Biomechanical and modelling analysis of shaft length effects on golf driving performance

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Abstract

The purpose of this thesis was to determine how shaft length affects golf driving performance. Shaft length effects on the golf swing have been of interest to several researchers (including Egret *et al.*, 2003; Reyes and Mittendorf, 1999 and Mitzoguchi and Hashiba, 2002). A range of drivers with lengths between 46" and 52", representing lengths close to the 48" limit imposed by the R&A Rules Limited (2004), were assembled and evaluated. A 5-camera three dimensional motion analysis system tracked skin markers attached to 9 low-medium handicapped (5.4 ± 2.8) golfers. Clubhead and ball launch conditions and drive distance and accuracy were determined for 5 low-medium handicapped golfers (5.1 ± 2.0) and 7 elite golfers (0.21 ± 2.41) who performed shots on a purpose-built practice hole. Finally, motion analysis was conducted for an elite golfer (+1 handicap) and experimentally obtained marker data was used to drive a large-scale musculoskeletal model. Low-medium handicapped golfers demonstrated more significant variation in performance due to shaft length than elite golfers. Postural kinematics remained largely unaffected, as were ball spin, launch angle and swing tempo. As shaft length increased from 46" to 52", initial ball velocity (+ 1.90 ms^{-1}, $p < 0.05$) and ball carry (+ 14 yds, $p < 0.001$) increased significantly for low-medium handicapped golfers. As shaft length increased from 46" to 50" initial ball velocity (+ 1.79 ms^{-1}, $p < 0.01$) increased significantly for elite golfers. Ball carry (+ 4.73 yds, $p = 0.152$) also showed NS increases for elite golfers. Furthermore, as shaft length increased, for all club comparisons there were NS decreases ($p = 0.063$) in shot accuracy for low-medium handicapped golfers, but no decrease in accuracy for elite golfers. Model simulated results, including posture, timing and predicted muscle force compared well with experimental results ($r > 0.98$, $p < 0.05$). Simulations showed that for the range of clubs modelled (46" to 50") hip/shoulder differential angle at the top of the backswing increased significantly (+ 6.13°, $p < 0.001$) as shaft length increased, and each 2" increase in shaft length required a NS additional 4.5 N force ($p = 0.117$) to maintain normal swing kinematics. The results from this thesis indicate that modest improvements in shot performance brought about by increasing driver length are the result of increased hip/shoulder differential angle at the top of the backswing and increased predicted muscle force.

Nomenclature

ADD	Address
CFD	Computational fluid dynamics
CNS	Central nervous system
COG	Centre of gravity
COM	Centre of mass
COR	Coefficient of restitution
DOF	Degree of freedom
GRF	Ground reaction force
IMP	Impact
MOCAP	Motion capture (data)
MRI	Magnetic resonance imaging
NS	Non-significant
PGA	Professional golfer's association
SSC	Stretch shortening cycle
TOB	Top of backswing
USGA	United States Golf Association

Declaration

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Research Communications

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CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

1.1 Research background

Golf's global market was reported as being worth £2.5 billion annually with equipment sales contributing 30% of this sum ('Golf UK', Mintel Report, 2003). Although it is difficult to estimate the number of golfers worldwide a figure of 55 million has been proffered (Farrally et al, 2003). It has been suggested that golf is an increasingly popular sport, attracting new players of nearly all ages and socio-economic groups (Hume *et al.*, 2005). Golf is a game which is constantly evolving and the governing bodies seek to maintain a balance between tradition and technology. The equipment is closely regulated, however golf equipment manufacturers are always seeking to improve their products within these bounds. Furthermore, enhanced teaching and improved fitness means that golfers are always improving. The present thesis will address both the human characteristics and club specifications, focusing specifically on the effect of driver shaft length on golf driving performance.

Cochran (2002) stated that whilst the benefit of high-tech equipment based on genuine science is real, it is small. Nonetheless, anecdotally, golfers often report greater performance benefits than testing and theory suggest, supporting the self-efficacy brought to the game by technologically advanced equipment. Whether a change in driver length will alter drive distance has been the interest of several researchers (including Egret *et al.*, 2003; Reyes and Mittendorf, 1999 and Mitzoguchi and Hashiba, 2002). The aim of the golf drive is to propel the ball as far as possible but with a reasonable level of control over the shape of the ball's flight and consequent displacement. The use of drivers of different length is perceived, rightly or wrongly, to alter both the distance that the ball will travel, and the level of control that can be maintained. Generation of long drive distances is one goal, but does not necessarily result in better scores if this is associated with loss of accuracy. Whether there is a gain in distance, a loss of accuracy, and a change in swing kinematics when long-shafted drivers are used are questions which will be examined in this thesis.

The latest edition of the Rules of Golf, as approved by the R&A Rules Limited and the United States Golf Association (30th Edition, Appendix II 1c (length), effective 1st January 2004), states that the overall maximum club length (excluding putters) must not exceed 48″ (1.2192m). Reyes and Mittendorf (1999) have discussed the significance of altering club length for the golf swing. It was concluded that there would be an increase in drive length as club length increased up to 60″, and that a 51″ driver would produce optimum performance in terms of shot distance. Several researchers have concentrated on clubhead and ballspeed as indicatiors of improved performance when using longer shafted clubs. Experimental and mathematical modelling studies have ascertained that increasing club length, up to 52″ in some cases (for example 50.3″ optimum length, derived experimentally by Werner and Greig, 2000), will provide greater drive distance. However, it should be noted that in the studies by Reyes and Mittendorf (1999) and Werner and Greig (2000), limited numbers of golfers were recruited. Reyes and Mittendorf (1999) collected experimental data from just one golfer, a PGA professional long-driving champion, on which to base calculations for their two dimensional mathematical model of the arm and club. And Werner and Greig (2000) studied four golfers with handicaps ranging from 0 to 27.5. Furthermore, clubs constructed for Werner and Greig's (2000) tests incorporated graphite shafts, as opposed to carbon composite shafts now commonly used, and all golfers used the same 'stiff' test clubs despite clubhead velocities measured whilst using their own drivers as ranging from 73.8 mph (33.0 ms^{-1}) to 114.1 mph (51.1 ms^{-1}).

Engineering product design concepts are increasingly realised using computer aided design (CAD) methods. In addition to the design process, products are also frequently being simulated and tested using computer-based methods. This permits a relatively rapid research process into the validation and effectiveness of different properties of a product before it goes into production. Modelling of the golfer and club is not a recent development, with pioneering work undertaken by Cochran and Stobbs in 1968. Experimental methods are likely to continue to be employed to test the golfer and equipment, but can prove time-consuming, costly, commonly include confounding subject variability, and it is often difficult to measure certain variables without affecting shot outcome. Farrally *et al.* (2003), in their paper that summarised golf science research at the beginning of the 21st century, highlighted the need for the inclusion of the golfer in computer models examining golf technology. At present many of the technological advances have been concerned with ball impact and flight models, with only partial human analyses and player-club interactions. This present study was designed to introduce the full human body into an environment including the club (driver) and the ground surface.

Computer simulation models permit the study of the complex interactions between biomechanical variables, yet their application to the scientific study of the golf swing is still in an early phase of development. There exists a number of research papers that have focused on kinematic and kinetic variations in the golf swing, whilst subjects used clubs of different dimensional properties (for example Egret *et al.*, 2003; Kaneko and

Sato, 2000; Mitzoguchi and Hashiba, 2002). Reyes and Mittendorf's (1999) model, which is discusssed in greater detail in Chapter 2 Section 2.1.2, showed that increasing club length, whilst aiming to keep all the other parameters fixed, would result in the clubhead lagging behind the grip, indicating a need for an alteration in swing mechanics (kinetics and kinematics) to permit correct timing.

In recent years researchers have developed models raising theoretical discussions on the effects of lengthening the driver shaft, moving a club's centre of mass distally (Sprigings and Neal, 2001), altering the moment of inertia (MOI) of the clubhead (Harper *et al.*, 2005) and investigating the effect of shaft flexibility (Miao *et al.*, 1998). However, few researchers have developed full-body computer models of the golf swing, most concentrating instead on single joint complexes such as the shoulder (Mitchell *et al.*, 2003), or multiple joint rigid-lever models, such as the double pendulum model (Pickering and Vickers, 1999). The greater number of assumptions which must be made when developing full-body models mean that the level of detail presented via most full-body models is often somewhat less than single joint, or simple lever models.

