-D forward-dynamics model was
created based on the average of the subject’s ten trials of the side-cutting task. For validating the model, the authors accepted any values of the variables within 2 standard deviations (SD) of the actual motion measured to be valid. All the simulations fell within this 2 SD criterion except for the variable of body tilt. Using this validated model approach, the authors investigated the effect of variability of NMC on peak anterior drawer force, valgus moment and internal rotation moment. Variability of NMC was calculated using random numbers added to the initial body segment and angular positions and linear and angular velocities. The results of the application of these random perturbations to the model resulted in significantly increased knee anterior force and valgus and internal rotations moments. The authors’ main conclusion was that the sagittal plane loading mechanism during sidestep cutting does not generate ACL loading. This study highlighted the potential of investigating the effect of perturbations on movement using a simulation approach.

2.4.3 Modelling Approaches: Inverse and Forward Dynamics

The methods employed in modelling have varied between an inverse dynamics and a forward dynamics approach or a combination of both approaches. Usually, the inverse dynamics approach involves body movement measurement (kinematics) and maybe a force measure (such as GRF) (Nigg and Herzog 2007), while the forward dynamic modelling approach requires the input of internal forces to calculate body motion. The main approaches that have been used in investigating the golf swing are shown in Figure 2.5.

Inverse dynamics approaches seek to determine internal forces such as joint moments and reaction forces. The calculations of these variables are uncomplicated and involve solving of a set of linear equilibrium equations. A problem for the inverse dynamics approach is the problem of redundancy when it comes to calculating the individual muscle forces. As there are a large number of joints and muscles in the human musculoskeletal system and each of these joints has one, two or three degrees of freedom, there is a problem due to the fact the Central Nervous System (CNS) can choose from only one of the numerous solutions. This adaptability of the CNS is beneficial in allowing the system to adapt to perturbations in the environment and enables skilled execution of the golf swing or tennis serve but is problematic from a modelling perspective as it is difficult to determine the one solution that is chosen by the CNS. Thus the system becomes redundant due to the possibly infinite number of
solutions (Hatze 2002). A solution to this as suggested by Rasmussen et al. (2003) is that as our movements are relatively consistent and that this recruitment of muscle must be based on a rational principle.

With respect to modelling the golf swing, to deal with the problem of redundancy, it is necessary to optimise the model using both an inverse and forward dynamics simulation approach while not necessarily using all muscle actuators in the model. By constraining the model through specification of the anatomical and physiological limits of the system, such as identifying muscle and tendon pre-stretch values and resting loads, joint angle ranges of motion and muscle maximal force outputs, the model can potentially produce the correct joint torque with the reduced number of muscle actuators. This approach of optimisation has been used in many models previously, e.g. (Li et al. 2006, Srinivasan and Ruina 2006), and has been shown to produce reliable and accurate simulations of movement while using a reduced number of muscle actuators.

![Figure 2.5 – Typical modelling approaches that may be undertaken. Taken from (Betzler et al. 2008)](image_url)

### 2.4.4 Model Validation

For a model to provide any informative results, it is important to acknowledge the importance of the validity of a model. It can of course be extremely misleading if one
follows the results of a model that is not validated. Thus, the validation of a model is imperative before the application of any research using modelling methods (Otten 2003).

Typically model validation takes the form of a statistical comparison using correlation analysis of simulated results with those recorded during experimentation. Models can be validated with any (or a combination of) the following approaches:

i. Analysis of Kinematics: Comparison of landmark trajectories, angles, their derivatives and temporal patterns.

ii. External Forces: Direct measurement of forces external to the system such as ground reaction forces and grip force.

iii. Muscle Forces: Use of EMG to directly measure muscle activation.

iv. Joint Kinetics: Internal forces comparing the joint kinetics calculated from the experimental motion data and that calculated from the simulated data.

For example, in the golf modelling studies discussed in the following sections, Nesbit (2005) developed a full-body 3-D analysis of the golf swing of a number of golfers in an effort to determine similarities and differences between golfers. Validation was carried out by comparing manually calculated joint torques, results from other studies and ground reaction force (GRF) data. GRF data was reported to display a 7% difference from experimental data after smoothing. The authors reported that kinematics of the model, in terms of joint and hand club angles, velocities and accelerations, “exactly reproduced the subjects’ motions”. In relation to joint torques, these were again reported to be identical between the model and that calculated through experimentation. In another full-body 3-D study of the golf swing, Kenny et al. (2008a) validated their subject-specific model through comparison of the trajectories of extra markers (markers not used to kinematically drive the model), comparison of the club head velocity measured experimentally and that predicted by the model. The results of the kinematic validation showed a high level of agreement between the motion and simulated data (overall $r=0.95$). There was a further attempt to validate the model by examining the grip force of the left hand and comparing it with grip forces documented in the literature.

The level of sophistication of model validation is increasing as can be seen in the detailed validation efforts of Nesbit (2005) and Kenny et al. (2008a). Therefore, it is
something that deserves strong consideration before proceeding to analyse the simulation results. Therefore, a model must be validated. In this thesis, the model will be validated through comparison of the kinematics of “extra” validation markers not used to drive the inverse dynamics simulation of the model and club head velocity in order to ensure the applicability of the results.

2.4.5 Modelling, Simulation and the Golf Swing

Golf, as much as any sport, has been the subject of numerous modelling investigations, probably in part owing to its huge popularity worldwide, but mainly due to the underlying complexity of the movement that is not easily explained through experimental techniques (Betzler et al. 2008). The approaches to modelling the swing have varied from the simple (double-pendulum) to the highly complex (full-body 3-D models). This section details selected modelling approaches that have been used in the analysis of the golf swing.

2.4.5.1 Two-Dimensional Models

Cochran and Stobbs (1968) proposed a simplified mechanical model of the downswing in order to gain an insight into the basic mechanics involved in the golf swing and the optimal coordination pattern of the golf swing. Their model consisted of a double pendulum with two segments, one representing (upper lever) the upper arms of the golfer and the other (lower lever) representing the club which was connected to the upper level by means of hinge joint (‘wrist’) which was assumed to act passively. The authors used this model to demonstrate that the combined effects of inertia and centripetal force that act on the lower lever can help create a well-coordinated downswing, if the correct force is used to operate the upper lever. This observation led to emergence of the concept natural wrist release in explaining the motion of the wrist in the downswing. However, as this was a simplified representation of the downswing, the authors showed traces of the club and hands in the photos of golfers that represented their motion as planar. The notion of a planar club head trajectory has been dismissed however in subsequent 3-D detailed analyses (Coleman and Rankin 2005, Coleman and Anderson 2007). This highlights the importance of using 3-D modelling analyses of human movement as the majority of movement occurs in three dimensions. Incorrect conclusions may be drawn from 2-D analyses. As stated previously, it is important that models employed are as complex as necessary to draw relevant conclusions.
Based on the double pendulum approach, Jørgensen (1970) developed a mathematical simulation model, with which it was aimed to analyse how wrist torque might possibly be used to improve performance. Using this model, it was found that club head impact velocity could be increased if there was a torque applied at the wrist hinge to prevent the club (lower lever) from changing its position too early, i.e. what is termed a ‘late release’ in golf coaching terminology.

Other examples of investigators using the double pendulum approach to the development of their models are the work by Milne and Davis (1992), Miura (2001) and White (2006), which looked at the effect of shaft bending throughout the swing, to ascertain whether a translational displacement of the central rotation axis of the system immediately prior to impact could increase the impact velocity and to investigate the fundamental physical principle effect on golf swing efficiency, respectively.

As there are only two body segments represented, the double-pendulum model of the golf swing does not account for arm rotations about the shoulder joint or torso rotations. As a result of this shortcoming some researchers have added an additional hinge in the model representing a simplified shoulder joint. Examples of three segment models include the work of Tsujiuchi et al. (2002), Sprigings and Neal (2001), Sprigings and Mackenzie (2002). However, despite the addition of another link, the fact remains that these models are two-dimensional in nature. A golf swing is performed in 3-D space. Thus in order to obtain a potentially more realistic view of the golf swing, 3-D models have been created and developed.

### 2.4.5.2 Three-Dimensional Models

Vaughan (1981), cited in Betzler et al. (2008), carried out one of the earliest studies of 3-D kinetics of the downswing phase of the swing. Through inverse dynamics and using a rigid model of a golf club, the torques and forces applied by four golfers to their clubs were analysed. It was found that the players analysed did not swing the club in one static plane. Through using a similar approach to Vaughan (1981), Neal and Wilson (1985) determined 3-D forces and torques that were applied to the club.

A model created by Tsunoda et al. (2004) was more complex than previous 3-D models which was based on recorded motion from golf swings. The increased complexity in the approach used by these authors meant that parameters were not as
easily modified and the mathematical model behind the simulation could only be solved by a specific multi-body kinetic software package (MADYMO). In terms of validation of this model, the model output correlated with the real swing measurements, however the model over-predicted the shaft strain in the important phase just before impact. Suzuki et al. (2005) used a 3-D model of the swing in order to characterise the relationship between the point of wrist release, shaft deformation and club head velocity. However, similar to the model of Tsunoda et al (2004), there were multiple shaft oscillations in their simulations, not typical for downswings. There was an apparent lack of dampening in this model in terms of the simulated shaft and the missing elasticity of the simulated hand-grip interface which could in theory have contributed to these oscillations.

2.4.5.3 Full-Body 3-D Models

The previous examples of models have focused on 2-D and 3-D simulations of the club and arms. In recent times, there have been some attempts to model full-body movement of the golfer. Mc Guan’s (1996) simulation was an early full-body model of the downswing. This model was developed with the multi-body dynamics software ADAMS. Data obtained from an actual golf swing were what the body segment trajectories for the simulation were based upon. Whilst this was an important paper in terms of its attempt at modelling the full-body golf swing, a shortcoming was that there were no details provided in this paper with regard to model validation. As discussed previously, this is a fundamental omission, as without it, the results of the model are open to question. Nesbit et al. (1994) also simulated the downswing of a golfer. The golfer consisted of 15 segments (of which only five were driven by motion data) and there was also a finite element model of the club. Like the model of McGuan (1996), this model was created using ADAMS software. A criticism of this paper was there was no detailed validation information given. More recent to this, Nesbit (2005) performed another simulation study with a more complex model to the previous paper. The aim was to characterise the 3-D kinematics and kinetics of the swings of several subjects (n=85) who all used the same driver for their recorded swings. Data to kinematically drive the joints of the golfer model were recorded from subject golf swings. Validation was carried out by comparing manually calculated joint torques, results from other studies and ground reaction force data. According to the author there was reasonable agreement for these. The results of this simulation study showed that overall coordination was important for creating maximum club head velocity. In contrast to previous 2-D simulation studies, it was found that subjects did not use hindrance
torques to create a delayed wrist action on the downswing and through impact, instead this is based upon the path of the hands and the initial wrist angle. This point highlights the importance of using full-body motion in golf swing simulations as sometimes incorrect conclusions may be drawn from 2-D data. Nesbit and McGinnis (2009) used the 3-D models developed from the previous study (Nesbit 2005) to investigate the hub path geometry and kinematics of four golfers. The results indicated that the hub path is geometrically complex which displays a constantly changing radius thus deviating from a constant radius path. When hub path of the best golfer in the group (0 handicap) was optimised, it indicated that a non-circular hub-path was more advantageous in terms of increasing club head velocity while simultaneously reducing the kinetic loading.

Another simulation study that included full-body motion was that by Kenny et al. (2006, 2008a). The first study's aim (Kenny et al. 2006) was to validate a full-body computer simulation for a golfer using the driver club of three different lengths (46, 38 and 50 inches). Motion analysis recordings of the subject performing swings with clubs of the specified lengths were recorded and used to drive the model. The full-body was scaled to the subject based on 54 anthropometric measurements. Inverse and forward dynamics simulations were done with the LifeMOD plug-in of the ADAMS software. The model was validated for recorded and simulated marker trajectories and club head velocities. There was good agreement with a reported Pearson’s correlation of 0.99 between experimental and simulated movement trajectories. There was an attempt to kinetically validate the model by comparing the muscle force output of the third left finger from the model with data from previous studies that measure hand grip force during the swing. There was reasonable agreement with these. This was an interesting attempt at kinetically validating the model. However, there was no direct measure of the grip force in the data collection phase. Betzler et al. (2006) used a similar approach to developing their model. The same software package was used (ADAMS with its LifeMOD plug-in) to develop a model of one subject golfer. Similar to what occurred in the Tsunoda et al. (2004) study, unrealistic oscillations were observed in the shaft deflection properties. There was an attempt to compare recorded and simulated ground reaction forces in this study also. The overall pattern of ground reaction force appeared similar however there were obvious differences between measured ground reaction force and simulated forces.

Kenny et al. (2008a) developed a model similar to methods of their previous study (Kenny et al. 2006), but this time developed a model of the subject swinging with a 7-
iron club as well as the driver club. The model was validated using club head velocity, additional markers used in experimentation that were not used to drive the model and comparing modelled muscle force and previously published grip force data. All showed a good level of agreement. The simulations were used to investigate proximal to distal segmental sequencing in the golf swing. It was found that peak magnitudes of kinetic energy increased in a sequence from proximal to distal segments for both the 7-iron and driver simulations. The results also showed that for the highly skilled subject such as that modelled in this study (handicap +1), that the order of sequencing can differ from what is purported to be the optimal segmental sequencing which suggested that there is a subject-specific optimal sequencing pattern. These studies both utilised an inverse-forward dynamics approach as detailed in Figure 2.6.

Sweeney et al. (2011) used a three-dimensional, 36 degrees of freedom, forward dynamics approach to investigate the role of trunk rotation (X-Factor) and wrist flexion in relation to club head velocity and loft angle. Club head dynamics were validated against empirical data collected from five golfers. In order to investigate the role of wrist flexion and X-Factor, both of these variables were set to zero degrees through the downswing with resultant club head velocity measured from the forward dynamics model. Results indicated that changing wrist flexion/extension angle to zero degrees produced the biggest change in club head velocity, with a reduction of 46% at impact. The change in trunk rotation did not have as large an effect on club head velocity. It was concluded that maintaining a correct wrist flexion angle is of importance to creating a large club head velocity. The change in both variables resulted in a significant ($p < 0.01$) increase in loft angle of the club head at impact. This study was an interesting use of a modelling approach to investigate the role of kinematic variables. Whilst detailed validation results pertaining to club head velocity were presented, no validation results of body kinematics were presented or discussed however. As previously discussed, no appropriate validation of model kinematics leaves the results of simulation open to question.
2.4.6 Modelling Summary

The previous section on modelling and simulation has highlighted the advantages and disadvantages of these methods. Research detailing different modelling approaches of the golf swing was presented. As can be seen from the papers presented, modelling efforts have progressed from 2-D models of the arm modelled as a double-pendulum, such as Jørgensen (1970), to more complex 3-D full-body of the complete golf swing, such as that of Nesbit (2005). Full-body 3-D models are more ideal than just arm and club models as they provide more information with regard to the overall coordination of
the body. The development of multi-body kinetics software packages such as MADYMO, AnyBody and ADAMS (with LifeMOD plug-in) has allowed the creation of 3-D full-body models that ease the process of calculating the equations of motion. These programmes allow for the many calculations of these complex models to be made more easily than previous methods. ADAMS, with its LifeMOD plug-in is the software to be used for the modelling section of this PhD. As has been highlighted through the studies of Nesbit (2005, 2005, 2009) and Kenny (2006, 2008a), full-body 3-D models of the golf swing has been published using this software previously thus justifying its use for this PhD.

2.5 SUMMARY AND FUTURE RESEARCH DIRECTION

Movement variability is a ubiquitous feature of human movement and as such previous suggestions of invariance in movement patterns being essential for producing a consistent outcome are not substantiated in the literature. It has been highlighted that there is no conclusion as to whether observed movement variability is beneficial or detrimental to movement outcome. Hamill et al. (2006) point out the role of variability is a significant question being addressed in the study of movement. The lack of research examining outcome, outcome variability and movement variability has been highlighted.

Examining movement variability within the motor skill of the full golf swing to date has not revealed the role that movement variability plays within the golf swing. Further research is required as has been highlighted by Glazier et al. (2011). In particular, an approach towards single-subject analysis is required at the elite level (Brown et al. 2011).

The computer modelling and simulation approach has been shown to offer the ability to investigate human movement in the virtual environment. The golf swing has been extensively modelled over the last number of years and has progressed to the point whereby full 3-D models can be constructed and analysed.

Based on this review of the literature, an investigation to understand the role of movement variability in the golf swing was undertaken. It was decided to combine the use of experimental and modelling techniques in order to perform this investigation. First, in order to ascertain the relationship between movement variability and outcome, an experimental study to quantify kinematic variability will be carried out on a number
of elite players performing full swings. This will be used to inform the next phase of the research.

To investigate the effect of movement variability of movement patterns on the outcome of the swing, a modelling approach will then be used in a similar way to the study of McLean et al. (2004) investigated random perturbations and their effect on knee loading. The literature review highlighted the need for more detailed individual analysis of the golf swing (Kenny et al. 2008c). There has also been a call for more subject-specific models created to improve the validity of models (Hatze 2005). Thus a single-subject approach will be used for the model creation phase. A method to randomly perturb the validated model based on the natural variability of the subject will be developed in order to assess the effect of movement variability on outcome.

2.6 REFERENCES


Is Movement Variability Relevant for the Elite Golfer?


Is Movement Variability Relevant for the Elite Golfer?


CHAPTER 3

METHODOLOGICAL ISSUES
3.0 ABSTRACT

Prior to embarking upon the major studies involved in this thesis, certain methodological concerns had to be addressed. These included the suitability of the motion capture system to record marker trajectories during golf swing experimentation and the ability of the launch monitor device to capture ball and club dynamics at impact for the high swing speeds of the subjects studied. Therefore, to test the motion capture system (Motion Analysis Corporation), it was compared against another commercially available system in a series of static and dynamic tests. The results of the dynamic analysis showed the two systems to agree strongly with respect to the marker trajectories recorded (mean $R^2=0.975 \pm 0.077$) value for all markers for all swing speeds. To test the launch monitor device (Accusport Vector Pro, System 1) used; it was compared against two other commercially available monitors (considered the benchmark industry leading launch monitors) with a robot performing golf swings at five different speeds. The results of this comparison showed strong agreement between the systems for ball velocity ($R^2=0.995$ for System 1 and 2 and $R^2=0.996$ for System 1 and 3) and club head velocity ($R^2=0.993$). These analyses showed the motion capture system and launch monitor device to be valid for use within subsequent studies.

3.1 INTRODUCTION

The review of literature performed in Chapter 2 identified the need for a more thorough investigation of movement variability in relation to the golf swing. Prior to carrying out the investigations of movement variability in the golf swing certain methodological issues had to be addressed such as:

- The suitability of the motion analysis system to measure body kinematics
- The ability of the launch monitor to measure club and ball launch characteristics

The following sections detail the studies undertaken in order to test the motion capture system (Section 3.2) and the launch monitor device (Section 3.3). In the case of the tests of both the motion capture and launch monitor systems; they were compared
against other commercially available, industry leading systems. These systems are used by the game’s governing body (The R&A) in their research.  

### 3.2 MOTION ANALYSIS SYSTEM

In order to record the movements of the golfers performing their trials, a system to record these 3-D movements was utilised. This system was a commercially available optical 3-D motion capture system which consisted of multiple cameras each equipped with their own LED or infrared light source. These cameras and their light sources allow recording of the 3-D trajectories of retro-reflective markers placed at various anatomical landmarks. These 3-D optical motion capture systems are frequently used to record 3-D body kinematics in golf studies such as the following examples; Mitchell et al. (2003), Zheng et al. (2008b), Chu et al. (2010), Healy et al. (2011) and Brown et al. (2011). The motion analysis system utilised for the data collection in Chapter 4 was the Motion Analysis Corporation (Santa Rosa, California), Eagle motion capture system.

To ensure that the recorded trajectories of markers were reliable and acceptable to be used in subsequent studies, an analysis was carried out to compare the Motion Analysis system with that of another commercially available motion capture system. The other commercially available system consisted of cameras with a similar construction to that of the Motion Analysis system except that it had an infrared light source instead of LED.

To perform this analysis, a series of static and dynamic tests were carried out where the two systems were recording simultaneously. As there is no ‘gold standard’ motion capture system available, the absolute accuracy of the motion capture systems could not be ascertained directly. In order to understand the accuracy of the motion capture systems better, a static analysis was carried out whereby the distance between markers was compared on a specially constructed ‘flat plate’ (see Figure 3.1) constructed from aluminium. This flat plate contained five markers with four of these placed at the corners and the fifth marker placed offset from the centre. The 2-D distances were accurately measured using an optical measurement microscope. This microscope is a device with traceable accuracy. A dynamic analysis of a robot arm performing a golf swing was also performed to ascertain the agreement between the

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2 Please note the comparison motion capture system and launch monitor devices are not named due to a request by The R&A to keep them anonymous.
systems with markers moving through 3-D space. For simplicity, the motion capture systems will be hereinafter referred to by a specific identification number as per Table 3.1.

<table>
<thead>
<tr>
<th>System ID</th>
<th>Motion Capture System Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>Motion Analysis Corporation system</td>
</tr>
<tr>
<td>System 2</td>
<td>Commercially available motion capture system</td>
</tr>
</tbody>
</table>

### 3.2.1 Methods

#### 3.2.1.1 Data Collection – Static Tests

To perform the static analysis, motion capture Systems 1 and 2 were both set-up in a similar fashion. Three cameras were used for each system and they were oriented towards the flat plate which was placed on the laboratory floor. The capture volume was identical for each system (1.5 x 1.2 x 0.7 m). Each system was calibrated according to the manufacturer’s instructions. System 1 was calibrated by first performing a static calibration with a frame containing four markers which defined the origin and orientation of the global coordinate system (GCS) of the motion capture system. Following this, a wand containing three markers which were a known distance apart (the distance between the two outermost markers was 500 mm) was moved through the capture volume in order to perform a dynamic calibration of System 1. System 2 was calibrated in a slightly different manner. The static and dynamic calibrations were performed simultaneously as determined by the manufacturer. The same static frame (in the exact same position) used for System 1 was used for this calibration of System 2. As the wand for dynamic calibration was different to that of System 1 (it had only two markers which were 501 mm apart), this differed between the systems. Each system recorded a trial for 5 seconds each at a sampling frequency of 400 Hz for four different orientations of the flat plate. The four different orientations related to which direction was pointing towards the laboratory door. Thus there were four different conditions with Top, Right, Bottom and Left directed at the laboratory door. The sampling frequency of 400 Hz was that used in the experimental data collection of the following chapters.
3.2.1.2 Data Collection – Dynamic Tests

To compare both systems in dynamic tests, 9 markers were placed on a robot arm (See Figure 3.2) that performed swings with a driver club. The marker placements and their relevant names can be viewed in Figure 3.2. A golf robot was used to perform this analysis as pilot tests demonstrated that it could perform repeatable swings (Suzuki et al. 2006). As in the static tests, three cameras were used for each system to record the robot swing motion (each system had a capture volume of 3 x 2.5 x 3 m). The systems were calibrated as per the statics tests described in Section 3.2.1.1.
The robot performed 10 swings at 3 different club head impact velocities. The three different velocities were approximately 35, 45 and 55 m.s\(^{-1}\). These club head velocities was selected in order to cover the potential range of velocities expected during experimental testing. Both systems were set-up to record the robot swings simultaneously using a trigger pulse.

### 3.2.1.3 Data Processing – Static Tests

The five markers on the flat plate were identified within the relevant software for System 1 and 2. Raw x, y, z coordinates of these markers from both systems were exported to Microsoft Excel for further analysis. Euclidean distances were calculated using the raw coordinates recorded by each system between the four corner markers and the centre marker of the flat plate for each of the four conditions. Therefore the four distances calculated were; Top-Right (TR) to Centre, Bottom-Right (BR) to Centre, Bottom-Left (BL) to Centre and Top-Left (TL) to Centre. As stated previously, the distance between the markers on the flat plate was determined through measurement on a highly accurate optical measurement Hawk microscope (Vision Engineering, UK) which was deemed to be the gold standard for this against which the distances calculated from the coordinates captured by each system would be compared.
3.2.1.4 Data Processing – Dynamic Analysis

The x, y, z raw coordinates of the 9 markers on the robot arm were tracked within the relevant software for System 1 and 2 for each trial captured simultaneously from each system. The data were cropped to include only address to impact portion of the robot swing for further analysis as this was where the three cameras of each system where concentrated. Address was defined as the frame before the robot initiated the swing and impact was the frame where the club struck the ball.

![Figure 3.3 – Address (left) and impact (right) positions used to define robot swing events](image)

3.2.1.5 Data Analysis – Static and Dynamic Tests

To ascertain the ability of System 1 and 2 to record the static positions of the flat plate described in Section 3.2.1.1, the distances calculated between the markers on the flat plate were compared. The differences in the distance calculated for each system and that of the gold standard microscope are presented in Section 3.2.2.1.

In relation to the dynamic tests, correlation (R²) was used to establish the level of agreement between the two systems for the trajectories of the markers recorded during the swing. The average of the correlations between the two systems of the x, y and z trajectories are presented in the Section 3.2.2.2. Further, selected inter-marker Euclidean distances were compared throughout the course of the dynamic test between the two systems.
3.2.2 Results and Discussion

3.2.2.1 Static Tests

The differences between the distances calculated using the coordinates of each system and that calculated using the microscope with traceable accuracy for the four different conditions are presented in Table 3.2. On average across all the calculated distances, there was an extremely low difference between System 1 and 2. The mean difference between the system measurement and gold standard across all conditions and distances was 0.11 mm for both System 1 and 2. These results demonstrate that both systems were reliable in terms of static measures and that System 1 performed similarly to another commercially available system in this regard when compared to a gold standard measure.

Table 3.2 – Absolute differences between each system and the microscope with traceable accuracy for each calculated distance (mm) for each condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>TR – Centre</th>
<th>BR – Centre</th>
<th>BL – Centre</th>
<th>TL – Centre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top (mm)</td>
<td>0.14</td>
<td>0.23</td>
<td>0.12</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>0.17</td>
<td>0.01</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Right (mm)</td>
<td>0.17</td>
<td>0.10</td>
<td>0.04</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>0.10</td>
<td>0.06</td>
<td>0.14</td>
</tr>
<tr>
<td>Bottom (mm)</td>
<td>0.30</td>
<td>0.01</td>
<td>0.03</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>0.18</td>
<td>0.02</td>
<td>0.18</td>
<td>0.06</td>
</tr>
<tr>
<td>Left (mm)</td>
<td>0.01</td>
<td>0.21</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.06</td>
<td>0.04</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*TR – Top Right BR – Bottom Right BL – Bottom Left TL – Top Left*

3.2.2.2 Dynamic Tests

The correlations between the trajectories of the 9 markers placed on the robot arm for the robot swings are presented in Table 3.3. With the exception of the shoulder marker, all markers showed a near perfect correlation. This highlights that the trajectories of these markers recorded by each system were perfectly comparable. Interestingly, the shoulder marker did not show good agreement between the two systems. On further inspection of the raw trajectories, it appeared that the data for these trajectories was noisy for System 1. This may have been a consequence of the shoulder marker being
at the edge of the capture volume and camera coverage may not have been ideal for System 1 at this point. This depended entirely on the capture volume set up for this experiment and does not represent a system flaw. Despite this lack of agreement between the two systems at this point, it is clear that for the other markers the trajectories agreed strongly. This indicates that System 1 did compare well for the dynamic test of a swing when tested with a similar system.

Table 3.3 – Correlations (R²) between System 1 and 2 marker trajectories over 10 trials at each speed

<table>
<thead>
<tr>
<th>Marker</th>
<th>Speed (m.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Shoulder</td>
<td>0.678</td>
</tr>
<tr>
<td>Arm-Front</td>
<td>1.000</td>
</tr>
<tr>
<td>Arm-Back</td>
<td>1.000</td>
</tr>
<tr>
<td>Plate-Front</td>
<td>1.000</td>
</tr>
<tr>
<td>Plate-Back</td>
<td>1.000</td>
</tr>
<tr>
<td>Wrist</td>
<td>1.000</td>
</tr>
<tr>
<td>Clamp-Single</td>
<td>1.000</td>
</tr>
<tr>
<td>Clamp-Front</td>
<td>1.000</td>
</tr>
</tbody>
</table>

A visual illustration of the closeness between the trajectories is presented in Figure 3.4, Figure 3.5 and Figure 3.6 for the arm-front marker for 200 frames of a selected trial. There is a slight offset between the coordinate values that is most likely due to a marginal difference between the exact definitions of the global coordinate system of each capture system. The trends in the shape of trajectories are identical between the systems however.
Figure 3.4 – x coordinate position of the arm-front marker for 200 frames during the backswing of a robot swing (club head velocity - 55 m.s\(^{-1}\))

Figure 3.5 – y coordinate position of the arm-front marker for 200 frames during the backswing of a robot swing (club head velocity - 55 m.s\(^{-1}\))
Euclidean inter-marker distances were compared between both systems. The averages of the absolute differences between each system for each robot speed are presented in Table 3.4. It can be observed that the differences 0.5 mm or under indicating that both systems were comparable.
Table 3.4 – Absolute differences of Euclidean inter-marker distance (mm) between each system

<table>
<thead>
<tr>
<th>Inter-Marker Distance</th>
<th>Speed (m.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Shoulder – Arm Front (mm)</td>
<td>0.3</td>
</tr>
<tr>
<td>Shoulder – Arm Back (mm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Arm Front – Arm Back (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Arm Front – Plate Front (mm)</td>
<td>0.4</td>
</tr>
<tr>
<td>Plate Front – Plate Back (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Plate Back – Arm Back (mm)</td>
<td>0.4</td>
</tr>
<tr>
<td>Wrist – Plate Back (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Wrist – Plate Front (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Wrist – Clamp Single (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Clamp Back – Clamp Front (mm)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

3.2.3 Conclusion

The results of these analyses indicated that the motion analysis system to be used in subsequent chapters performed strongly in comparison with another commercially available system when recording the position of markers in a static and dynamic test. Collectively, these results were deemed to demonstrate that System 1 was an acceptable motion capture system to capture body kinematics during the golf swing.

3.3 LAUNCH MONITOR

An important aspect of any of the experimental tests to be undertaken in this thesis was the ability to capture shot outcome in order to effectively examine the relationship between movement variability and outcome variability. This would involve the use of a launch monitor device to capture these measurements at impact such as ball velocity, club head velocity, ball spin and launch angle. It was necessary to test the accuracy
and precision of the launch monitor that was to be used in experimental tests in order to ascertain what measures of outcome could be used reliably. To perform this analysis, the launch monitor available for the experimental tests in this research was compared against two other launch monitor devices. Monitor 1 was the Vector Pro launch monitor that was to be used in experimental testing in subsequent chapters of this thesis.

This monitor consisted of two high-speed cameras surrounded by infrared beams. Monitor 2 was a radar based launch monitor that tracked the entire flight of the ball from impact to final position after landing. Monitor 3 was a stereoscopic launch monitor that contained two high speed cameras and a light source.

Table 3.5 – Description and ID number given to the launch monitors used in this comparison

<table>
<thead>
<tr>
<th>Monitor ID</th>
<th>Launch Monitor Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor 1</td>
<td>Vector Pro launch monitor</td>
</tr>
<tr>
<td>Monitor 2</td>
<td>Radar based launch monitor</td>
</tr>
<tr>
<td>Monitor 3</td>
<td>Stereoscopic launch monitor</td>
</tr>
</tbody>
</table>
3.3.1 Methods

3.3.1.1 Data Collection

A golf robot was used for this analysis. The robot performed 10 swings at five different club head velocities of approximately 35, 40, 45, 50 and 55 m.s\(^{-1}\) using a driver club. Ten swings were performed by the robot at each speed resulting in 50 shots in total. As per the motion capture system tests, these speeds were selected to cover the range of velocities that could be encountered during experimental testing. The launch monitors could be used simultaneously as pilot testing determined there was no interference in each other’s operations when recording the same swing. Monitors 1 and 3 were both placed opposite the ball and perpendicular to the target line. Monitor 2 was placed behind the ball pointing down the target line. All monitors were placed in their recommended positions. Each ball was marked with a black strip around its circumference to allow Monitors 1 and 3 perform its measurements at impact.

3.3.1.2 Data Processing and Analysis

The measurements from each monitor were exported to Microsoft Excel for further analysis. For each measure, the mean and standard deviation was calculated over the ten trials at each velocity. The measures compared between Monitor 1 and 2 were; club head velocity, ball velocity, side angle and launch angle. The measures compared between Monitor 1 and 3 were ball velocity, back spin and side spin, side angle and launch angle (see Appendix A2.1 for definitions of these variables\(^3\)). Ball spin measures were only compared between Monitor 1 and 3 as Monitor 3 was considered the benchmark monitor in this regard. However, Monitor 3 did not measure club head velocity due to its positioning relative to impact and thus this measure was not considered for comparison between Monitor 1 and 3.

Correlation (R\(^2\)) was used to examine the relationship between the mean of each measure at every club head velocity. In order to ascertain absolute differences between data sets that could be masked by correlation, root mean square difference (RMSD) was also calculated.

\(^3\) A data sheet for the Vector Pro launch monitor was requested but was not provided due to being proprietary information of Accusport Inc.
3.3.2 Results and Discussion

The results of the comparison of Monitor 1 and 2 are shown in Table 3.6. The results displayed for this comparison show strong agreement between the monitors with respect to club head and ball velocity over the 50 shots. However, ball side angle and launch angle ($R^2=0.565$) results did not show a strong relationship between monitors. In particular ball side angle results showed a poor correlation ($R^2=0.147$) with a large RMSD value ($2.27^\circ$). To contextualise this difference, in a study of seven category 1 golfers, Kenny et al. (2008c) measured side angle with a stereoscopic to be $1.4^\circ \pm 3.7^\circ$ with their own driver over 8 shots. In the same study of Kenny et al. (2008c) launch angle was calculated as $8.9^\circ \pm 2.3^\circ$ for the same cohort.