The present study utilised ADAMS™ engineering software combined with Biomechanics Research Group's (BRG) LifeMOD™ toolkit to develop a human and driver club model. Nesbit et al (1994) have been the only other research group known to date to have utilised ADAMS™ [1] software, in their case to develop a rigid-body model of a golfer and parametric model of a golf club to investigate joint torque throughout the swing. The present study takes this work significantly further, whereby a 19 segment, 18 tri-axis joints, 42 degrees-of-freedom (DOF) subject-specific (anthropometrically tailored) human model, with 111 muscles has been developed. The model is driven using experimental three-dimensional kinematic data, combining inverse and forward dynamics techniques, and is able to simulate swing kinematics, joint torques, ground and club handle reaction forces, and the predicted muscle force needed to perform a given golf swing.

Experimental techniques and modelling were used in this thesis to investigate the biomechanical mechanism by which changes in the golf swing are caused. Modelling the golfer and club and simulating movement allows for rapid kinematic and kinetic data to be produced, describing those changes when using clubs of different shaft length properties.

1.2 Contribution to research and thesis outline

Relatively little is known about the detailed mechanics occurring during the golf swing for the full human body and the interaction between the golfer and club. The detailed study of the kinematics of the golf swing is used in this thesis to develop computational analyses of the golfer-club system. Experimental data captured in the studies leading up to the main computer simulation of the golfer include whole-body kinematic analyses of elite and non-elite golfers; analysis of the effect on drive performance of the testing environment, and the investigation of the effects of club length on driving performance (distance and accuracy) for elite golfers. Inter-subject variability between low-medium

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[1] MSC ADAMS (Ver. 7.0) and ADAMS/ANDROID (Ver. 1.0)

handicapped golfers was examined to justify the single-subject design in the modelling process.

In Chapter 2 a review of the pertinent literature available on the topic of golf biomechanics and sports biomechanics modelling is presented. Previous research on golf swing kinematics (temporal patterns, kinetic chain, X-factor, and control), kinetics (ground reaction force (GRF), club grip force and muscle force production), and control and accuracy of linear and angular motion are discussed. These are issues most commonly presented in the literature in an attempt to characterise and discuss the effects of driver shaft length on the golf swing. Also discussed in this chapter is research on the effects of club properties on shot performance, and human and club modelling to represent the swing and the club/ball impact.

In chapter 3 methodological issues relating to the studies involved in this thesis are presented. This covers: selection and fitting of clubheads, shafts and grips for the test clubs; appropriate selection of a launch monitor to track the clubhead prior to impact and ball immediately after impact; a pilot-study involving examination of inter- and intra-subject variability within the subject population considered, and a study of the effect of kinematic test equipment, i.e. reflective skin markers, on drive performance.

Chapter 4 is concerned with the first of the research studies undertaken in this thesis. A kinematic analysis of the golf swings for low-medium handicapped golfers using drivers of different shaft lengths was undertaken to determine shaft length effects on posture, trunk rotational velocity and timing of the phases of the swing.

Chapter 5 presents an analysis of experimental data on driving accuracy and shot performance for low-medium handicapped golfers using drivers of different shaft length based on measures of initial ball velocity, carry and dispersion. This study also examined the effect of the test environment on the subject by comparing shot performance (ball velocity) during tests performed in the laboratory and on the range.

Chapter 6 is an analysis of driving performance, for a group of elite golfers, tested on the golf course, examining the effects shaft length has on ball carry and drive accuracy. Whilst several other researchers have reported variations in drive distance using drivers of different length for tests conducted in the laboratory, the present study provides data for tests performed on the golf course. Ball launch conditions are also examined, to identify whether spin rate and trajectory change as drivers of different shaft length are used. Furthermore, the correlation between launch conditions and carry and dispersion will be examined.

The final research study prescribed in Chapter 7 concerns the prediction of the effect of shaft length using a full-body human computer model of the golf swing. The model is based on the swing of an elite male golfer. The process of model construction, validation, refinement and simulation is discussed

Finally, Chapter 8 provides conclusions from the studies and suggests recommendations for future study in the area of golf biomechanics and computer simulation of the golf swing.

1.3 Aims of the research

The three main aims of the present study were:

1. To investigate the effects of driver length on swing kinematics,
2. To examine the effects of driver length on shot performance, and
3. To develop a full-body computer model to simulate a golfer's swing for driving clubs of different length.

Detailed aims which relate to the four individual studies have been formulated. These are presented at the beginning of each respective chapter.

CHAPTER 2

REVIEW OF LITERATURE

2.0 Introduction

A number of studies, aimed at ascertaining the effects of different club properties on the golf swing, have utilised shot outcome measures and biomechanical techniques at various levels of experimental and modelling complexity. These studies can be generally grouped into four categories:

i. Shot performance measures based on launch conditions and/or final ball placement.
ii. Kinematic and electromyographic (EMG) analyses of the swing.
iii. Mathematical modelling of the golfer/club interaction.
iv. Computer simulation of the partial and full-body human and club interaction during the swing.

This chapter critically examines the main findings in the literature for each type of analysis as they appertain to the biomechanical effects, including the underlying kinetics of altering club properties on performance outcomes for the golf drive.

Whilst each approach provides valuable data, it will be suggested that if the relevance of club properties to the golf swing is to be fully understood it is more pertinent to utilise both experimental and theoretical approaches, with a case made for computer simulation. A critical review of the experimental protocols used and the variables analysed in previous studies will be used to justify the aims and methods employed in the present study. Experimental studies will be reviewed first, with swing kinetics, kinematics and motor control examined, before studies involving biomechanical modelling are introduced.

Initially a Medline search was conducted on studies carried out between 1960 and the present. The keywords used were ‘golf’, ‘biomechanics’, ‘biomechanical modelling’, ‘golf swing’, ‘golf club’, ‘golf ball’, ‘EMG’, ‘kinetic chain’ and ‘skill’. The same terms were also applied to the search engine ‘Google Scholar’ which in most cases produced the same search results. Results led initially to the leading journals in the biomechanics and sports engineering field: Journal of Biomechanics, Journal of Applied Biomechanics, Journal of Sports Biomechanics, Research Quarterly, Sports Medicine

(ADIS), British Journal of Sports Medicine, Journal of Sports Sciences, Sports Engineering and the Journal of Minerals, Metals and Materials Society (Journal Citation Reports, 2002). Two further invaluable sources of reference were the 4 volumes of the 'Proceedings of Science & Golf World Congress' (1990, 1994, 1998 and 2002) and the 'Proceedings of the International Sports Engineering Conferences' (1996, 1998, 2000, 2002, 2004 and 2006).

Papers from the abovementioned conference and journal sources were deemed most relevant and reliable in terms of rigorous scientific research. This search was supplemented by tracking all key references in these papers and those cited in conference abstracts. Thus, further papers were selected based on the status of their source (international or national peer-reviewed journal or conference, and citings score) and methods rigour (subject numbers, age and skill levels, sampling and filtering frequencies of image-based work, surface marker numbers and orientation, and detail of statistical analyses).

Firstly, an overview of the main effects that club parameters will have on the golf drive will be discussed in the context of the Rules of Golf (2004).

2.1 Effect of equipment on drive performance

Research into and the application of modern scientific methods to golf equipment production has grown and enjoyed a surge of activity in the last ten to fifteen years. Thus the outcome is the changed appearance and construction of golf clubs compared to thirty years ago (Farrally *et al.*, 2003). Few sports require such a range of equipment as does the game of golf. A professional player is permitted to carry up to fourteen clubs, comprised of 'woods', irons and putters. Woods, and in particular the driver, which is the focus of the present study, usually comprise a titanium or traditionally steel bulbous hollow head and a shaft typically made from steel or graphite. Development of materials and fabrication methods have brought about the use of larger driver heads via thinner and larger faces, lighter and stronger shafts with varying degrees of flexibility, and ease with which clubs may be tailored for an individual golfer's swing (Olsavsky, 1994). Wound construction balls are practically unheard of now, certainly in the elite game, with two, and multi-layer construction balls commonly used, and a wide range of flight characteristics enabled depending on launch characteristics via ball dimple number, pattern and impact deformation (Smits and Ogg, 2004)

There exists a number of methods by which a club may be tailored to suit a particular swing to achieve greater distance and purported accuracy, or even physical characteristics of the driver that a golfer may wish to consider when purchasing a club. Whilst driver length is the specific focus of the present study, it is important to contextualise other components of the driver and their individual, and combined, effects on the golf shot.

2.1.1 Shaft

Whilst not having received quite as much attention as the clubhead and ball regarding academic research, the driver shaft and the variations of shaft physical properties that are available are crucial to shot performance. Indeed, both Butler and Winfield (1994) and Jackson (1993) consider it to be the most important component of the golf club. The shaft in an iron can serve to aid control of the approach shot, but the shaft in a driver has been developed in recent years with the aim to aid production of drive distance, with a degree of control offered depending on the choice of shaft. Bending stiffness or shaft flex, mass, damping, torsional stiffness, and bend point are widely accepted as being the five main shaft properties that affect performance in golf (Wallace and Hubbell, 2001).

Yet with regard to shaft flex, Milne and Davis (1992) stated

> *"…shaft bending plays a minor dynamic role in the golf swing…",* and that *"…if golfers are asked to hit golf balls with sets of clubs having different shafts but identical swingweights the success rate in identifying the shaft is surprisingly low."*
>
> (pp 975)

It would appear, therefore, that shaft properties have either changed since then or indeed enhanced methods of shaft characterisation have become available. The general dynamic behaviour of the shaft has been determined through measurements by Butler and Winfield (1994) and Horwood (1994). And whilst at this time (early 1990's) golfers were only changing from the traditional steel driver shaft to graphite shafts, as opposed to the composite fibreglass lightweight shafts that are used my most professional golfers[2] and keen amateurs, at present.

Perceived wisdom dictates that the weaker player is suited to a more flexible shaft, whilst the professional or strong amateur should use a stiffer shaft. Maximum flexion of the shaft occurs approximately 100ms into the downswing (Milne and Davis, 1992), with the clubhead bent back from a direct line from the hands. Only immediately prior to impact does the torsional pull and centrifugal stiffening of the shaft cause the clubhead to catch up with the position that the hands have obtained (Figure 2.1). With correct matching of bending and torsional characteristics, a swing from a golf swing robot has been shown to enhance a ‘kick’ effect where the shaft leads the clubhead, imparting additional energy to the ball (Newman *et al.*, 1997; Masuda and Kojima, 1994).

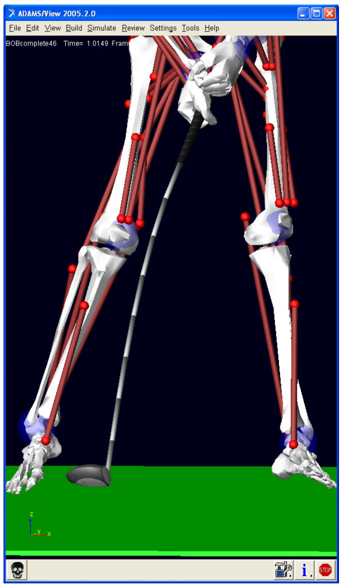

Figure 2.1 Representation of clubhead kick as a result of club shaft flexibility

Shaft stiffness and clubhead velocity trade off each other. A slower clubhead velocity will not cause as much bend in the club throughout the downswing and will not generate as high an impact force on the ball, but a more flexible shaft will permit a degree of bend even at relatively low swing speeds, adding to the ‘kick’ by the driver onto the ball. If the shaft is too flexible for the golfer, it springs forward to too great an extent, thereby increasing the effective loft and closing the clubface, and if the shaft is too stiff it will remain deflected backwards at the point of impact, decreasing loft and leaving the face open (Tolhurst, 1989). Indeed, it remains difficult for manufacturers, with the emergence of very large titanium driver heads, to control rotation, thus torsional stiffness, of the shaft and club. Torsional stiffness, referred to as torque by Brumner (2003) remains one of the most expensive aspects to control, and is usually only a major concern and component of high-end shafts benefiting the best players. Milne and Davis' (1992) model did show that at the moment of impact the rate of increase of clubhead deflection, thus clubhead velocity, is well past its peak. Maximum clubhead velocity is commonly found to be prior to impact, with only some elite golfers able to accelerate the clubhead through impact.

2.1.2 Shaft length

A club physical characteristic that has received more interest via the press than currently through scientific study, is the effect of club length on driving performance. Physics principles would suggest that using a longer lever to strike the ball will create greater linear velocity at the distal end of the lever, thus imparting a greater initial velocity to the ball. This depends on body rotational angular velocity being maintained as a longer club is used, or at least that the increase in club length has a greater effect than any small decrease in angular velocity the body may experience in moving the longer driver. However, as the mass and the first and second moments (swingweight and moment of inertia) of the golf club all increase with increasing club length this is not necessarily the case.

$$v = r\,\omega \qquad \text{(Equ. 1)}$$

Equation 1 shows the basis for this principle, where v is the clubhead linear tangential velocity at impact, r is the radial lever which is the driver shaft length, and ω is the angular velocity of the rotating body. In tests where a golf robot has been used (Mizoguchi and Hashiba, 2002), accuracy determinants have not been considered (Egret *et al.*, 2003), or where the study has been theoretical (Reyes and Mittendorf, 1999), increasing driver shaft length has been shown to increase clubhead velocity at impact.

[2] More than 90% of PGA Tour players use graphite (composite) shafts in their drivers (Brumer, 2003).

To some extent this remains true in the game of golf. However, there exist marked differences between robot tests or modelled systems and dynamic human testing. For example, lack of kinaesthetic feedback or 'feel' during robot tests.

The feel of a drive has been related to the length of the club. Whilst golfers often aim to achieve the longest drive possible, any small error at the point of impact may cause the ball to deviate by a large amount by the time it comes to rest. Thus the average driver length on the PGA Tour at present is 44.5″, which is approximately 0.5″ to 1.5″ shorter than what the majority of amateurs buy based on what is commercially available (Wishon, 2004). That professionals generally use a shorter driver than amateur players is based on the premise that they are highly skilled and capable of such swing speeds and launch characteristics that the ball will carry sufficiently far, and that a higher level of accuracy may be achieved (Wishon, 2004). In being able to control the clubface of the driver, a more efficient impact may be created by presenting the centre of the face to the ball at the optimum position for the swing type. There remain, though, a number of golfers, professional and amateur, that are physically capable of driving long distances, and have taken to using a driver in excess of what is considered average shaft length (Johnson, 2006).

Further research in the area seems to have concentrated on clubhead velocity and ball velocity increases as an indication of the benefits of using a longer shafted driver. This is misleading in that drive accuracy is not examined, and few studies have investigated accuracy for shots performed away from the laboratory (for example Werner and Greig, 2000). Few studies have been carried out relating to performance measures concerning variations in shaft length. Those that have been conducted are a mixture of mathematical theory and experimental work. Reyes and Mittendorf (1999) developed a two-dimensional mathematical model based on a long-driving champion to investigate the effects that altering shaft length, clubhead mass and torque (referring actually to torsional stiffness) applied to the club would have on drive distance. Equations were written and derived for the two-dimensional model using Lagrange's modifications of Newton's laws and included the upper and lower arms, club and the shift force, torque and gravity applied to the shoulder, and two torques applied at the elbow and wrist. The model itself was validated via comparison with Jorgensen's (1994) measured clubhead speeds of two professional golfers. Their data analysis showed 1) a linear relationship between ball velocity and ball carry, and 2) a constant coefficient of restitution for the given clubhead velocities were determined from the masses of the clubhead and the ball and the velocities of the clubhead and the ball, and that using the coefficient of restitution (C.O.R.)[3], ball velocities and carries were determined. Measured clubhead velocities and ball carry of 55.88-56.77ms^{-1} and 292-305 yards (267-279m) and 56.77-58.56ms^{-1} and 305-340 yards (279-311m) for a 47″ and a 51″ driver respectively were shown to compare well the modelled results of 56.77 ms^{-1} and 296 yards (271m) and 58.12 ms^{-1} and 302 yards (276m). In applying torque/shift force of 70 lb-ft/ 20 lb (311.4 N/ 89.0 N), clubhead velocity was therefore shown to increase by 1.35 ms^{-1} (2.4%) for an increase of 4″ in shaft length, with 5 yards (4.6m) or 1.8% greater ball carry (Reyes and Mittendorf, 1999). More detailed launch conditions were not described in their paper.