<table>
<thead>
<tr>
<th></th>
<th>Correlation ($R^2$)</th>
<th>RMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Club head velocity (m.s$^{-1}$)</td>
<td>0.993</td>
<td>1.23</td>
</tr>
<tr>
<td>Ball velocity (m.s$^{-1}$)</td>
<td>0.995</td>
<td>0.80</td>
</tr>
<tr>
<td>Side angle ($^\circ$)</td>
<td>0.147</td>
<td>2.27</td>
</tr>
<tr>
<td>Launch angle ($^\circ$)</td>
<td>0.565</td>
<td>1.99</td>
</tr>
</tbody>
</table>

The results of the comparison of Monitor 1 and 3 are shown in Table 3.7. Similar to the comparison of Monitor 1 and 2, there was a strong correlation for the ball velocity measure. Back spin had a less strong correlation than ball velocity. A large discrepancy between the monitors was observed for side spin with a large RMSD value for this measure. The coefficient of determination ($R^2$) value is slightly misleading here as the actual correlation coefficient ($r$) value was negative indicating a negative relationship between the two monitors for this measure. Side angle and launch angle correlations were similar to that of the comparison of Monitor 1 and 2.
Table 3.7 – Correlation ($R^2$) and RMSD for club head and ball measures between Monitor 1 and 3

<table>
<thead>
<tr>
<th>Measure</th>
<th>Correlation ($R^2$)</th>
<th>RMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball velocity (m.s$^{-1}$)</td>
<td>0.996</td>
<td>0.73</td>
</tr>
<tr>
<td>Back spin (rpm)</td>
<td>0.747</td>
<td>251</td>
</tr>
<tr>
<td>Side spin (rpm)</td>
<td>0.620</td>
<td>1080</td>
</tr>
<tr>
<td>Side angle (°)</td>
<td>0.236</td>
<td>2.54</td>
</tr>
<tr>
<td>Launch angle (°)</td>
<td>0.593</td>
<td>2.38</td>
</tr>
</tbody>
</table>

Analysing these results collectively indicates that Monitor 1 compared favourably with two other launch monitors tested for club head and ball velocity. However, other measures such as ball spin, side angle and did not agree strongly with other benchmark launch monitors. This informed the decision on which variables to focus on in subsequent studies.

### 3.3.3 Conclusion

The results of this comparison of the Vector Pro launch monitor (Monitor 1) with two other monitors suggests that it is more suited to measuring ball and club head velocity than other variables tested given the close agreement with the other two systems for these velocity measures. Therefore, ball velocity will be the shot outcome measure focused upon in subsequent experimental chapters with club head velocity being the focus of the simulation chapters.

### 3.4 SUMMARY

To summarise, preliminary work has been carried out to address two methodological issues. Firstly, the motion capture system to be used to record body kinematics subsequent chapters was found to agree with another commercially available system strongly in static and dynamic tests. Therefore, the motion capture system to be used in this research was found to be satisfactory for capturing marker trajectories during the golf swing. Secondly, the launch monitor device that is to be used in this research to capture club and ball launch characteristics at impact was found to agree strongly for
ball and club head velocities but not for other ball launch characteristics such as ball
spin or launch angle. Consequently, ball and club head velocity will be the outcome
measures focused upon in subsequent chapters.

3.5 REFERENCES

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CHAPTER 4

DEVELOPMENT OF A CALCULATION TECHNIQUE TO QUANTIFY MOVEMENT VARIABILITY OF MARKER TRAJECTORIES DURING THE GOLF SWING
4.0 ABSTRACT

The effect of movement variability on shot outcome in the golf swing has not yet been extensively researched or established. In order to examine this relationship effectively, it is necessary to quantify the levels of movement variability before this relationship can be examined. Therefore, the aim of this chapter was to develop a novel calculation technique to quantify movement variability at 14 body locations of participants performing driver swings. 16 highly skilled (handicap ≤5) participants each performed 10 swings wearing retro reflective markers which were tracked by a 3D motion analysis system operating at 400 Hz. Standard deviations were calculated for the three-dimensional positional data for the 14 body locations for the ten time normalised trials. Several procedures were examined to combine the three-dimensional variability into a single number that represented the movement variability for that participant. The combination of tri-axial variability method into a single number was adopted to enhance the players and coaches understanding of the movement variability quantified. Ultimately a volume procedure that calculated the mean volume of an ellipsoid over time was adopted. The calculated mean variability volume was then standardised to the markers relevant path distance in order to create a calculation comparable to coefficient of variation. The results indicated which markers contained the highest level of movement variability on average across all participants. Across the cohort of participants, the wrists were found to contain the most movement variability with femoral condyle at the knee containing the least movement variability. Thus, a novel calculation technique was developed that calculated the three-dimensional movement variability of marker trajectories for each participant. This calculation technique will be used in a subsequent analysis of movement variability in the golf swing.

4.1 INTRODUCTION

Despite movement variability being a ubiquitous feature of human movement (Davids et al. 2003), the review of literature highlighted that there was a dearth of literature (Section 2.3.3.1) that examined this feature of movement in relation to the golf swing. However, movement variability in the golf swing has been highlighted as an important area to research (Williams and Sih 2002, Farrally et al. 2003, Glazier 2011). Within this and subsequent chapters, movement variability refers to kinematic variability of body landmarks and outcome variability refers to variability of shot outcome measures such as ball or club head velocity.
It would appear golf swing coaches tend to base their teaching methods on principles of ball flight as described by Wiren (1990) and also personal opinion, with their focus typically on a common optimal movement pattern that everyone should attain (Bradshaw et al. 2009). As variability of movement is inherent both within and between all individuals (Davids et al. 2003), the common optimal swing approach is incorrect when considered from a dynamical systems perspective. The principles of dynamical systems theory (DST) state that movement patterns arise and develop from the synergistic organisation (coordinative structures) of the neuromuscular system as a result of morphological factors, task constraints, and environmental factors (Kurz and Stergiou 2004) and resultantly an invariant movement pattern is unlikely. To hit the ball successfully and consistently, players need to exhibit low variability with respect to the task criterion (club head dynamics at impact) but it is possible they may need variable movement patterns to achieve this goal (Knight 2004); i.e. a player may have high movement variability on certain parameters linked with a low outcome variability. The method of achieving the goal of low variability in the shot outcome remains unclear. Indeed, it has been stated that the ‘role of variability in movement is currently a significant question being addressed in the movement sciences’ (Hamill et al. 2006). It has yet to be ascertained to what degree movement variability may be detrimental or beneficial to outcome variability in relation to the golf swing.

There have been efforts in recent years to study movement variability golf swing and shot outcome. Bradshaw et al. (2009) investigated the effect of movement variability on golf swing performance, with a 5-iron being struck towards a target by high- (n=10) and mid-handicapped (n=10) golfers. Variability of kinematic measures, such as club head velocity, lead wrist angle, trunk angle, trail forearm angle and many more from key technical positions were calculated using 2-D video images. It was concluded that invariance in the key technical positions at address, mid backswing and top of backswing was the more favourable technique for the skilled golfers. This study was welcome in terms of examining variability of the golf swing and its effect on shot outcome but it was limited in certain ways. The golf swing was examined with two-dimensional video operating at 50 Hz and looked only at discrete measures. Given that the swing occurs in three-dimensions (Coleman and Rankin 2005, Coleman and Anderson 2007), a more accurate picture of the movement will be acquired through three-dimensional motion analysis. Further, it is questionable whether a sampling frequency of 50 Hz is sufficient to capture enough kinematic information given the high velocity particularly of the arms and club during the golf swing. Discrete variables, while
informative, do not allow a thorough understanding of the entire movement pattern performed over time and thus continuous methods may be more advantageous (James 2004). Continuous methods such as angle-angle plots and time-series graphs represent movement variability as a function of time or other parameter. A recent study by Horan et al. (2011), examined gender differences in segmental movement variability and club head trajectory at three phases of the downswing along with inter-segmental coupling of the pelvis and thorax for a cohort of 38 skilled golfers. This study examined movement variability differences in the measures previously mentioned and indeed it was reported that females exhibited higher axial rotation variability at two of the phases examined in the downswing while both genders displayed decreasing variability of hand and club head trajectory towards ball contact. The study of Horan et al. (2011) did provide some interesting findings in terms of gender differences with respect to inter-segmental variability and variability of club head trajectories; however the relationship between the exhibited movement variability and outcome was not detailed.

For coaches to provide effective feedback on the golf swing, it is essential that the measures that most affect outcome are established. Knowledge of the measures that have the most influence on outcome may improve coaching as teaching professionals can focus on those influential measures in the coaching of the swing. Therefore it is important to investigate how movement variability affects outcome and thus better inform golf coaches. As was suggested by Knight (2004), a more effective teaching strategy is possibly a strategy that reduces variability in the components of the swing that have the most influence on shot outcome variability whilst allowing increased variability in the swing components that do not influence shot outcome variability. In order to implement a strategy such as this, it is necessary to identify the parameters in which movement variability affects shot outcome variability the most. Before this can be examined in depth, movement variability needs to be examined more thoroughly in the golf swing.

4.1.1 Aims

Based on the need to assess movement variability more in depth in relation to the full golf swing, the aims of this chapter were to:

- Develop a continuous calculation technique to quantify movement variability of marker trajectories.
To perform a preliminary examination of the movement variability levels quantified in the golf swings of participants.

A continuous calculation method is one in which movement variability is represented as a function of time or other parameter and in which temporal and spatial characteristics can be represented (Hamill et al. 2000).

4.2 METHODS

4.2.1 Participants

Sixteen (6 male, 10 female, age 26.3 ± 5.6 years, body mass 67.0 ± 10.3 kg, height 1.7 ± 0.1 m, handicap 2.8 ± 3) highly skilled (handicap ≤5) right-handed golfers were recruited to participate in this study. Ethical approval was obtained from the Faculty of Education and Health Sciences Research Ethics Committee and all participants were familiarised with the experimental procedure and all possible risks before providing written consent to participate.

4.2.2 Data Collection

All testing sessions took place in a purpose-built indoor golf testing facility. For the testing session, each participant performed a number of shots with their own driver into a net five metres away (See Figure 4.1 for test set-up) until ten acceptable trials were obtained. Participants provided their own feedback about the quality of each shot struck. Where a player was unhappy with their shot, or it deviated more than 20 metres from the target (result from the launch monitor analysis), it was removed from the analysis. The participants wore dark, tight, non-reflective clothing with retro-reflective markers attached.
Is Movement Variability Relevant for the Elite Golfer?

Figure 4.1 – Experimental set-up showing overview of camera and launch monitor placement and coordinate system used

Retro-reflective markers were placed at various body landmarks in order to track body motion throughout the swing. In total 37 markers were placed on each participant and two markers were placed on the driver shaft to aid event identification, with a further marker (small reflective disc) on the ball. 40 markers were used in total. The majority of the markers used in this marker set closely followed that used for tracking body motion in the golf swing by Mitchell et al. (2003) with additional markers included to track the entire body. The entire marker set used is listed in Table 4.1.
<table>
<thead>
<tr>
<th>Marker</th>
<th>L Greater Trochanter</th>
<th>R Acromion Process</th>
<th>L Head</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>L Greater Trochanter</td>
<td>R Acromion Process</td>
<td>L Head</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R Greater Trochanter</td>
<td>L Acromion Process</td>
<td>R Head</td>
<td>L ASIS</td>
<td></td>
</tr>
<tr>
<td>R Medial Malleolus</td>
<td>Base Club Shaft</td>
<td>L Calcaneus</td>
<td>R ASIS</td>
<td></td>
</tr>
<tr>
<td>L Medial Malleolus</td>
<td>R Mid-Humerus (P)</td>
<td>R Calcaneus</td>
<td>Sacrum</td>
<td></td>
</tr>
<tr>
<td>L Inferior Patella</td>
<td>L Mid-Humerus (P)</td>
<td>R Mid-forearm (P)</td>
<td>Ball</td>
<td></td>
</tr>
<tr>
<td>R Inferior Patella</td>
<td>L Femoral Condoyle</td>
<td>L Mid-forearm (P)</td>
<td>C7</td>
<td></td>
</tr>
<tr>
<td>L 2\textsuperscript{nd} Metatarsal Head</td>
<td>R Femoral Condoyle</td>
<td>L Malleolus</td>
<td>L Hand</td>
<td></td>
</tr>
<tr>
<td>R 2\textsuperscript{nd} Metatarsal Head</td>
<td>Top Club Shaft</td>
<td>R Malleolus</td>
<td>R Hand</td>
<td></td>
</tr>
<tr>
<td>L Mid-Shank (P)</td>
<td>R Humeral Epicondyle</td>
<td>L Mid-Thigh (P)</td>
<td>L Wrist</td>
<td></td>
</tr>
<tr>
<td>R Mid-Shank (P)</td>
<td>L Humeral Epicondyle</td>
<td>R Mid-Thigh (P)</td>
<td>R Wrist</td>
<td></td>
</tr>
</tbody>
</table>

\textit{R - Right L – Left}

\textit{(P) indicates that a pedestal marker was used}

A graphical illustration of body marker locations can be seen in Figure 4.2. For mid-segment identification, pedestal markers of 1 inch stem length were used in order to allow tracking of the rotational movements of these segments.
Each participant was allowed an unlimited self-directed warm-up to ensure they became accustomed to swinging with the markers on and so prepare them for performing the trial swings. For this warm-up period, each participant was permitted a number of practice shots until such time that they felt appropriately ready to commence data collection. For the data collection, each participant was instructed to swing the driver to hit the ball towards the target-line, aiming to maximise both distance and accuracy, as if in a competitive situation on the golf course. Participants were instructed to do this in order to produce swings typical of their shots performed during a golf round. Each participant was instructed to perform 10 shots with their own driver at a target positioned behind the net. The net was approximately five metres from the ball. There was a rest period of 1 minute between each shot to ensure sufficient physical recovery. The motion of the markers were recorded by six 400 Hz Eagle digital cameras (Motion Analysis Corporation Ltd., Santa Rosa, California). This motion capture system was found to agree with another commercially available system in a preliminary study (see Section 3.3). The cameras and performance area were calibrated over a volume of 3.5 x 2.8 x 3 m according the manufacturers’ protocol. The calibration results indicated an average residual marker position error of 0.57 mm. An Accusport Vector Pro launch monitor (Accusport Inc., North Carolina) was used to
measure ball and club head characteristics at impact. The launch monitor was calibrated according to the manufacturers' instructions (see Appendix A2 for launch monitor information). The Vector Pro launch monitor captures two images of the golf ball immediately after impact from two cameras located on the unit itself to calculate ball velocity. Ball velocity is calculated the difference between the forward displacement (horizontal) of the ball between the images. This launch monitor was found to agree strongly with two other commercially available launch monitors for ball velocity as described in Section 3.3.

4.2.3 Data Processing Prior to Development of Calculation Technique

The raw marker data were tracked within the Motion Analysis software, Cortex. A reverse pass fourth–order Butterworth filter with a cut-off frequency \( F_c \) of 12 Hz was applied to the data. A residual analysis (Winter 2005) of selected markers was performed and 12 Hz was deemed, through this residual analysis and visual inspection of the curves, to be the most suitable \( F_c \) for the x, y and z trajectories of the data (see Appendix A6.3). Further, this cut-off frequency has been used in golf swing kinematic data by Mitchell et al. (2003) and Kenny et al. (2008a). Each trial was then cropped to leave only the data from address to the end of the swing. Address was defined as the frame before the club initiates movement away from the ball. The end of the swing was determined as the point where the z (vertical) coordinate of the club top shaft marker reached its maximum positive vertical position during the follow-through (see Figure 4.3). The filtered 3-D coordinates were then processed to calculate the variability of each marker's x, y, and z coordinates over the ten trials using a custom written programme (see Appendix A6.1) in LabVIEW (9.0.1, National Instruments, Austin, Texas).
Figure 4.3 – Follow-through position where z coordinate of club shaft marker reaches its highest trajectory after impact

At this point, the data were ready to develop the calculation technique for movement variability quantification. The number of body locations where movement variability was quantified was reduced from the total number of markers placed on the participant. Only 14 of the body markers were used in this calculation process. The extra markers (beyond the 14 examined) were necessary for the simulation work of Chapter 6. The markers selected for the movement variability analysis were selected to include all body segments involved in the golf swing. This reduction process was carried out in order to focus on the major body segments involved in the swing. The markers used for this process are listed in Table 4.2.
### Table 4.2 – Markers used for movement variability calculation, their anatomical name and body location used to describe movement variability calculation

<table>
<thead>
<tr>
<th>Anatomical Name</th>
<th>Body Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>L Acromion Process</td>
<td>Shoulder</td>
</tr>
<tr>
<td>L Humeral Lateral Epiconoyle</td>
<td>Elbow</td>
</tr>
<tr>
<td>L Wrist</td>
<td>Wrist</td>
</tr>
<tr>
<td>R Acromion Process</td>
<td>Shoulder</td>
</tr>
<tr>
<td>R Humeral Lateral Epiconoyle</td>
<td>Elbow</td>
</tr>
<tr>
<td>R Wrist</td>
<td>Wrist</td>
</tr>
<tr>
<td>R Temple</td>
<td>Head</td>
</tr>
<tr>
<td>T4</td>
<td>T4</td>
</tr>
<tr>
<td>L Greater Trochanter</td>
<td>Hip</td>
</tr>
<tr>
<td>L Lateral Femoral Condoyle</td>
<td>Knee</td>
</tr>
<tr>
<td>L Lateral Malleolus</td>
<td>Ankle</td>
</tr>
<tr>
<td>R Greater Trochanter</td>
<td>Hip</td>
</tr>
<tr>
<td>R Lateral Femoral Condoyle</td>
<td>Knee</td>
</tr>
<tr>
<td>R Lateral Malleolus</td>
<td>Ankle</td>
</tr>
</tbody>
</table>

*R – Right  L – Left*

Movement variability was calculated for the 14 body markers listed above. As all the participants stood in slightly different positions for each shot (this is inherent and ultimately unavoidable) the data had to be transformed to ensure that the variability calculated was variability of movement and not variability of standing position. To do this, the mean position of the ball (calculated from the marker on the ball) at address for the 10 trials was calculated. The difference between the position of the ball for each trial and the mean position was calculated. The coordinates of all 14 markers for each trial were then transformed in all three dimensions, according to this difference. Previous researchers (Horan et al. 2010) have used a body-centric reference (i.e. mid-point of calcanei markers) to do this. It was decided in this analysis to use a reference external to the body (i.e. the ball) because in the case of the body reference (e.g. the
malleoli), a subtle movement at the malleoli with no movement elsewhere in the body would cause all other markers to be transformed to this difference and thus be incorrectly transformed. After transformation, each trial was time normalised to 1001 points using a cubic spline algorithm in order to allow calculation of variability over all 10 trials.

4.3 DEVELOPMENT OF THE MOVEMENT VARIABILITY CALCULATION TECHNIQUE

Following normalisation, the standard deviation was calculated for the x, y, and z coordinates at each of the 1001 points for all 10 trials for each participant such that there was a standard deviation score for each of the 1001 points for each of the three axes for each participant.

4.3.1 Definition of Specific Aims of Calculation Technique

This is the initial stage of development of a calculation technique for quantifying movement variability. The criteria for the developed calculation technique were specified at this point.

1. The calculation technique must produce one value representative of the average movement variability of the participant.
2. The calculation technique must combine the variability in the three-dimensions into one number.
3. The calculation technique should have some basis in theoretical logic.
4. The calculation technique must be based on coordinate data.

The rationale behind the stipulation of criteria 1 and 2 are interlinked. The reasoning for expressing movement variability in a single number is that from coaching/learning standpoint, it is difficult to provide feedback to a participant with respect to the three different axes. The golf swing is a rotational movement occurring in three-dimensions. In order to make the movement variability score easier to understand and more practical for both coach and participant alike, the combined axes approach was used here so that one number representative of the variability in all three axes is used. A number of methods were considered that are listed below, all of which combined the three-dimensional variability into one value:
1. Mean procedure
2. Multiplication procedure
3. Cube root procedure
4. Volume procedure

It was deemed important that the method also satisfied the criterion of having been based in theoretical logic (criterion 3). Whilst the aim was for this technique to be novel, it is important that the calculation is grounded in mathematical logic. This calculation technique must be based on movement variability quantification of coordinate data (criterion 4). The rationale for use of coordinate data instead of a relative measure such as the angle between adjoining segments or segment velocities is related to the direction of this research. Simulation techniques will be the focus of subsequent chapters where variability will be analysed with a computer model. To kinematically drive this computer model, positional data of each marker is needed. The results of this analysis (Chapter 4 and 5) will be used to inform the direction of investigation within the simulation chapters. Thus in order to analyse variability in this regard, movement variability of coordinate data will be analysed here.

After calculation of variability with a described procedure, it was assessed to verify if it was in agreement with the defined specific criteria listed above. To aid the clarity of results presentation, the results section of each procedure breaks the results down into those for the torso and head, legs and arms.

### 4.3.2 Mean Procedure

#### 4.3.2.1 Methods

This procedure calculated the mean of the standard deviations of the x, y, and z axis at each point in time to produce a value in mm as illustrated in Equation 4.1. The calculated value at each point in normalised time was then summated to produce a total value over time. The mean of this value was then calculated as described in Equation 4.1. This produced a value representative of the mean variability over time.
Equation 4.1

\[
AV = \frac{\sum_{i=1}^{1001} \left( sd_{x(i)}^{(i)} + sd_{y(i)}^{(i)} + sd_{z(i)}^{(i)} \right)}{3} / 1001
\]

Where,  
\( AV \) = Mean variability for a given marker over 1001 points  
\( sd_{x(i)}^{(i)} \) = standard deviation in x direction for measure at point i over the 10 trials  
\( sd_{y(i)}^{(i)} \) = standard deviation in y direction for measure at point i over the 10 trials  
\( sd_{z(i)}^{(i)} \) = standard deviation in z direction for measure at point i over the 10 trials

4.3.2.2 Results and Discussion

The results of the calculation of the mean procedure can be observed in Figure 4.4, Figure 4.5 and Figure 4.6 for three different body regions. Figure 4.4 shows the average variability for the head and torso region. The movement variability for the legs as quantified using the mean procedure is presented in Figure 4.5. The only body marker that appeared to be high relative to the other markers for the majority of participants was the left greater trochanter which indicates the participants did not produce a consistent movement pattern at this body location. The left and right wrists were the arm markers that displayed the highest movement variability quantities as highlighted in Figure 4.6.
Figure 4.4 – Scatterplot of movement variability quantification using the mean procedure for the right head and T4 markers for each participant

Figure 4.5 – Scatterplot of movement variability quantification using the mean procedure for the leg markers for every marker for each participant
4.3.2.3 Conclusion

Table 4.3 compares the ability of this procedure to meet the criteria defined at the outset. This method of combination of 3-D axes calculated the mean of the three standard deviation scores at each point of normalised time. Although the procedure satisfied three of the specified criteria (criteria 1, 2 and 4), it was decided to proceed with an alternative method due to the lack of support from a theoretical rationale perspective. Therefore an alternative method was then pursued.
Table 4.3 – Ability of mean procedure to satisfy initial criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Specific Criteria</th>
<th>Accomplished</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The calculation technique must produce one value representative of the average movement variability of the participant</td>
<td>✔</td>
</tr>
<tr>
<td>2</td>
<td>The calculation technique must combine the variability in the three-dimensions into one number</td>
<td>✔</td>
</tr>
<tr>
<td>3</td>
<td>The calculation technique should have some basis in theoretical logic.</td>
<td>✗</td>
</tr>
<tr>
<td>4</td>
<td>The calculation technique must be based on coordinate data</td>
<td>✔</td>
</tr>
</tbody>
</table>

4.3.3 Multiplication Procedure

4.3.3.1 Methods

This procedure involved the multiplication of the standard deviations of the x, y and z axes together to produce a value of mm$^3$. This was based on probability theory from mathematics whereby the probability of two or more independent events is calculated by multiplying the values of the individual probabilities together (Grinstead and Snell 1997). This essentially calculates the volume of a cube at each point. The mean of these multiplied values was then calculated to provide a number representative of the mean variability over the 10 trials. The calculation procedure is described by Equation 4.2.

$$V = \frac{\sum_{i=1}^{1001} (sd_{x(i)} \cdot sd_{y(i)} \cdot sd_{z(i)})}{1001}$$

Equation 4.2

Where,
- $V = \text{Mean variability for a given marker over 1001 points}$
- $sd_{x(i)} = \text{standard deviation in x direction for measure at point } i \text{ over the 10 trials}$
- $sd_{y(i)} = \text{standard deviation in y direction for measure at point } i \text{ over the 10 trials}$
- $sd_{z(i)} = \text{standard deviation in z direction for measure at point } i \text{ over the 10 trials}$
4.3.3.2 Results and Discussion

The results of the movement variability quantified using the multiplication procedure is presented in Figure 4.7, Figure 4.8 and Figure 4.9 for all markers. The trends for these results were largely similar to that observed in the mean procedure results for the head and torso (Figure 4.7); however the absolute differences between markers were much larger than the mean procedure. Left and right wrists were the markers with the most variability for each participant for the arm markers as evidenced by Figure 4.9.

![Figure 4.7 – Scatterplot of movement variability quantification using the multiplication procedure the right head and T4 markers for each participant](image-url)
Figure 4.8 – Scatterplot of movement variability quantification using the multiplication procedure for the leg markers for every marker for each participant

Figure 4.9 – Scatterplot of movement variability quantification using the multiplication procedure for the arms and shoulder for every marker for each participant
4.3.3.3 Conclusion

Table 4.4 compares the ability of this multiplication procedure to meet the criteria defined at the outset for the calculation technique. The multiplication procedure described combined the tri-axial variability at each point in normalised time and thus satisfied that pre-defined criteria. This method of combination allowed the calculation of the mean variability over the time normalised points thereby satisfying that criteria. However, in spite of the multiplication of the axes being based on the theoretical basis of multiplied probabilities and calculation the volume of a cube, the relatively high values of the cubic values of the arm markers (Figure 4.9) made results difficult to interpret. Therefore an improvement of this procedure was considered.

<table>
<thead>
<tr>
<th>#</th>
<th>Specific Criteria</th>
<th>Accomplished</th>
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<tbody>
<tr>
<td>1</td>
<td>The calculation technique must produce one value representative of the average movement variability of the participant</td>
<td>✔</td>
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<tr>
<td>2</td>
<td>The calculation technique must combine the variability in the three-dimensions into one number</td>
<td>✔</td>
</tr>
<tr>
<td>3</td>
<td>The calculation technique should have some basis in theoretical logic.</td>
<td>✗</td>
</tr>
<tr>
<td>4</td>
<td>The calculation technique must be based on coordinate data</td>
<td>✔</td>
</tr>
</tbody>
</table>

4.3.4 Cube Root Procedure

4.3.4.1 Methods

This was developed in conjunction with the multiplication procedure described previously. The cube root of the multiplied standard deviations was calculated after multiplication of the standard deviations (as per Equation 4.3) at each point to produce a linear value (mm) as opposed to a cubic value (mm$^3$). The motivation behind producing a linear value was stimulated through examining the high values of movement variability quantified with the multiplication method (Figure 4.9) and thus the aim was to produce a value more easily understood by coaches and practitioners. The
mean of these values was then calculated to provide a number representative of the
mean variability over the 10 trials as highlighted in Equation 4.3.

\[
V = \frac{\sum_{i=1}^{1001} \sqrt[3]{sd_{x(i)} \cdot sd_{y(i)} \cdot sd_{z(i)}}}{1001}
\]

**Equation 4.3**

Where, \( V = \) Mean variability for a given marker over 1001 points

\( sd_{x(i)} = \) standard deviation in x direction for measure at point i over the 10 trials

\( sd_{y(i)} = \) standard deviation in y direction for measure at point i over the 10 trials

\( sd_{z(i)} = \) standard deviation in z direction for measure at point i over the 10 trials

### 4.3.4.2 Results and Discussion

The movement variability quantified using the cube root procedure is presented in
Figure 4.10, Figure 4.11 and Figure 4.12. Participants 3 and 8 had the lowest and
highest T4 movement variability respectively (Figure 4.10). The left greater trochanter
was the measure at the higher ranges of movement variability for many of the
participants with the left lateral malleolus at the lower range of movement variability for
the legs (Figure 4.11). The wrists were the highest measures of movement variability
for the arm again for each participant (Figure 4.12).
Figure 4.10 – Scatterplot of movement variability quantification using the cube procedure method for the right head and T4 markers for each participant

Figure 4.11 – Scatterplot of movement variability quantification using the cube root procedure for the leg markers for every marker for each participant
4.3.4.3 Conclusion

Table 4.5 compares the ability of this cube root procedure to meet the criteria defined at the outset for the calculation technique. Similar to the two previously discussed procedures of combination of axes, the method satisfied the criteria of combining the axes and allowing calculation of a mean value of variability over time. However, this procedure like the multiplication procedure was not found to be cited previously within a movement analysis context and therefore was deemed not acceptable on this basis.
Is Movement Variability Relevant for the Elite Golfer?

Table 4.5 – Ability of cube root procedure to satisfy initial criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Specific Criteria</th>
<th>Accomplished</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The calculation technique must produce one value representative of the average movement variability of the participant</td>
<td>✔</td>
</tr>
<tr>
<td>2</td>
<td>The calculation technique must combine the variability in the three-dimensions into one number</td>
<td>✔</td>
</tr>
<tr>
<td>3</td>
<td>The calculation technique should have some basis in theoretical logic.</td>
<td>✗</td>
</tr>
<tr>
<td>4</td>
<td>The calculation technique must be based on coordinate data</td>
<td>✔</td>
</tr>
</tbody>
</table>

4.3.5 Volume Procedure

4.3.5.1 Methods

To represent the three-dimensional aspect of variability of movement at each point in a single number, the respective x, y, and z standard deviation scores were combined via multiplication. This method of combination is an adaptation of similar principles used in balance studies, such as that of Lin et al. (2009) where a 95% confidence ellipse area is calculated from centre of pressure (COP) excursion in the medio-lateral and anterior-posterior and its deviation from its mean position. The deviation from the mean position in each direction is taken and multiplied to calculate an area of an ellipse. The approach outlined here takes the next logical step and progresses this concept to include the third dimension (vertical axis) such that the volume of an ellipsoid is calculated by multiplying the $s_{dx}$, $s_{dy}$ and $s_{dz}$ together (see Equation 4.4). Using this volume calculation procedure, the volume of a scalene ellipsoid was calculated which is representative of the three-dimensional nature of variability for that participant at each of the 1001 points.

The mean (n=1001) of these variability volumes was calculated resulting in one number representing the mean variability volume (VV) of that marker for that specific participant as described in Equation 4.4. The units of this calculation are $mm^3$. 
Where, \( VV \) = Mean variability volume for a given marker

\[ VV = \frac{\sum_{i=1}^{1001} \frac{4}{3} \pi (sd_{x(i)} \cdot sd_{y(i)} \cdot sd_{z(i)})}{1001} \]

4.3.5.2 Results and Discussion

The results of the volume method are presented in Figure 4.13, Figure 4.14 and Figure 4.15. Like all other methods, participant 3 was found to have the lowest value of movement variability for the T4 with participant 8 displaying the highest movement variability value for this measure as can be seen in Figure 4.13. For the leg measures (Figure 4.14), participant 3 was at the lower range of variability for all leg markers. Certain markers for particular participants displayed notably higher levels of variability compared to other markers of the leg such as the right greater trochanter for participants 1, 2 and 11 (see Figure 4.14), with the right lateral malleolus for participant 14 being high relative to the other markers for that participant. As was the case with the other three procedures described, the right and left wrists (Figure 4.15) were the arm markers with consistently the highest level of movement variability for each participant relative to the other markers. This could be due to the inherent high velocity and large path distance of the wrists at the end of the kinematic chain.
Figure 4.13 – Scatterplot of movement variability quantification using the volume procedure for the right head and T4 markers for each participant

Figure 4.14 – Scatterplot of movement variability quantification using the volume procedure for the leg markers for every marker for each participant
Figure 4.15 – Scatterplot of movement variability quantification using the volume procedure for the arms and shoulder for every marker for each participant

4.3.5.3 Conclusion

Table 4.6 compares the ability of this volume procedure to meet the criteria defined at the outset for the calculation technique. This procedure combined the three-dimensional values through calculation of a scalene ellipsoid volume at each point in of normalised time and then calculating the mean of these volumes. Therefore this procedure met criteria 1 and 2 of the pre-defined requirements for this method. There is precedence for its use in that the ellipse volume method has been used in balance studies with 2-D ellipse areas (95% confidence ellipse areas). This method has origins in studies of end-point variability quantification of movements to target. For example, in the work of van den Dobbelsteen et al. (2001) end point variability was quantified through calculating the volume of a 3-D ellipsoid to illustrate the variance from the end position of an effector and its desired target. Similarly the volume of an ellipsoid was calculated to represent the variability of finger movements in an aiming task in a study by Hansen and Elliot (2009). In this calculation, the standard deviation scores are used to represent the radii for calculation of a volume and substituted into the equation for calculation of the volume of an ellipsoid (Hansen et al. 2008). This measure provides an indication of the 3-D volume through which the movement pattern of that particular marker varied. Given there is justification for the use of 3-D volume calculation in mathematical theory (ellipsoid volume calculations) and this volume calculation is an
adaptation of this calculation technique in movement variability studies previously (Hansen et al. 2008), this volume method was adopted as the method of combining tri-axial variability.