In another paper addressing a similar situation, Mittendorf and Reyes (1997), however, noted that whilst their model showed increases in peak clubhead velocity using longer drivers, the clubhead would tend to lag behind the hands at impact. Such theoretical analysis does not take into account swing kinematics, which would need to be altered, therefore affecting the ability to maintain and apply the torque needed to swing a longer club.

Further experimental studies that have investigated the effect of using longer-shafted drivers include Mizoguchi and Hashiba (2002), who recruited 13 golfers, comprised of both males and females, low-handicapped and novices. Using a ‘speed sensor’, E.M.G., a four-camera kinematics tracking system and two force plates, they determined the kinetic and kinematic differences that using 45″, 46″, 47″ and 48″ driver would have on the golf swing. Clubhead velocity data for the golfers, in their respective groups (0-5 handicap male group 1, 15-25 handicap male group 2, skilled females group 3, and unskilled females group 4) were compared to that captured using a golf swing robot. They showed that for the robot, operated with constant arm rotation speed, the rate of peak clubhead velocity increase per inch shaft length was 0.94~1.32ms^{-1}, compared to

[3] C.O.R. - a measure of the mechanical energy of a collision between two bodies. The ratio of the relative speeds of the colliding bodies after impact to that before impact. Can take a value between zero and one.

1.13~2.32ms^{-1} for group 1, 0.28~0.79ms^{-1} group 2, 0.25~0.70ms^{-1} group 3 and 0.73~0.83ms^{-1} group 4. Taking the elite golfers and the robot results as the best indicator of valid, low variability data, it was suggested that using a longer shaft had the effect of developing longer drives. In addition, no clear differences in swing kinematics whilst using longer drivers were found, whilst peak moment and weight movement by the right foot decreased as club length increased, indicating that the action of the right foot becomes passive as club shaft length increased. Also, a number of E.M.G. measurements taken indicated that some muscles become passive when using longer shafts.

Furthermore, Wallace *et al.* (2004) examined the influence of driver shaft length on swing tempo and posture in skilled golfers. Nine male skilled (5.4 ± 2.8 handicap) golfers, performed 10 shots in laboratory setting using each of 46″, 47″, 49″ and 52″ drivers, all of which increased also in swingweight accordingly. A five camera MAC™ kinematic analysis system tracked golfers' motion throughout the swing and a fourteen segment model was derived to examine each swing. It was shown that club length increases had no effect on lower limb joint angles at address or throughout the swing,

Position relative to the ball meant increased stance width and increased feet-to-ball distance as club length increased. Backswing and downswing temporal ratios in terms of overall swing time were consistent for all club lengths which suggested that all phases of the swing maintained a common relative association. It was concluded that golfers attempted to maintain their normal posture and swing characteristics when using drivers which varied by shaft length. Nagao and Sawada (1973) also conducted a kinematic analysis of elite golfers (Japanese male professionals), but for a driver and a 9 iron. In that there is a significant shaft length difference, amongst other obvious club physical differences, the results are valid for the purposes of shaft length literature review here to highlight differences between nine irons and drivers. Using a sixteen camera motion analysis system, it was found that club shaft angle with the horizontal at the top of the backswing (24.8° to -1.9°) and follow-through time (63.2 s to 53.6 s) decreased as the golfers moved from using a 9 iron to a driver. Also, stance width (0.44 m to 0.65 m), downswing time (21.8 s to 23.8 s), clubhead velocity immediately prior to impact (35.5 ms^{-1} to 46.6 ms^{-1}) and ball initial velocity (42.1 ms^{-1} to 66.6 ms^{-1}) all increased as the golfers moved to using the driver. This highlighted the differences in the swing between the driver and a short iron indicating a marked variation in timing, albeit clubs with markedly different swingweights.

Egret *et al.* (2003) conducted a study to investigate the influence of three different clubs: a driver, a 5 iron and a pitching wedge on the kinematic patterns in the golf swing. Use of these clubs presented results from a range of marked different lengths of club (Table 2.1). Three dimensional kinematics were examined for seven male right-handed golfers (0.4 ± 1.1 handicap). Egret and colleagues were conducting the investigation due to the contrasting opinions on swing mechanics when using different clubs. Whilst Nagao and Sawada (1973) claimed that the swing differed significantly when using clubs of different length, Yu-Ching *et al.* (2001) and Neal *et al.* (1990) noted no significant variability in clubhead velocity or swing kinematics.

Table 2.1 2006 Commercially available average club lengths

	Men's Standard Length (″ / m)	
	Graphite	Steel
Driver	45 / 1.143	n/a
3 Wood	43 / 1.092	42 / 1.067
5 Wood	42 / 1.067	41 / 1.041
7 Wood	42 / 1.067	41 / 1.041
9 Wood	42 / 1.067	41 / 1.041
11 Wood	42 / 1.067	41 / 1.041
1 Iron	40.25 / 1.022	39.75 / 1.100
2 Iron	39.75 / 1.100	39.25 / 0.997
3 Iron	39.25 / 0.997	38.75 / 0.984
4 Iron	38.75 / 0.984	38.25 / 0.972
5 Iron	38.25 / 0.972	37.75 / 0.959
6 Iron	37.75 / 0.959	37.25 / 0.946
7 Iron	37.25 / 0.946	36.75 / 0.933
8 Iron	36.75 / 0.933	36.25 / 0.921
9 Iron	36.25 / 0.921	35.75 / 0.908
PW	36.25 / 0.921	35.75 / 0.908
SW	36.25 / 0.921	35.75 / 0.908
LW	36.25 / 0.921	35.75 / 0.908
Putter	n/a	34 / 0.864

(Adapted from Pinemeadow Golf, 2006)

Egret *et al.* tracked 12 reflective skin markers using a VICON^{TM} five camera system operating at 50Hz whilst clubhead velocity was recorded using a 'Bell-Tronics^{TM} swing made detector'. Each golfer performed six shots with each randomly assigned club in a laboratory setting. Data showed no significant temporal differences between the clubs. Kinematic data for hip joint rotation angle, shoulder joint rotation angle, right knee joint angles, and stance width were processed. Zero reference of the hip and shoulder joint rotation angles was obtained when the biacromial and bitrochanterian lines were in the frontal plane at the start of the golf swing, and the zero reference of the knee joint angles was obtained when the lower limbs were in absolute extension. It was shown that the golfers had a tendency to adopt a more closed shoulder stance at address as club length decreased, rotated the shoulders and hips less as club length decreased, and adopted a narrower stance width also as club length decreased. Also, right knee flexion was significantly different between the driver and the other clubs, more pronounced flexion occurring only when the driver was used. Trunk angular velocity was not recorded. Finally, clubhead velocity was significantly different for the three clubs, driver peak clubhead velocity being 10 % faster than the 5 iron, and the 5 iron 10 % faster than the pitching wedge at 44.9 ms^{-1}, 40.8 ms^{-1} and 37.0 ms^{-1} respectively. It was concluded that whilst there was identical swing timing for the three clubs tested, the kinematics and peak clubhead velocity were different. Egret *et al.* also noted caution should be taken in evaluating the results as the experiment was conducted indoors, with no reference target.

Cochran and Stobbs (1968) were among the first to study and comment on the length of drivers, noting that the longer the club is, the more difficult it would be to bring the clubface squarely to the ball, but also noted that a golfer should be able to swing a longer-shafted driver faster. In swinging a longer shaft, thus overcoming the greater inertia, one also has to overcome greater aerodynamic drag. Driver lengths over 4 feet (48″), Cochran and Stobbs (1968) claimed, would cause resistances that would cancel out any advantages a long driver may have. They also stated that a 47″ driver, at the time of their testing using persimmon-headed, steel-shafted drivers, would be near optimal for long driving, based on their two-lever rigid model calculations. Their experimental tests showed that a 55″ driver produced trajectories higher than normal and that its carry was longer than a conventional driver (43″) although total drive distance (carry and roll) was shorter due to high ball trajectory. Importantly, one in three of all shots during their tests was a mishit, as most golfers found it difficult to strike the ball true, compared to one in seven mishits in testing with a normal driver. This indicated learning issues associated with using drivers longer than normal.

Further to this, Werner and Greig (2000) conducted a study where 9 drivers were constructed, 3 with 43″ shafts, 3 with 46″ shafts and 3 with 49″ shafts. Within each length grouping, clubhead masses of 140g, 170g and 200g were fitted. Using ‘hit tape’ they found that clubface hit patterns were independent of club length. They deduced that the driver that would yield maximum drive distance was one that had a 50.3″ shaft and a 192g clubhead, but depended on golfer size, handicap, and gender. Hit pattern which was defined as deviation of the ball’s final resting position from the fairway centre line, was shown to be somewhat larger for the 49″ drivers, and for the 43″ drivers with 140g clubheads, indicating that longer or shorter shafts and/or heavier/lighter heads reduced drive distance. They concluded that a light 46″ shaft with 194g clubheads produced drive distance that was very close to the aforementioned optimum, and which was able to be managed with ease, that is, swung comfortably and transported easily. It was noted that:

“…no driver design can gain more than about 2 yards over this practical compromise.”
(Werner and Greig, 2000, pp97)

Iwatsubo and Nakajima (2006) also commented on shot accuracy for golfers using drivers of different shaft length. Using 4 clubs ranging in length from 42" to 51", 2 golfers of “high and middle level” ability aimed at a 20m x 20m target positioned vertically, 170 yards from the tee. It was found that the probability of hitting the target fell from just over 70% with the 42" driver, to 66% for the 45" and 48" drivers, and 40% for the 51" driver.

2.1.3 Swingweight

The feel of a club, mentioned in section 2.1.2, is often referred to in terms of its swingweight. Maltby (1982) defines swingweight as:

> *“The measurement of a golf club’s weight distribution about a fulcrum point which is established at a specific distance from the grip end of the club.”* (pp560)

Therefore swingweight is equivalent to the first mass movement of a golf club. The general concept when fitting a set of golf clubs is that each club should have the same swing feel. Player's subjective perceptions of the characteristics, suitability and quality of sports equipment will have a bearing on their equipment selection. Swingweighting is one method whereby the feel of a club is adjusted and is an established industry method of achieving a matched club feel, where club adjustments are made by adding or removing mass from the clubhead. Previous research on swingweight has been carried out for various pieces of sports equipment including tennis rackets (Mitchell *et al.*, 2000), baseball bats (e.g. Fleisig *et al.*, 2000) and softball bats (Smith *et al.*, 2003). Cross and Bower (2006) quantified the effects of mass and swingweight on swing speed using metal rods, recruiting 4 subjects to swing 3 rods that had the same mass but differing swingweight, and 3 rods that had different mass but identical swingweight. When swinging with maximal effort, swing speed was shown to decrease as swingweight increased, but swing speed remained constant as mass increased.

Swingweight depends on the club's overall mass, as well as the length of the club, and the distribution of mass (concentration of mass at the clubhead). The most widely used swingweight scale in the golf industry is the Lorythmic scale (Harper *et al.*, 2005). The scale has a fulcrum located 14″ from the grip end and when a club is placed onto the scale, a moment is generated about this fulcrum by the weight of the club. A known mass 'm' is positioned to balance the club and swingweight is calculated by multiplying 'm' by the distance 'd' between the fulcrum and 'm', providing a value measured in inch-ounces, where 2 inch-ounces are equal to one swingweight. Industry convention allocates swingweight measurements with alphanumeric values ranging from A0 to G9, where numeric values range from 0 to 9 before the subsequent letter starts again at zero. Furthermore, several swingweighting scales have been devised, including the 'Official Scale' which uses a 12″ fulcrum to eliminate the correction factor of swingweighting irons two swingweights lighter than drivers, helping maintain a sense of 'sameness' between irons and drivers. (Maltby, 1982).

Harper *et al.* (2005) recruited thirty male golfers, fifteen of which had a handicap less than 5, and 15 had a handicap from 6 to 12. Each golfer performed a series of shots with different drivers to determine the most suitable shaft flex (light, regular, firm and strong) for their particular swing which was determined from strain gauges on the shaft and a computer system called ‘ShaftLab’. Following this each golfer performed 10 shots with four drivers set up for their shaft flex but with differing swingweight (C7, D0, D5 and E0). Clubhead velocity prior to impact, impact location using powder spray on the club face, and ball velocity, launch angle and backspin were recorded, as were subjective perceptions of swingweight for each club/shot (‘head light’ to ‘head heavy’ on a 1 to 9 scale). A significant relationship between club swingweight and clubhead peak clubhead velocity was apparent, where an increase in swingweight of a club resulted in a reduction of clubhead velocity (2.64 ms^{-1} / 5.9 mph peak difference, 1.30 ms^{-1} / 2.9 mph mean difference). No significant difference was found between swingweight and impact location, launch angle or backspin, suggesting the effect of swingweight on golfer control is negligible, and that the majority of golfers were only able to detect very large changes in swingweight of five or more swingweight points. Overall, changes to golf weight distribution were found to have little effect on player performance, and that manufacturing tolerances for component masses appear to offer sufficient control over club weight distribution, allowing for less stringent, therefore less expensive, manufacturing procedures.

2.1.4 Effect of materials on dynamic performance

The materials evolution of the driver, since the early 1990’s, has included overall weight reduction, club length increase from around 43″ (1.09 m) to 45″ (1.14 m), a decrease in shaft mass to between 45g and 60g through development and construction using graphite and carbon fibre (compared to 115g for steel), and a decrease in the mass of the grip, from 50g to around 40g (Shira and Froes, 1997). The weight of the clubhead remains the same, at approximately 200g, but by using a hollow titanium (casting) construction, the clubhead is commonly considerably bigger, with mass concentrated around the periphery of the face. The net result are driver clubs that manufacturers claim provide greater distance and straighter shots (Shira and Froes, 1997).

<u>Clubhead</u>

A major breakthrough in golf equipment occurred with the introduction of hollow titanium (Ti) driver clubheads (Shira and Froes, 1997). Titanium-headed drivers first emerged onto the commercial market in 1995 (Daly, 1996). The design, which was hollow and large in volume, gave the clubhead a high moment of inertia, thus larger than normal clubface area where efficient impact could be made with the ball. Therefore golfers could gain an increased tolerance to mishits, via reduction in ball sidespin, as those shots that did not strike the clubface in its centre would be influenced by decreased rotation of the clubhead around the shaft pivot (gear effect) (Froes, 1999).

Shaft

Advancement of materials science, particularly polymers used in a wide range of medical, aerospace and industrial applications has seen the golf industry adopt and apply some of this technology to shaft design. Due to a good damping capability, a high stiffness-to-weight ratio and a high strength-to-weight ratio, polymeric materials have attracted the attention of the club designer. Composite carbon fibre, as is commonly used in modern shafts, has several advantages over the steel, and even graphite. It is possible to fabricate composite shafts to match individual swing types by adjusting the prepreg (preimpregnation- combination of mat, fabric, unwoven material) stacking sequence (Lee and Kim, 2004). Furthermore, the visco-elastic property of carbon epoxy composites allows the golf shaft to closely match its flex and torque characteristics to the golfer's swing so that the shaft experiences less flex for harder swings. This characteristic enables increased deflection recovery rate of the shaft, ensuring that the golfer's hands and the clubhead reach impact position at the same time, reducing effective torsional stiffness (torque) and providing a more stable club face thus a straighter shot (Lee and Kim, 2004). Lee and Kim (2004) suggested that only golfers with a very aggressive downswing, a delayed wrist release and a peak clubhead velocity in excess of 53 ms^{-1} (c. 120 mph) should consider a torque measurement under 2.5 degrees. Generally, torque varies between 1° and 5°, and the lower the torque the stiffer the shaft will feel.

Customisation and design of carbon fibre as applied to golf club shafts has reached an advanced level. Thinner but stronger sheets of carbon fibre are commonly used which applies more polymer fibres than epoxy resin filler. This means that a process that used 10 plies of graphite 0.1mm thick can now use 20 sheets that are 0.05mm thick. And wrapping the sheets in various patterns has been shown to produce the subtle differences in the way a shafts bend during the downswing. Huntley *et al.* (2004) experimentally tested a number of carbon-fibre composite (CFC) driver shafts for bending frequency and microstructural characterisation, and found significant variation in results for repeated testing of a number of shafts of the same type. Difference were thought to result in two to three metres variation in drive distance.

Difference in shot performance may also be observed for different types of golf ball. Whilst of apparent simplicity, few pieces of sports equipment have been subjected to the level of study as has the golf ball.