### Table 4.6 – Ability of volume procedure to satisfy initial specific criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Specific Criteria</th>
<th>Accomplished</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The calculation technique must produce one value representative of the average movement variability of the participant</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>The calculation technique must combine the variability in the three-dimensions into one number</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>The calculation technique should have some basis in theoretical logic.</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>The calculation technique must be based on coordinate data</td>
<td>✓</td>
</tr>
</tbody>
</table>

### 4.3.6 Progression of Volume Procedure

Following the selection of the volume procedure as the means of combing the variability in three dimensions, the method had to be refined further in order to ensure it was calculating movement variability appropriately. More specifically, to compare the movement variability between markers, a standardisation process had to be carried out in order to ensure that the inherent differences in magnitudes of movement (i.e. ranges of motion) were not affecting any assessment of variability. When analysing this mean variability score (Equation 4.4 - mean of the variability volumes), it is important to consider the range of motion of each of the markers. This will be different between markers and therefore needs to be considered because this can affect the absolute movement variability calculated (James 2004). This difference of range of motion between selected markers is illustrated in Figure 4.16 where the trajectories of three different markers are highlighted.
Figure 4.16 – Trajectories of the right femoral conoyle (red trace), greater trochanter (blue trace) and right wrist markers (green trace) from address to follow-through of a selected participant shown to display the differences in range of motion. Approximate positions of address and top of the backswing events are highlighted on each trajectory.

In kinematic studies this involves the mean value of the measure being considered in conjunction with the standard deviation and thus the coefficient of variation is calculated such as in the studies of Bradshaw et al. (2009) and Brown et al. (2012). The coefficient of variation is calculated as described in Equation 4.5. Bradshaw et al. (2009) used the coefficient of variation to calculate the variability of parameters such as foot width, wrist and trunk angle in participants performing golf swings. Brown et al. (2012) calculated the coefficient of variation for ankle and knee angles for participants carrying out single leg jump landings.

\[
CV = \frac{\sigma}{\mu}
\]

Equation 4.5

Where, 

\( CV = \) Coefficient of variation
\( \sigma = \) standard deviation value for measure
\( \mu = \) mean value for measure
The standardisation of the standard deviation to the mean is an important issue to consider. However, the traditional coefficient of variation measure cannot be applied in this instance as one has to consider the data type that is being utilised. Coordinate data is the data type used in this analysis in the quantification of standard deviations. When calculating the mean of this data type, the zero is arbitrary unlike in parameters such as force or velocity. It is not possible to calculate a mean value based on the arbitrary value of zero for the coordinate data. Thus, it is not possible to quantify coefficient of variation directly for this particular data type. However, it is important that the range of motion of each marker is considered in this method of calculating variability (James 2004). Therefore, this has been taken this into consideration by standardising the mean variability volume (calculated by Equation 4.4, Section 4.3.5.1) to the total three-dimensional distance travelled by each marker over the course of the swing.

To do this, each mean variability volume was standardised to the three-dimensional distance travelled by that particular marker from the start of the swing to the end. The calculation of this mean three-dimensional path distance (PD) over the 10 trials is described by Equation 4.6, the units of which are mm:

$$ PD = \frac{\sum_{n=1}^{10} \sum_{i=1}^{1001} \sqrt{(x_{(i+1)} - x_{(i)})^2 + (y_{(i+1)} - y_{(i)})^2 + (z_{(i+1)} - z_{(i)})^2}}{10} $$

**Equation 4.6**

Where,  
- $PD$ = Three-Dimensional distance for a given marker  
- $n$ = trial number  
- $x_{(i+1)} = x$ position at point $i+1$  
- $x_{(i)} = x$ position at point $i$  
- $y_{(i+1)} = y$ position at point $i+1$  
- $y_{(i)} = y$ position at point $i$  
- $z_{(i+1)} = z$ position at point $i+1$  
- $z_{(i)} = z$ position at point $i$

Therefore the final calculation of movement variability (MV) is the mean variability volume (Equation 4.4) divided by the mean three dimensional distance (Equation 4.6) travelled by that marker over the 10 swings as described by Equation 4.7:
Equation 4.7

\[
MV = \frac{\sum_{i=1}^{1001} \frac{4}{3} \pi (sd_{x(i)} \cdot sd_{y(i)} \cdot sd_{z(i)})}{1001}
\]

\[
= \frac{\sum_{i=1}^{10} \left( \sum_{j=1}^{1001} \sqrt{(x_{(i+1)} - x_{(i)})^2 + (y_{(i+1)} - y_{(i)})^2 + (z_{(i+1)} - z_{(i)})^2} \right)}{10}
\]

Where, \( MV \) = Movement variability

- \( sd_{x(i)} \) = standard deviation in x direction for measure at point i over the 10 trials
- \( sd_{y(i)} \) = standard deviation in y direction for measure at point i over the 10 trials
- \( sd_{z(i)} \) = standard deviation in z direction for measure at point i over the 10 trials
- \( n \) = trial number
- \( x_{(i+1)} \) = x position at point i+1
- \( x_{(i)} \) = x position at point i
- \( y_{(i+1)} \) = y position at point i+1
- \( y_{(i)} \) = y position at point i
- \( z_{(i+1)} \) = z position at point i+1
- \( z_{(i)} \) = z position at point i

Unlike the coefficient of variation where the units are dimensionless, the units of this calculation are technically mm², but in reality those units do not apply to this type of measure as mm² implies it is the calculation of an area. The equation provides a volume per distance measure and thus the units of mm³.mm⁻¹ are deemed more appropriate.

4.3.6.1 Data Analysis

Movement variability, measured in mm³.mm⁻¹, and calculated as described in Section 4.3.6 was calculated for each marker for each participant. This allowed comparison of variability levels for each marker between participants.

4.4 FINAL RESULTS

This section presents the results of the volume method. The volume method was that which was deemed most appropriate to combine tri-axial variability into one value.
4.4.1 Mean Variability Volume (VV) Calculation

The results of the calculation (as described in Equation 4.7) of the non-standardised mean variability volume are presented in Figure 4.13, Figure 4.14, and Figure 4.15 in Section 4.3.5.2. The mean of these variability volumes across all players was calculated and the resulting values were ranked from lowest to highest. A summary can be viewed in Table 4.7. Results highlight that the lowest ranked variability scores were for lower limb markers (lateral malleoli and femoral condyles) with the highest ranked being the wrists. These results provide evidence of general increase in proximal (malleoli at ankles) to distal (wrists attached to the club) movement variability along the kinematic chain. This has been reported in previously in basketball free throw shooting with an increase from the shoulder to elbow to wrist joint motion variability (Robins et al. 2008). This study (Robins et al. 2008) only reported variability in the form of standard deviation and did not standardise to the mean value and so is a comparable calculation to the mean variability volume calculation of this chapter. This provides validation of the mean variability volume calculation.
### Table 4.7 – Mean variability volumes of markers of all participants and their ranking from lowest to highest

<table>
<thead>
<tr>
<th>Rank</th>
<th>Marker</th>
<th>Variability Volume (mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L Lateral Malleolus</td>
<td>1409.0</td>
</tr>
<tr>
<td>2</td>
<td>L Lateral Femoral Condoyle</td>
<td>2025.2</td>
</tr>
<tr>
<td>3</td>
<td>R Lateral Femoral Condoyle</td>
<td>2130.6</td>
</tr>
<tr>
<td>4</td>
<td>R Lateral Malleolus</td>
<td>2653.0</td>
</tr>
<tr>
<td>5</td>
<td>L Greater Trochanter</td>
<td>3219.3</td>
</tr>
<tr>
<td>6</td>
<td>T4</td>
<td>3903.8</td>
</tr>
<tr>
<td>7</td>
<td>R Greater Trochanter</td>
<td>4033.6</td>
</tr>
<tr>
<td>8</td>
<td>R Head Marker</td>
<td>4081.4</td>
</tr>
<tr>
<td>9</td>
<td>R Acromion Process</td>
<td>4815.8</td>
</tr>
<tr>
<td>10</td>
<td>L Acromion Process</td>
<td>5675.9</td>
</tr>
<tr>
<td>11</td>
<td>R Humeral Later Epiconoyle</td>
<td>12011.6</td>
</tr>
<tr>
<td>12</td>
<td>L Humeral Lateral Epiconoyle</td>
<td>14577.8</td>
</tr>
<tr>
<td>13</td>
<td>R Wrist</td>
<td>48148.1</td>
</tr>
<tr>
<td>14</td>
<td>L Wrist</td>
<td>48332.7</td>
</tr>
</tbody>
</table>

*R - Right L – Left*

#### 4.4.2 Movement Variability Calculation (Path Distance Standardised)

The effect of standardisation of the mean variability volumes to path distance are shown in the revised rankings in Table 4.8. The standardisation process allows better comparison across all measures examined by taking into account the inherent property of the magnitude of the movement of the marker. The rank order has change in that the malleoli are now ranked near the higher end of movement variability across all participants.
### Table 4.8 – Movement variability score standardised to distance travelled and their ranking from lowest to highest

<table>
<thead>
<tr>
<th>Rank</th>
<th>Marker</th>
<th>Mean Variability Volume (mm³/mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L Lateral Femoral Condoyle</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>R Lateral Femoral Condoyle</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>T4</td>
<td>4.3</td>
</tr>
<tr>
<td>4</td>
<td>R Acromion Process</td>
<td>4.4</td>
</tr>
<tr>
<td>5</td>
<td>L Greater Trochanter</td>
<td>4.7</td>
</tr>
<tr>
<td>6</td>
<td>L Acromion Process</td>
<td>5.1</td>
</tr>
<tr>
<td>7</td>
<td>R Lateral Humeral Epicondoyle</td>
<td>6.1</td>
</tr>
<tr>
<td>8</td>
<td>R Greater Trochanter</td>
<td>6.1</td>
</tr>
<tr>
<td>9</td>
<td>L Lateral Humeral Epicondoyle</td>
<td>7.0</td>
</tr>
<tr>
<td>10</td>
<td>L Lateral Malleolus</td>
<td>7.3</td>
</tr>
<tr>
<td>11</td>
<td>R Head</td>
<td>8.0</td>
</tr>
<tr>
<td>12</td>
<td>R Lateral Malleolus</td>
<td>10.3</td>
</tr>
<tr>
<td>13</td>
<td>R Wrist</td>
<td>12.9</td>
</tr>
<tr>
<td>14</td>
<td>L Wrist</td>
<td>13.4</td>
</tr>
</tbody>
</table>

*R - Right L – Left*

The results of standardisation of the mean variability volume to path distance (Equation 4.7) are presented in Figure 4.17, Figure 4.18 and Figure 4.19. It can be observed from Figure 4.19 that participants 3 and 10 had the lowest levels of variability for the arm markers with participant 7 displaying movement variability levels in the higher ranges with for example a right wrist movement variability value of 34 mm³/mm⁻¹ compared to movement variability values of 3.3 mm³/mm⁻¹ and 2 mm³/mm⁻¹ for participants 3 and 10 respectively. The trends in which markers exhibited more variability across the participants also become apparent from this graph for the different body regions with wrists being the highest values of the arm region. Figure 4.17 reveals the head to be the higher of the values in the head and torso region for all participants. Figure 4.18
shows the lateral malleoli as the most frequent markers in the higher ranges of movement variability. Further examination of Figure 4.17, Figure 4.18 and Figure 4.19 reveals that some participants had a large range from the marker with lowest variability to that which had the highest variability, for example, participants 7 and 8 show large ranges of 29.5 and 20 mm$^3$.mm$^{-1}$ respectively, for the arm markers whereas participants 10 and 13 show smaller ranges in comparison of 0.9 and 1.1 mm$^3$.mm$^{-1}$ respectively for the arm markers. Participants 1 and 14 had the highest ranges for the leg markers with a range of 19.3 and 55.2 mm$^3$.mm$^{-1}$ respectively, while participants 13 and 16 had the lowest ranges of 3.9 and 3.2 mm$^3$.mm$^{-1}$ respectively for these markers. The high range of movement variability values for participant 14 was due to the high movement variability value (58.8 mm$^3$.mm$^{-1}$) for the right lateral malleolus.

**Figure 4.17 – Movement variability scores standardised to path distance for the right head and T4 markers for each participant**
Is Movement Variability Relevant for the Elite Golfer?

Figure 4.18 – Movement variability scores standardised to path distance for the leg markers for each participant

Figure 4.19 – Movement variability scores standardised to path distance for the arm and shoulder markers for each participant
4.5 OVERALL DISCUSSION

The aims of this study were firstly to develop a calculation technique to quantify performance variability of movement at numerous body locations using three-dimensional positional data and secondly perform a preliminary analysis of the results obtained.

The calculation technique developed considered many potential procedures to combine the three axes into one representative value. The volume calculation procedure was deemed to be the best representation of this three-dimensional variability owing to the fact that the method agreed with the pre-determined criteria which the other procedures did not fully satisfy. The effect of standardising the mean variability volumes to the path distance of the marker can be viewed in Table 4.8. The values in Table 4.7 represent the absolute movement variability of each marker but this does not take into account the magnitude of the range of motion of each marker. The ranking of the measures which contained the lowest to highest movement variability changed once this standardisation process was undertaken. This highlighted the importance of standardisation to the path distance given the problems with the data in terms of calculating the coefficient of variation measure which has been traditionally used in movement variability studies. This allowed effective comparison of movement variability values between markers. The calculation technique developed to quantify movement variability from three-dimensional coordinates allowed the calculation of the mean variability of movement for a number of body positions during the golf swing and the ability to express this as a single representative number.

Through examination of the variability scores in Figure 4.17, Figure 4.18 and Figure 4.19, it appears that the left and right wrists were the body positions displaying most movement variability over the swing. On average, the right and left femoral condyles at the knee were the measures with least variability according to Table 4.8 across all 16 participants. The parameter in closest contact to the club grip at the open end of the chain, i.e. wrists, had the most movement variability. This is an interesting finding as the wrist is the last joint connected to the club grip and theoretically has the most influence on the movement of the club. The results show that the wrists, lateral malleoli and head displayed the most movement variability across all participants while the femoral condyles displayed the least movement variability. Thus, the points at the open and closed end of the chain were found to be the most variable when
standardised to distance travelled. Previous work by Horan et al. (2011), has shown that variability of hand movement reduces from top of the backswing to ball contact in both male and female participants, suggesting that there is a controlling influence of the hands. It should be noted that the methods here include the entire swing but Horan et al. (2011) calculated hand variability at only 3 points on the downswing.

4.6 CONCLUSION

A novel calculation technique has been developed to quantify the mean movement variability over the entire golf swing using the standard deviations of normalised 3-D coordinate data as described by the following equation:

\[
MV = \frac{4}{3} \pi \sum_{i=1}^{1001} \left( \frac{sd_{x(i)} \cdot sd_{y(i)} \cdot sd_{z(i)}}{1001} \right) 
\]

\[
= \frac{10}{1001} \sum_{n=1}^{10} \left( \sum_{i=1}^{1001} \sqrt{\left( x_{(i+1)} - x_{(i)} \right)^2 + \left( y_{(i+1)} - y_{(i)} \right)^2 + \left( z_{(i+1)} - z_{(i)} \right)^2} \right)
\]

The aforementioned calculation technique can produce ellipsoid volumes standardised to range of motion representative of position variability at various anatomical landmarks in 3-D space. Thus it is a volume (mm$^3$) per distance (mm) travelled variability calculation. This calculation technique can be applied to any movement pattern where movement variability is to be quantified. The method developed within this chapter quantified movement variability over the entire swing and included post-impact data. Therefore, this method will be used in subsequent chapters to quantify movement variability in different phases of the golf swing and examine these movement variability values in relation to outcome variability.

4.6.1 Thesis Context

The development of this method was necessary to allow quantification of movement variability of marker trajectories. The method developed will be used in the following chapter to examine movement variability in different phases of the golf swing.
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CHAPTER 5

AN EXAMINATION OF MOVEMENT VARIABILITY IN DIFFERENT PHASES OF THE GOLF SWING AND ITS RELATIONSHIP WITH SHOT OUTCOME VARIABILITY
5.0 ABSTRACT

Following the development of a calculation technique to quantify movement variability of marker trajectories in Chapter 4 of the full swing including post-impact data, the aim of this chapter was to quantify movement variability in the backswing and downswing phases of the golf swing and assess whether there was any statistically meaningful relationship between movement variability and outcome variability. 16 highly skilled (handicap ≤5) participants each performed 10 swings wearing retro reflective markers which were tracked by a 3D motion analysis system operating at 400 Hz. A launch monitor captured ball launch conditions at impact. Movement variability was quantified for 14 marker trajectories for each participant for the backswing and downswing phases of the golf swing. Outcome variability was the coefficient of variation of ball velocity for the 10 trials. The results revealed the movement variability per path distance travelled of the ankle to be the measure with the highest movement variability for both the backswing and downswing phases. The relationship between movement variability for each marker trajectory and outcome variability revealed no statistically significant Pearson’s correlation coefficients ($p > 0.05$). This suggests at the elite level of golf performance, a common optimal approach to the golf swing with the driver club is not advisable given how movement variability levels differed among participants with no common trends apparent. Consequently, an individual-based approach is recommended in determining the effect of movement variability on shot outcome.

5.1 INTRODUCTION

As discussed previously in Section 2.2.2.3, dynamical systems theory advocates learning a variety of different solutions (Davids et al. 2003) to provide the performer with the ability to adapt their movement pattern if needed. This adaptability might be necessary in golf in order to allow the player adapt to environmental demands such as a change in weather, or in the position the ball is lying in (i.e. the ball could be on a flat or inclined surface). To produce a consistent, accurate outcome in golf, variability of the club head dynamics at impact (shot outcome variability) must be low. The mechanism of how this (low outcome variability) is achieved is unknown. Therefore it is first necessary to quantify movement variability in the golf swing in elite golfers and examine this movement variability with respect to outcome variability.
Bradshaw et al. (2009) quantified movement variability of the golf swing in both low and high handicap golfers and analysed its relationship with a shot outcome variable (club head velocity). One limitation with this analysis was that study employed 2-D analysis and examined movement variability of discrete variables at key points of the swing. Discrete variables give a snapshot of the movement at specific events but do not allow a thorough understanding of the entire movement pattern (James 2004). Horan et al. (2011) also examined movement variability in the downswing phase of the golf swing on discrete and continuous variables in male and female participants. However, shot outcome was not recorded and therefore the relationship between shot outcome and movement variability was not quantified.

In order to fully understand the effect of movement variability on the outcome of the golf swing, it is necessary to investigate this connection further. Chapter 4 detailed the development of a calculation technique to quantify movement variability of marker trajectories in the full swing. The results in Chapter 4 included data beyond the impact event of the swing. It is more instructive to reduce the analysis of movement variability into different phases of the golf swing prior to impact. To better inform coaching techniques, it is necessary to determine in what phase of the golf swing, if any, that movement variability has an effect on shot outcome. It is therefore necessary to only analyse until impact in order to effectively examine the relationship between movement variability and shot outcome, since what happens beyond this point in the swing does not influence shot outcome with respect to the analysis discussed in this chapter.

### 5.1.1 Aims

The aims of this study were to:

- Quantify movement variability levels for participants in the backswing and downswing phases of the golf swing using the calculation technique developed in Chapter 4.
- Examine the relationship between the movement variability quantified and shot outcome variability.
5.2 METHODS

The methods undertaken in this chapter were similar to those described in Section 4.2. To avoid duplication of the methods described, reference will be made to relevant sections in the previous chapter where the procedures were the same.

5.2.1 Participants

The participants in this analysis were the same cohort as that used in Chapter 4. (See Section 4.2.1 for a description of the participants who volunteered for this study.)

5.2.2 Data Collection

The data collection methods were the same as that adopted in Chapter 4. (See Section 4.2.2 for the data collection procedure).

5.2.3 Data Processing

5.2.3.1 Data Filtering

After data collection, the raw x, y z trajectories of the markers were filtered with a low-pass, fourth-order Butterworth filter with a cut-off frequency of 12 Hz as described in Section 4.2.3.

5.2.3.2 Swing Events and Phases

Following filtering of the raw data, the data were cropped to the relevant phases of the swing. The following definitions were used to define swing events:

- **Address (ADD):** This was defined as the frame before the club initiates movement away from the ball.
- **Top of the backswing (TOB):** This was defined as the frame where the bottom club shaft marker reached its minimum velocity (in the medio-lateral (x) direction) between the start and end of the data (see Figure 5.1).
- **Impact (IMP):** This was defined as the frame where the ball marker was first moved. This was also the point where the launch monitor captured ball launch conditions (see Figure 5.1).
Based on these swing events, each trial was then cropped to remove any irrelevant swing data beyond these events. Two phases of the swing were defined between these swings events. These phases were:

- **The backswing (ADD-TOB):** This was the phase of the swing between address (ADD) and top of the backswing (TOB).
- **The downswing (TOB-IMP):** This was the phase of the swing between top of the backswing and impact.

### 5.2.3.3 Movement Variability Calculation

The development of the movement variability calculation technique was described in Section 4.3. This section briefly details the steps in carrying out the calculations. The calculations were carried out using the developed calculation technique in a custom-written programme (see Appendix A6.1) in LabVIEW (v9.0.1, National Instruments, Austin, Texas). Movement variability was quantified for 14 markers that best encompass the segments that are involved in the movement of the golf swing. These are the same 14 body landmarks used to develop the movement calculation technique described in Chapter 4. See Table 4.2 in Chapter 4 for markers used and their relevant body location.
The first stage of the calculation process involved transformation of the data. This was performed to account for participants standing in slightly different positions for each trial and thereby ensure that variability quantified was that of movement variability and not of standing position. All markers were transformed according to the mean ball position of the ten trials. See Section 4.2.3 for more information on this process. This transformation was carried out for both phases of the swing. The phases of the swing, backswing and downswing, were then each normalised to 1001 points using a cubic spline algorithm. Following this normalisation process, the standard deviation was calculated for the x, y, and z coordinates at each of the 1001 points for all 10 trials for each participant such that there was a standard deviation score for each of the 1001 points for each of the three axes for each participant.

The next phase combined the tri-axial variability into a single number. This involved the calculation of a scalene ellipsoid volume at each point of normalised time. This method followed on from a method described by Hansen et al. (2008). In the Hansen et al. (2008) method, a 3-D ellipsoid volume was calculated to quantify end-point variability (of a finger) in a pointing task. The calculation of the ellipsoid volumes is described by Equation 5.1.

$$VV = \frac{\sum_{i=1}^{1001} \frac{4}{3} \pi (sd_{x(i)} \cdot sd_{y(i)} \cdot sd_{z(i)})}{1001}$$

Equation 5.1

Where, $VV =$ Mean variability volume for a given marker (mm$^3$)
$sd_{x(i)} =$ standard deviation in x direction for measure at point i over the 10 trials
$sd_{y(i)} =$ standard deviation in y direction for measure at point i over the 10 trials
$sd_{z(i)} =$ standard deviation in z direction for measure at point i over the 10 trials

Following this, the mean variability volume calculated by Equation 5.1 was standardised to the 3-D path distance travelled by that marker. This was performed in order to allow comparison between the markers without the effect of the markers’ range of motion affecting the results. The calculation of the mean total path distance travelled over the 10 trials by a given marker is described in Equation 5.2.
\[ PD = \frac{\sum_{n=1}^{10} \left( \sum_{i=1}^{1001} \sqrt{(x_{(i+1)} - x_{(i)})^2 + (y_{(i+1)} - y_{(i)})^2 + (z_{(i+1)} - z_{(i)})^2} \right)}{10} \]

**Equation 5.2**

Where, \( PD \) = Three-Dimensional distance for a given marker (mm)

\( n \) = trial number

\( x_{(i+1)} \) = x position at point \( i+1 \)
\( x_{(i)} \) = x position at point \( i \)

\( y_{(i+1)} \) = y position at point \( i+1 \)
\( y_{(i)} \) = y position at point \( i \)

\( z_{(i+1)} \) = z position at point \( i+1 \)
\( z_{(i)} \) = z position at point \( i \)

Therefore the calculation of movement variability (MV) is the mean variability volume (VV) divided by the average three dimensional path distance (PD) travelled by that marker over the 10 trials as described in Equation 5.3. The units of this calculation are \( \text{mm}^3.\text{mm}^{-1} \). Thus, this calculation is of the mean variability volume per distance travelled over the ten trials.

\[ MV = \frac{\sum_{n=1}^{10} \left( \sum_{i=1}^{1001} \pi (sd_{x(i)} \cdot sd_{y(i)} \cdot sd_{z(i)}) \right)}{1001 \cdot \sum_{n=1}^{10} \left( \sum_{i=1}^{1001} \sqrt{(x_{(i+1)} - x_{(i)})^2 + (y_{(i+1)} - y_{(i)})^2 + (z_{(i+1)} - z_{(i)})^2} \right)} \]

**Equation 5.3**

Where, \( MV \) = Movement variability (\( \text{mm}^3.\text{mm}^{-1} \))

\( sd_{x(i)} \) = standard deviation in x direction for measure at point \( i \) over the 10 trials (mm)
\( sd_{y(i)} \) = standard deviation in y direction for measure at point \( i \) over the 10 trials (mm)
\( sd_{z(i)} \) = standard deviation in z direction for measure at point \( i \) over the 10 trials (mm)

\( n \) = trial number

\( x_{(i+1)} \) = x position at point \( i+1 \)
\( x_{(i)} \) = x position at point \( i \)

\( y_{(i+1)} \) = y position at point \( i+1 \)
\( y_{(i)} \) = y position at point \( i \)

\( z_{(i+1)} \) = z position at point \( i+1 \)
\( z_{(i)} \) = z position at point \( i \)
The final movement variability calculation (Equation 5.4) in its abbreviated form is as follows.

\[ MV = \frac{VV}{PD} \]

**Equation 5.4**

Where,
- \( MV \) = Movement variability (mm³.mm⁻¹)
- \( PD \) = Three-dimensional distance for a given marker as calculated by Equation 5.2 (mm)
- \( VV \) = Mean variability volume for a given marker as calculated by Equation 5.1 (mm³)

### 5.2.3.4 Outcome Variability

A Vector Pro launch monitor (Accusport Inc., North Carolina) captured ball launch conditions at impact. Ball velocity, measured in m.s⁻¹, was selected as the shot outcome measure as this measure is an important determinant of ball displacement, i.e. shot outcome (Moriyama et al. 2004) and it was a direct measure available from the launch monitor data. Further, a preliminary study found this launch monitor to be valid for ball velocity (see Section 3.3). The standard deviation and mean of ball velocity over the ten trials were calculated for each participant and subsequently coefficient of variation was calculated to represent outcome variability (see Equation 5.5).

\[ CV_v = \frac{\sigma_v}{\mu_v} \]

**Equation 5.5**

Where,
- \( CV_v \) = Coefficient of variation of ball velocity
- \( \sigma_v \) = standard deviation value of ball velocity
- \( \mu_v \) = mean value of ball velocity

### 5.2.4 Data Analysis

Movement variability values for each participant for both phases of the golf swing were analysed. Correlation statistics (Pearson's correlation coefficient (r)) were carried out using PASW v 18 (SPSS Inc, USA) to analyse whether there was any statistically meaningful relationships between the movement variability quantified for each marker.
and shot outcome variability across the group. As the direction of the relationship between the movement variability values and outcome variability could not be predicted, a two-tailed test was used and statistical significance was set at $p \leq 0.05$ (Field 2009). This statistical analysis was performed for each phase of the swing defined in Section 5.2.3.2.

5.3 RESULTS AND DISCUSSION

This section presents and discusses the results of the movement variability per path distance quantified for the marker trajectories of the backswing and downswing (see Section 5.3.1). Please see Appendix A3.1 for results of path distance and variability volume quantified for each participant. The results presented in Section 5.3.1 are movement variability per path distance results.

Outcome variability results are then presented in Section 5.3.2. The results of the statistical analysis for the backswing and downswing are provided in Section 5.3.3.

5.3.1 Movement Variability

5.3.1.1 Backswing

Of the arm and torso markers, the head displayed more movement variability per distance travelled than the T4 marker for all participants (Figure 5.2). The right and left lateral femoral condyle of the knee were at the lower ranges of movement variability for the leg markers for most participants (Figure 5.3). The left and right malleoli were at the higher range of movement variability for these leg markers. The wrist markers were at the higher range of movement variability for most participants for the arm markers (Figure 5.4). Interestingly, the movement variability per distance travelled of the leg markers was quite high relative that of the arms and head and torso in the backswing (in particular the malleoli compared to the wrists). Certain participants (for example, participants 3, 5, 12 and 16) showed narrow ranges of low to high movement variability relative to other participants for the leg markers (for example, participants 2, 9, 13 and 15).
Figure 5.2 – Scatterplot of movement variability scores quantified for the backswing of the head and torso markers for each marker for every participant.

Figure 5.3 – Scatterplot of movement variability scores quantified for the backswing of the leg markers for each marker for every participant.
Across all participants, the lateral malleoli at the ankles were the marker trajectories that displayed the highest movement variability (see Table 5.1). In particular, right lateral malleolus movement variability was high (61.1 mm$^3$.mm$^{-1}$) relative to the other markers movement variability values. The average movement variability of both the left and right lateral humeral epicondyles was in the lower range. The left and right acromion process movement variability was also in the lower range. It appears that on average participants maintained low movement variability in these measures for the backswing while having relatively higher variability in the wrists.

**Figure 5.4 – Scatterplot of movement variability scores quantified for the backswing of the arm and shoulder markers for each marker for every participant**
Table 5.1 – Average movement variability values across all participants for the backswing and the ranking of each marker from lowest to highest movement variability

<table>
<thead>
<tr>
<th>Rank</th>
<th>Marker</th>
<th>Average Movement Variability (mm^3/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R Acromion Process</td>
<td>4.6</td>
</tr>
<tr>
<td>2</td>
<td>L Lateral Humeral Epicondoyle</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>L Lateral Femoral Condyle</td>
<td>5.2</td>
</tr>
<tr>
<td>4</td>
<td>R Lateral Humeral Epicondoyle</td>
<td>5.7</td>
</tr>
<tr>
<td>5</td>
<td>L Acromion Process</td>
<td>6.4</td>
</tr>
<tr>
<td>6</td>
<td>L Greater Trochanter</td>
<td>6.5</td>
</tr>
<tr>
<td>7</td>
<td>T4</td>
<td>6.6</td>
</tr>
<tr>
<td>8</td>
<td>L Wrist</td>
<td>8.0</td>
</tr>
<tr>
<td>9</td>
<td>R Wrist</td>
<td>8.5</td>
</tr>
<tr>
<td>10</td>
<td>R Lateral Femoral Condyle</td>
<td>9.2</td>
</tr>
<tr>
<td>11</td>
<td>R Head</td>
<td>18.9</td>
</tr>
<tr>
<td>12</td>
<td>R Greater Trochanter</td>
<td>21.3</td>
</tr>
<tr>
<td>13</td>
<td>L Lateral Malleolus</td>
<td>24.9</td>
</tr>
<tr>
<td>14</td>
<td>R Lateral Malleolus</td>
<td>61.1</td>
</tr>
</tbody>
</table>

5.3.1.2 Downswing

Movement variability values for the downswing again showed the head to be more variable per distance travelled than the T4 marker (Figure 5.5). Movement variability of the leg markers did not have values as high as that for the backswing (see Figure 5.3 and Figure 5.6). In particular, the movement variability values for the lateral malleoli were much reduced in the downswing compared to the backswing, where over half of the participants had a right malleolus movement variability value over 40 mm^3/mm for the right lateral malleolus (Figure 5.6). These values for the downswing were all below 40 mm^3/mm with the exception of participant 14. In the backswing, eight of the
participants had movement variability values over 40 mm$^3$.mm$^{-1}$ for the right lateral malleolus. Participants 3, 10, 12 and 15 all had movement variability values below 5 mm$^3$.mm$^{-1}$ for the arm markers (Figure 5.7). These participants also had low ranges of movement variability for the arm markers in the backswing, highlighting that they reduce movement variability relative to other participants in these parameters for both phases of the swing until impact.

Figure 5.5 – Scatterplot of movement variability scores quantified for the downswing of the head and torso markers for each marker for every participant
For the downswing, the malleoli and head were the markers with the highest movement variability across on average all participants (see Table 5.2). Therefore across both phases (backswing and downswing), the malleoli consistently displayed high...
movement variability on average across all participants. The left lateral femoral condyle at the knee displayed the least movement variability across all participants. This was also at the lower rankings of the values for the backswing, suggesting that participants consistently maintain low movement variability in this relative to the other measures for the backswing and downswing phase. Three landmarks located on the left side of the body were those with the least movement variability on average across the cohort suggesting that participants reduced movement variability in these measures across in the downswing.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Marker</th>
<th>Average Movement Variability (mm$^3$.mm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L Lateral Femoral Condoyle</td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>L Lateral Humeral Epicondoyle</td>
<td>6.00</td>
</tr>
<tr>
<td>3</td>
<td>L Acromion Process</td>
<td>6.3</td>
</tr>
<tr>
<td>4</td>
<td>T4</td>
<td>7.8</td>
</tr>
<tr>
<td>5</td>
<td>R Acromion Process</td>
<td>8.1</td>
</tr>
<tr>
<td>6</td>
<td>R Lateral Femoral Condoyle</td>
<td>8.1</td>
</tr>
<tr>
<td>7</td>
<td>L Wrist</td>
<td>8.1</td>
</tr>
<tr>
<td>8</td>
<td>R Wrist</td>
<td>8.2</td>
</tr>
<tr>
<td>9</td>
<td>R Lateral Humeral Epicondoyle</td>
<td>8.5</td>
</tr>
<tr>
<td>10</td>
<td>L Greater Trochanter</td>
<td>9.9</td>
</tr>
<tr>
<td>11</td>
<td>R Greater Trochanter</td>
<td>11.9</td>
</tr>
<tr>
<td>12</td>
<td>L Lateral Malleolus</td>
<td>19.5</td>
</tr>
<tr>
<td>13</td>
<td>R Lateral Malleolus</td>
<td>19.9</td>
</tr>
<tr>
<td>14</td>
<td>R Head</td>
<td>21.7</td>
</tr>
</tbody>
</table>
5.3.2 Outcome Variability

Ball velocity was measured directly by the launch monitor. Ball velocity is a determinant of ball displacement from the tee (Moriyama et al. 2004). Mean ball velocity calculated for all participants was $59.6 \pm 6.4 \text{ m s}^{-1}$ (n=160). Variability in this measure can potentially affect performance because if a player varies this, then landing distances from the tee may be inconsistent (shorter or longer than expected). The golfer needs to be aware of their carry distance ability with the driver on the course in order to plan a strategy to play a hole. To emphasise that each player did hit at or near their maximum velocities, the ball velocities were normalised to their best shot (where 1.00=best shot) and the mean normalised ball velocity for all players was $0.98 \pm 0.02$ (n=160), thus demonstrating players were hitting at or near their maximum ball velocity. Outcome variability (coefficient of variation %) scores are presented in Figure 5.8.

Participant 14 had the highest outcome variability (3.68%) with participant 3 displaying the lowest value (0.77%) for this measure. No participant was completely invariant in outcome variability.

![Figure 5.8 – Outcome variability (CV %) for ball velocity variability scores for each participant](image)

---

4 Ball velocity results are presented (mean ± sd) for each participant in Appendix A3.2
5.3.3 Statistical Analysis

The results of the statistical analysis revealed that only one measure in both the backswing and downswing had a statistically significant correlation with outcome variability. Right lateral femoral condyle movement variability in the downswing showed a significant positive correlation with outcome variability. This positive correlation would indicate that as movement variability for this marker trajectory increased, shot outcome variability increased also. At this point, all scatterplots of each movement variability measures and outcome variability measures were examined in order to visually inspect the correlations calculated. On further examination of the scatterplot of the significant correlation (right femoral condyle movement variability), it appeared that this correlation coefficient was heavily influenced by the high movement variability value for participant 14. To test the effect of this participant’s value on the calculation of the correlation coefficient, this participant’s value was removed and the correlation coefficient was recalculated. Once this value was removed from the analysis, the correlation coefficient was reduced to 0.085. This was the only instance found where one participant’s value affected the correlation coefficient significantly. This indicates that with the exception of participant 14, that high right lateral femoral condyle movement variability was not significantly correlated with outcome variability. Thus, the significance of this correlation is questionable and therefore the strength of the correlation (with all participants considered) is non-significant.
Table 5.3 – Pearson’s correlation coefficient values (r) between movement variability levels quantified and outcome variability

<table>
<thead>
<tr>
<th>Marker</th>
<th>Backswing</th>
<th>Downswing</th>
</tr>
</thead>
<tbody>
<tr>
<td>L Acromion Process</td>
<td>0.190</td>
<td>0.156</td>
</tr>
<tr>
<td>L Humeral Lateral Epiconoyle</td>
<td>0.280</td>
<td>0.072</td>
</tr>
<tr>
<td>L Wrist</td>
<td>0.353</td>
<td>0.085</td>
</tr>
<tr>
<td>R Acromion Process</td>
<td>-0.081</td>
<td>-0.129</td>
</tr>
<tr>
<td>R Humeral Lateral Epiconoyle</td>
<td>0.007</td>
<td>0.017</td>
</tr>
<tr>
<td>R Wrist</td>
<td>0.220</td>
<td>0.075</td>
</tr>
<tr>
<td>R Head</td>
<td>-0.111</td>
<td>0.021</td>
</tr>
<tr>
<td>T4</td>
<td>0.075</td>
<td>0.134</td>
</tr>
<tr>
<td>L Greater Trochanter</td>
<td>0.098</td>
<td>-0.007</td>
</tr>
<tr>
<td>L Lateral Femoral Condoyle</td>
<td>-0.100</td>
<td>0.195</td>
</tr>
<tr>
<td>L Lateral Malleolus</td>
<td>-0.129</td>
<td>0.253</td>
</tr>
<tr>
<td>R Greater Trochanter</td>
<td>-0.186</td>
<td>-0.074</td>
</tr>
<tr>
<td>R Lateral Femoral Condoyle</td>
<td>-0.069</td>
<td>0.568*</td>
</tr>
<tr>
<td>R Lateral Malleolus</td>
<td>0.184</td>
<td>0.436</td>
</tr>
</tbody>
</table>

* Denotes significance at p< 0.05

Note: These values include participant 14

5.3.4 Combined Discussion

As discussed previously in Section 2.3.3.1, there has been a dearth of research examining movement variability in the golf swing and resultantly, there have been calls to research it more intensively (Williams and Sih 2002, Farrally et al. 2003, Glazier 2011). This chapter progresses this research into movement variability of the golf swing through firstly, quantifying the movement variability (per distance travelled) of marker trajectories at specific body landmarks using a previously developed method in Chapter...
4 and secondly, examining the relationship between the movement variability quantified and outcome variability of each participant.

In the study of Horan et al. (2011), it was reported that all golfers showed a reduction in hand trajectory variability from the top of the backswing to mid downswing and to impact suggesting that the hands had a controlling influence on club head variability. Interestingly, in this analysis, there was no consistent reduction in movement variability of the wrists across participants from the backswing to the downswing. Half of the participants actually increased the movement variability at the left wrist marker between the backswing and downswing while almost half of the cohort increased movement variability at the right wrist marker between backswing and downswing. It is difficult to directly compare the research of this chapter with the work of Horan et al. (2011) as their work examined three discrete points on the downswing and this work examined variability over the entire backswing and downswing.

The results of this analysis across the highly-skilled cohort of participants indicated that for the backswing and downswing, the malleoli were the marker trajectories that contained the highest levels of movement variability on average across all participants. Analysing the results qualitatively indicates no trends between increased movement variability and increased outcome variability. For example, participants 8 and 9 had higher movement variability in the arm and shoulder markers in the downswing (Figure 5.7) relative to the other participants yet other participants displayed higher outcome variability (Figure 5.8) than them (i.e. participants 4, 10 and 14). This suggests that higher movement variability in the arm marker trajectories did not directly relate to high variability in shot outcome. The statistical analysis confirmed this qualitative evaluation as it revealed no statistically significant correlations between the movement variability values across all participants and outcome variability. This lack of significant relationship between movement variability and shot outcome variability indicates for this group of highly skilled participants, that participants used their own unique performance strategies in order to minimise their shot outcome variability. Given the high skill level of these performers, it could be that they exploit their natural movement variability and are capable of performing their swing within specific ranges of variability that does not affect their outcome (i.e. ball velocity variability). It has been shown that elite golfers find their own specific solution to optimising club head speeds (Brown et al. 2011). It is suggested from the results of this chapter that movement variability is
specific to the individual and each participant had their own strategy of optimising ball velocity variability (outcome variability).

Therefore, at the elite level of performance where participants have developed a stable movement pattern, it is potentially more beneficial to adopt a more individual-based analysis. It is also worth considering the variability of multi-segment coordinative measures in future group analyses of movement variability as this may reveal more information on the coordination of movement of segments. At higher levels of skill, the coaching of invariant swings or using another person’s swing upon which to base their teaching methods is not recommended based on the results of this study. Given the movement variability displayed by each participant was individual-specific with no group trends obvious across the cohort, analysing the effect of movement variability specific to that individual may be more successful in reducing shot outcome variability. Modelling and simulation methods offer the potential to investigate this individual-based movement variability analysis.

5.4 CONCLUSION

The analysis of movement variability using a previously developed calculation technique in Chapter 4, revealed no relationship across the group of participants with respect to movement variability of marker trajectories at 14 body locations in the backswing and downswing of the golf swing. Given the elite profile of the cohort, it is postulated that individual participants used their own strategies in order to control their movement variability such that it had no effect on outcome variability. Therefore, at the elite level of golf performance, single-subject analysis is merited and will be the focus of subsequent work.

5.4.1 Thesis Context

This chapter analysed movement variability of marker trajectories in the backswing and downswing phase of the golf swing. This chapter identified that individual based analyses may be more appropriate in the future. The following chapters focus on this individual approach whilst using modelling and simulation methods. The chapter immediately following this details the first stage of this approach; the creation and validation of a full-body model of the swing of one participant.
5.5 REFERENCES


CHAPTER 6

CREATION AND VALIDATION OF A FULL-BODY COMPUTER MODEL OF THE GOLF SWING
6.0 ABSTRACT

The purpose of this chapter was to create, develop and validate a full-body musculoskeletal model and computer simulation of a golfer performing a swing with their driver club. An elite female participant performed ten shots with her driver while wearing retro-reflective markers. A number of these markers were to be used to drive the model created whilst additional markers were included to perform the validation of the model. An optical 3-D 6-camera system captured the kinematics of the markers at 400 Hz on the participant for each trial. A launch monitor device recorded the ball and club head conditions at impact. The kinematic data from one trial was selected to drive inverse and forward dynamics simulations of a created musculoskeletal model. A full-body 19-segment computer model of the participant with 44 degrees of freedom was subsequently constructed in ADAMS/LifeMOD modelling software. A physical environment of driver club and a ground surface was also modelled. The kinematic data captured experimentally was used to drive the inverse simulation. The internal joint torques and muscle forces calculated from the inverse dynamics simulation were used to drive the forward dynamics simulation. The validation results showed a high level of agreement between experimental and simulated trajectories for selected markers (mean $r=0.966 \pm 0.03$). There was a difference of 0.26 m.s$^{-1}$ (0.66%) between the modelled and experimental peak club head velocity. Swing temporal data in the form of backswing and downswing time were identical. Thus, a large-scale model of the golf swing has been created and validated and can be used in future research.

6.1 INTRODUCTION

Movement variability has typically been examined using traditional experimental techniques (Hamill et al. 1999, Wilson et al. 2008, Horan et al. 2011). The potential problem with experimental studies has been documented previously in that the amount and type of variability cannot be controlled if the aim of the study is to ascertain a causal relationship between movement variability of a specific measure and the outcome of the movement. Computer modelling offers the advantage of allowing the imposition of controlled amounts of movement variability on the model in order to ascertain its effect on movement outcome. For this reason, modelling and simulation methods are adopted for this phase of research.
The overall objective of this research was to apply variability to a number of kinematic parameters individually within the computer model and ascertain the effect of this on movement outcome. This could, in theory, determine the most influential factors in the golf swing for the participant in question and therefore potentially be used in the future in a feedback type situation to improve the effectiveness of the participant’s golf swing. The first stage of the use of modelling and simulation to investigate movement variability involves the creation and validation of a computer model of the golf swing.

Due to the overwhelming complexity of the golf swing movement sequence, many attempts have been made to model the swing or components of the swing in an effort to better understand the physics of the golf swing and the main determinants of a successful swing. In fact, the golf swing is probably one of the most modelled of all sporting movements (Betzler et al. 2008).

Modelling of the golf swing has developed from simplistic 2-D double-pendulum models (Cochran and Stobbs 1968, Miura 2001, White 2006) to more complex 3-D full body models (Nesbit 2005, Nesbit and Serrano 2005, Betzler et al. 2006, Kenny et al. 2006, Kenny et al. 2008a, Nesbit and McGinnis 2009). Models constructed should only be as simplistic or complex as the research question demands. Full-body 3-D models allow for a better representation of the golf swing movement patterns than 2-D models due to the 3-D nature of the golf swing. This advantage of 3-D analysis, coupled with recent advancements in large-scale modelling of the human body, led to the implementation of a full-body 3-D model of the golf swing in order to attempt to answer the research question in focus here.

Nesbit (2005), Nesbit and Serrano (2005), Nesbit and McGinnis (2009) created their models of the golf swing within the ADAMS (Automatic Dynamic Analysis of Mechanical Systems, MSC Software Corporation, USA) engineering software. This process of creating the human model in the current study used ADAMS software but in conjunction with the LifeMOD (The LifeModeler Inc., USA) toolkit which has an interface with the ADAMS software. The process of creating full-body models of the golf swing with ADAMS and LifeMOD has been used in the case of Kenny et al. (2006, 2008a) and Betzler et al.(2006).

Due to the call for more single-participant approaches in modelling (Hatze 2005) in order to improve the validity and biofidelity of models created, and the discontent with
group statistics (Dufek et al. 1995, Bates 1996), a single-participant approach was pursued for this modelling method. Single-participant analysis and the statistical approaches necessary for these single-case designs have been discussed previously by statisticians (Bates 1996, Bates et al. 2004, Kinugasa 2004).

6.1.1 Aims

The first stage of this modelling approach to investigate movement variability involves the creation and validation of a computer model of the participants swing. Therefore, the aims of this chapter were to:

- Develop a large-scale, full-body, human model of a golfer and a driver club.
- Validate the model thus ensuring the human model and its motion in the simulations was a valid representation of the participant in question and their motion.

This validated model of the participant performing a golf swing with their driver was then to be used in a future study examining the effect of different levels of movement variability on the outcome of the golf swing.

6.2 METHODS

This methods section details the procedures involved in the creation of the model. The first part of the methods describes the participant used for the modelling approach and the capture of experimental data from this participant necessary to produce movement in the model. The second part of the methods explains the procedures that were undertaken in the construction of the human model and the physical environment. This part also describes the application of experimental motion data to move the human model. The third and final part details the parameters from the experiment and model that were to be examined in order to satisfy the chapter aim of validating the created model.

As the experimental data collection followed that described previously, a concise account of that aspect of the methods is provided. See Section 4.2.2 for additional information with regard to this.
6.2.1 Data Collection and Processing for Model

6.2.1.1 Participant

This study employed a single-participant methodology. As discussed previously, single-participant analysis was preferred in this research in order to improve model validity and account for individual specific movement patterns that exist in participants. One elite (Ladies European Tour Professional) female participant (24 years, 1.7 metres, 59.2 kg) was selected from the cohort of participants described in Section 4.2.1 to be modelled. The participant was familiarised with the experimental procedure before providing written consent to participate as approved by the Faculty of Education and Health Sciences Research Ethics Committee.

6.2.1.2 Experimental Data Collection

The experimental data collection procedures have been detailed elsewhere (see Section 4.2.2). Briefly, the experimental testing took place in a purpose built indoor golf testing facility in the university. The participant completed an unlimited self-directed warm-up that included her typical stretches and mobilisation exercises that she would normally perform prior to a competitive round or practice session. Retro-reflective markers were placed on various anatomical landmarks on the body of the participant. These marker locations were based on the recommendation of LifeModeler (2010). The participant performed a number of practice shots prior to the data collection period with the retro-reflective markers attached in order to familiarise with the set-up. The locations of these markers are detailed in Table 6.1 – Table 6.5. Specifically, the markers used to drive the inverse simulation of the computer model are detailed in Table 6.1 – Table 6.5.
### Table 6.1 – Torso and pelvis markers

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoracic 4(^{th}) Vertebra</td>
<td>Spinous Process of 4(^{th}) thoracic vertebra</td>
</tr>
<tr>
<td>L ASIS</td>
<td>Placed directly over the left anterior superior iliac spine</td>
</tr>
<tr>
<td>R ASIS</td>
<td>Placed directly over the right anterior superior iliac spine</td>
</tr>
<tr>
<td>Sacrum</td>
<td>Placed mid-way between the posterior superior iliac spines (PSIS).</td>
</tr>
</tbody>
</table>

### Table 6.2 – Foot and golf shaft markers

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Metatarsal Head</td>
<td>Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot</td>
</tr>
<tr>
<td>Right Metatarsal Head</td>
<td>Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot</td>
</tr>
<tr>
<td>Right Heel</td>
<td>Placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker</td>
</tr>
<tr>
<td>Left Heel</td>
<td>Placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker</td>
</tr>
<tr>
<td>Golf Shaft Marker</td>
<td>Marker placed on the golf shaft 10 inches from the centre of the right hand. Frontal plane</td>
</tr>
</tbody>
</table>
Table 6.3 – Arm markers

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Shoulder</td>
<td>Flat portion of the acromion</td>
</tr>
<tr>
<td>Right Humeral Wand</td>
<td>A pedestal marker placed on the upper arm halfway between the elbow and shoulder. Laterally in anatomical ref position</td>
</tr>
<tr>
<td>Right Epicondyle</td>
<td>Placed on lateral epicondyle approximating elbow joint axis</td>
</tr>
<tr>
<td>Right Forearm Wand</td>
<td>A pedestal marker placed on the lower arm halfway between the elbow and the wrist, along radial line. Should be placed symmetrically with Left Forearm Wand</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>Right wrist lateral centre</td>
</tr>
<tr>
<td>Left Shoulder</td>
<td>Flat portion of the acromion</td>
</tr>
<tr>
<td>Left Humeral Wand</td>
<td>A pedestal marker placed on the upper arm halfway between the elbow and shoulder. Laterally in anatomical ref position. Should be placed symmetrically with Right Humeral Wand</td>
</tr>
<tr>
<td>Left Epicondyle</td>
<td>Placed on lateral epicondyle approximating elbow joint axis</td>
</tr>
<tr>
<td>Left Forearm Wand</td>
<td>A pedestal marker placed on the lower arm halfway between the elbow and the wrist, along radial line. Placed symmetrically with Right Forearm Wand</td>
</tr>
<tr>
<td>Left Wrist</td>
<td>Left wrist lateral centre</td>
</tr>
</tbody>
</table>
Table 6.4 – Leg markers

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Femoral Condyle</td>
<td>Placed on the lateral epicondyle of the right knee</td>
</tr>
<tr>
<td>Right Femoral Wand</td>
<td>A pedestal marker placed on the right thigh, viewed in the anatomical ref position, halfway between lateral epicondyle of right knee and greater trochanter. Just below the swing of the hand</td>
</tr>
<tr>
<td>Right Malleolus</td>
<td>Placed on the right lateral malleolus along an imaginary line that passes through the transmalleolar axis</td>
</tr>
<tr>
<td>Right Tibial Wand</td>
<td>Similar to the thigh markers, these are placed midway along the shank, laterally in anatomical ref position, to determine the alignment of the ankle flexion axis. Pedestal marker</td>
</tr>
<tr>
<td>Left Femoral Condyle</td>
<td>Placed on the lateral epicondyle of the left knee</td>
</tr>
<tr>
<td>Left Femoral Wand</td>
<td>A pedestal marker placed on the left thigh, viewed in the anatomical ref position, halfway between lateral epicondyle of left knee and greater trochanter. Just below the swing of the hand</td>
</tr>
<tr>
<td>Left Malleolus</td>
<td>Placed on the left lateral malleolus along an imaginary line that passes through the transmalleolar axis</td>
</tr>
<tr>
<td>Left Tibial Wand</td>
<td>Similar to the thigh markers, these are placed midway along the shank, laterally in anatomical ref position, to determine the alignment of the ankle flexion axis. Pedestal marker</td>
</tr>
</tbody>
</table>

The markers listed previously in Table 6.1 – Table 6.4 were used to drive the model in the inverse dynamics stage and were part of the plug-in set used for golf analysis in the
LifeMOD software. In order to improve the ability of the model to replicate actual head movement, the base marker set was augmented with head markers to improve the representation of this movement. Additionally, markers were placed on other landmarks that were important to the validation of the model. Reflective tape was placed on the ball and an extra marker was placed on the club shaft to aid identification of swing events. The list of these extra markers is presented in Table 6.5.

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Greater Trochanter</td>
<td>Left Inferior Patella</td>
</tr>
<tr>
<td>Right Greater Trochanter</td>
<td>Right Inferior Patella</td>
</tr>
<tr>
<td>Right Medial Malleolus</td>
<td>Left Medial Malleolus</td>
</tr>
<tr>
<td>Base of Club Shaft</td>
<td>Ball</td>
</tr>
<tr>
<td>Left Head</td>
<td>Left Hand</td>
</tr>
<tr>
<td>Right Head</td>
<td>Right Hand</td>
</tr>
<tr>
<td>C7</td>
<td></td>
</tr>
</tbody>
</table>

For data collection, the participant was instructed to swing the driver to hit the ball towards the target-line, aiming to maximise both distance and accuracy, as if in a competitive situation on the golf course. The participant was instructed to do this in order to produce swings typical of her swing performed during a golf round. The participant performed ten shots with both kinematic and launch monitor data captured simultaneously. A trial was accepted once the 3-D data was tracked completely and the launch monitor recorded the shot correctly. There was a rest period of 1 minute between each shot to ensure sufficient physical recovery before the subsequent shot. In addition, an experimenter wiped the surface of the club face clean with Mineral Spirits in order to ensure the contact surface was clean prior to each shot. The motion of the markers were recorded using six Eagle digital cameras (Motion Analysis Corporation Ltd., Santa Rosa, California) operating at a recording frequency of 400 Hz. The cameras and performance area were calibrated over a volume of 3.5 x 2.8 x 3 m according the manufacturers’ protocol. The calibration results indicated an average residual marker position error less than 1 mm. A Vector Pro launch monitor (Accusport
Inc., North Carolina) was used to measure ball and club head characteristics at impact. The launch monitor was calibrated according to the manufacturers’ instructions.

6.2.1.3 Experimental Data Processing

The raw marker data were then tracked within the Motion Analysis software, Cortex. A low-pass fourth–order Butterworth filter with a cut-off frequency ($F_c$) of 12 Hz was applied to the data. See Section 4.2.3 for more information on this filtering process. Each trial was then cropped to leave only the relevant information from address to the end of the swing. Address was defined as the frame before the club initiates movement away from the ball. The end of the swing was determined as the point where the $Z$ coordinate of the club top shaft marker reached its maximum positive vertical position during the follow-through. See Section 6.2.2.5.2 for definition of all swing events.

Following this, a representative trial from the ten shots performed was selected. This trial was selected by first calculating the median ball velocity (outcome measure) from the ten trials. The trial that was closest to the median was then deemed the representative trial. However, occasionally when data is imported to the ADAMS/LifeMOD software, the motion splines cannot be generated to drive the model (this appears to be an anomaly of the software). Therefore the determination of the representative trial was linked to its data’s ability to work within the ADAMS/LifeMOD software. The trial that was closest to the median and functioned once imported into ADAMS/LifeMOD was then deemed to be the best representative trial and thereby was the trial to be modelled for this participant.

The cropped trajectory data from the representative trial was then converted to the slf format for use in the modelling software, ADAMS, with its LifeMOD plug-in.

6.2.2 Model Construction

The following subsections detail the processes involved in construction of the human model, how it was positioned in the physical environment and how movement was produced in the model. The model was created within the ADAMS/LifeMOD software. Several stages were involved in the development of this model which are described in the following sections.
6.2.2.1 Segment and Bone Creation

The human model creation process began with the construction of the base level segment set. By default, LifeMOD generates 19 segments. Sometimes it is necessary to reduce the number of or redefine the fidelity of the individual segments depending on the research question; however this was not performed in this case as it was the intention to create a large-scale model of the articulations of all these segments of the golf swing. The 19 model segments included in the construction of this model are listed in Table 6.6.

<table>
<thead>
<tr>
<th>Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
</tr>
<tr>
<td>Neck</td>
</tr>
<tr>
<td>Upper Torso</td>
</tr>
<tr>
<td>Central Torso</td>
</tr>
<tr>
<td>Lower Torso</td>
</tr>
<tr>
<td>Left &amp; Right Scapular</td>
</tr>
<tr>
<td>Left &amp; Right Upper Arm</td>
</tr>
<tr>
<td>Left &amp; Right Lower Arm</td>
</tr>
<tr>
<td>Left &amp; Right Hand</td>
</tr>
<tr>
<td>Left &amp; Right Foot</td>
</tr>
<tr>
<td>Left &amp; Right Upper Leg</td>
</tr>
<tr>
<td>Left &amp; Right Lower Leg</td>
</tr>
</tbody>
</table>

The segments were created from the Generator of Body Data (GeBOD) anthropometric database available within the LifeMOD software from the gender, age, height and mass of the participant. The GeBOD database (Cheng et al. 1994), which was developed by the Modelling and Analysis Branch of the Air Force Aerospace Medical Research Laboratory and the University of Daytona Research Institute, was based on an anthropometric survey of over 1900 females. The segments created from the regression equations of the database generated the segment masses, dimensions and inertia tensors. It also defines the location of the joints which connect the segments. This approach, of using the GeBOD database to generate participant’s anthropometrics, has been used in many modelling studies (de Jongh et al. 2007, Serveto et al. 2009, Cavallo et al. 2012).
Following construction of the segments, bone properties were added in order to provide physical rigidity to the model and also for graphical representation. The base human bone set can be seen in Figure 6.1. The model included every bone in the human body. The bone material constructed is based on actual density, Young’s modulus and Poisson’s ratio values for bone. The bones are scaled according to the anthropometric measurements generated from the GeBOD database.

6.2.2.2 Joints

After model segment construction, joints were created between the segments. These joints were kinematic constraints which connected two adjoining segments of the body. The joints consisted of a tri-axis hinge and passive or active forces acting on its degrees of freedom. In order to allow the segments to exhibit more realistic and anatomically correct movements, it was necessary to constrain the joints to certain degrees of freedom. The joints modelled and their relevant degrees of freedom (DOF) allowed are presented in Table 6.7.
Table 6.7 – Joints created in the model, the segments they connect and their relevant degrees of freedom (DOF)

<table>
<thead>
<tr>
<th>Segment</th>
<th>Joint</th>
<th>Number of Joints</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Atlantoaxial</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Trunk/Spinal Column</td>
<td>Intervertebral (3)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Arm/Scapular</td>
<td>Glenohumeral (2)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Scapular/Upper Torso</td>
<td>Sternoclavicular (2)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Upper Arm/Lower Arm</td>
<td>Elbow (2)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Lower Arm/Hand</td>
<td>Wrist (2)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Lower Torso/Upper Leg</td>
<td>Hip (2)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Lower/Upper Leg</td>
<td>Knee (2)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Lower Leg/Foot</td>
<td>Ankle (2)</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Taking into account the segments in the model and the DOF of each articulation between segments, the model had a total of 44 DOF. Hatze (2005) defined a large-scale model as that which contains at least 15 segments. Thus, this definition can be applied to the 19 segment model with 44 DOF created here. It is worth noting that this is a simplified representation of all articulations in the body that is based on known movements of the golf swing and the recommendations from LifeMOD for golf models.

Trainable passive joints were created that had a torsional spring force with user-specified stiffness, damping, angular limits and limit stiffness values. The original values for these parameters were as per LifeMOD suggestions in the golfing tutorial (LifeModeler 2010). Some of these values for joint stiffness and damping were fine-tuned through a trial and error process. These joints were used in an inverse dynamics (described later in Section 7.2.5.1) simulation to record the joint angulations while the model was driven with motion agents containing the experimental motion data. The forward dynamics simulation used the joint torques and muscle forces calculated from the joint angulations recorded by the passive joints in order to simulate movement. The upper-body joint representations can be viewed in Figure 6.2.
6.2.2.3 Muscles (Soft Tissues)

Muscles were the soft tissues modelled for this human model. Other soft tissues such as skins and fats were not modelled. These muscles produce tension forces between bone attachments. The model was constructed with 178 muscles which were available in the LifeMOD database. The muscles were attached to the 19 base segments at predefined, scalable attachment points. The origin and insertion points of all muscles were verified through consultation with relevant textbooks with the correct attachment points of muscles detailed (Warfel 1993a, Warfel 1993b, Floyd and Thompson 2004). During the inverse simulation, the muscles with their trainable elements recorded the shortening-lengthening patterns of the muscles. The trainable elements learn and record shortening/lengthening patterns, while motion capture data drives the model in an inverse dynamics simulation. These trainable elements then served as actuators for the forward dynamics simulations. The muscle set used in the construction of this model can be seen in Figure 6.3. A detailed list of muscles can be seen in Appendix A4.1.
Muscle geometry was scaled to the age, height, mass and gender of the participant utilising a built-in decision tree algorithm and allometric scaling (McMahon 1984). The muscle actuators were programmed not to exceed the physiological limits of the individual model.

Muscle physiological properties that were considered included:

- Physiological cross-sectional area (pCSA)
- Resting load ($F_{\text{resting}}$)
- Force output filter ($F_{\text{filter}}$)
- Maximum tissue stress ($M_{\text{stress}}$)
- Overall muscle tone ($M_{\text{tone}}$)

This meant that pCSA, $F_{\text{resting}}$ and $M_{\text{stress}}$ were defined for every muscle. The factors listed previously allowed the establishment of the upper limit of the muscle force ($F_{\text{max}}$) for each muscle. The values of these parameters were established through the following means:
• The LifeMOD database allowed establishment of pCSA and $M_{\text{stress}}$ scaled to the participant’s age, height, gender and mass.

• The pCSA could be further scaled using the overall muscle tone ($M_{\text{tone}}$) which directly scales the pCSA from 0 to 500%. In this model pCSA was set at 100%.

• $F_{\text{max}}$ was calculated by multiplying the pCSA for each muscle to a maximum tissue stress ($M_{\text{stress}}$) value derived from previous studies (Hatze 1981).

• $F_{\text{resting}}$ is usually a nominal value and the default value provided by LifeMOD was used in this model.

An optimised, net-force approach was adopted as the method of determining the force of each muscle. Muscles produced the necessary forces that were required to replicate the motion of the body while bound to the defined physiological limits.

### 6.2.2.4 Environment and Contacts

The previously described human model was then placed in a physical environment with the modelled ground surface and driver club. The ground was modelled as a block shape with the left and right feet attached through a bushing element on the base of each foot. A bushing element is essentially a 3-D spring damper used to provide a connection with six degrees of freedom allowing transmission of forces and moments. The left foot was connected with a cylindrical bushing. This bushing was used for the left foot to allow for inversion and eversion movements that are typical of the left foot in the swing. The right foot was connected with a spherical bushing which allowed inversion/eversion, and plantar/dorsi-flexion of the foot. The feet bushings are shown in Figure 6.4.

---

6 Even when a muscle is at rest, some motor units are always active. Motor units are randomly stimulated so that there is a constant tension in the attached tendon.
A driver club was constructed to represent the driver of the participant. The modelled driver consisted of three main constituents: the grip, the shaft and the club head. Firstly, the grip and club head were imported from the LifeMOD library. The physical properties of these parts were adjusted from their default values to better represent the club of the player. The mass of the grip was specified as 0.05 kg as this is the typical mass of golf grips. The club head properties matched that of the participant insofar as possible. The mass was adjusted to 0.2 kg and the material was stipulated as titanium. The default properties of density, Poisson’s Ratio and Young’s Modulus available in ADAMS were used for this. In order to predict club head velocity during simulations, a massless virtual marker was placed on the toe of the club head. The club head used in these simulations can be seen in Figure 6.5.

Figure 6.4 – Feet constraints
Following on from this, the shaft was constructed. The shaft length was set to that of the participant’s own driver, 1.1176 metres (converted from 44 inches). This construction process was more involved than that of the grip and club head. Carbon fibre was the material used to construct the shaft. As this material was not available within the ADAMS material library, it had to be created within ADAMS and its physical properties manually inputted. As the physical properties of this material can vary widely, typical values (Poisson’s ratio, Young’s modulus, density) were obtained through consultation with previously determined values in our research group. The shaft was created as a flexible link of 8 interconnected segments. In order to create a shaft of “regular” flex as used by the participant in question, a trial and error approach was used to determine the correct damping ratio of the shaft. Fixed joint constraints were used to connect the shaft to the butt end of the grip and to the hosel end of the golf club. The shaft length was set to that of the participants’ own driver shaft length. The shaft connected to the grip and club head can be viewed in Figure 6.6. The right hand was connected to the left hand with a fixed joint constraint. The grip end of the golf club was connected to the hands at this one contact point with a fixed element bushing.
6.2.2.5 The Application of Motion to the Model: Inverse and Forward Dynamics Simulations

Once the human model was constructed, the next stage involved running the inverse and forward dynamics simulations. This involved the application of the motion data of the participant collected experimentally to the model. To do this, the file containing the motion data, described in Section 6.2.1.3, was imported. This file contained the participant’s age, height, mass and gender, joint specifications and motion data.

To run the simulations, the slf file containing the motion data was imported to the previously created human model. This created the motion splines which dictated the path of a marker. This motion data was then used to drive elements termed motion agents in the model (yellow sphere in Figure 6.7). These motion agents were massless parts fixed to a body segment using virtual spring attachments. These can see in Figure 6.7. The red sphere was rigidly attached to the relevant body segment whilst the massless yellow sphere contained the motion data for that particular data captured during experimentation. Thus the yellow sphere exactly followed the path of the marker recording during the experimentation whereas the red sphere followed the models interpretation of that path. Where there was an obvious difference between these two trajectories, there was a subsequent refining of the joint or muscle parameters.
The validation of this model undertook an inverse-forward dynamics approach in order to fully ascertain the model was an acceptable representation of the participant and their motion. Firstly, the inverse simulation was processed whereby the motion data was used to drive the relevant body segments. It was the motion data of the markers described in Table 6.1 – Table 6.4 that were used to drive the model. The joint angulations and muscle stretch histories were recorded after this phase. These values, along with the segmental inertial properties determined from the participant’s anthropometrics, were used to calculate the internal kinetics that would be required to reproduce that particular movement pattern. The determined internal kinetics were then used in the forward dynamics simulation. To perform the forward dynamics simulation, the motion agents were disabled and the previously determined internal kinetics were used to reproduce the movement from the inverse simulation. Both the inverse and forward simulations calculations were automated processes within the ADAMS/LifeMOD programme.

The previously described process was repeated 10 times. As can be seen in Section 6.3.1 of the results, there was no variation in the parameter highlighted. This was the case for club head velocity and all validation marker trajectories. Therefore, this emphasised the invariance of the model and the suitability of the modelling approach for analysing the effect of movement variability.
6.2.2.6 Swing Events

The following definitions of swing events were used for both the experimental and modelled data for determining swing phases and examining temporal factors:

- **Address (ADD):** This was defined as the frame before the club initiates movement away from the ball. This was the first frame of the modelled data.
- **Top of the backswing (TOB):** This was defined as the frame where the shaft marker reached its minimum velocity between the start and end of the data.
- **Impact (IMP):** This was defined for the experimental data as the frame where the ball marker was first moved. This was also the point where the launch monitor captured ball launch conditions. For the modelled data where there was no ball modelled, IMP was deemed to be the frame where club toe marker was closest to the X-position of the ball which was determined through experimentation.
- **Follow through (FT):** FT was determined as the point where the Z coordinate (vertical) of the club top shaft marker reached its maximum positive position during the follow-through. This was the last frame of the modelled data.
- **Backswing:** This was defined as the swing phase between ADD and TOB.
- **Downswing:** This was defined as the swing phase between TOB and IMP.
- **Total swing:** This was the entire swing between ADD and FT.