<u>Ball</u>

Balls are now constructed using a variety of materials in a range of methods, as manufacturers attempt to provide both the professional and amateur markets with balls that achieve more desirable flight characteristics. Researchers have examined the material and club/ball impact effects on drive distance with consideration of ball dimples and spin characteristics, drag properties, launch characteristics (impact efficiency, spin, launch angle), and ball/turf interaction. For example, materials advances means that materials with varying degrees of hardness can be combined to produce a certain impact 'feel' or flight characteristic.

Manufacturers have strived to develop balls that provide the optimal flight characteristics depending on impact velocity and spin rate. Aoyama (1990) examined lift and drag for balls for drop tests, showing that lift and drag coefficients were lower for icosahedron dimple patterns than low-dimple anti pattern balls. Smits and Smith (1994) used wind tunnel testing to develop an aerodynamic model of the ball, following on from work at the USGA Research and Test Centre (Far Hills, New Jersey) which demonstrated the benefits of indoor testing for obtaining high quality data for ball flight characteristics (Zagarola *et al.*, 1994).

2.2 Performance measures in golf

How a golfer performs on the golf course in competitive situations, or under test conditions on the range or in the laboratory can vary depending on the performance criteria. During the game itself, drive distance, drive accuracy, approach accuracy, and putting are all needed for good overall performance, combined with athletic skills such as strength, agility, coordination, and endurance (Geisler, 2001). For the purposes of driver testing, however, most research in the area has focused on the inference that increases in peak clubhead velocity will also increase drive distance. Both theoretical studies (for example Sprigings and Neal, 2001; Nagao and Sawada, 1973; Mizoguchi and Hashiba, 2002; Reyes and Mittendorf, 1999) and experimental studies (including Egret *et al.*, 2003) have shown this to be the case. Each study has purported that increases in peak clubhead velocity or ball velocity immediately after impact may benefit a golfer's game due to an increase in drive length. None of these studies, though, have combined an investigation of laboratory clubhead or ball speeds, with outdoor drive distance measurement and dispersion accuracy measurements.

Olsavsky (1994) and Werner and Greig (2000) included ball launch characteristics in their studies, presenting data that showed variation in ball spin, launch angle, and ball velocity. The inclusion of consideration to golfer handicap, carry and dispersion descriptives and clubhead and ball launch characteristics would also be useful in assessing overall drive performance.

2.2.1 Handicap

There remains a question surrounding the validity of investigations concerning anything other than elite level golfers. On one hand, it could be said that the best data pertaining to variation in shot performance due to different club parameters are obtained by using only elite golfers, or category 1, being less than 5 handicap. This helps to reduce performance deviation, and inter- and intra-subject variability as the golfers are generally more skilled and able to reproduce quality shots more easily. However, such is the nature of golf, variability is pervasive throughout the multiple levels of movement organisation and occurs both within and between individuals. Variability exists because of the many complex systems and constraints that must interact in order to produce movement and is a direct result of the degree-of-freedom coordination problem expressed by Bernstein (1967). Variation in the structure or function of biological systems within an individual, interacting with the constraints provided by the task, the environment, and the individual's psychological state at the time of movement execution, contributes to movement variability (Higgins, 1977; James and Bates, 1997). Highly skilled acts are characterised more by the consistency of their output or results than by the consistency of the muscular contractions needed to achieve them. Whenever it is the aim to hit the golf ball with the driver, the hands and club will come at it from a slightly different angle each time, even if it is just a fraction of a degree variation. Similarly, depending on the lie of the ball on the fairway and the level of the turf, an iron shot can be perfectly executed without having to adopt exactly the same body position as the last iron shot that was performed.

However, elite golfers constitute only a very small proportion of the golfing population and several researchers have studied groups of non-elite golfers to study variations in swing kinematics and kinetics, impact characteristics, and shot performance. Williams and Sih (2002) recruited 28 golfers with handicaps from 0 to 36 (24 males and 4 females) to study clubface orientation at impact whilst golfers used a driver and 5 iron and 2 different types of spiked shoes. There was found to exist a wide range of results for measures such as clubhead velocity prior to impact (± 5.7 ms^{-1}), dynamic loft angle (± 4.14°), clubhead orientation (open/closed ± 5.43°) and angle of swing plane (± 3.89°). They concluded that it would be worthwhile to later examine a more limited set of players (lower handicap) to further study launch characteristics and clubhead orientation. Furthermore, Mizoguchi and Hashiba (2002), in their study to match individual swing motion to shaft length, a wide range of handicaps were used, ranging from male golfers of 0 to 5 and 15 to 25 handicap, and female golfers without handicaps and classified as 'skilled' and 'unskilled'. It was shown that lower handicaps and unskilled golfers were not as able to demonstrate the technique needed to differentiate between clubs of different length as well as more skilled golfers. They showed a weaker correlation between increases in peak clubhead velocity with shaft length, thus raising the question whether testing on less skilled golfers is able to distinguish between intra-subject deviation and actual shots differences due to the club. Wallace *et al.* (1990) also highlighted the deviation in shot performance between high and low handicapped golfers, for foot to ground pressure patterns. Two subjects were examined using two force platforms, one subject with a handicap of 6, the other of 24. The high handicapped golfer showed higher standard deviation between trials for 4 of the 6 measures (top of backswing, mid downswing, impact, and follow through pressure), but a one-factor

ANOVA showed no significant difference between trials for either player. The need for larger numbers of subjects in future studies was noted.

The use of elite golfers, however, in academic research into the golf biomechanics and club engineering studies, are more common. Lindsay *et al.* (2002) recruited 44 male professional golfers to study trunk motion when a driver and 7 iron was used. Roberts *et al.* (2005) used 15 elite golfers (including two European Tour professionals, 5 club professionals, 1 assistant professional, and 5 amateurs with handicaps from +2 to 2) to evaluate the vibrotactile sensations in the feel of a golf shot. Subjective measurements of feel (hard/soft, vibration levels, impact speed) and objective accelerometer vibration levels were recorded. Good correlation was found between mean subject results for vibration levels. Additionally, in their study of the 3D kinematics of the golf swing for a driver, five iron and pitching wedge, Egret *et al.* (2003) examined the swings of seven male golfers with handicaps ranging from 0 to 3. Inter- and intra-subject variability was shown to be relatively small, with only one subject demonstrating high deviation for average peak clubhead velocity.

Fradkin *et al.* (2004) conducted a study to examine how well clubhead velocity correlates with golf handicaps. 45 male golfers volunteered for the study, aged 18 to 80 years, and with handicaps ranging from 2 to 27. 13 golfers fell within the 2 to 10 handicap range, 14 within the 11 to 20 range and 18 in the 21 to 27 handicap range. A high-speed camera operating at 250 Hz recorded ten swings of the golfer's own five iron. A very strong linear relationship was found between golfers' mean clubhead velocity at impact and handicap ($p<0.001$, $r = 0.950$). As handicap increased, clubhead velocity at impact decreased. An equation was derived (Equ. 2) whereby, using the 45 golfers studied, clubhead velocity could be derived from handicap, thus:

$$\text{Mean clubhead velocity} = e^{4.065 - 0.0214 \times \text{handicap}} \qquad \text{(Equ. 2)}$$

They concluded that the strong relationship between handicap and clubhead velocity suggested that handicap is a valid measure of a golfer's performance, in the laboratory setting. The study also showed intra-subject variance of between 1.2 ms^{-1} and 4.1 ms^{-1}

for clubhead velocity for the 10 shots that each golfer performed, increasing as handicap and age of the subject increased.

2.2.2 Carry & dispersion

US PGA Tour and the European Tour statistics that are commonly presented concern golfers' average drive accuracy and distance. Average drive distance by the PGA Tour's top 30 longest drivers has increased by 35.5 yards since widespread measurements began in 1980, to the present day (calculations based on 'golfweb' raw data performed 19th February 2006, see Figure 2.2). Concomitantly, driving accuracy, that is the percentage of shots that land on the fairway has not demonstrated an equivalent increase (Figure 2.3). In fact 2006 PGA Tour statistics for the top 30 most accurate drivers show a poorer average than 1980.