A visual depiction of the swing events is provided in Figure 6.8.
6.2.3 Model Validation

In order to ensure that the model was a valid representation of the player modelled, a series of comparisons between results gathered from experimentation and those predicted by the model. The model was validated from three points of view:

1. Kinematic measures
2. Outcome measure
3. Temporal measures
6.2.3.1 Kinematic Validation

A number of markers were placed on the participant during experimentation that were additional to the marker set required to drive the model as described in Table 6.5. These markers did not drive the model during the inverse simulation. The positions of these markers were replicated on the model and their trajectories were recorded during the inverse and forward dynamics simulation of the model. A Pearson’s (r) correlation analysis (PASW v 18 (SPSS Inc, USA)) and root mean square difference (RMSD) analysis was carried out to statistically quantify the relationship between the experimental and model trajectories for the validation markers. These markers were placed bilaterally on the greater trochanters, inferior patellae and hands in order validate the motion at the proximal (knee and hips) and distal (hands) ends of the kinetic chain. The displacements of selected markers between selected swing events were also compared between simulated and experimental data.

6.2.3.2 Outcome Validation

It is important to verify that the human model is moving correctly, but it also important to verify the human model is interacting with the physical environment correctly. As the club-ball interaction at impact was not modelled due to its inherent complexity (Tanaka et al. 2006), club head velocity was chosen as the outcome measure. Thus, the club head velocity captured during experimentation with the launch monitor device was compared with the predicted club head velocity from the simulation using the virtual marker placed on the toe of the modelled club head.

6.2.3.3 Temporal Validation

A further validation of the model was carried out with respect to the temporal aspect of different phases of the swing. Backswing and downswing times were compared between experimental and model swing times.

6.3 RESULTS

6.3.1 Model Variance

Selected measures were compared over the 10 repeated forward simulations. Table 6.8 provides the means and standard deviations of the maximum and minimum values
of club head velocity and the x, y, z trajectories of left hand and right greater trochanter validation markers. This highlighted the invariance of the model. This is to be expected given the initial conditions are the same and it is a mathematical calculation based on these, however it was important to verify this.

Table 6.8 – Club head velocities and selected x trajectories of selected markers showing average maximum and minimum value for each over repeated simulations

<table>
<thead>
<tr>
<th></th>
<th>Max (±SD)</th>
<th>Min (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Club Head Velocity (m.s⁻¹)</td>
<td>39.398 ± 0.000</td>
<td>0.000 ± 0.000</td>
</tr>
<tr>
<td>Left Hand – x path (m)</td>
<td>-0.122 ± 0.000</td>
<td>-1.047 ± 0.000</td>
</tr>
<tr>
<td>Right Greater Trochanter – x path (m)</td>
<td>-0.441 ± 0.000</td>
<td>-0.722 ± 0.000</td>
</tr>
<tr>
<td>Left Inferior Patella –x path (m)</td>
<td>-0.299 ± 0.000</td>
<td>-0.438 ± 0.000</td>
</tr>
</tbody>
</table>

The validation results show the comparisons between the experimental and forward dynamics simulations. The inverse and forward dynamics simulations were examined to ensure that they were not producing different movement patterns from each other and it was found they were invariant. Figure 6.9 shows how the path of the left hand in the x-axis was invariant between the inverse and forward simulations. The absolute differences (in the form of root mean square difference (RMSD)) between the simulations for selected variables are presented in Table 6.9. This shows that either the forward or inverse dynamics simulation could be used for future work with the validated model.
Table 6.9 – Comparison (RMSD) between inverse and forward simulations for selected variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>RMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Club Head Velocity (m.s(^{-1}))</td>
<td>0.14</td>
</tr>
<tr>
<td>Left Hand – x path (m)</td>
<td>0.0013</td>
</tr>
<tr>
<td>Left Hand – y path (m)</td>
<td>0.0006</td>
</tr>
<tr>
<td>Left Hand – z path (m)</td>
<td>0.0018</td>
</tr>
<tr>
<td>Right Greater Trochanter – x path (m)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Right Greater Trochanter – y path (m)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Right Greater Trochanter – z path (m)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Left Femoral Condoyle – x path (m)</td>
<td>0.0003</td>
</tr>
<tr>
<td>Left Femoral Condoyle – y path (m)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Left Femoral Condoyle – z path (m)</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Figure 6.9 – Comparison of path of left hand x-trajectory for the inverse and forward simulations
6.3.2 Kinematic Validation

The first method of validation evaluated the level of agreement between experimental and simulated for the combined x, y, z trajectories. The results of the Pearson’s correlation ($r$) and the RMSD between actual and simulated marker paths from the forward dynamics simulation are presented in Table 6.10. The results of this validation indicated that there was a high level of agreement between simulated and experimental marker trajectories of upper and lower regions of the body. Indeed, all measures were significantly correlated ($p < 0.01$).

<table>
<thead>
<tr>
<th>Marker Path</th>
<th>$r$</th>
<th>RMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>L Greater Trochanter</td>
<td>0.962*</td>
<td>0.027</td>
</tr>
<tr>
<td>R Greater Trochanter</td>
<td>0.970*</td>
<td>0.025</td>
</tr>
<tr>
<td>L Inferior Patella</td>
<td>0.924*</td>
<td>0.047</td>
</tr>
<tr>
<td>R Inferior Patella</td>
<td>0.945*</td>
<td>0.035</td>
</tr>
<tr>
<td>L Hand</td>
<td>0.998*</td>
<td>0.040</td>
</tr>
<tr>
<td>R Hand</td>
<td>0.997*</td>
<td>0.020</td>
</tr>
</tbody>
</table>

*R - Right L - Left

* Denotes significance at $p < 0.01$

In addition, the displacements of these markers between key swing events were determined and compared between the experimental and simulated golf swing. The average of the x, y, and z displacements were compared and are presented in Table 6.11. Overall they compared favourably with close agreement between the ranges of motion for the markers.
Table 6.11 – Differential values of displacements between experimental (Exp) and model (Mod) for two different phases of the swing

<table>
<thead>
<tr>
<th></th>
<th>ADD – TOB (m)</th>
<th>TOB – IMP (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L Greater Trochanter</td>
<td>0.077</td>
<td>0.071</td>
</tr>
<tr>
<td>R Greater Trochanter</td>
<td>0.020</td>
<td>0.027</td>
</tr>
<tr>
<td>L Inferior Patella</td>
<td>-0.017</td>
<td>-0.013</td>
</tr>
<tr>
<td>R Inferior Patella</td>
<td>0.009</td>
<td>0.013</td>
</tr>
<tr>
<td>L Hand</td>
<td>0.019</td>
<td>0.019</td>
</tr>
<tr>
<td>R Hand</td>
<td>0.000</td>
<td>-0.008</td>
</tr>
</tbody>
</table>

*Positive value for difference indicates higher displacement for experimental swing
Negative value for difference indicates higher displacement for model swing*

6.3.3 Outcome Validation

The peak club head velocity as measured by the aforementioned club head toe marker in the model and the club head velocity as measured and calculated by the Vector Pro launch monitor can be seen in Table 6.12. There was a difference between the experimental and modelled data of 0.26 m.s\(^{-1}\).

Table 6.12 – Comparison of model and experimental club head velocities

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Club Head Velocity (m.s(^{-1}))</td>
<td>39.14</td>
<td>39.40</td>
</tr>
</tbody>
</table>

6.3.4 Temporal Validation

Using the swing events defined in Section 6.2.2.5.2, temporal factors between the experimental and modelled swing were compared. Backswing time and downswing time were analysed. The duration of these swing phases were identical between the simulated and experimental swing. As can be seen from Table 6.13, these values were identical for both the experimental and simulated swing.
Table 6.13 – Comparison of backswing (T_{bs}), downswing (T_{ds}) and total swing (T_{tot}) time for the modelled and experimental swings

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{bs}$ (s)</td>
<td>0.8275</td>
<td>0.8275</td>
</tr>
<tr>
<td>$T_{ds}$ (s)</td>
<td>0.3050</td>
<td>0.3050</td>
</tr>
<tr>
<td>$T_{tot}$ (s)</td>
<td>1.3450</td>
<td>1.3450</td>
</tr>
<tr>
<td>$T_{bs}$ (% of $T_{tot}$)</td>
<td>61.52</td>
<td>61.52</td>
</tr>
<tr>
<td>$T_{ds}$ (% of $T_{tot}$)</td>
<td>22.68</td>
<td>22.68</td>
</tr>
</tbody>
</table>

6.4 DISCUSSION

6.4.1 Human Model and Physical Environment Construction

In recent years, large-scale computer models of the golf swing have been utilised to analyse an associated research question. For example, Nesbit (2005) built a large-scale model of the golfer with a flexible golf club using ADAMS software in order to ascertain the 3-D kinematics and kinetics of the swing. Kenny et al. (2008a) used their validated musculoskeletal model to examine kinetic energy profiles of different segments in the golf swing and reported that the segmental sequencing pattern did not follow the traditional proximal to distal sequencing. Thus it is evident that full-body 3-D models of the golf swing are being increasingly used in order to gain a thorough understanding of the effect of equipment on the movement of the golfer and also in order to gain a better understanding of individual swing characteristics.

This full-body musculoskeletal model has progressed from those previously published (Kenny et al. 2008a). Specifically, the head segment was driven with motion data, additional joint torque actuators were utilised via additional muscles, and validation markers were placed on the hands. Extensive validation results are presented in Section 6.3 which are discussed in Section 6.4.2. The construction process for this particular model, detailed in Section 6.2, highlighted the level of detail required in refining this model to best represent the participant in question. The model created was specific to the female participant in question. The concern expressed with group analyses (Bates et al. 2004) and the large inter-participant variability in golfers, even at
the elite level (Kenny et al. 2008b, Brown et al. 2011), led to the adoption of a single-participant approach for this model. This also followed recommendations of increased specificity of models to a single-participant (Farrally et al. 2003, Hatze 2005). As evidenced by the results in Section 6.3.1, the model was invariant over repeated simulations and thereby confirms its suitability for investigating the application of variability to it in order to determine an effect, if any.

6.4.2 Model Validation

Appropriate model validation is a fundamental procedure that must be carried in any modelling procedure. The detailed construction of the human model and the physical environment described in this chapter would have been futile had the model not produced acceptable movement patterns in agreement with those captured experimentally. The model must be biofidelic and produce reliable, realistic and accurate movement patterns in order to be utilised to answer a research question.

With respect to kinematic validation, there was a high level of correlation between simulated and experimental trajectory data for the validation markers listed. The addition of validation markers outside of those used to drive the model is a relatively new development in modelling and has been only reported in the models of Kenny et al. (2006, 2008a) in relation to golf swing models. The inclusion of these markers enhanced the overall validation process. For the six kinematic measures, there was a strong average correlation value of 0.966 ± 0.03 with all measures significantly correlated. The RMSD between experimental and simulated data was low also with an average value of 0.032 ± 0.010 m. The analysis of the differences in displacements of the validation markers showed there were average differences of 0.024 m and 0.025 m for the backswing and downswing phase respectively. This again indicated that the movement patterns were comparable between recorded and simulated motion. The interaction of the human model with the modelled club was acceptable also. This was highlighted in the outcome results with good agreement between the simulated peak club head velocity and the measured club head velocity in experimentation. Temporal factors such as backswing time and downswing time were identical between the simulated and experimental swing.
Taking these validation results into account, it can be accepted with confidence that the model presented in this study can accurately reproduce and predict the swing kinematics of the participant in question.

It is important to acknowledge some limitations of the current model:

- The hands were connected to the club at one contact point.
- The feet were connected to the floor at one contact point.
- The shaft properties were estimated.
- More validation markers at the shoulder, and torso would have enhanced the validation of this model.

Whilst these are acknowledged limitations of the created musculoskeletal model, it is important to consider that there is always a balance between the complexity and simplicity with any given model. In this instance the previously listed limitations were accepted in the context of the model created. It is believed that, through the detailed construction and validation process, the current model is more than acceptable given the advancements made on previously published golf swing models.

### 6.5 CONCLUSION

A large-scale full-body musculoskeletal model of the golf swing from a single-participant has been developed. This model was used to simulate the golf swing of a single highly-skilled participant. Validation results indicated that there was strong agreement (average $r = 0.966 \pm 0.03$) between experimental and simulated movement patterns. Outcome validation in the form of peak club head velocity indicated that there was a marginal difference (0.66%) between experimental and simulated results. Temporal factors were identical between the modelled and experimental swing.

Thus, a validated model has been created that will be utilised in future research to investigate movement variability and its effect on movement patterns and the movement outcome.
6.5.1 Thesis Context

This chapter detailed the first stage of the use of the modelling and simulation approach in the description of the creation and validation of a full-body model of a participant’s swing. The following chapter focuses on the next stage of the use of this modelling approach; the development of a calculation technique to create theoretical data sets to apply movement variability to the model created and validated within this chapter (Chapter 6).

6.6 REFERENCES


CHAPTER 7

DEVELOPMENT OF A TECHNIQUE TO CREATE THEORETICAL DATA SETS TO EXAMINE MOVEMENT VARIABILITY OF MARKER TRAJECTORIES
7.0 ABSTRACT

The purpose of this chapter was to develop a technique to create theoretical data sets to examine movement variability with the created computer model from Chapter 6. This chapter outlines the development of a method to create theoretical data sets based on the exhibited movement variability of a participant. The purpose of these developed data sets was to apply them to a computer simulation of the golf swing of a nominated participant. The development of this method involved three major phases with positional data from anatomical landmarks processed from the participant’s experimental data trials (ten shots) captured in Chapter 4. Natural variability was quantified using standard deviation of the time normalised trials performed by the participant. Phase one involved the application of variability to the normalised curve with the average standard deviation. An excessive rate of change was observed between consecutive points. Phase two used the original non-normalised curve and applied variability with a scaled standard deviation curve. A key frame approach was adopted to deal with the issue of excessive rate of change between points. An issue with a shift in time was detected after phase two that was affecting the variability calculation. The third and final phase involved an increase in the number of points to counter the issue of shift in time observed in phase two. Also, to ensure the technique calculated low to high variability, containment limits were included in the calculation equation. Analysis of the curves with RMSD and Bland-Altman indicated that the produced variability curves agreed with pre-defined criteria and therefore this final phase of the technique was that which was adopted. In conclusion, a method has been developed that allows the application of variability to the original trial curve that is based on the natural movement variability of the participant and allows the creation of data sets that are ranged from high to low variability. This technique can be used in subsequent work to examine the effect of variability of individual kinematic parameters on shot outcome using the computer model developed previously.

7.1 INTRODUCTION

Movement variability, as has been described elsewhere in this thesis (see Section 2.2), is an ever-present feature of human movement patterns (Newell and Corcos 1993, Davids et al. 2003). The effect of movement variability on movement outcome remains an unanswered question (Hamill et al. 2006). In Chapters 4 and 5, an experimental approach was employed to examine this question in relation to kinematic variability of elite golfers. However, the problem with this approach is that in order to truly ascertain
the effect of variability in any individual kinematic parameter on the movement outcome, the variability in the other measures would have to be minimised. When analysing ‘real’ participants the amount and type of variability cannot be controlled and minimisation of variability is not possible. Therefore, in order to analyse the effect of movement variability of one kinematic parameter on outcome, an alternative approach was needed.

Computer modelling and simulation have been suggested as alternatives to analyse complex human movement, particularly the golf swing (Betzler et al. 2008). The golf swing is a complex movement pattern and one that has been extensively modelled to date using a number of methods (Betzler et al. 2008). In experimental investigations examining movement variability (Bradshaw et al. 2009, Horan et al. 2011), there has been no cause and effect of movement variability on movement outcome ascertained fully. In terms of improving the effectiveness of golf coaching, a dynamical systems theory approach has been advocated. Knight (2004) argued that variability should only be minimised in the swing components that exert the greatest influence on the outcome of the shot. Utilising an experimental approach, it is not possible to identify these swing components to ascertain as outlined previously. The effect of perturbations based on the movement variability of a participant, applied to a human swinging a golf club has not been examined. To the author’s knowledge, there has been one published case that examined the effect of variability of neuromuscular control on knee loading in a side-cutting task in relation to injury risk (McLean et al. 2004). However, this has not been examined in the golf swing in the published literature. This approach, of using modelling to examine variability of movement patterns, offers the ability to impose artificially controlled variability in order to ascertain its effect on movement.

Chapter 6 detailed the first stage of this process of the use of modelling and simulation methods. A computer model of a participant’s golf swing was created and validated. The model created in Chapter 6 answered the call for a participant-specific model of human motion (Hatze 2005), in particular the golf swing (Farrally et al. 2003). The next stage of the use of the modelling and simulation approach requires that a method is developed to apply variability to perturb the model. This involves the development of a technique to create theoretical data sets that are based on the natural movement variability of the participant. When these theoretical data sets are used in conjunction with a full-body 3-D computer model operating inverse and forward dynamics simulations, a change in outcome or performance measure and other joint kinematics...
or kinetics can be predicted. The advantage this process offers over traditional techniques is the ability to directly control and quantify the amount of variability introduced into the test data.

7.1.1 Aims

The aim of this chapter was to:

- Develop a method, centred on specific criteria, to create theoretical data sets based on the movement variability of the participant in question.

These theoretical data sets were required to input into a validated computer model and thereby examine the effect of movement variability on outcome in relation to the golf swing.

7.2 PRELIMINARY ISSUES PRIOR TO TECHNIQUE DEVELOPMENT

7.2.1 Participant and Data Collection

The participant used in this analysis was the same as that used in Chapter 6. See Section 6.2.1.1 for a description of this participant. The data collection for the participant was as per Section 4.2.2. A computer model of a representative trial of this participant was created and validated as described in Chapter 6.

7.2.2 Definition of Specific Aims for the Theoretical Data Sets

Prior to embarking on the task of developing the required method, a number of criteria were defined in terms of what was required for the final data sets produced by the developed method.

The defined criteria for the theoretical data sets created were:
1. The theoretical data sets created must be based on the positional data because relative measures such as angles, velocities and accelerations could not be used to drive the model.

2. The theoretical data sets must contain the main characteristics of the base curve (i.e. the curve from the trial in question).

3. The theoretical data sets produced must be based on the “natural variability” exhibited by the participant during the data collection session. Natural variability refers to the mean ± one standard deviation for the kinematic parameter in question over the ten trials.

4. The theoretical data sets produced using the designated method must be movement patterns that are possible to replicate for the model, i.e. the rate of change between consecutive points is appropriate for human movement.

5. The technique developed must allow production of data sets that contain low to high levels of variability so that a range of variability perturbations can be assessed in the computer model/simulation.

7.2.3 Calculation of Variability

To create the theoretical data sets based on the natural variability of the participant, their respective variability for all markers was calculated. The variability the participant exhibited over the ten trials captured during experimentation was deemed their ‘natural variability’ for their driver swing in this analysis. As the participant stood in slightly different positions for each shot, the data had to be transformed to ensure that the variability calculated was variability of movement and not variability of standing position. See Section 4.2.3 for a detailed description of this process. The mean position of the ball (calculated from the marker on the ball) at address for the ten trials of that specific participant was calculated. The difference between the position of the ball for each trial and the mean position was calculated. The coordinates of all markers for each trial were then transformed in all three dimensions, according to this difference. After transformation, each trial was normalised to 1001 points using a cubic spline algorithm. Following normalisation, the standard deviation was calculated for the x, y, and z coordinates at each of the 1001 points for all ten trials for each participant such that there was a standard deviation score for each of the 1001 points for each of the three axes for each player. This resulted in an SD curve for the participant representing their exhibited movement variability for each marker. Thus, there was a specific SD curve for the x, y, and z data of each marker and these curves represented their ‘natural variability’ for the purposes of this analysis. The SD curves of the three axes for
the left wrist and right shoulder are presented in Figure 7.1 and Figure 7.2. These markers were selected in order to ascertain the effect of the developed calculation technique on different curve shapes.

Figure 7.1 – Standard deviation curves of the left wrist marker x, y and z curves

Figure 7.2 – Standard deviation curves for the right shoulder marker x, y and z curves
7.3 TECHNIQUE DEVELOPMENT PROCESS

To develop this method, sample data was taken from the trial that was to be modelled (see Section 6.2.1.3 for a description of the selection of this representative trial). The left wrist and right shoulder x, y and z coordinate data, that were processed as described in Section 4.2.3, were the data sets that were used for the purposes of developing this method. After data was generated at each phase of the technique development, the data sets produced were analysed to ensure they conform to the criteria determined in Section 7.2.2.

Due to the nature of the white noise based pseudo-random data that were used at all stages of the development process, it was essential to examine if the theoretical data sets followed the proposed pattern, e.g. does the 65% variability data set exhibit more variability than the 45% variability. To do this, a combination of visual inspection of the curves, a Bland-Altman type analysis (Bland and Altman 1986) and Root Mean Square Difference (RMSD) calculation, were used to ascertain the level of agreement between the theoretical data sets produced and the criteria defined previously.

Bland-Altman (B&A) analyses are typically used to compare two measurements of the same variable. As each data point from the theoretical data set has a corresponding data point on the original trial curve (they are the same length), it was therefore considered a valid method of comparison. In this instance, certain constituents of the B&A Analysis were used. The 95% confidence interval ((CI), $1.96 \times$ standard deviation of differences between the curves) from the 95% limits of agreement (LOA) calculation in the B&A analysis and the RMSD analysis were used to assess the amount of variability contained within each theoretical data set and the mean difference from the B&A analysis was used to assess if the gross pattern of the base (trial) curve had been altered.

The precise manner in which the constituents of the B&A analysis were used and are presented within this chapter is detailed graphically in Figure 7.3.
Figure 7.3 – Schematic of the use of Bland-Altman analyses, specifically 95% CI and mean difference to examine the theoretical data sets produced.
7.3.1 Phase One: Point-to-Point calculation and Average SD

7.3.1.1 Methods

This technique was developed based on the normalised curve (1001 points) of the trial that was to be modelled. The average standard deviation ($SD_{avg}$) was used to signify the average amount of naturally occurring variability in the standardised trial data, i.e. variability not caused by an external factor such as fatigue. This was calculated as the mean of the SD curve computed in Section 7.2.3 for each marker. See Figure 7.4 and Figure 7.5 for examples of the $SD_{avg}$ values for the standard deviation curves of the $x$-axis for left wrist and right shoulder. Thus, for each marker, there was an $SD_{avg}$ value for each of the three axes.

![Figure 7.4 – Standard deviation over 1001 points for the left wrist x-curve and its $SD_{avg}$ value](image)
Variability was added to the trial curve at twenty different levels of variability, the maximum variability curve was created by adding a random number between $\pm SD_{\text{avg}}$ to each data point. This random number was based on white noise and thus has a distribution with mean and median of zero. As the random number had containment limits of the $\pm SD_{\text{avg}}$ value, it was considered pseudo-random only. Other data sets were created by reducing the pseudo-random number magnitude in 5% decrements to a minimum of 5% $SD_{\text{avg}}$. As a result, twenty data sets were created each with differing variability content; set one $\pm 100\% SD_{\text{avg}}$, set two $\pm 95\% SD_{\text{avg}}$ to set twenty $\pm 5\% SD_{\text{avg}}$ etc. This calculation process was performed for the coordinate data in the x, y, and z axis (see Appendix A6.5 for calculation sheet in Microsoft Excel) and the calculation technique performed at each point along the curves is shown in Equation 7.1.

**Figure 7.5 – Standard deviation over 1001 points for the left wrist x-curve and its $SD_{\text{avg}}$ value**
\[ P_i = Q_i + K \times [R(\pm SD_{avg})] \]

Equation 7.1

Where,

- \( P_i \) = base curve with variability at point \( i \)
- \( Q_i \) = base curve at point \( i \)
- \( K \) = variability fraction being calculated for the curve
- \( R \) = random number between the values specified between the brackets

This created the twenty data sets which ranged from high (100%) to low (5%) variability for each movement plane which resulted in a total of sixty data sets. Selected data sets can be seen for the left wrist and right shoulder in Figure 7.6 and Figure 7.7 (these are focused on 100 frames of the movement to aid clarity of presentation). It became evident, through visual inspection of the created curves that the rate of change in position from point-to-point was very high, particularly at the higher levels of variability. As the random number was based on white noise, the data occurring at this intermediate stage was not representative of the main characteristics of the base data due to relatively large rates of change between consecutive data points. This did not satisfy the pre-defined criteria that the data sets produced should have rates of change between successive points that are appropriate for human movement nor does it maintain the characteristic of the trial curve. To remove this inconsistency from the data a fourth order reverse pass Butterworth filter with a cut off frequency at 12 Hz was applied to the data. As the over-riding objective was variability addition in a controlled manner, this filter was not optimised for each data set as the intention was not to completely remove this excessive point-to-point noise. This cut-off frequency was determined through visual inspection of filtered curves. The filter was only applied to combat the issue in relation to the rate of change. The filter was applied to the 100% variability data of the left wrist data in the x-axis. However, the application of the filter removed too much of the applied noise as deemed from visual inspection of the filtered curve and was deemed not to be an adequate solution to the problem. The filtered 100% x curve for the left wrist is shown in Figure 7.9 and Figure 7.10.
7.3.1.2 Results and Discussion

Figure 7.6 – Selected variability levels of theoretical data sets calculated using the calculation method in phase for the x-coordinate data of the left wrist (frames 300 – 400 highlighted)

Figure 7.7 – Selected variability levels of theoretical data sets calculated using the calculation method in phase for the x-coordinate data of the right shoulder (frames 300 – 400 highlighted)
Example data sets created for the x-axis of the left and right shoulder are presented in Figure 7.6 and Figure 7.7 respectively. It can be seen that the calculation technique did produce the range of variability in that the 100% variability curve appears to contain more noise than the 25% curve. To quantitatively assess that the theoretical data sets were producing a range of variability, the root mean square difference (RMSD) between the original curve and the variability curve at each level of variability was calculated in order to assess the quantity of variability added to the base curve (see Table 7.1). This resulted in an RMSD value for data set at each level of variability. It was observed that these RMSD values did increase for each additional variability increment as is evidenced by the correlation between the RMSD value and variability level ($r = 0.99$ for x, y and z curves). Further, a Bland-Altman (B&A) analysis was carried out in order to assess this ability of the calculation technique to quantify the movement variability across the different data sets using the 95% confidence interval (CI) and the mean difference values quantified. It is apparent from Figure 7.8 that the 95% CI increased as more variability was added to the base data for the x, y and z data sets (left wrist data presented). It was clear that the mean difference remained close to zero (no greater than 1 mm) for the x, y and z data sets across the increasing levels of variability which indicated that the variability was equally distributed above and below the base curve.

<table>
<thead>
<tr>
<th>Table 7.1 – Correlations ($R^2$) between variability level and RMSD value for left wrist and right shoulder data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Left Wrist</td>
</tr>
<tr>
<td>Right Shoulder</td>
</tr>
</tbody>
</table>
However, excessive changes in position between consecutive points were evident in which the rate of change was deemed not to be representative of the rate of change that would be normally produced in the participant’s movement. To do this the gradient was visually inspected between points and compared against that of the original trial data. As this was consistent for both the right shoulder and left shoulder data, this was deemed to be a systematic problem in the variability calculation method. This led to the application of a Butterworth filter to the data in order to resolve this issue.
A graphical representation of the effect of this filter can be seen in Figure 7.9 and Figure 7.10. As can be seen, the application of the filter with a cut-off frequency of 12
Hz appears to be removing too much of the applied noise. This can be seen in Figure 7.10 where the filtered 100% variability curve was very close to the original trial data with no variability applied. Therefore, this method of variability calculation did not satisfy one of the specific criteria (criteria 4) stipulated previously.

Table 7.2 compares the capabilities of phase one of this technique development to the specific criteria that were defined from the outset. These criteria were deemed central to the effectiveness of the final technique. The ✓ symbol indicates that the specific criterion was met while the ✴ symbol indicates that the specific criterion wasn't met or only partially met.

### Table 7.2 – Ability of phase one of technique development to meet initial specific criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Specific Criteria</th>
<th>Accomplished</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The theoretical data sets must be based on the positional data as relative measures such as angles, velocities and accelerations could not be used to drive the model</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>The produced theoretical data sets must contain the main characteristics of the base curve (i.e. the curve from the trial in question)</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>The theoretical data sets produced must be based on the “natural variability” exhibited by the participant during the data collection session</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>The data sets produced using the designated method must be movement patterns that are possible to replicate, i.e. rate of change between consecutive points is appropriate for human movement</td>
<td>✴</td>
</tr>
<tr>
<td>5</td>
<td>The technique developed must allow production of data sets that contain low to high levels of variability so that a range of variability perturbations can be assessed in the model</td>
<td>✓</td>
</tr>
</tbody>
</table>
7.3.1.3 Conclusion

Phase one of this technique development did provide a technique that did comply with the majority of the specific criteria; however the data produced did not satisfy the criteria of producing movement patterns that would be considered “normal”. The rate of change between consecutive points was too great, particularly at the higher levels of variability. The attempt to resolve this issue through application of a Butterworth filter, with a cut-off frequency of 12 Hz, was not successful as it was believed to be removing too much of the noise. Therefore, an advancement of the method developed was required.

7.3.2 Phase Two: Key Frame and Scaled SD

7.3.2.1 Methods

As the issue of rate of change between consecutive points was not resolved through the application of the filter in phase one, the aim of the next phase (phase two) was to develop an alternative approach than calculating variability at each individual point. Therefore, a key frame approach was adopted. This would involve calculating the variability at specific or “key” frames using the calculation technique described above in Section 7.3.1.1. Once the variability at each key frame was calculated, a cubic spline algorithm was applied to the key frames to create a curve the length of the trial, i.e. 539 points. Key frame multiples were trialled starting at 5 (i.e. variability calculation every fifth frame) and moving upwards in increments of 5 to 100. For simplicity, abbreviations will be used when referring to the different key frame multiples, e.g. KF 5 will refer to the method whereby variability was applied to every fifth frame etc., KF 10 will refer to the method whereby variability was applied to every tenth frame. Each key frame had the common point of the first point, point 0, for commencing its variability calculation across the curve. Thereinafter, each key frame calculated at its respective multiple, e.g. for KF 5 variability was calculated every five frames after the first point (point 0), for example at the 0th 5th, 10th 15th frame and so on. Ultimately a key frame multiple had to be selected for future use.

At this point, it was also decided that the SD_{avg}, which was used in the calculation previously, might not best represent the variability at specific points of the movement. In order to attempt to improve this aspect of the calculation, a scaled SD approach (SD_{scaled}) was used. This involved resampling the SD curve which was 1001 points to
the trial length (539 points). This scaled SD approach was adopted in order to allow a more realistic SD to calculate variability at each point. Therefore, the SD value at a specific point in time was used in the calculation, i.e. if there was a variability value being calculated at point five, and then the SD value at point five was used in the calculation. This calculation is explained through Equation 7.2.

\[ P_i = Q_i + K \times [R(\pm SD_{\text{scaled}(i)})] \]

Where, \( P_i \) = base curve with variability at point \( i \)
\( Q_i \) = base curve at point \( i \)
\( K \) = variability fraction being calculated for the curve
\( R \) = random number between the values specified between the brackets ()

Therefore, the three major alterations in the enhanced method from that of phase one was that:

i. The calculation was based on a key frame approach as opposed to point by point method across the trial (base) curve.
ii. The calculation equation included SD\text{scaled} as opposed to SD\text{avg}.
iii. The calculation was based on the original curve of 539 points instead of the normalised curve of 1001 points.

### 7.3.2.2 Results and Discussion

The correlations of RMSD and the relevant variability level are presented in Table 7.3. A sample scatterplot of RMSD and variability level for the data sets calculated for the x-axis left wrist using KF 20 is also presented (Figure 7.11). This was performed in order to quantitatively assess that the theoretical data sets were producing a range of variability from high to low. As can be seen from the results there are relatively few key frames that produce a strong correlation. The strongest \( R^2 \) value was that for the X data set calculated using the KF 5 (\( R^2 = 0.812 \)) calculation. The relatively low correlation values for these key frames indicate that the curves from the data sets produced were not creating a range of variability from high to low.
Figure 7.11 – Scatterplot of RMSD and variability level for left wrist x curves at KF 20

$R^2 = 0.0227$
Table 7.3 – Correlations ($R^2$) between RMSD and variability level for left wrist data with different key frame calculations for the x, y and z data sets

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>KF 5</td>
<td>0.812</td>
<td>0.044</td>
<td>0.652</td>
</tr>
<tr>
<td>KF 10</td>
<td>0.226</td>
<td>0.279</td>
<td>0.157</td>
</tr>
<tr>
<td>KF 15</td>
<td>0.043</td>
<td>0.052</td>
<td>0.036</td>
</tr>
<tr>
<td>KF 20</td>
<td>0.023</td>
<td>0.017</td>
<td>0.002</td>
</tr>
<tr>
<td>KF 25</td>
<td>0.000</td>
<td>0.034</td>
<td>0.391</td>
</tr>
<tr>
<td>KF 30</td>
<td>0.078</td>
<td>0.014</td>
<td>0.027</td>
</tr>
<tr>
<td>KF 35</td>
<td>0.117</td>
<td>0.224</td>
<td>0.055</td>
</tr>
<tr>
<td>KF 40</td>
<td>0.071</td>
<td>0.170</td>
<td>0.133</td>
</tr>
<tr>
<td>KF 45</td>
<td>0.035</td>
<td>0.177</td>
<td>0.036</td>
</tr>
<tr>
<td>KF 50</td>
<td>0.034</td>
<td>0.010</td>
<td>0.023</td>
</tr>
<tr>
<td>KF 55</td>
<td>0.015</td>
<td>0.037</td>
<td>0.000</td>
</tr>
<tr>
<td>KF 60</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>KF 65</td>
<td>0.052</td>
<td>0.001</td>
<td>0.026</td>
</tr>
<tr>
<td>KF 70</td>
<td>0.256</td>
<td>0.001</td>
<td>0.013</td>
</tr>
<tr>
<td>KF 75</td>
<td>0.050</td>
<td>0.150</td>
<td>0.051</td>
</tr>
<tr>
<td>KF 80</td>
<td>0.305</td>
<td>0.080</td>
<td>0.129</td>
</tr>
<tr>
<td>KF 85</td>
<td>0.005</td>
<td>0.057</td>
<td>0.005</td>
</tr>
<tr>
<td>KF 90</td>
<td>0.018</td>
<td>0.001</td>
<td>0.051</td>
</tr>
<tr>
<td>KF 95</td>
<td>0.029</td>
<td>0.067</td>
<td>0.015</td>
</tr>
<tr>
<td>KF 100</td>
<td>0.001</td>
<td>0.027</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Further analysis of the data sets produced using a B&A analysis confirmed that there wasn’t a range of variability from low to high being produced as variability was added to the curve in the calculation. This can be seen for KF 25 and KF 50 in Figure 7.12 and
Figure 7.13 when examining the 95% CI data for the x, y and z data sets of variability. There was no correlation between the 95% CI value and the level of variability added to the base curve. The values of both the 95% CI and RMSD were noted to be higher than for all key frame multiples than the theoretical data sets produced in phase one. The mean difference also appeared to have more of a systematic offset and greater values than what was observed in phase one. The theoretical data sets created in phase one had mean difference values which were close to zero (±1 mm) and fluctuated above and below the zero value. The mean difference values that can be seen in Figure 7.12 and Figure 7.13 for KF 25 and KF 50 do not fluctuate above and below zero, they are consistently above or below zero. Their magnitude was much higher than that in phase one. All mean difference values for the data sets developed in phase one were between ±1 mm whereas the values for phase two, in particular KF 25 and KF 50, ranged between -40 mm to +22 mm. The combination of the relatively high RMSD, 95% CI and mean difference values led to further analysis of the theoretical data sets produced using the technique.