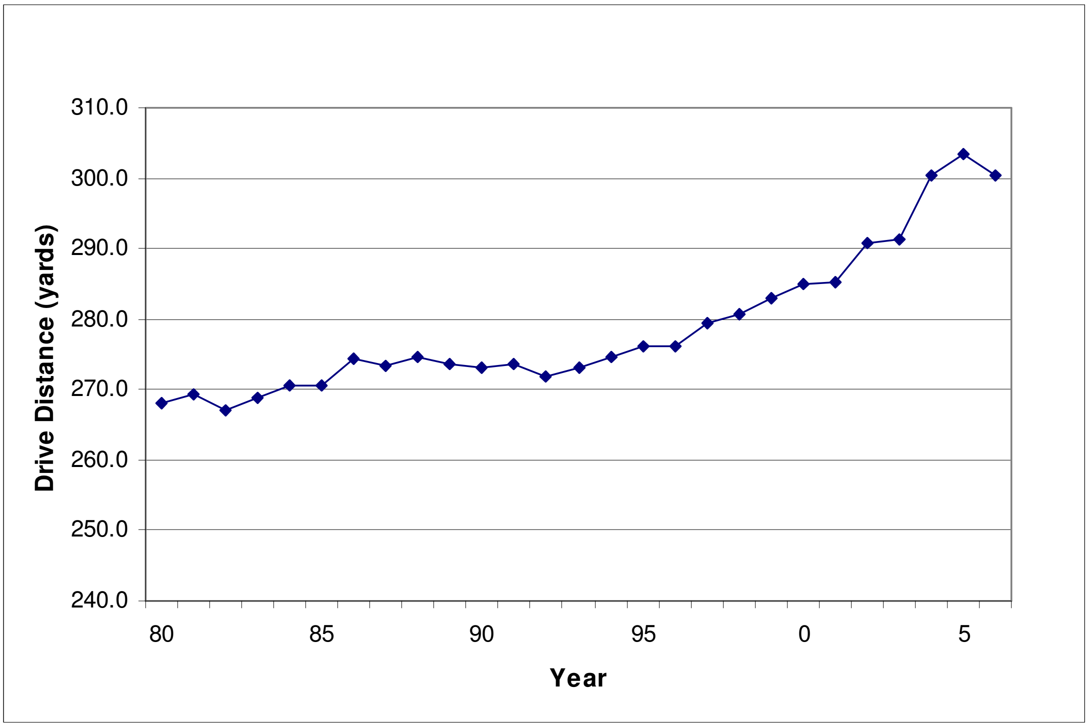

Figure 2.2 PGA Tour top thirty golfers' average drive distance

(Derived from data available at www.golfweb.com)

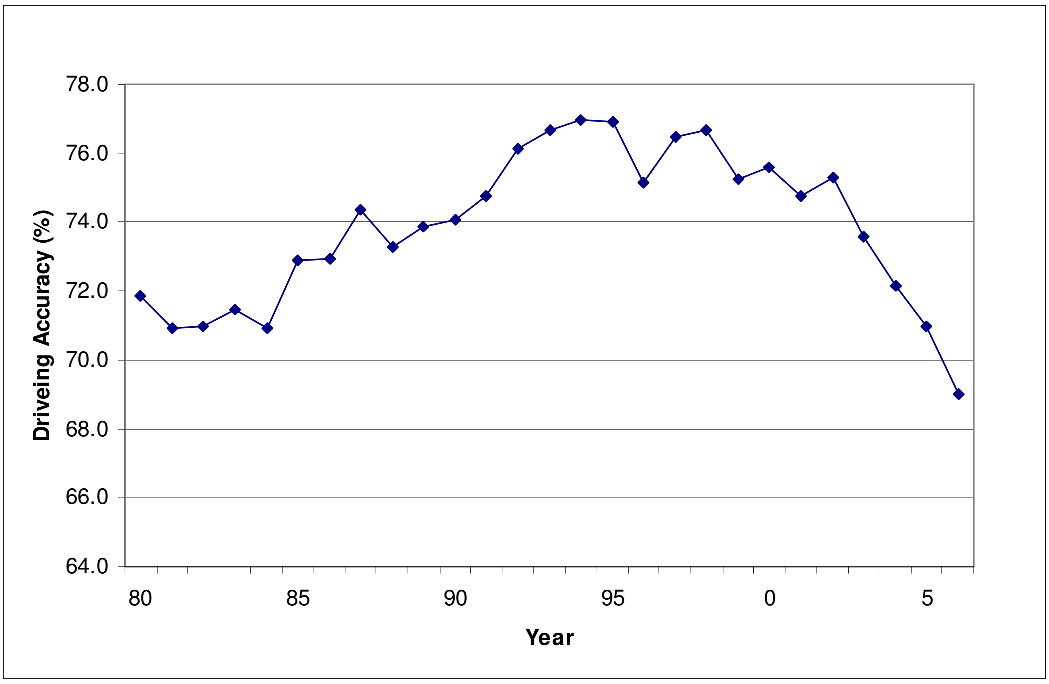

Figure 2.3 PGA Tour top thirty golfers' drive accuracy

(Derived from data available at www.golfweb.com)

Figure 2.3 shows that driving accuracy increased significantly from 1980 to 1995 (76.9 % maximum), after which it seems to have decreased rapidly to 69.0 %. It would seem, therefore, that accuracy had been sacrificed in the pursuit of distance gains in the golf drive. However, it should be noted that scoring average by the top 30 golfers in the PGA Tour in 2006 (up to 15.8.06) was lower than it was in 1996 and 1986, with scores of 69.98 ± 0.37, 70.16 ± 0.30 and 70.76 ± 0.27 respectively (derived from data available at www.golfweb.com).

2.2.3 Clubhead & Launch characteristics

The flight of a golf ball is influenced greatly by ball launch conditions of initial ball velocity, ball backspin and launch angle (Moriyama *et al.*, 2004). The path the ball takes depends on the nature of the clubhead and ball impact characteristics, which includes clubhead velocity, clubface loft, clubface orientation (open or closed), impact point (in relation to the heel/toe/sole/crown), ball spin (backspin and sidespin component), and ball launch angle (rise) and side angle (deviation). Williams and Sih (2002) examined a number of these components in their investigation of changes in clubface orientation following impact with the ball. 28 golfers with handicaps ranging from 0 to 36 each hit 14 shots with a driver and a 5 iron in an indoor testing facility where a MAC^{TM} Motion Analysis System operating at 200 Hz tracked three markers attached to the clubs which defined the local coordinate system based in the club. Clubface orientation angles (loft, open/closed), ball impact position on the face, clubhead swing plane, and clubhead velocity and ball velocity after impact were determined. Significant inter-subject differences were found for clubface orientation, loft angle and clubhead and ball velocity for both clubs. It was noted that a more limited set of players, of lower handicap, would need to be examined to specifically address clubface orientation changes and shot performance.

2.3 Limitations to previous club effects studies

Previous research has concentrated mainly on inferring drive distance via clubhead velocity and launch characteristics (Mizoguchi and Hashiba, 2002; Egret *et al.*, 2003), or predicted measures of drive distance (including Reyes and Mittendorf, 1999; Cochran and Stobbs, 1968), whilst only one it seems has looked at accuracy of the drive as well (Werner and Greig, 2000). With the apparent diminution in drive accuracy that PGA statistics show (Figure 2.4), a detailed investigation of the determinants of accurate drives, and inter- and intra-subject variability is warranted. Studies utilising a golf robot, whilst eliminating human error and variability, does not replicate the whole swing as a golfer would perform, including variation in grip torque input, vibrotactile feedback and uncocking of the wrists during the downswing. Furthermore, the follow-through performed by the golf robot differs from that of the golfer's in that deceleration of the clubhead is often greater by the robot, resulting in greater stress on the club shaft, thus differences in clubhead orientation following impact. Furthermore, few studies have examined the effects of drivers alone, nor the effects of variations in driver physical properties, either on the range or in the laboratory. The present study will address both, investigating the effects on launch conditions, of variations in driver shaft length both in the controlled laboratory environment, and on the range in a more realistic situation.

In addition, there appears to be a lack of clear protocol as to the population to whom researchers should be examining when investigating the effects of alterations in club physical characteristics. It is important to examine the effect that changes in club characteristic will have on different handicapped golfers, but to ascertain that intra-subject variability is not accounting for any change in shot performance detected, rather than the desired club variable, is important. Furthermore, the nature of golf, and the nature of human movement, means that no two golfers will exhibit exactly the same swing, therefore it can prove useful to examine single subjects, particularly highly skilled performers with little inter-trial variation. Indeed, single-subject analysis is adopted for Study 4 to develop a subject-specific model (as called for by Hatze, 2005).