![Diagram showing 95% CI and mean difference values for each variability level](image)

**Figure 7.12** – 95% CI and mean difference values for each variability level of the x, y, z variability theoretical data sets created for KF25. The $R^2$ value of the correlation between 95% CI value and variability level is provided also.
Is Movement Variability Relevant for the Elite Golfer?

Figure 7.13 – 95% CI and mean difference values for each variability level of the x, y, z variability theoretical data sets created for KF50. The $R^2$ value of the correlation between 95% CI value and variability level is provided also.

Further examination of the data sets highlighted that there was a shift effect in the variability curves of the data sets produced. The local minima and maxima of the variability curves appeared shifted to the right compared to the original trial curve. This shift in time was the process that was affecting the ability of the theoretical data sets to produce a range of high to low variability. An example of this for the left wrist can be seen in Figure 7.14. Therefore, this was a critical issue that had to be rectified in the next phase of the technique development. This issue had to be resolved prior to the determination of which key frame multiple to use for future theoretical set creation.
Figure 7.14 – 100% variability theoretical data sets for KF 25, 40 and 60 and the original curve of the left wrist

Table 7.4 compares the capabilities of phase two of this technique development to the specific criteria that were defined from the outset. These criteria were deemed central to the effectiveness of the final technique. The ✓ symbol indicates that the specific criterion was met while the ⋈ symbol indicates that the specific criterion wasn't met or only partially met.
Table 7.4 – Ability of phase two of technique development to meet initial specific criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Specific Criteria</th>
<th>Accomplished</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The theoretical data sets must be based on the positional data as relative measures such as angles, velocities and accelerations could not be used to drive the model</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>The produced theoretical data sets must contain the main characteristics of the base curve (i.e. the curve from the trial in question)</td>
<td>✗</td>
</tr>
<tr>
<td>3</td>
<td>The theoretical data sets produced must be based on the “natural variability” exhibited by the participant during the data collection session</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>The data sets produced using the designated method must be movement patterns that are possible to replicate, i.e. rate of change between consecutive points is appropriate for human movement</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>The technique developed must allow production of data sets that contain low to high levels of variability so that a range of variability perturbations can be assessed in the model</td>
<td>✗</td>
</tr>
</tbody>
</table>

7.3.2.3 Conclusion

During phase two, an attempt to correct the problem in the rate of change between consecutive points was carried out through the use of a “key frame” approach to calculating variability curves. However, two issues were detected with these analyses that have been documented in the results and discussion section, namely that of the failure of the method to create a range of variability from low to high and the issue of shift in time of the variability curves. Therefore these issues had to be rectified in the next phase of development before a logical decision on which key frame multiple to utilise could be made.
7.3.3 Phase Three: Additional Data and Containment Limits

7.3.3.1 Methods

As a result of work to rectify the previous concerns raised in phase one, certain issues, such as the excessive rate of change from point to point, were resolved. It was decided to proceed with the calculation based on the original, non-normalised curve (different from the time normalised curve used in Phase 1) and the use of $SD_{scaled}$ as opposed to $SD_{avg}$ in the calculation.

However, a number of other factors arose in the process of developing phase two. As can be seen from the B&A and RMSD results (Figure 7.12 and Figure 7.13), the produced data sets did not provide a range of variability from high to low (there was a low $R^2$ value), thus not satisfying the criteria defined previously in Section 7.2.2. Further, another factor that became apparent was that there appeared to be a shift in the variability curve in time relative to the original trial curve as can be seen in Section 7.3.2.1.

With respect to the calculation technique not satisfying the criterion of creating theoretical data sets of a low to high range of variability, an adjustment of the previous calculation equation, Equation 7.2, was performed. The improved calculation method ensured the random number chosen was incremented based on the variability percentage calculation that was being computed. In the calculation method for phase two, the percentage variability (e.g. 50%) was multiplied by a random number between $\pm SD_{scaled}$ at the key frame in question. To illustrate the problem with this technique with an example, this potentially meant that, for an $SD_{scaled}$ value of 3 mm, a random number between $\pm 3$ mm could be chosen. This could mean that a random number of 1 mm could be chosen for the 50% variability calculation at the appropriate frame and thus 0.5 mm ($1 \text{ mm} \times 50\%$) would be added to the base curve at that point. For the 20% calculation, a random number between $\pm 3$ mm of 3 mm could be chosen meaning that 0.6 mm ($3 \text{ mm} \times 20\%$) would be added to the base curve. Consequently, this would result in the 20% variability calculation containing more variability at that point in time compared to the 50% calculation. This obviously means that the calculation technique, depending on the random numbers chosen, was not fully satisfying the criteria of producing theoretical data sets of a consistent high to low range of variability. The adjusted technique accounted for this more effectively by ensuring that the random number selected to be added or subtracted to the base curve was restricted to certain
values based on the percentage variability being calculated. To explain this, take for example an $SD_{\text{scaled}}$ value of 5 mm and a 95% variability calculation. The new method would only allow the random number chosen to be between 95% of $SD_{\text{scaled}}$, in this case 4.75 mm, and 90% of $SD_{\text{scaled}}$, which in this example is 4.5 mm. There was also a random process introduced to determine whether the variability calculated was added to or subtracted from the base curve. Equation 7.3 shows the mathematical form of calculating the equation.

$$P_i = Q_i \pm \left[ R \left( K \times SD_{\text{scaled}(i)}, K - 5 \times SD_{\text{scaled}(i)} \right) \right]$$

Equation 7.3

Where, $P_i$ = base curve with variability at point $i$
$Q_i$ = base curve at point $i$
$K$ = variability fraction being calculated for the curve
$R$ = random number between the values specified between the brackets ()
The $\pm$ allocation in the equation is random also

In relation to the stated problem of the shift in the variability curve relative to the base curve, it was found on further inspection this appeared to be a problem present in the use of the key frame approach and the cubic spline technique. For example, with the original non-normalised curve of 539 points and using KF 25, the last point where variability would be calculated is point 526 whereas point 539 was the final point. This resulted in "missing" data from point 526-539 and introduced a form of end-point error when applying the cubic spline algorithm to create the 539 points. This can be seen graphically in Figure 7.15 in an example for KF 25.
Figure 7.15 – Illustration of the shift effect for KF 25 whereby the green curve represented the curve splined to 539 points from the points (in red) of KF 25. There is no variability added to any of the points on the curve.

This effect was more pronounced in the key frames that had their last variability point calculated point further from the last point, e.g. KF 60 where the last variability calculation is at point 481. To deal with this problem of missing data, extra data beyond the end point was included up to the next hundred, in this case that meant point 600. This extra data was taken from the collected trial which in effect was extra data kinematic data beyond the follow-through swing event. Therefore, the key frames were taken up to 600 data points as opposed to the actual length of 539 in order to avoid the problem of missing data from the end point. These changes in application of the spline to the curve lead to the elimination of certain key frames from the analysis. This rounding up to the next multiple of a hundred meant that the key frames that were not multiples of 600 were first removed as they would not include the last point (600) in their calculation, i.e. KF 30, KF 35, KF 45, KF 55, KF 65, KF 70, KF 80, KF 85, KF 90 and KF 95. In order to make this method more applicable to data sets of varying duration of time, other key frame multiples were removed, namely KF 15, KF 30, KF 40, KF 60 and KF 75 as they are not applicable in all multiples of hundred. These processes of elimination lead to KF 5, KF 10, KF 20, KF 25, KF 50 and KF 100 to remain as potential key frame multiples to use. Once the variability calculations were applied at each key frame, the key frames were splined to 600 points. Following this, the extra points beyond the original trial length (i.e. the 61 points beyond the original
length of 539), were deleted from the splined curve to produce a curve of the original trial length (539 points). In order to determine the most appropriate key frame multiple to use, an examination of the data sets produced by each key frame using the aforementioned visual inspection, RMSD and B&A analysis were performed.

Therefore, the main advancements in this final phase of the development of the method from that previously were:

i. The number of data points were increased to the next multiple of a hundred to deal with the issues of a shift in which led to the elimination of certain key frame multiples as potential key frame multiples to use in the final developed method.

ii. The variability calculation equation was adjusted to better ensure that the random number chosen to be added or subtracted to the base curve was incremented based on the percentage variability being calculated.

7.3.3.2 Results and Discussion

Sample curves produced by the different key frame multiples can be viewed in Figure 7.16 and Figure 7.17. It can be observed that there issue of shift in the variability curves in time was rectified through the change in splining technique as described previously.
At this point, being satisfied that the issue of the shift in time was resolved, it was necessary to determine which key frame multiple was to be utilised to create the
variability curves. This was performed, keeping in mind the specific criteria the produced data sets had to adhere to, through visual inspection of the data sets produced and examining the RMSD and B&A analysis of the key frame multiples that remained. The key frame multiples that remained were, KF 5, KF 10, KF 20, KF 25, KF 50 and KF100. Based on visual inspection of the 100% variability curves produced by each key frame multiple, KF 5 and KF 10 were eliminated immediately due to excessive rates of change between consecutive points. The 100% variability curves for the x-axis are presented in Figure 7.17. The curves appear quite noisy every fifth or tenth frame which was quite similar to the rate of change issue identified in phase one.

Following the elimination of KF 5 and KF 10 from the analysis, the remaining key frame multiples were analysed using the RMSD values and B&A analysis to assess the level of variability in the produced data sets and whether they satisfy the criteria defined previously. The RMSD results for the relevant key frame multiples are presented in Table 7.5. After this stage, KF 100 was removed from the analysis due to the low correlation between RMSD magnitude and variability level for the x, y and z variability curves thus indicating the failure of this key frame multiple to satisfy the criterion of producing a range of variability from high to low. Visual inspection of the KF 100 data sets produced also confirmed that the curves for this key frame multiple did not maintain the characteristics of the original curve. Given there were only six key frames for this particular multiple, this is an indication that more points than this were needed to calculate a variability curve that included the main characteristics of the base curve.
Figure 7.18 – Scatterplot of variability level and RMSD for KF 25 left wrist (z data)

Table 7.5 – Correlations ($R^2$) between variability level and RMSD value for KF 20, 25, 50 and 100 left wrist

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>KF 20</td>
<td>0.969</td>
<td>0.966</td>
<td>0.916</td>
</tr>
<tr>
<td>KF 25</td>
<td>0.960</td>
<td>0.936</td>
<td>0.936</td>
</tr>
<tr>
<td>KF 50</td>
<td>0.500</td>
<td>0.411</td>
<td>0.867</td>
</tr>
<tr>
<td>KF 100</td>
<td>0.110</td>
<td>0.062</td>
<td>0.044</td>
</tr>
</tbody>
</table>

The remainder of the key frame multiples, KF 20, KF 25 and KF 50, were further analysed using B&A analysis. The 95% CI and mean difference for each key frame multiple are presented in Figure 7.19, Figure 7.20 and Figure 7.21. The 95% CI values showed a low correlation with variability level for KF 50 for the x, y and z curves. This coupled with the lower correlation values for the RMSD correlations with variability level, led to the elimination of KF 50 as a potential key frame multiple to utilise.
Figure 7.19 – 95% CI and mean difference values for each variability level of the x theoretical data sets of KF 20, KF 25 and KF 50. The $R^2$ value of the correlation between 95% CI value and variability level is provided also.

Figure 7.20 – 95% CI and mean difference values for each variability level of the y theoretical data sets of KF 20, KF 25 and KF 50. The $R^2$ value of the correlation between 95% CI value and variability level is provided also.
Figure 7.21 – 95% CI and mean difference values for each variability level of the z theoretical data sets of KF 20, KF 25 and KF 50. The $R^2$ value of the correlation between 95% CI value and variability level is provided also.

The elimination of both KF 50 and KF 100 meant that only KF 20 and KF 25 remained as possible key frame multiples to use. Through inspection of the RMSD correlations and the results of the B&A analysis, it can be observed that there was little difference between the key frame multiples in terms of the ability to produce a range of low to high variability levels. Bearing this in mind, it therefore meant that visual inspection of the data sets produced was the next tool used to decide upon the appropriate key frame multiple. This visual inspection examined the overall shape of the curves, especially their local maxima and minima. A selection of variability levels for the x-axis curves for KF 20 and KF 25 were examined using Figure 7.22 and Figure 7.23. It was decided to utilise KF 20 based on this visual inspection of the curves produced. In reality, both key frame multiples could have been utilised as they both satisfy the specific criteria defined previously. They both produced data sets with similar quantities of variability as evidenced from the 95% CI in the B&A analysis in Figure 7.19, Figure 7.20 and Figure 7.21.
It was necessary at this stage to finally ascertain that the method developed at this stage did perform as intended. Table 7.6 compares the capabilities of phase three of this technique development to the specific criteria that were defined from the outset which were deemed central to the effectiveness of the final technique. The ✓ symbol indicates that the specific criterion was met while the ✗ symbol indicates that the specific criterion wasn’t met or only partially met.
Table 7.6 – Ability of phase three of technique development to meet initial specific criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Specific Criteria</th>
<th>Accomplished</th>
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</thead>
<tbody>
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</tr>
<tr>
<td>2</td>
<td>The produced theoretical data sets must contain the main characteristics of the base curve (i.e. the curve from the trial in question)</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
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</tr>
<tr>
<td>5</td>
<td>The technique developed must allow production of data sets that contain low to high levels of variability so that a range of variability perturbations can be assessed in the model</td>
<td>✓</td>
</tr>
</tbody>
</table>

### 7.3.3.3 Conclusion

In the third and final phase of this technique development, several issues that became evident in phase two were corrected through an adjustment of the calculation formula and an increase in the number of data points for splining the key frames to the trial length. Once these issues were rectified, the most appropriate key frame multiple was determined. KF 20 was deemed the most appropriate key frame to use for this process after examination of RMSD, Bland-Altman analysis and visual inspection of the curves. Thus, after three rigorous development stages, a method has been developed that satisfies the pre-determined conditions that were deemed necessary for the theoretical data sets created.
7.4 SUMMARY

Figure 7.24 – Flow chart illustrating the main processes and phases involved in the development of the method
To summarise the process of method development, in the first phase a calculation equation was devised to calculate variability based on the average standard deviation of the measure in question and the normalised trial curve (base curve) of 1001 points. Whilst this satisfied the majority of the specific criteria that the data sets, the rate of change between consecutive data points was quite large. To rectify this through application of a Butterworth filter did not alleviate the problem completely.

In phase two, the method of calculation was altered. Firstly, the calculation was no longer used the time normalised trial curve, it was now calculated based on the actual trial length. The SD curve was resampled from the normalised length to the trial length. Calculation of variability at every point in the curve was changed to a key frame method whereby variability was calculated at certain points along the curve depending on the key frame multiple being calculated and the key frames calculated were then splined to the original trial length using a cubic spline algorithm. A scaled SD approach was used here where the specific SD value at the key frame being calculated was used instead of the average SD value. The data sets containing variability did not appear to agree with the criteria defined previously and therefore further improvements were needed in the next phase of development.

In phase three, the issue of a time shift in the produced data sets containing variability was rectified through the addition of extra data up to the next multiple of a hundred and calculating the variability for those extra frames. The calculation equation was amended to better control the rates of variability being calculated. These main improvements in the technique in this phase led to the adoption of KF 20 as the key frame multiple to be used and the use of the calculation equation finalised in phase three in the development process as the data produced agreed with the specific criteria. The left wrist final curves with calculated variability from 5 – 100% are presented in Figure 7.25, Figure 7.26 and Figure 7.27.
Figure 7.25 – All left wrist x-axis variability curves for all levels of variability (5 – 100% at 5% increments)

Figure 7.26 – All left wrist y-axis variability curves for all levels of variability (5 – 100% at 5% increments)
Figure 7.27 – All left wrist z-axis variability curves for all levels of variability (5 – 100% at 5% increments)

7.5 CONCLUSION

In conclusion, a method has been developed that creates theoretical data sets that are based on the natural variability of the participant in question. In theory, this method can be applied to any participant once their variability of movement is quantified in the same manner as it is here. The method developed here can be used for coordinate data (as is used here), angular data and their derivatives. Coordinate data was used in this case as the model discussed in Chapters 6 was driven by coordinate data.

The final phase of this method development has been analysed visually and statistically and has been found to agree with the specific criteria that were defined from the outset. The method for creating theoretical data sets based on the movement variability of the participant, as described in this chapter, is a fundamental component of Chapter 8. Thus, a calculation technique has been developed to create theoretical data sets based on the natural variability of the participant and can be used in subsequent work to examine the effect of applying these variability data sets to the computer model created in Chapter 6.
7.5.1 Thesis Context

This chapter detailed the second stage in the use of modelling and simulation methods to analyse movement variability; the creation of data sets to analyse movement variability. The following chapter progresses to the third stage of the use of simulation methods; the application of the theoretical data sets created as per the technique described in this chapter to the validated computer model detailed in Chapter 6.

7.6 REFERENCES


CHAPTER 8

AN INVESTIGATION INTO THE EFFECT OF MOVEMENT VARIABILITY WITHIN MARKER TRAJECTORIES ON SHOT OUTCOME
8.0 ABSTRACT

Chapter 6 detailed the creation and validation of a full-body musculoskeletal model of a golfer performing a swing. Chapter 7 described the development of a technique to apply movement variability to the validated model. Subsequently, the aim of the current study was to assess the effect of the application to the model of different levels of movement variability on a shot outcome measure: club head velocity. Movement variability was applied to the computer model on eleven measures sequentially throughout the body. Four different levels of variability, 25%, 50%, 75% and 100% variability were applied to x, y and z positional data of the aforementioned measures. Simulations were then performed with ADAMS/LifeMOD software for each level of movement variability applied to the measures in question. Club head velocity was measured during the simulation with a marker on the toe of the club head. Results showed more change in peak club head velocity at the highest levels of movement variability with reductions of 0.95 and 0.74 m.s\(^{-1}\) for 100% variability, compared to 0% variability, at the left and right wrists respectively. When extrapolating the effect of these changes in club head velocity on total drive distance, decreases of 5 and 4 metres were calculated for the 100% variability levels for the left and right wrist respectively. The changes in peak club head velocity for variability applied at the other measures translated into a maximum change (decrease) of 1.3 metres. The results suggest that movement variability application at these landmarks does not have an effect on outcome. These results potentially have implications for the coaching of the participant.

8.1 INTRODUCTION

Despite studies examining movement variability in the golf swing using experimental techniques in recent years (Kenny et al. 2008b, Bradshaw et al. 2009, Horan et al. 2011), it has not been established what effect, if any, movement variability in the golf swing has on shot outcome (Glazier 2011). The potential problem with experimental studies has been documented previously in that the amount and type of variability cannot be controlled within participants if the aim of the study is to ascertain a causal relationship between movement variability of a specific measure and the outcome of the movement. Computer modelling offers the advantage of allowing the imposition of controlled amounts of movement variability on the model in order to ascertain its effect on movement outcome.
Computer models have previously been used to examine technique optimisation in movements such as running jumps (Wilson et al. 2011) and tumbling (King and Yeadon 2004). It was possible to identify only one published study that examined the effect of varying neuromuscular control (NMC) on injury causing mechanisms in the knee during a side-cut task (McLean et al. 2004) using previously developed and validated models (McLean et al. 2003). Based on the imposition of varying NMC on the male and female forward dynamics models, the authors ascertained that sagittal plane loading did not affect the loading of the Anterior Cruciate Ligament (ACL) and thus advised that altering sagittal plane mechanics would not reduce ACL injury. This highlighted the potential of using modelling techniques to examine the effect of movement variability on outcome.

Previous chapters have discussed the call for examination of the golf swing with participant-specific computer models (Farrally et al. 2003). In response to this, a validated participant-specific computer model of the golf swing was developed in Chapter 6. A method to create theoretical data sets to perturb the model based on the natural variability of the participant being modelled was created in Chapter 7.

### 8.1.1 Aims

Using a validated computer model created in Chapter 6 and a method to create variability data sets to apply variability to the model described in Chapter 7, the aims of this chapter were to:

- Examine the effect of movement variability in marker trajectories of specific body parts on club head velocity (outcome measure).
- Determine the practical implications of any detected change in club head velocity on total drive distance.

### 8.2 METHODS

The following sections detail how variability data sets were applied to the validated computer model. The technique of variability data set creation and model validation have previously been detailed. To avoid repetition of these procedures detailed previously, reference should be made to Sections 4.2, 6.2 and 7.2.
8.2.1 Participant

The participant selected for this analysis was the same participant used in Chapters 6 and 7. See Section 6.2.1.1 for a description of the single participant utilised in this chapter.

8.2.2 Data Collection

This entailed collecting kinematic data from the participant performing golf swings to drive the model and to calculate variability to create the theoretical data sets. See Section 4.2.2 for a detailed description of the kinematic data collection.

8.2.3 Data Processing

8.2.3.1 Model Creation and Validation

The processing of the kinematic data to create the model was described previously (see Section 4.2.3). A participant-specific model of the participant with 44 degrees of freedom (DOF) performing a golf swing was created within ADAMS/LifeMOD software. The creation and validation of the computer model of the golf swing of this participant has been detailed in Section 7.2.

8.2.3.2 The Determination of Measures to Vary

The measures examined in this analysis were selected based on those examined in Chapters 4 and 5. Fourteen measures representative of single point variability at various anatomical landmarks were examined in Chapters 4 and 5. A constraint on this selection procedure was that a measure could only be selected if it was used to drive the model. This constraint allowed 11 of the 14 measures to be examined. The measures analysed in this study are presented in Table 8.1.
<table>
<thead>
<tr>
<th>Measure</th>
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<tbody>
<tr>
<td>Left Wrist</td>
</tr>
<tr>
<td>Right Wrist</td>
</tr>
<tr>
<td>Left Humeral Epicondyle</td>
</tr>
<tr>
<td>Right Humeral Epicondyle</td>
</tr>
<tr>
<td>Left Acromion</td>
</tr>
<tr>
<td>Right Acromion</td>
</tr>
<tr>
<td>Left Lateral Femoral Condoyle</td>
</tr>
<tr>
<td>Right Lateral Femoral Condoyle</td>
</tr>
<tr>
<td>Left Malleolus</td>
</tr>
<tr>
<td>Right Malleolus</td>
</tr>
<tr>
<td>T4</td>
</tr>
</tbody>
</table>

### 8.2.3.3 Variability Data Sets Creation

The next step involved creation of the data sets containing variability to apply to the validated computer model. This technique to create participant-specific data sets containing a range of low-high natural variability has been developed as described in Chapter 7. This technique involved calculating a variability amount to add or subtract to the original curve (which was 539 frames (captured at 400 Hz = 1.345 s) in duration) every twenty frames for a range of high to low variability using the calculation technique specified in Section 7.2. This procedure was performed on the x, y, and z coordinate data of 600 data points (extra data beyond the trial length of 539 frames was used for this calculation) for each axis. The calculated points along the curve at each key frame, of which there were 31, were then splined to 600 frames using a cubic spline algorithm and then reduced to the original trial length, 539 points. This resulted in data sets that contained a range of variability from high to low for the measures examined. This procedure was carried out for the measures identified in Section 8.2.3.2. Variability was applied at four different levels of 25%, 50%, 75% and 100% to the original curve representing low to high movement variability.

### 8.2.3.4 The Application of Variability Data Sets to the Model

To apply the variability data sets to the computer model the curve containing variability, as calculated in Section 8.2.3.2, was inputted to the previously created slf file, replacing...
the original trial curve. The only alteration to the original slf file of the validated computer model was the replacement of the original curve of the measure with the curve containing variability. Thus the only detail that differed from the original model was the x, y and z motion data of the measure being examined (e.g. left wrist motion). All other parameters from the previously validated model were identical for the human model and club construction. This motion data in the slf file was used to drive the model during the inverse dynamics simulations. Inverse dynamics simulations of the model were deemed appropriate for this analysis given the close agreement observed between the inverse and forward dynamics simulations as detailed in Section 6.3.1.

8.2.4 Data Analysis

8.2.4.1 Verification of Variability Data Sets

A Bland-Altman (B&A) (Bland and Altman 1986) analysis was carried out in order to ensure the variability data sets created were appropriately incremented, i.e. that the 50% variability curve contained more variability than the 25% curve and less than the 75% and 100% curve, along with examination of the mean difference calculated. The 95% confidence interval (CI) from the B&A analysis was used to assess the amount of variability contained within each variability data set and the mean difference from the B&A analysis was used to assess if the gross pattern of the base (original) curve had been altered. The correlation ($R^2$) between the 95% confidence interval (CI) values and variability level was ascertained in order to verify that the amount of variability added to the curves was appropriately incremented.

8.2.4.2 The Effect of Movement Variability Application

In order to ascertain the effect of the variability on the modelled swing, peak club head velocity was examined at each level of variability through a virtual marker applied to the toe of the modelled club head.

To ascertain the effect of any changes in club head velocity as reported in Section 8.2.4.1 with respect to the end point of the ball after impact with the club, the change in total drive distance was approximated. Total drive distance is the distance between ball impact and where the ball comes to rest (i.e. ball carry and roll). To calculate this approximation of total drive distance, the results of a technical report carried out by Quintavalla (2006) were used. In the aforementioned report, approximate total drive
distance data was predicted from club head velocity measured at impact from a mechanical robot golfer performing swings over a range of velocities from approximately 40 m.s\(^{-1}\) to 55 m.s\(^{-1}\) with five different conditions (different golf ball types) at each tested club head velocity. The conversion factor for the change in club head velocity with the change in drive distance was not explicitly stated but was calculated by Ball (2006) to be a change in drive distance of 5.2 m for every change in club head velocity of 1 m.s\(^{-1}\). This conversion factor was used here to calculate the approximate total distance for a given club head velocity.

8.3 RESULTS

8.3.1 Verification of Variability Data Sets

The results of the B&A analysis are presented in Table 8.2 for all x, y, z curves created for all measures. The table depicts the correlation (R\(^2\)) between the 95% CI and variability level. The correlation values are presented in Table 8.2. These correlation values illustrate a strong correlation between variability level and 95% CI for each level highlighting that at each increment of variability there was more movement variability added to the original data. A sample graph of this correlation for variability applied to the x-axis curves of T4 is provided in Figure 8.1.

![Figure 8.1 – 95% CI and mean difference values for each variability level of the T4 x-axis curves](image-url)
### Table 8.2 – Correlation ($R^2$) between 95% CI, calculated from the B&A analysis, and variability level for the x, y and z curves of the all examined measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>x</th>
<th>y</th>
<th>z</th>
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</thead>
<tbody>
<tr>
<td>Left Wrist</td>
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<td>Right Malleolus</td>
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<td>1.000</td>
</tr>
</tbody>
</table>

### 8.3.2 The Effect of Movement Variability Application

#### 8.3.2.1 Shot Outcome: Club Head Velocity

The effect of variability on club head velocity for each of the measures varied is presented in Figure 8.2 – Figure 8.12. The figures presented show peak club head velocity for each level of variability, i.e. for 25%, 50%, 75% and 100% variability. The results for the original model with no variability applied are also presented as 0% in each figure.

Figure 8.2 shows the peak club head velocity for variability applied to the left wrist. It can be seen from this graphical illustration that club head velocity decreased across each level of variability. However, no clear pattern was observed as there was a decrease of 0.39 m.s$^{-1}$ from 0% (the original validated model) to the 25% variability simulation compared to a decrease of 0.14 m.s$^{-1}$ from the 0% to the 50% variability
The biggest decrease was observed between the 0% and 100% variability simulation with a reduction of 0.95 m.s\(^{-1}\) peak club head velocity.

![Figure 8.2 – Simulated predicted peak club head velocity for increasing levels of applied variability at the left wrist](image)

The effect of variability applied to the right wrist can be observed in Figure 8.3. There was a small increase in peak club head velocity of 0.04 m.s\(^{-1}\) from the 0% to 25% variability simulations. There was a noticeable drop off in peak club head velocity between the 0% and 75% simulations of 0.37 m.s\(^{-1}\) and between the 0% and 100% variability simulations of 0.74 m.s\(^{-1}\).
The results of the application of variability to the left malleolus are presented in Figure 8.4. There was a similar decrease in peak club head velocity between the 0% and 25% variability simulations and 0% and 50% variability simulations of 0.01 m.s\(^{-1}\). An increase was observed at the next two increments of variability. There were increases of 0.09 m.s\(^{-1}\) between the 0% and 75% variability simulations and 0.12 m.s\(^{-1}\) between the 0% and 100% variability simulations.
The effect of variability imposed at the right malleolus is illustrated in Figure 8.5. Again no obvious trend was observed for increasing variability applied at this landmark. There were small decreases between the 0% and 25%, 50% and 100% variability simulations with a decrease of 0.05, 0.08 and 0.04 m.s\(^{-1}\) respectively. There was an increase of 0.01 m.s\(^{-1}\) between the 0 and 75% variability simulations is also shown (Figure 8.4).

![Figure 8.5](image)

**Figure 8.5 – Simulated predicted peak club head velocity for increasing levels of applied variability at the right malleolus**

Variability imposed at the left lateral humeral epicondyle of the arm resulted in marginal changes in peak club head velocity. Compared to the 0% level, there was no change at the 25% level whilst there was a reduction of 0.12 m.s\(^{-1}\) at the 50% level. Increases of 0.06 and 0.11 m.s\(^{-1}\) were noted at the 75% and 100% level respectively in comparison to the 0% variability level (Figure 8.6).
Figure 8.6 – Simulated predicted peak club head velocity for increasing levels of applied variability at the left lateral humeral epicondyle

The imposition of variability applied at the right lateral epicondyle resulted in decreases in peak club head velocity of 0.1 m.s\(^{-1}\) at both the 50% and 100% level compared to the 0% level. There was a smaller decrease of 0.01 m.s\(^{-1}\) at the 75% level with an increase of 0.07 m.s\(^{-1}\) at the 25% level compared to the 0% level (Figure 8.7).

Figure 8.7 – Simulated predicted peak club head velocity for increasing levels of applied variability at the right lateral humeral epicondyle

Movement variability applied to the left acromion process resulted in minor increases of club head velocity of 0.11 m.s\(^{-1}\) at the 25% and 75% level compared to the 0% level.
Increases of 0.03 and 0.08 m.s\(^{-1}\) were recorded at the 50% and 100% variability level respectively in comparison to 0% variability (Figure 8.8).

![Figure 8.8 – Simulated predicted peak club head velocity for increasing levels of applied variability at the left acromion process](image)

The application of variability to the right acromion process resulted in increases in peak club head velocity of 0.1, 0.12 and 0.01 m.s\(^{-1}\) at the 25%, 50% and 100% level respectively in comparison to 0% variability. There was no change in peak club head velocity at the 75% level compared to 0% variability (Figure 8.9).

![Figure 8.9 – Simulated predicted peak club head velocity for increasing levels of applied variability at the right acromion process](image)
In the case of variability applied to the left lateral femoral condyle of the knee, there were decreases of 0.07 m.s\(^{-1}\) at the 25 and 50% levels, with a decrease of 0.09 m.s\(^{-1}\) at the 75% level compared to 0% variability. At 100% variability, there was a recorded increase of 0.07 m.s\(^{-1}\) compared to 0% variability (Figure 8.10).

![Bar chart showing peak club head velocity for increasing levels of variability at the left lateral femoral condyle](chart.png)

**Figure 8.10** – Simulated predicted peak club head velocity for increasing levels of applied variability at the left lateral femoral condyle

Movement variability applied at the right lateral femoral condyle of the knee resulted in respective decreases in peak club head velocity of 0.25 and 0.05 m.s\(^{-1}\) at the 25% and 100% level compared to the 0% level. At the 50% and 100% variability levels, peak club head velocity increases of 0.07 and 0.13 m.s\(^{-1}\) respectively, were noted (Figure 8.11).
The imposition of variability to the T4 vertebra resulted in increases in peak club head velocity of 0.03, 0.14 and 0.02 m.s\(^{-1}\) at the 25%, 50% and 75% levels compared to the 0% level. There was a recorded decrease of 0.06 m.s\(^{-1}\) at the 100% level when compared to the 0% variability level (Figure 8.12).

Figure 8.11 – Simulated predicted peak club head velocity for increasing levels of applied variability at the right lateral femoral condyle

Figure 8.12 – Simulated predicted peak club head velocity for increasing levels of applied variability at T4
8.3.2.2 Practical Effect of Changes in Club Head Velocity

In order to gain an understanding of the practical implications of club head velocity values at each level of variability level, approximate total drive distance was calculated using the work of Quintavalla (2006). The club head velocities of each simulation performed for this analysis ranged from 38.56 m.s\(^{-1}\) to 39.63 m.s\(^{-1}\) and were deemed sufficiently close to the lower end of the club head velocities used in the work of Quintavalla (2006) to be used for this analysis. The calculated total drive distances using the calculation factor stated in Section 8.2.4.2 for each variability level are presented in Table 8.3. The biggest recorded change in total drive distance was a reduction of 5 metres at the 100% variability level for the left wrist with small changes observed for the all other measures of no more than 1 metre.

<table>
<thead>
<tr>
<th>Left Wrist (m)</th>
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<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
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<tr>
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<td>203.7</td>
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<td>205.8</td>
<td>206.0</td>
</tr>
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<td>205.8</td>
<td>204.9</td>
<td>205.4</td>
<td>204.9</td>
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<td>Right Acromion (m)</td>
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<td>205.1</td>
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<td>205.0</td>
<td>205.4</td>
<td>205.2</td>
</tr>
</tbody>
</table>
8.4 DISCUSSION

The purpose of this study was to apply variability to a validated computer model of a participant performing a golf swing and ascertain the effect of this on the shot outcome measure of club head velocity. The variability data was created as per the procedure outlined in Section 8.2.3.3. To this author’s knowledge, this analysis is the first of its kind in relation to the examination of movement variability and the golf swing.

Variability was applied to the measures that were examined during experimental data collection with 16 elite participants in Chapters 4 and 5. This resulted in variability being applied to 11 measures throughout the body. The results indicated that there was no consistent effect as a result of the imposition of this variability with respect to shot outcome (club head velocity) across all measures being varied. However, it is worth noting that the biggest changes in peak club head velocity were clearly associated with the application of left wrist variability with a change in peak club head velocity of 0.95 m.s\(^{-1}\) at the 100% variability level. Variability applied at the left wrist resulted in a reduction of peak club head velocity across all variability quantities whilst a similar result was evident for right wrist variability at the two highest increments of variability, 75% and 100%. Analysing right and left wrist results collectively suggests that variability at the highest ranges of the natural movement variability of the participant could potentially result in a loss of club head velocity for this participant. The changes in peak club head velocity were noticeably smaller with respect to other measures examined. This suggests variability at these specific landmarks does not affect shot outcome in the form of club head velocity for this participant. In fact marginal increases in peak club head velocity of 0.13 m.s\(^{-1}\) relative to the original validated model (0% variability) were evident to the higher ranges of variability (75% level) for the right lateral femoral condyle.

The practical effect of the change in club head velocities, calculated using approximate total drive distance, was small for most levels of variability. The biggest change in drive distance was a reduction of 5 metres from 0% variability to the highest level of left wrist variability and 4 metres at the highest level of right wrist variability.

In order to contextualise the difference in club head velocities recorded, it is informative to compare the club head velocities with the natural variation recorded during the data collection session of the participant in question. The club head velocities ranged from a
minimum of 38.6 to a maximum of 40.3 m.s\(^{-1}\). This was just the variation in outcome from ten shots performed on one day. Using the 2011 statistics from 186 professional players of the PGA Tour (2011) and applying the same mean range in club head velocities would result in a range of 37.16 to 41.86 m.s\(^{-1}\) over the course of the year for this participant. The application of variability at the eleven anatomical landmarks did not result in a change in club head velocity outside the range. Therefore, a change in total drive distance of 5 metres (the largest change in driving distance) is most likely within the typical variation of this player. Therefore this does not constitute a change in outcome that would ordinarily affect the strategy of the player on the course.

It is worth noting that the only shot outcome measure examined here was club head velocity. Further work should examine changes in club head orientation (whether the club face was open or closed to the target line) in order to examine the effect of variability on shot accuracy as well as distance. In acknowledging this limitation, it is important to emphasise that the use of club head velocity is informative to investigate as club head velocity as this is related to distance travelled by the ball (Hume et al. 2005) and can help a player/coach interpret the effect of variability on their carry distance from the tee which is an important factor in terms of its impact on the strategy of the player.

It is apparent from the results presented here that only at the highest levels of variability at the wrist had the largest effect on the club head velocity in comparison with other measures. However, this effect is within the natural variation in club head velocity that would be expected of a player over the course of many golf rounds. The application of variability at single body landmarks such as that performed in this chapter is valuable in determining the effect of variability at these specific locations on club head velocity. However, to expand the use of this technique and advance understanding of the effect of variability on the outcome of the participants swing, it is important to examine measures that pertain to the coordination of movement of the participant. These higher order parameters, such as measures of coordination between segments, contain more information than single point parameters (Hamill et al. 2006).

### 8.5 CONCLUSION

To conclude, the effect of the application of movement variability on shot outcome at specific landmarks on a participant-specific computer model has been performed. The
results showed greater changes in peak club head velocity when variability was applied at the wrists compared to other measures examined. The practical effect of this club head velocity change on total drive distance was estimated. Variability applied at body locations other than the wrist were found to be less influential in terms of a change in club head velocity and thus approximated drive distance but ultimately movement variability applied at all locations did not elicit any changes outside the natural range of variability for club head velocity. The computer model used in this analysis is participant-specific but can be tailored for another participant through adjustment of participant anthropometrics. Therefore, the technique used here can be applied to another participant in order to ascertain the effect of movement variability on their shot outcome. It can also be used to determine the effect of more complex measures such as coordination measures which will be the focus of the next chapter.

8.5.1 Thesis Context

This chapter detailed the final stage of the use of modelling and simulation methods to examine movement variability, that of the application movement variability using the calculation technique developed in Chapter 7 to the model created in Chapter 6, in order to examine its effect on the outcome of the golf swing. In order to use the methods described in Chapter 6 – Chapter 8 to more complex measures, the focus on the following chapter will be on the movement variability of a multi-segment measure.

8.6 REFERENCES


Quintavalla, S. J. (2006) *Experimental Determination of the Effects of Clubhead Speed on Driver Launch Conditions and The Effects on Drive Distance for Balls used by the PGA Tour*, USGA Technical Report RB/cor2006-01, USGA.

CHAPTER 9

THE EXAMINATION OF MOVEMENT VARIABILITY IN A MULTI-SEGMENT MEASURE IN THE GOLF SWING:
TORSO-PELVIC SEPARATION ANGLE
9.0 ABSTRACT

Previous work identified no relationship between movement variability of anatomical landmarks and shot outcome variability (Chapters 5 and 8). This study focused on investigating the movement variability of a multi-segment parameter across a group of participants. Torso-pelvic separation angle (X-Factor angle) has been researched by many biomechanists in recent years e.g., Myers et al. (2008), Chu et al. (2010), Healy et al. (2011) and thus was the multi-segment coordinative parameter examined in this study. The current study also used the previously developed modelling and simulation work (Chapters 6 and 7) to investigate the effect of movement variability of this parameter at the individual level. 16 highly skilled (handicap ≤5) participants each performed 10 swings wearing retro reflective markers which were tracked by a 3D motion analysis system operating at 400 Hz. A launch monitor captured ball launch conditions at impact. Movement variability was quantified for the torso-pelvic separation angle for each participant for the backswing and downswing phases of the golf swing. Outcome variability was quantified as the coefficient of variation of ball velocity for the 10 trials. The results of this analysis revealed there was no significant relationship between torso-pelvic separation angle movement variability and outcome variability in either the backswing ($r = 0.305, p=0.251$) or the downswing ($r = -0.052, p = 0.85$). For the individual-based analysis, participant-specific movement variability at eight levels (25%, 50%, 75%, 100%, 150%, 200%, 250% and 300%) was applied to the torso-pelvic separation angle of the participant. Simulations were then performed using the previously developed computer model for each level of applied movement variability. Club head velocity was measured during the simulation with a marker on the toe of the club head. Results showed more change in peak club head velocity at the highest levels of movement variability (100% - 250%) with an increase of 0.31 m.s$^{-1}$ for the 100% variability level compared to the original trial. The largest change detected was a reduction of 0.67 m.s$^{-1}$ at the 250% variability level. Extrapolating the effect of these changes in club head velocity in terms of total drive distance, showed the largest change in driving distance being a reduction of 3 metres compared to the original trial. Collectively, these results highlight that if torso-pelvic separation angle is varied even to the high level, there is no effect on club head velocity or ball velocity variability at the elite level.
9.1 INTRODUCTION

Previous work identified no relationship between movement and outcome variability across a group of elite performers (Chapter 5). Furthermore, in an individual analysis using modelling methods, variability for single marker trajectories (e.g. the wrist) was found only to have no effect on a shot outcome measure (Chapter 8).

These findings highlight that movement variability of marker trajectories at single anatomical points had no relationship with shot outcome (ball and club head velocity). Therefore, to progress the examination of movement variability in the golf swing, it would be appropriate to focus on measures that incorporates more than one anatomical landmark (i.e. a multi-segment measure). It has been stated that these coordinative measures contain more information than single point measures (Hamill et al. 2006) and thus may be more informative in providing an insight into movement strategies adopted by participants.

The review of literature (see Section 2.3.2.2) demonstrated the torso-pelvic separation angle about the vertical axis (commonly referred to in the coaching literature as X-Factor) to be a kinematic measure investigated by numerous authors in the golf swing. The torso-pelvic separation angle measure has been significantly correlated with ball velocity (Chu et al. 2010) and club head velocity (Meister et al. 2011). In research into this parameter, it has typically been investigated as a discrete measure in terms of the value at the top of the backswing (McTeigue et al. 1994) or the values at specific events in the downswing (Healy et al. 2011). There has been little research investigating this parameter over the entire swing (i.e. as a continuous measure).

Variability of the rotation of the pelvis and thorax coupling has been examined by Horan et al. (2011). The results of this study indicated that participants displayed similar levels of variability in the backswing but gender differences were evident at the halfway point of the downswing. However, this study did not examine any relationship between variability quantified and any outcome measure. As this parameter has been investigated and has been proposed as a performance variable for coaches and players to focus on, (Cheetham et al. 2000, Myers et al. 2008, Chu et al. 2010), it is important to investigate what role, if any, movement variability in this parameter has on shot outcome.
9.1.1 Aims

The aims of this study were to:

- Quantify the torso-pelvic separation angle variability for each participant and examine the relationship between torso-pelvic separation angle variability and outcome variability.
- Perform an individual based analysis where the effect of movement variability in this measure is ascertained for one elite participant using modelling and simulation methods.

9.2 EXPERIMENTAL METHODS: GROUP-BASED ANALYSIS

9.2.1 Participants

The participants in this analysis were the same cohort as that used in Chapter 4. See Section 4.2.1 for a description of the participants who volunteered for this study.

9.2.2 Data Collection

The data collection methods were the same as what was adopted in Chapter 4. See Section 4.2.2 for the data collection procedure.

9.2.3 Data Processing

The raw marker data were tracked within the Motion Analysis software, Cortex. After data collection, the raw x, y, z trajectories of the markers were filtered with a low-pass, fourth-order Butterworth filter with a cut-off frequency of 12 Hz as described in Section 4.2.3. Following filtering of the raw data, the data were cropped to the relevant phases of the swing as described in Section 5.2.3.2. This data were then exported to Visual3D software (C-Motion Inc., USA) for further analysis. Within Visual3D, a model was then generated for each participant.
9.2.3.1 Torso-Pelvic Separation Angle Calculation

Previously, some researchers have calculated the torso and pelvis segment angles by projecting a line from the left and right of each segment onto the global horizontal plane and the angle is then calculated between them. This is appropriate for calculating rotation about the vertical axis of the torso and pelvis in an upright standing posture. It must be considered that in the golf swing, the person is generally in a posture that is tilted forward about the medio-lateral axis and thus when calculating torso-pelvic separation angle using the global horizontal plane method, there may be errors in the calculation (Wheat et al. 2007, Healy et al. 2011). In the present analysis, the rotation of the torso segment about its vertical axis relative to the same rotation of the pelvis segment was calculated.

This model used medial and lateral markers at the distal and proximal ends of the segment to establish the local right-handed orthogonal coordinate system of the segment. This segmental local coordinate system originated at the proximal end of each segment and used the same reference direction as the global coordinate system (e.g. X = medio-lateral, Y = anterior-posterior, Z = vertical). The torso segment was derived from the position of the acromial markers and ASIS markers in the static trial. Tracking markers were used on C7 and T4 to estimate the position and orientation of the torso segment during the trials. The pelvis segment was derived from the left and right ASIS markers and the sacral marker. The segment local coordinate systems are illustrated in Figure 9.1.

The torso-pelvic separation angle was calculated as the joint angle created by the torso relative to the pelvis, extracting the Z joint angle values using Euler angles and the Cardan sequence XYZ. This calculation process was automated within Visual3D. A torso-pelvic separation angle of 0° indicates that both segments are equally rotated about their respective local vertical (Z) axes.
9.2.3.2 Torso-Pelvic Separation Angle Variability Calculation

Torso-pelvic separation angle was calculated for each participant for each trial. To calculate the variability of this parameter in the backswing and downswing phase of the swing, the torso-pelvic separation angle was time normalised in each phase to 1001 points using a cubic spline algorithm as performed in Chapters 4 and 5. The standard deviation of each point across the ten trials was calculated such that there was a standard deviation value at each point across time. To calculate a value representative of movement variability in that measure over time, the mean of these standard deviation values over the 1001 points was calculated. Thus each participant had a value representative of their movement variability in this parameter for the backswing and downswing phase of their golf swing. In several previous studies of movement variability, variability has been represented by the coefficient of variation (Bradshaw et al. 2007, Brown et al. 2012) in place of the standard deviation used in this analysis. Coefficient of variation only works well for parameters with clear true zero values such as force and velocity and therefore does not work with angular and positional data as it can create spurious data, particularly as the mean approaches zero (see Section 4.3.6). In addition, it is perhaps more likely that reporting movement variability in

Figure 9.1 – Local coordinate systems of the torso (X_t, Y_t, Z_t) and the pelvis (X_p, Y_p, Z_p) shown with and without segment skeleton. The segment local coordinate systems are located at the segment centre of mass for illustration purposes.
degrees or millimetres as opposed to percent of position is more understood by coaches and performers alike (Fleisig et al. 2009).

9.2.3.3 Visual 3D Model Verification

To confirm that the model in Visual 3D was calculating the relative torso-pelvic separation angle accurately, a verification process was undertaken. To do this, the torso and pelvis segments were perfectly aligned artificially and the torso segment was then rotated in a series of known rotations.

The rotations undertaken were as follows:

- **Condition 1**: With the xy plane (horizontal) of both segments aligned, the torso was positioned with no rotation (0°) and about the longitudinal (vertical) axis and then the torso was rotated about the longitudinal axis in positive (anticlockwise looking at the segment from a superior perspective) and negative rotations (clockwise) of 30°, 45°, 60°, and 90° about the C7 marker (consider C7 the origin and centre of rotation).

- **Condition 2**: With the xy plane of torso segment rotated 45° relative (negative rotation) to that of the pelvis (rotation about the medio-lateral axis), the torso was positioned with no rotation (0°) about the longitudinal axis and then rotated about the C7 markers with negative and positive rotations of 30°, 45°, 60° and 90°.

- **Condition 3**: With the xy plane of torso segment rotated 45° relative (positive rotation) to that of the pelvis (rotation about the medio-lateral axis), the torso was then rotated about the C7 markers with negative and positive rotations of 30°, 45°, 60° and 90°.

- **Condition 4**: With the xy plane of torso segment rotated 90° relative (negative rotation) to that of the pelvis (rotation about the medio-lateral axis), the torso was positioned with no rotation (0°) about the longitudinal axis and then rotated about the C7 markers with negative and positive rotations of 30°, 45°, 60° and 90°.

- **Condition 5**: With the xy plane of torso segment rotated 90° relative (positive rotation) to that of the pelvis (rotation about the medio-lateral axis), the torso was positioned with no rotation (0°) about the longitudinal axis and then rotated about the C7 markers with negative and positive rotations of 30°, 45°, 60° and 90°.
Examples of these rotations for each condition are illustrated in Figure 9.2 - Figure 9.6.

**Figure 9.2** – Condition 1 with rotations of (a) 0° (b) -30° (c) +45° and (d) -90° about the longitudinal axis. The local coordinate systems of the segments are shown only with the top LCS that of the torso and the bottom LCS that of the pelvis.

**Figure 9.3** – Condition 2 with rotations of (a) 0° (b) -30° (c) +45° and (d) -90° about the longitudinal axis. The local coordinate systems of the segments are shown only with the top LCS that of the torso and the bottom LCS that of the pelvis.

**Figure 9.4** – Condition 3 with rotations of (a) +30° (b) -45° (c) -60° and (d) +90° about the longitudinal axis. The local coordinate systems of the segments are shown only with the top LCS that of the torso and the bottom LCS that of the pelvis.
Figure 9.5 – Condition 4 with rotations of (a) 0° (b) +45° (c) +60° and (d) -90° about the longitudinal axis. The local coordinate systems of the segments are shown only with the top LCS that of the torso and the bottom LCS that of the pelvis.

Figure 9.6 – Condition 5 with rotations of (a) +30° (b) -45° (c) -60° and (d) +90° about the longitudinal axis. The local coordinate systems of the segments are shown only with the top LCS that of the torso and the bottom LCS that of the pelvis.

These artificially rotated segments were then imported into Visual3D and the torso-pelvic separation angle was calculated. Results indicated the calculation was carried out in Visual 3D as intended. See Table 9.1 for results.
### Table 9.1 – Results of torso-pelvic separation angle model quantification model verification for each rotation about the Z axis at each condition

<table>
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<th>0°</th>
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<th>+45°</th>
<th>+60°</th>
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<td>-90.00</td>
</tr>
<tr>
<td>Condition 3</td>
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<td>30.00</td>
<td>45.00</td>
<td>60.00</td>
<td>90.00</td>
<td>-30.00</td>
<td>-45.00</td>
<td>-60.00</td>
<td>-90.00</td>
</tr>
<tr>
<td>Condition 4</td>
<td>0.00</td>
<td>30.00</td>
<td>45.00</td>
<td>60.00</td>
<td>90.00</td>
<td>-30.00</td>
<td>-45.00</td>
<td>-60.00</td>
<td>-90.00</td>
</tr>
<tr>
<td>Condition 5</td>
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<td>30.00</td>
<td>45.00</td>
<td>60.00</td>
<td>90.00</td>
<td>-30.00</td>
<td>-45.00</td>
<td>-60.00</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

### 9.2.4 Data Analysis

Correlation statistics (Pearson’s correlation coefficient ($r$)) were calculated using PASW v 18 (SPSS Inc, USA) to analyse whether there was any statistically meaningful relationship between quantified torso-pelvic separation angle variability and shot outcome variability (coefficient of variation % of ball velocity) across the group. Shot outcome variability was that quantified as described in Section 5.2.3.2. As the direction of the relationship between movement variability and outcome variability could not be predicted, a two-tailed test was used and statistical significance was set at $p \leq 0.05$ (Field 2009). This statistical analysis was performed for the backswing and downswing phase of the golf swing.

### 9.3 MODELLING AND SIMULATION METHODS: INDIVIDUAL-BASED ANALYSIS

#### 9.3.1 Participant

The participant selected for this analysis was the same as that used in Chapters 6, 7 and 8. See Section 6.2.1.1 for a description of the participant utilised in this chapter.
9.3.2 Data Collection and Data Processing

This entailed collecting kinematic data from the participant performing golf swings to drive the model and to calculate variability to create the theoretical data sets. See Section 4.2.2 for a detailed description of the kinematic data collection.

9.3.3 Model Creation and Validation

The processing of the kinematic data to create the model was described previously (see Section 4.2.3). A participant-specific model with 44 degrees of freedom (DOF) performing a golf swing was created within ADAMS/LifeMOD software. The creation and validation of the computer model of the golf swing of this participant has been detailed in Chapter 6.

9.3.4 Torso-Pelvic Separation Angle Variability Application to the Model

In order to drive the motion of the model, coordinate data was required. Therefore, the application of movement variability to this angle parameter could not be done directly to drive the model. A solution to this problem was to apply variability using the technique developed and described in Chapter 7 to the torso-pelvic separation angle for the trial being modelled. Eight different levels (25%, 50%, 75%, 100%, 150%, 200%, 250% and 300%) were applied to the original angle (from the trial modelled). This method of calculation of the 8 different variability curves (25% - 300%) of the torso-pelvic separation angle is described as ‘routine 1’. Variability was applied beyond the 100% range in order to ascertain the effect of variability beyond the designated natural variability range of the participant. The 300% level is considered an outlier to the normal range as this represents three times the standard deviation applied to the original curve. This value of three standard deviations or more from the mean is a measure undertaken to identify outliers in research (Anderson et al. 2010).

As there were an infinite number of coordinate solutions for the markers that comprise the torso-pelvic separation angle variability curves, a process was carried out in order to find a coordinate solution to the angles. Another routine, ‘routine 2’, was employed to find coordinate solutions for the markers of the torso-pelvic separation angle. In ‘routine 2’, variability was applied to the markers that comprise the torso-pelvic separation
angle with the technique described in Section 9.2.1.3.1. These generated variability coordinates were then imported to Visual 3D to calculate the torso-pelvic separation angle created by the varied coordinates.

A procedure based on the inherent randomisation process involved in the variability calculation was applied. With regard to routine 1, it can be seen that over five iterations of the calculation, five different curves, albeit similar are calculated (see Figure 9.7). In order to quantify the absolute difference between the five iterations of routine 1, a root mean square difference (RMSD) calculation was carried out. This analysis indicated that there was an inherent deviation between the five iterations as a result of the pseudo-random calculation process.

![Figure 9.7 – Illustration of the effect of the pseudo-random calculation process for five iterations of the 75% variability calculation in routine 1](image)

Subsequently, five iterations of the calculation process of routine 2 were carried out. With the aim of finding the most appropriate solution from routine 2 that agreed with the direct angle variability calculation of routine 1, an RMSD analysis was carried out between the results of the first iteration of routine 1 and each iteration of routine 2 at every variability level. A correlation analysis was also performed between each of these in order to ascertain the agreement between the curves of routine 1 and 2 also. Thus,
the RMSD and correlation values were the criteria used to determine the best solution from routine 2. The solution chosen at each level of variability of routine 2 was dependent on the lowest RMSD value and the strongest correlation with the first iteration of routine 1. The iteration of routine 2 selected was also visually inspected to check its agreement with the first iteration of routine 1. In this way, it was ensured that the solution chosen had the lowest absolute difference with the first iteration of routine 1 and also the shape of the curve of the selected iteration of routine 2 was similar to the first iteration of routine 1. An overview of this entire process is provided in Figure 9.8.
Figure 9.8 – Overview of process of selection of variability curves to drive model

All curves used to input into the model are presented in Figure 9.9.
9.3.5 Data Analysis

9.3.5.1 Verification of Variability Data Sets

A Bland-Altman (B&A; Bland and Altman 1986) analysis was carried out in order to ensure the variability data sets created using routine 2 described in Section 9.2.2.4 were appropriately incremented, e.g. that the 50% variability curve contained more variability than the 25% curve and less than the 75% and 100% curve, along with examination of the mean difference calculated. The 95% confidence interval (CI) from the B&A analysis was used to assess the amount of variability contained within each variability data set and the mean difference from the B&A analysis was used to assess if the gross pattern of the base (original) curve had been altered. The correlation ($R^2$) between the 95% CI and variability level was ascertained in order to determine that the amount of variability added to the curves was appropriately incremented.
9.3.5.2 The Effect of Movement Variability in the Torso-Pelvic Separation Angle

As in Section 8.2.4.2, in order to ascertain the effect of the variability of the torso-pelvic separation angle on the modelled swing, peak club head velocity was examined at each level of variability through a virtual marker applied to the toe of the club head.

Also, as in Section 8.2.4.2, to ascertain the practical effect of any change in peak club head velocity, total drive distance was approximated using the work of Quintavalla (2006).

9.4 RESULTS

9.4.1 Experimental Methods: Group-Based Analysis

Torso-pelvic separation angle variability for the backswing and downswing phase for each participant of the golf swing is presented in Figure 9.10 and Figure 9.11. Outcome variability (coefficient of variation %) is also included on both Figures. It is evident that there was no clear pattern of increased movement variability for this measure between the backswing and downswing. Seven of all sixteen participants had increased variability in this measure in the downswing compared to the backswing while the other nine participants had increased variability in the backswing compared to the downswing. It was noticeable that certain participants, namely participants 7, 10, 13 and 14, had quite a large increase (increases of greater than 50%) in movement variability from backswing to downswing. Other participants (participants 3, 6, 9 and 15) had a relatively low change of less than 10% in movement variability from backswing to downswing.
Is Movement Variability Relevant for the Elite Golfer?

Figure 9.10 – Scatterplot of torso-pelvic separation angle variability vs. outcome variability for each participant in the backswing phase of the swing

Figure 9.11 – Scatterplot of torso-pelvic separation angle variability vs. outcome variability for each participant in the downswing phase of the swing
The results of the statistical analysis revealed that torso-pelvic separation angle variability for either the backswing or downswing had no statistically significant relationship with outcome variability. There was a stronger positive correlation, albeit non-significant, for the backswing results compared to the downswing (see Table 9.2).

<table>
<thead>
<tr>
<th>Table 9.2 – Pearson’s correlation coefficient ($r$) between torso-pelvic separation angle variability and outcome variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backswing</td>
</tr>
<tr>
<td>Correlation ($r$)</td>
</tr>
</tbody>
</table>

9.4.2 Modelling and Simulation Methods: Individual-Based Analysis

9.4.2.1 Verification of Variability Data Sets Applied to Model

The results of the B&A analysis are illustrated in Figure 9.12 for the torso-pelvic separation angle variability curves created. This graph depicts the correlation ($R^2$) between the 95% confidence interval (CI) values and variability level. The correlation ($R^2$) between the 95% CI and variability level was 0.915 indicating a strong correlation between variability level and 95% CI for each level. This highlights that at each increment of variability there was more movement variability added to the original data. It is clear that the mean difference remained close to zero (the maximum mean difference was -1.27°) for data sets across the increasing levels of variability, which indicated that the variability was equally distributed above and below the base curve.
9.4.2.2 Shot Outcome: Club Head Velocity

Peak club head velocity values for each increment of variability are presented in Figure 9.13. There was a marginal change detected (reduction of 0.01 m.s\(^{-1}\)) in this measure between 0% and 25%. A larger change was observed from the 0% to the 100% variability level with an increase of 0.31 m.s\(^{-1}\) in peak club head velocity between these levels. Upwards from the 50% variability level, there was a trend of increasing peak club head velocity with increasing movement variability applied. With the application of variability beyond 100%, there was a reduction in peak club head velocity at the 150%, 200% and 250% levels. Interestingly, at the level of 300%, there was an increase again to a peak club head velocity closer to that of the original 0% variability. The natural variation (the range of maximum and minimum of club head velocities recorded during experimentation) is included in Figure 9.13. This provides a frame of reference for ascertaining the effect of changes in club head velocity in tandem with the study of the practical effect of recorded club head velocity changes in Section 9.3.2.3.
9.4.2.3 Practical Effect of Changes in Outcome

As described in Section 9.2.2.5.2, the results of a Quintavalla (2006) analysis were used to calculate the practical effect of the club head velocity in terms of predicted total drive distance at each variability level. The calculated total drive distances are shown for each variability level in Table 9.3.

Table 9.3 – Approximate total drive distances for each variability level (0% - 300%)

<table>
<thead>
<tr>
<th>Variability Level</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>205.5</td>
</tr>
<tr>
<td>25%</td>
<td>205.4</td>
</tr>
<tr>
<td>50%</td>
<td>205.9</td>
</tr>
<tr>
<td>75%</td>
<td>206.2</td>
</tr>
<tr>
<td>100%</td>
<td>207.1</td>
</tr>
<tr>
<td>150%</td>
<td>206.0</td>
</tr>
<tr>
<td>200%</td>
<td>204.0</td>
</tr>
<tr>
<td>250%</td>
<td>202.0</td>
</tr>
<tr>
<td>300%</td>
<td>206.0</td>
</tr>
</tbody>
</table>

9.5 DISCUSSION

Torso-pelvic separation angle has been correlated with ball velocity (Myers et al. 2008) and club head velocity (Meister et al. 2011); however the analysis of this measure has generally been focused on a discrete measure, i.e. the value at the top of the backswing (also termed the X-Factor) or the maximum value at the beginning of the
downswing (termed the X-Factor Stretch). To this author’s knowledge, this study was the first study to analyse the variability of this measure and its effect on shot outcome variability in a group or individual analysis. Thus, this is a novel analysis of torso-pelvic separation angle and its relationship to shot outcome and shot outcome variability.

9.5.1 Experimental Methods: Group-Based Analysis

The mean standard deviation of the torso-pelvic separation angle was calculated for the backswing and downswing of each participant. Qualitatively analysing the results suggested no obvious trends in terms of a consistent increase or decrease in variability of this parameter from backswing to downswing across all participants. The results of this group-based analysis indicated that there was no statistically significant relationship between movement variability in torso-pelvic separation angle in either the backswing \( (r = 0.305, p = 0.251) \) or downswing \( (r = 0.052, p = 0.85) \) and shot outcome variability. Thus, with no statistically significant relationship observed, it indicates that variability in this parameter does not have an effect on outcome variability. However, as indicated by the observation that nearly half of participants increased their variability in torso-pelvic separation angle from backswing to downswing whilst the remaining participants did the opposite may suggest that control of variability in this angle is again specific to the individual.

9.5.2 Modelling Methods: Individual-Based Analysis

The results of application of variability in the torso-pelvic separation angle up to 100% variability resulted in a small increase in peak club head velocity at the higher levels of movement variability (50%, 75% and 100%). However when the practical effect of these changes were estimated, it suggested that no change would occur in total drive distance at the 25% or 50% level. A small increase of 1 metre at the 75% and 100% variability level was predicted. Beyond the 100% level (natural variability), it was apparent that there was a reduction in peak club head velocity at the 150%, 200% and 250% level. The largest observed decrease of the analysis was observed between the 0% variability level (original trial) and 250% level of 0.67 m.s\(^{-1}\). The practical effect of this change was estimated to translate to a reduction of 3 metres in terms of total drive distance. At the 300% level, there was an increase to a value greater than the original trial of 0.18 m.s\(^{-1}\). This suggests that increasing variability in the torso-pelvic separation angle beyond the 100% level could potentially lead to a change in shot outcome in
terms of reducing peak club head velocity, however the relative importance of this change is questionable. It is also worthy of noting that at the 300% level that peak club head velocity was actually slightly increased relative to the 0% level. This suggests that this participant has the ability to withstand variability in this movement at the outlier range without affecting shot outcome. It is important to contextualise these differences in club head velocity and ultimately, carry distance. The changes that were evident in club head velocity were all within the natural range of variability in this parameter from the participant during data collection. Taking the statistics from the PGA tour6 (PGA 2011), it would appear that a change in club head velocity of 0.67 m.s\(^{-1}\) (i.e. the largest detected change in the analysis of this study) is within the natural variation of club head velocity recorded over the course of a year of a professional golfer as recorded by a radar based launch monitor on the golf course. Translating the statistics of the PGA tour to this participant means a range of 37.16 to 41.86 m.s\(^{-1}\), larger than the natural range displayed during data collection.

Increased torso-pelvic separation angle has been purported to increase club head and ball velocity through utilisation of the stretch shortening cycle (Cheetham et al. 2000). At the levels of movement variability where there was a reduction in club head velocity for this participant, it is possible this stretch-shortening cycle mechanism is interrupted and therefore power production in the downswing was affected because if there is any delay between the eccentric and concentric phases (backswing and downswing phases), the augmentation in muscle force production could be lost (Hume et al. 2005).

The implications of these findings for this individual are that up to 300% variability, there is no effect on outcome for this participant. This suggests that the golfer can allow her torso-pelvic separation angle to vary within this range with no effect on club head velocity. The changes in club head velocity are within the natural variation observed during data collection and within the natural variation that is observed in professional golfers over the course of a year.

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6 These statistics are from the PGA tour for 2011. This is the male golf professional tour – these club head velocity values were not available for the female professional tour.
9.6 CONCLUSIONS

The results presented in this chapter indicate that movement variability of the torso-pelvic separation angle does not have a statistically significant relationship with shot outcome variability in with the backswing or downswing phase of the golf swing. Therefore, from a dynamical systems theory perspective, at the elite level of golf performance, focusing on maintaining a consistent torso-pelvic separation angle in order to maintain a consistent drive distance is not advocated. Analysis at the individual level suggested that increases in variability beyond the natural range (150-250%) showed a reduction in club head velocity but not outside the individual’s natural variation in outcome. Therefore, coaches should focus more on the individual performer and at what specific levels of their movement variability affects their shot outcome.

9.6.1 Thesis Context

This chapter completes the thesis through use of all methods that have been used throughout this thesis to investigate movement variability of a multi-segment measure. The group-based analysis used in Chapter 5 was adopted in order to ascertain the relationship between movement variability and outcome variability of the torso-pelvic separation angle. The chapter also used modelling and simulation methods to analyse individual-specific movement variability in torso-pelvic separation in relation to its effect on shot outcome.

9.7 REFERENCES


Quintavalla, S. J. (2006) Experimental Determination of the Effects of Clubhead Speed on Driver Launch Conditions and The Effects on Drive Distance for Balls used by the PGA Tour, USGA Technical Report RB/cor2006-01, USGA.
CHAPTER 10

Thesis Conclusions and Implications
10.0 THESIS OVERVIEW

The main focus of this thesis was to investigate the effect of movement variability in the golf swing on outcome using both experimental and modelling methods. Prior to data collection with participants, preliminary experimental work was undertaken in order to examine the validity of the experimental measurement devices. Initially, the focus of the thesis was directed at examining the link between movement variability quantified and outcome variability using group experimental methods. This involved the development of a technique to quantify movement variability of marker trajectories and then the application of this technique to examine movement variability in the downswing and backswing phase of the golf swing. The results of this study showed no statistically significant relationship between movement variability of 14 anatomical landmarks and outcome variability in either the backswing or downswing. The results, did however, highlight that individuals used their own strategies of managing movement variability.

These results, in combination with the literature review showed that individual analyses could perhaps be more fruitful than group based analyses at elite levels of performance. This led to the adoption of an individual based approach for examining the effect of movement variability using modelling and simulation methods in Chapters 6 – 8. The first stage (Chapter 6) of this process involved creating and validating a participant-specific computer model of their golf swing. The next stage (Chapter 7) was the development of a technique to apply variability to the kinematic data streams of the participant in order to use this varied data to impose movement variability on the computer model. Following on from this, the developments of Chapters 6 and 7 were used in Chapter 8 in order to ascertain the effect of movement variability application to the model at specific anatomical landmarks. This identified that movement variability had no effect on outcome outside of the natural variation range.

The final section endeavoured to extend the use of previously developed techniques in the thesis in order to ascertain the effect of movement variability on a multi-segment measure. The literature review had identified torso-pelvic separation angle to be a highly researched measure in the context of the golf swing. This led to the selection of torso-pelvic separation angle to be the investigated multi-segment measure. This study performed a group-based analysis quantifying the movement variability of torso-pelvic separation angle. The results of this analysis showed no significant correlation between movement variability and outcome variability in this measure. An individual-based
analysis was also performed using similar methods to those adopted in Chapter 8. Variability was applied to the torso-pelvic separation angle using the technique developed in Chapter 7 and imposed on the computer model validated in Chapter 6. The results showed no effect on outcome in terms of club head velocity.

The implications of these findings are discussed in Section 10.2.

10.1 THESIS RECOMMENDATIONS

The work conducted within this thesis has followed a logical, informed line of thinking from the development of a calculation technique to quantify movement variability to the use of modelling and simulation techniques to assess movement variability. Based on this research, it is believed that the work carried out in this thesis adequately addressed the aims of the thesis and adds to the scientific literature. However, this thesis also gives rise to a number of suggestions for future research that would extend the work presented.

The initial objective of this thesis was to examine movement variability and its relationship to movement outcome. In the studies in this thesis, movement outcome focused on ball and club head velocity determined by the results of preliminary tests with the launch monitor carried out in Chapter 3. However, ball velocity is only one aspect of shot outcome. Shot accuracy, in terms of deviation from intended target line, is another important aspect. Therefore, in order to obtain a more thorough understanding of the relationship between movement variability and outcome, it is imperative that all aspects of shot outcome (velocity, launch angle, spin and club head orientation) are examined.

This thesis examined movement variability in the context of the golf swing being performed with the driver club. The driver is an important club to consider as it is the club that is typically struck first from the tee on par 4 and par 5 holes and thus an important club with which to examine movement variability. However, it is also worthy to investigate movement variability with other clubs, in particular the iron clubs. The environmental conditions (i.e. how the ball is lying in the rough or fairway) can vary from shot to shot, as with an iron, unlike the driver club; the ball is not teed up. Therefore, it would be informative to investigate movement variability in the context of iron clubs.
Keeping environmental factors in mind, with the very recent improvement in optical electronic systems that can now function outdoors in direct sunlight (e.g. the Raptor-4 System from Motion Analysis Corporation); it would be advantageous to conduct full 3-D movement variability investigations outdoors, thus preserving ecological validity and perhaps providing a better representation of golfer’s movement variability. Note this system was not available at the commencement of this thesis.

The limitations of the musculoskeletal model were discussed within Section 6.4.2. In order to improve upon the model presented, it is recommended to increase the number of contacts between the model and the club and ground. This amelioration of the model could provide a greater insight into the mechanism of the golfer’s interaction with the environment. If the number of contacts at the feet were increased, the ground reaction force patterns could be examined and compared with that captured experimentally in order to kinetically validate the model. Kinetic validation of the model would allow examination of parameters such as joint torques recorded during simulation.

As stated, the computer model can be used to model the swing of any individual as long as the motion data imported is taken from a trial from that individual and is tailored to the anthropometrics of the individual. It would be beneficial to determine the effect of variability in other elite golfers. In this way multiple case studies could be conducted in order to discover any commonalities, if any, between the effects of movement variability imposition on the models.

Whilst being satisfied that the computer model developed in this thesis was an acceptable representation of the participant’s swing, future efforts will be concentrated on modifying the created and validated computer model, specifically at the hand and foot contacts. Once this is completed, more individuals will be modelled and movement variability effects will be assessed within their models.

10.2 THESIS IMPLICATIONS

It is imperative that understandings of the relationship between movement variability and outcome are improved upon and investigated more thoroughly, as the role of movement variability is not fully understood. In the golf swing, it is important that this relationship is fully understood in order to inform teaching practises of the golf swing. The methods developed and applied in this thesis are designed with this aim in mind.
The results of this thesis do not support the notion of a common optimal golf swing technique. Movement variability in the kinematic parameters examined was shown to have no effect on shot outcome variability at a group level with no common trends in movement variability patterns evident. Therefore from a coaching perspective, a coach should not advocate a common optimal invariant movement pattern if they are trying to make the outcome more consistent. Further it has been stated that by Adlington (1996) that ‘There is no one swing for everybody but for everybody there is one swing’ (p.10). The results of this thesis do not support this notion. Whilst the gross movement pattern of an individual may be similar from shot to shot, there isn’t evidence within these studies to suggest that this must be invariant. The variability quantified in this study may be integral to how the players produce their consistent outcome. It is important for coaches to have an understanding of the variability bandwidth of a player. This would entail coaches providing instruction, not on the basis of a limited number of shots in one session, but multiple shots over a number of days, thereby understanding their individual natural variability.

The findings of the thesis support the work of Arutyunan (1968, 1969) and Bernstein (1967) who found that there can be relatively high movement variability with no effect on outcome. The results of the individual-based analysis with modelling and simulation methods in which movement variability was applied at single anatomical points and a multi-segment measure certainly support the notion that elite performers can have levels of variability even outside their natural variation with no effect on outcome. This variability may be essential to the performer and allow them have a number of kinematic patterns that produce a consistent outcome. The results of this thesis provide support for the tenet of dynamical systems theory. This theory suggests that that if their neuromuscular system is perturbed, they have that capability to adapt with no appreciable effect on outcome.

10.3 THESIS CONCLUSIONS

This thesis describes a novel investigation of movement variability in the golf swing and its effect on movement outcome. To summarise, it has been shown that there was no relationship between either movement variability at single anatomical points or in a multi-segment measure in either the backswing or downswing phase of the swing. Therefore based on the results of this thesis, movement variability has no relationship with outcome or outcome variability at the elite level of golf performance.
The thesis presents a series of interlinked studies, which combine to address the main focus of investigating movement variability in the golf swing and its relationship with outcome and outcome variability. A thorough literature review informed the need to address movement variability and the use of modelling and simulation methods to aid this research. It was identified that there was a dearth of research investigating movement variability in the golf swing, hence the golf swing was the motor skill examined in the context of movement variability.

This thesis used a logical, informed approach to investigate its main aim. To summarise, after development of a calculation technique to quantify movement variability of marker trajectories, movement variability was quantified in the backswing and downswing phase of the golf swing. The relationship between this movement variability and outcome variability was analysed statistically. Following this, in Chapters 6 – 8, a modelling approach was undertaken focusing on an individual. This encompassed the development and validation of a full-body computer model of a participant’s golf swing, application of movement variability to individual anatomical landmarks to the model based on the natural variability of the participant and an assessment of the effect of the applied movement variability on outcome. Finally, variability of a multi-segment measure in the golf swing was analysed within a group-based perspective using experimental results and an individual-based framework using simulation techniques.

Consequently, the following conclusions can be drawn based on the aforementioned work. Figure 10.1 illustrates the inter-connectivity of these conclusions and their placement in the thesis structure using the same outline as Figure 1.1.

**C1 -** Current understandings of movement patterns do not fully recognise or comprehend the role of movement variability.

**C2 -** Currently, golf swing coaching research does not appear to have addressed the applied coaching nature of inter-individual or inter-individual movement variability.

**C3 -** Despite the advancement of modelling and simulation methods, particularly in the modelling of the golf swing, there has not been extensive research carried out using these methods in the investigations of the effect of movement variability on outcome.
C4 - There was no relationship between movement variability and outcome (ball velocity variability) across a group of elite (≤5 handicap) participants in either the backswing or downswing phase of the golf swing.

C5 - Movement variability at single anatomical points over the backswing and downswing phases are individual-specific with no group trends evident.

C6 - Using a validated computer model of a participant's golf swing and a calculation technique developed to apply variability to 11 specific marker trajectories, there was no practical effect in variability applied to any of these marker trajectories in terms of club head velocity changes.

C7 - Variability in torso-pelvic separation angle is not related to shot outcome variability across elite participants tested.

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**Figure 10.1** – Inter-connectivity of conclusions and position in thesis structure

→ Information Flow
To conclude and return to the original research question of ‘is movement variability relevant for the elite golfer?’, it is apparent from the research conducted within this thesis that movement variability does not appear to be relevant for this skill level of golfer in terms of its effect on club head and ball velocity.

10.4 REFERENCES


Appendix A1

Related Publications
INTRODUCTION: Recently, a large amount of research has been focused on the effect of movement variability on human performance in sport. It is now generally accepted that specific amounts of variability are essential to a high level of performance (Davids et al. 2003). When studying the effect of movement variability on outcome performance, the usual method involves collecting numerous data sets from an individual, assuming that these data sets will all be different (i.e., contain variability), and attempt to connect the amount of variability to the change in outcome or performance measure using a number of statistical techniques. The aim of this study is to remove the requirement to collect a large amount of data which, by chance, may contain the level of variability required and shorten the data collection phase significantly by using the proposed process to create theoretical data sets containing alterable variability content while still exhibiting major characteristics of the actual data. When these theoretical data sets are used in conjunction with a full-body 3D computer model operating inverse and forward dynamics simulations a change in outcome or performance measure can be predicted. The advantages this process offers over traditional techniques is the ability to directly control and quantify the amount of variability introduced into the test data and a significant reduction in data collection time.

METHOD: Initially, a full body, 42 degrees of freedom 3D computer model was created and validated using a single-subject analysis. One elite female golfer (handicap 0) performed 12 shots with her own driver club. A 6-camera MotionAnalysis infrared camera system operating at 400 Hz recorded the kinematic data of the 27 markers located on the subject and this data were used to drive the computer model created in ADAMS/LifeMOD software; model construction methods closely follow that of Nesbit (2005). The results illustrate a high level of correlation ($r^2=0.90$) between the kinematic data collected in experimentation and the predicted trajectory of the validation markers of the model. The long-term focus of this work is on the effect of variability at one joint and the resultant change in both outcome measure and kinematics of other joints. However, the first stage of this process is to create the theoretical data sets. To ensure the amount of variability within the theoretical data sets were controlled and realistic, the original data was analysed and used as the base data set. All 12 trials were used - the right knee angle data were all normalised to 101 points, a mean ensemble curve was created from the base data sets and the average standard deviation ($sd_{avg}$) occurring over the whole trial was calculated. The average standard deviation was used to signify the maximum amount of naturally occurring variability in the standardised trial data, i.e., variability not caused by an external factor such as fatigue. Variability was added to the mean ensemble curve at 20 different levels, the maximum variability curve
was created by adding a random number between $\pm sd_{avg}$ to each data point; as the random number had containment limits it is considered pseudo-random only. Other data sets were created by reducing the pseudo random number magnitude in 5% decrements to a minimum of 5% $sd_{avg}$. As a result 20 data sets were created each with differing variability content; set one $\pm 100\%$ $sd_{avg}$, set two $\pm 95\%$ $sd_{avg}$ etc. As the random number is based on white noise (having a distribution with mean and median of zero), the data occurring at this intermediate stage was not representative of the original data sets as some data sets exhibited relatively large rates of changes between consecutive data points. To remove these inconsistencies, all 20 data sets were filtered using a 4th order reverse pass Butterworth filter with a cut off at 12Hz (a cut-off which has been proposed to be useful for golf related data – Mitchell et al., 2003). The filter was not optimised for each data set as it was not the intention to remove the noise only reduce the issue related to rate of change. As a result of this process, 20 data sets were created each with a different amount of variability imposed on the base data. This variability was based on the characteristics of the original 12 data curves and as such are proposed to be representative and realistic data sets. Due to the nature of the white noise based pseudo-random data, it is essential to examine if the theoretical follow the proposed pattern, e.g. does the data set based on 65% $sd_{avg}$ exhibit more variability than that based on 45% $sd_{avg}$. To do this a Bland-Altman analysis (B&A) was completed; B&A is used to compare two measurement of the same variable. As the data presented here is time normalised, each data point on the theoretical data set has a corresponding data point on the mean ensemble curve and therefore it is considered a valid method of comparison. The 95% limits of agreement (LOA) from the B&A analysis will be used to assess the amount of variability contained within each theoretical data set and the bias will be used to assess if the gross pattern of the mean ensemble curve has been altered.

RESULTS AND DISCUSSION: The B&A analysis indicates that the LOA reduces as less variability is added to the data; from 1.44 at 100% $sd_{avg}$ to 0.267 at 5% $sd_{avg}$ (see Table 1). Further analysis reports an $r^2$ of 0.9264 when correlating the LOA values and the magnitude of the random number. The bias remains close of zero on each curve, indicating that the variability is equally distributed above and below the ensemble curve.

<table>
<thead>
<tr>
<th>% of $sd_{avg}$</th>
<th>Bias (°)</th>
<th>LOA (°)</th>
<th>% of $sd_{avg}$</th>
<th>Bias (°)</th>
<th>LOA (°)</th>
<th>% of $sd_{avg}$</th>
<th>Bias (°)</th>
<th>LOA (°)</th>
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<tr>
<td>5</td>
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<td>40</td>
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<td>0.533</td>
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<td>-0.093</td>
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<tr>
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<td>45</td>
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<td>80</td>
<td>0.048</td>
<td>0.922</td>
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<tr>
<td>15</td>
<td>0.010</td>
<td>0.249</td>
<td>50</td>
<td>0.019</td>
<td>0.737</td>
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<td>0.108</td>
<td>1.161</td>
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<tr>
<td>20</td>
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<td>0.380</td>
<td>55</td>
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<td>0.811</td>
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<td>0.068</td>
<td>0.664</td>
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<td></td>
</tr>
</tbody>
</table>

CONCLUSION: The method outlined here, utilising a mean ensemble curve in conjunction with the addition of pseudo random data and Butterworth filtering enables the practitioner to create valid and representative theoretical data sets which do not remove the main characteristics of the original data sets; as illustrated by the Bland & Altman analysis. The combination of these theoretical data sets, where the amount of variability can be controlled, with a full body 3D computer model of the golf swing leads to the ability to assess the impact of variability on both performance and outcome measures within human movement without having to acquire large amounts of data. The combination of these techniques expedites the reporting process within a sports setting, and allows a dramatic reduction in subject involvement during initial data
acquisition compared with more traditional methodologies. Future work will concentrate on the affect the variability of joint angles has on the outcome measures, e.g. ball speed, ball carry spin rates and performance measures within golf, e.g. weight shift patterns, x-factor stretch and swing plane. The research will further assist biomechanists in assessing the impact of levels of variability on human movement.

REFERENCES:
Development of a large-scale golfer computer model to study swing kinematics

Catherine B. Tucker*, Ian C. Kenny, Ross Anderson

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Despite an increase in the number of full-body three-dimensional computer models of the golf swing reported in the literature, many authors do not report in detail how the models are validated. Therefore, the aim of this study was to create and validate a three-dimensional full-body computer model of a golfer with a driver in terms of its kinematic output. Single-subject analysis was used whereby one elite female golfer (handicap 0) performed 16 shots with her own driver club. A 6-camera Motion Analysis infrared camera system operating at 400 Hz recorded the kinematic data of the 27 markers located on the subject and golf club. Subsequently, this data was used to drive a computer model created in ADAMS/LifeMOD software. Model construction methods closely follow that of Nesbit (2005). Additional markers were placed on the subject and were used for model validation as opposed to driving the model. In order to initiate the movement of the model, inverse and forward dynamics calculations were carried out with the imported motion data captured from one representative trial captured during experimentation. The results illustrate a high level of correlation (average r=0.949) between the kinematic data collected in experimentation and the predicted trajectory of the virtual markers of the model. Furthermore, a comparison of the difference between the simulated and actual displacements of these markers between certain key events of the golf swing indicated there were on average small differences (0.06 m between address and top of backswing and 0.06 m between top of backswing and impact) between the model simulation and the displacement recorded during experimentation. An analysis of the temporal differences of key events (i.e. swing tempo) indicated that there was little difference (0.59% difference in both backswing and downswing time between model and actual trial) in this variable between the model and the experimental trial used to drive the model. Collectively, these results indicate that this model can accurately predict the kinematic movement pattern of the subject used to drive the model. Future work will encompass kinetic validation. At present, a full-body computer model was created and validated in terms of its kinematic output; future work will utilize data derived from this model to further investigate the golf swing.

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Keywords: computer simulation; golf swing; kinematics; validation
A METHOD TO QUANTIFY MOVEMENT VARIABILITY OF HIGHLY SKILLED GOLFERS PERFORMING DRIVER SWINGS

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Variability has been described as inherent in the golf swing (Bradshaw et al., 2009), yet its impact on outcome is not understood. It is necessary to quantify the levels of movement variability before this relationship can be examined effectively. Thus, the aim of this study was to develop a method to quantify movement variability of golfers performing driver swings. 16 highly skilled golfers each performed 10 swings wearing retro reflective markers which were tracked by a 3D motion analysis system operating at 400Hz. Movement variability was calculated for each marker using scalene ellipsoid volume methods; a score representative of the 3D variability over 10 trials was then calculated. The variability levels calculated using this method showed increasing variability from the closed end of the chain (malleoli) to the open end of the chain (wrists).

KEY WORDS: golf, three-dimensional variability, ellipsoids.

INTRODUCTION: For the seemingly simple task of hitting a ball with the club, the golf swing is an extremely complex multi-segmental movement, where the player has to constrain and coordinate many degrees of freedom in order to achieve the goal of hitting the ball with accuracy and consistency. As a result of the individual-specific performer, environmental, biomechanical and task constraints (Higgins, 1997), the notion of a common optimal movement pattern or invariance in certain key technical positions toward which each individual golfer must aspire, is not strongly supported in the literature. Movement variability has been described as being inherent in the golf swing (Bradshaw et al., 2009) yet there has been a dearth of literature which both quantifies and examines in depth, the levels of intra-subject variability across golfers. To understand resulting performance, it is important to quantify movement variability and examine the effect of this variability on the outcome, i.e. launch characteristics of the ball. The aim of this study was to quantify movement variability in the golf swing from positional coordinate data.

METHODS: Six male and ten female (n=16) highly skilled golfers (age 26.3 ± 5.6 years, body mass 67.0 ± 10.3 kg, height 1.7 ± 0.1 m, handicap 2.8 ± 3.0) were recruited to participate in this study. All subjects were right-handed golfers. Ethical approval for this study was obtained from the University’s relevant research board. All testing sessions took place in a purpose-built indoor golf testing facility. For the testing session, each player performed 10 shots with their own driver into a net 5 metres away. Each player had a number of reflective markers placed at 14 various anatomical landmarks. The motions of these markers were recorded using 6 Eagle digital cameras (Motion Analysis Corporation Ltd., Santa Rosa, California) operating at 400Hz. Each trial was then cropped to remove any extraneous data such that all that remained was the data from address to the end of the swing. These motion curves were then filtered with a fourth-order low-pass Butterworth filter with a cut-off frequency of 12Hz (Mitchell et al., 2003). The filtered coordinates were then processed to calculate the variability of each markers’ x (medio-lateral direction), y (anterior-posterior direction), and z (vertical
direction) coordinates over the ten trials, in a custom written programme in LabVIEW (v. 9.0.1, National Instruments, Austin, Texas).

To counteract the effect of the player standing in slightly different positions between shots the data was transformed. The mean position of the ball (calculated from a small flat marker on the ball) at address for the 10 trials was calculated. The difference between the position of the ball for each trial and the mean position was calculated. The coordinates of all 14 markers for each trial were then transformed according to this difference.

After transformation, each trial was normalised to 1001 points using a cubic spline algorithm. Following normalisation, the variability measure was calculated for the x, y, and z coordinates at each of the 1001 points over the 10 normalised trials. This resulted in a standard deviation score for each of the 1001 points for all 3 axes for each player. To represent the three-dimensional aspect of variability of movement at each point in one number, the respective x, y, and z standard deviation scores were multiplied together, following similar principles to those used in balance studies such as that of Lin et al., (2009) where a 95% confidence ellipse area is calculated from centre of pressure excursion in the medio-lateral and anterior-posterior direction by multiplying the COP values in both directions together. The approach outlined here takes the next logical step and progresses this concept such that the volume of an ellipsoid is calculated by multiplying the $sd_x$, $sd_y$ and $sd_z$ together (see equation below for exact calculation procedure). This calculates the volume of a scalene ellipsoid representative of the three-dimensional nature of variability for that subject at each of the 1001 points. The equation for calculation of variability over 10 trials is:

$$\frac{1001 \times \frac{4}{3} \pi (sd_x \times sd_y \times sd_z)}{1001}$$

In order to provide a result which is meaningful in practice, the cube root of this volume was then calculated such that a linear number is provided (mm and not mm$^3$). The average of these variability scores (n=1001) was calculated resulting in one number representing the average variability of movement of that marker for that specific player.

RESULTS AND DISCUSSION:

![Figure 1 - Variability scores for each marker for all subjects](image_url)
Figure 1 illustrates the variability score for each subject as outlined previously. The development of this method has allowed the quantification and examination of which body markers are most variable across the golf swing. The results of this as shown in Figure 1 suggest that movement variability increased from the closed end of the chain (i.e. malleoli at feet) to the open end of the chain (i.e. wrists).

**CONCLUSION:** A method has been developed to quantify average movement variability over the entire swing using the standard deviations of normalised three-dimensional coordinate data. The aforementioned method can produce ellipsoid volumes representative of the body position variability in 3D space. The results we have reported have used the linear quantities as calculated using cube root of the ellipsoid volume values thus demonstrating that this method can provide many uses in examining variability of human movement. Future work will examine the relationship between these levels of movement variability calculated using this method and a performance outcome such as ball velocity.

**REFERENCES:**

**Acknowledgement**

The authors would like to acknowledge the Irish Council for Science, Research and Technology Council (IRCSET) for their support in this paper.
NOVEL METHOD FOR CALCULATION OF MOVEMENT VARIABILITY IN GOLF

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INTRODUCTION
It would appear golf swing coaches base their teaching methods on that of ball flight laws (e.g. Wiren, 1990) and personal opinion, with their focus on a common optimal movement pattern that everyone should attain (Bradshaw et al., 2009). As variability of movement is inherent both within and between all individuals (Davids et al., 2003) the common optimal swing approach is incorrect when considered from a dynamical systems perspective. Knight (2004) suggests a more effective strategy is to reduce variability in the components of the swing that have the most influence on shot outcome variability. However, the effect of movement variability on shot outcome in the golf swing has not yet been established in order to identify these components. In order to examine this relationship effectively, it is necessary to quantify the levels of movement variability in the swing. This research reports the development of a novel calculation technique to quantify movement variability.

METHODS
16 highly skilled golfers (6 male, 10 female; age 26.3 ± 5.6 yrs.; mass 67.0 ± 10.3 kg; stature 1.7 ± 0.1 m; handicap 2.8 ± 3; all right handed) each performed 10 swings in a purpose-built indoor golf testing facility. Ethical approval for this study was obtained from EHS-REC and all participants were familiarised with the experimental procedure and all possible risks before providing written consent to participate. Fourteen retro-reflective markers were tracked at 400 Hz by a 6-camera 3D motion analysis system (Motion Analysis Eagle, CA, USA); all data were filtered at 12 Hz (Mitchell et al., 2003).

\[
\begin{align*}
MV &= \frac{\sum_{i=1}^{10} (sd_{x(i)} \times sd_{y(i)} \times sd_{z(i)})}{1001} \\
PD &= \frac{\sum_{i=1}^{10} (V_{x(i)} - x_{0(i)})^2 + (V_{y(i)} - y_{0(i)})^2 + (V_{z(i)} - z_{0(i)})^2}{10} \\
VV &= \frac{MV}{PD}
\end{align*}
\]

Equations 1 (top), 2 (middle) and 3 (bottom) where MV = movement variability; VV = mean variability volume for a given marker; PD = 3d distance for a given marker.

\[
\begin{align*}
sd_{x(i)} &= \text{standard deviation in } x \text{ direction at point } i \text{ over the 10 trials;} \\
sd_{y(i)} &= \text{standard deviation in } y \text{ direction at point } i \text{ over the 10 trials;} \\
sd_{z(i)} &= \text{standard deviation in } z \text{ direction at point } i \text{ over the 10 trials;}
\end{align*}
\]

n = trial number; \( x_{0(i)} \) = x position at point i; \( y_{0(i)} \) = y position at point i; \( z_{0(i)} \) = z position at point i; \( x_{1(i)} \) = x position at point i+1; \( y_{1(i)} \) = y position at point i+1; \( z_{1(i)} \) = z position at point i+1.

Standard deviations were calculated for the three-dimensional positional data for each of the 14 body locations for the ten time normalised trials for each subject. Data were then further processed via custom software (LabView, National Instruments, TX, USA) to calculate the variability of each anatomical marker over the ten trials; see equations 1-3.

RESULTS
From Table 1 it is clear that the points at the open and closed end of the kinetic chain were found to be the most variable. As such the technique described here, producing results that agree with the kinetic link theory model, can be seen as a valid method for describing movement variability of anatomical markers within movement.

CONCLUSION
A novel calculation technique based on ellipsoid volumes has been developed to quantify the mean movement variability over the entire golf swing using the standard deviations of normalised 3-D coordinate data.

REFERENCES
Appendix A2

Launch Monitor Information
A2.1 Club and ball launch variables referred to in Chapter 3

Club head velocity refers to the velocity the club head is travelling at impact.

Ball velocity refers to launch ball velocity at impact. This is influenced by club head velocity but is not directly proportional to it and it provides an indication of carry distance which varies depending on impact location on club head.

Back spin is the backward rotation of the golf ball when in flight along its horizontal axis.

Side spin is the spin component of a ball where the axis is not horizontal which results in a spin which is not true backspin. This spin results in spin to the left (anticlockwise) or right (clockwise) of the intended target.

Side angle is the measurement in degrees of where the golf ball relative to the target line.

Launch angle is the angle relative to the ground when immediately after the ball leaves the clubface.

A2.2 Launch Monitor Calibration Set up and Measurement Image from Launch Monitor Cameras

A2.2.1 Composite Images of ball from two cameras where measurement is taken by Vector Pro
A2.2.2 Set up of launch monitor from behind player and above; calibration screen on software and sheet set-up also shown
Appendix A3

Additional Data to Accompany Chapter 5
A3.1 Variability Volume and Path Distance (Mean of all Participants)
Calculations used to Calculate Movement Variability

A3.1.1 Backswing

<table>
<thead>
<tr>
<th>Marker</th>
<th>Variability Volume (mm$^3$)</th>
<th>Path Distance (mm)</th>
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<tr>
<td>R Head</td>
<td>2225.09</td>
<td>128.09</td>
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<tr>
<td>L Acromion Process</td>
<td>2559.126</td>
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<td>4348.478</td>
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<td>L Wrist</td>
<td>11272.93</td>
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<td>R Lateral Humeral Epicondoyle</td>
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<td>R Wrist</td>
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<td>T4</td>
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<tr>
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### A3.1.2 Downswing

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A3.2 Ball Velocity Results (m.s\(^{-1}\)) for each participant

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<td>Participant 2</td>
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<td>Participant 3</td>
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<td>0.77</td>
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<td>Participant 4</td>
<td>66.2</td>
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</tr>
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<td>Participant 5</td>
<td>50.6</td>
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<td>1.41</td>
</tr>
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<td>Participant 6</td>
<td>68.1</td>
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<td>Participant 7</td>
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<td>Participant 8</td>
<td>49.4</td>
<td>0.9</td>
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<td>Participant 9</td>
<td>58.8</td>
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<td>1.5</td>
<td>2.84</td>
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<td>0.8</td>
<td>1.15</td>
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Appendix A4

Additional Model Information
A4.1 Full Body Muscle Set of Model

Upper Arm Muscle Set

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Lower Arm Muscle Set

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## Neck/Trunk Muscle Set

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Appendix A5

Miscellaneous
A5.1 Subject Information Sheet

Title:
An Examination Of Human Variability- The Creation Of 'Virtual' Subjects Through Mathematical Modelling

What is this study about?
I am a postgraduate research student studying here in the University of Limerick. The sport involved in this study is golf. I am currently carrying out a study to investigate at the concept of movement variability and the effect of variation in the golf swing on shot outcome.
A precondition of this study is that you currently hold an official CONGU handicap and are a member of an affiliated golf club. To participate in this study you must either be a declared professional or hold a valid CONGU handicap.

What will I have to do?
Prior to the testing session, a familiarisation session will be held for approximately 20 minutes in order to allow you become someway familiar with the experimental set-up.
On the day of testing, you will be required to perform 40-60 shots into a net 4-5 metres away with a golf club. You will have to use your own personal golf clubs for this analysis. Your performance will be measured using 3D motion analysis and also force platform analysis. For the purpose of the 3D analysis you will be required to wear tight fitting black dark coloured clothing. Markers will then be placed on different body parts e.g. the head, elbow, knee, hip, ankle etc. Grip pressure will also be measured using a specialised glove (e.g. Sensoglove® which you will wear. For the force plate analysis you will be required to perform the shots while standing on the force plates (one leg on each platform). The force platforms are flush with the floor level. The force plate analysis will occur at the same time as the 3D motion analysis. The testing session will take approximately 70 minutes. The results from your trials will be used to create a virtual model of your swing. A launch monitor device placed a couple of metres from the ball will also record the motion of your club head and ball at impact of the golf swing.
The total time taken up by you to participate in this study will be 90 minutes (20 minutes familiarisation session and 70 minute testing session).

What are the benefits?
Through carrying out this study it is hoped to find out the effect of movement variability within the golf swing on shot outcome

What are the risks?
Muscle soreness, damage and fatigue are possibilities as a result of taking part in this study. However, these risks are no greater than your normal golf practice session.
What if I do not want to take part?
Should the participant feel at any stage during the testing that they want to discontinue being a participant then this is dealt with in an unhesitating and confidential manner where they have the option of pulling out without the risk of information being disclosed.

What happens to the information?
The information retrieved from the experiment will be dealt with and handled in complete confidence whereby results of the participants as well as their confidentiality are the first priority of the researchers carrying out the experiment. The study be video recorded, any recording will be strictly confidential and will be used exclusively by the investigation team. After the completion of the study it will be destroyed.

Who else is taking part?
In all there will be approximately 30 participants taking part.

What if something goes wrong?
In the unlikely event that something goes wrong, the testing procedure will immediately cease and the PESS department emergency procedures will be followed.

What happens at the end of the study?
At the end of the study the information will be used to present results but the information here will be completely anonymised. Some aspects will be held by the principal investigator for up to 7 years in a password-protected computer at UL.

What if I have more questions or do not understand something?
If a subject does not understand any aspect of the experiment we would urge him or her to come forward to myself the researcher, or indeed the principal investigator. It is important that the participant feels completely at ease throughout the experiment.

Project Investigator Contact Details:

**Supervisors:**
Dr. Ross Anderson, PESS Dept. University of Limerick, Tel: (061) 202810
Email: ross.anderson@ul.ie

Dr. Ian Kenny, PESS Dept. University of Limerick, Tel (061) 234308
Email: ian.kenny@ul.ie

**Other investigator:**
Catherine Tucker  Postgraduate Research Student Tel (086) 3846645  Email: catherine.tucker@ul.ie

This study has been approved by the ethics committee of the Physical Education & Sport Sciences Department. If you have any concerns about this study and wish to contact someone independent, you may contact:
The Education and Health Sciences Research Ethics Committee,
Room E1003,
University of Limerick,
Limerick.
Tel: (061) 234101
Email: ehsresearchethics@ul.ie

Thank you for your time
A5.2 Informed Consent Form

Title of study: An Examination Of Human Variability- The Creation Of 'Virtual' Subjects Through Mathematical Modelling

- I have read and understand the volunteer information sheet
- I understand what the project is about and what the results will be used for
- I have completed the pre-test questionnaire
- I am fully aware with the procedures involving myself, and of any risks or benefits associated with the study
- I understand that other volunteers of the study may know of my participation, if I am seen at or during practise sessions
- I am aware that the tests will be recorded using a 3D motion analysis system
- I know that my participation is voluntary and that I can withdraw from the project at any stage without giving any reason
- I am aware that my results will be kept confidential

Volunteer’s name ___________________________
Volunteer’s signature ___________________________
Date ___________________________
Experimenter’s signature ___________________________
Appendix A6

Multimedia
The CD attached to the inside back cover of this thesis can be viewed on any PC and contains the following items:

A6.1 LabVIEW Code

A6.2 Modelling- Simulation Data

A6.3 Residual Analysis

A6.4 Statistical Analysis

A6.5 Calculation Technique for Theoretical Data Sets

A6.6 Thesis in Electronic Format
Appendix A7

Thesis Bibliography
A7.1 Thesis Bibliography


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Is Movement Variability Relevant for the Elite Golfer?

August 17-21, Biomechanics Research Unit, University of Limerick, Ireland, 343-346.


Quintavalla, S. J. (2006) *Experimental Determination of the Effects of Clubhead Speed on Driver Launch Conditions and The Effects on Drive Distance for Balls used by the PGA Tour*, USGA Technical Report RB/cor2006-01, USGA.