Lastly, there seems to have been a lack of relevance placed on the possible effect of swingweight with alterations on shaft length from several studies. Whilst swingweight matching is not absolutely necessary to compare driver length effects, it should be taken into account and reported, with reasons given explaining why matching swingweight was or was not carried out.

2.4 Co-ordination in swing patterns

The general sequence of muscle stimulation patterns has been investigated in a number of studies (including Bobbert and van Ingen Schenau, 1988; van Ingen Schenau *et al.*, 1987). These authors all indicated that the initiation of muscle activation occurs in a coordinated proximal to distal direction. The term 'coordination' may be defined in the following ways:

1. 'The concerted action of the muscles in producing the movement. And as such, it is ultimately determined by timing, sequencing and amplitude of muscle activation' (Bobbert and van Ingen Schenau, 1988).

2. An alternative to the aforementioned computational approach to coordination is that inspired by Bernstein (1967), who suggested that coordination is 'the result of mastering the redundant degrees-of-freedom of the action system in order to conserve only those that are functional for the realisation of the task'.

According to Bernstein (1967), the musculoskeletal system has a large number of degrees of freedom, which allow goal-directed tasks to be accomplished in a variety of ways. As stated above, both the task and mechanical constraints help to reduce the large number of degrees of freedom to a clearly recognisable and relatively invariant movement pattern. When learning a novel motor problem, the subject can resolve the problem by rigidly fixing (freezing) certain components and/or strongly coupling their displacements, thus reducing the number of initial degrees-of-freedom. In the course of practice, these couplings could then be relaxed to permit more economical coordination through the use of the internal and external forces acting on the system. These hypotheses formulated by Bernstein have been confirmed by one study in which the subjects had to acquire a novel cycle or discrete coordination pattern (Temprado *et al.*, 1997). Latash *et al.*'s (2002) study reported that "an essential feature" of a coordinative structure is that if one of the component parts introduces an error into the common output, the other components automatically vary their contribution to movement organisation and minimise the original error. It is apparent that Bernstein's definition of coordination places the emphasis on the conceptual, cognitive aspect in contrast to Bobbert and van Ingen Schenau (1988), who concentrate on the learning or examining of simpler movement tasks. The present study will adopt the computational approach of Bobbert and van Ingen Schenau (1988) to analyse the data because it fits the purpose and conditions of the protocol used here.

Coordination of the golf swing, a relatively simple and repeatable movement, involves the correct sequencing positioning of the body. It may be examined and is evidenced via temporal factors, the kinetic chain, segmental contributions, muscular and neural input, and simple analogies such as the X-factor and pendulum movements.

2.4.1 Kinetic chain

The kinetic chain action involves the initiation of the golf swing with the legs and hips, followed by movement of the trunk and shoulders, and finally the hands and wrists.

> *"If executed correctly, the amount of kinetic energy is greater than the sum of the parts (i.e. there is summation of forces)"*
>
> (Hume *et al.*, 2005, pp435)

Correct initiation concerns the movement of the correct body parts in the correct sequence and with a temporal pattern that suits the swing type. A skilled golfer can use centripetal force and the maintenance of angular momentum[4] to help achieve maximum clubhead velocity (Milburn, 1982). In an investigation of segmental velocities in the golf swing, Milburn (1982) represented the downswing phase as a double pendulum pivoted at the shoulder joint (upper segment) and hinged at the wrist to the lower segment (the club). Four golfers were studied (3 'university players' and 1 low-handicapped club golfer) whereby a series of drives were recorded by a high-speed camera operating at 300Hz. Known coordinates of the left shoulder, left wrist and heel of the club determined arm and club length. Derivation of linear kinematics from analysis of the videos of drives by the golfers produced results for angular displacement and linear velocity. It was concluded that an initial delay in the uncocking of the wrist (alteration of temporal and segmental activation) would allow:

i. Greater acceleration of the arm
ii. Acceleration of the club to be summed with the existing angular acceleration of the proximal segment

The ability of the body segments to combine, force originating proximal to create optimum distal acceleration and clubhead velocity at impact, has received attention from researchers via experimental kinematics, kinetics, computer and mathematical modelling, and physiological testing. Greatest clubhead velocity has been reported as achieved in three ways:

i. Greater muscular force applied through limb segments
ii. Increased distance over which the force acts
iii. The number of segments that are brought into action and the sequence in which they contribute to the final velocity

(Milburn, 1982, pp60)

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[4] $H = mk^2\omega$, angular momentum of rotating body, H equals body's mass, m, times the square of the distribution of mass with respect to axis of rotation, k^2, times angular velocity of body.

These three factors interact whereby the third factor influences the first two and require coordination via sequencing and timing of the body. In considering the third factor, the ability to develop force, and that the contribution of several segments aid the summation of forces, Footnote 4 details the conservation of momentum for a rigid lever and single rotating object. However, if summation of forces are to be considered and the action of wrist cocking and uncocking, for example, included, then the principle of conservation of momentum for a multisegmented object applies:

$$H = I_s \omega_s + mr^2 \omega_g \qquad \text{(Equ. 3)}$$

where the conservation of momentum, H, equals a segment's moment of inertia, I_s, times the segment's angular velocity, ω_s, in local terms, added to the segment's mass, m, times the distance of the segmental centre of gravity from the total body centre of gravity squared, ω^2, multiplied by the angular velocity of the segmental centre of gravity about the principal transverse axis, ω_g. Figure 2.4 schematically illustrates the principle.

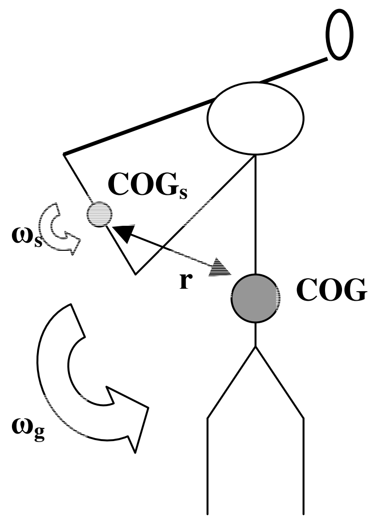

Figure 2.4 Schematic representing the sum of angular momentum of given body segments. Angular momentum of the swinging forearm is the sum of its local term, I_s ω_s, and its remote term, mr^2 ω_g.

The sequencing of movement that best induces conservation of momentum in this manner involves rotation of the legs, then hips, trunk and shoulders around the longitudinal axis of rotation, followed by the upper and lower arms and hands rotating about their own transverse axis of rotation. Optimisation calculations have confirmed that maximum clubhead velocity is achieved when torque generators, or muscular innervation, commence in sequence from proximal to distal (Sprigings and Neal, 2000). Sprigings and Mackenzie (2002) also examined the delayed release (wrist uncocking) in the golf swing via a computer simulation, noting that the main source of power delivered to the club in the swing originated from passive joint forces created at the wrist, but that sequencing of forces meant that the shoulder joint delivered the greatest power (800W) followed by the wrists (600W) and the torso (390W). Linear contribution of joints to the golf swing has been determined using three dimensional analysis and suggests the major contribution comes from the wrists (70%) and shoulders (20%) with lesser contribution from the hips (5%) and spine (5%) (Milburn, 1982), at least in terms of power.

Further examination of the interactions and sequencing of the golf swing was carried out by Burden *et al.* (1998) as they investigated the hip and shoulder rotations during the golf swing for eight sub-10 handicap players. Two genlocked video cameras operating at 50 Hz filmed hub movement of subjects within a calibrated volume in an outdoor testing facility. Twenty one anatomical landmarks (surface markers) were digitised defining a 14-segment model and points on the club and ball. Results concentrated on hip angle (horizontal plane joining hip centres and a line parallel to the y axis between the tee and the flag), shoulder angle (horizontal plane between a line joining the glenohumeral joint centres and a line parallel to the y axis between the tee and the flag), and the position of the centre of mass (location of whole body centre of mass in the horizontal plane in relation to its location at address). Results were analysed for the discrete positions during the swing for address, backswing, top of backswing, downswing, impact and total swing. It was noted that 70% of golfers' (n = 6) shoulder rotation was completed after the hips initiated downswing, thus adhering to the summation of speed principle. The principle, first described by Bunn (1972) states that, to maximise the speed of the club head at the distal end of the system, the golf swing should start with movements of more proximal segments and progress with faster movements of the more distal segments. Thus, in accordance with this principle, the peak velocity of hip rotation is followed by a greater peak velocity of the shoulder rotation during the downswing. And acceleration of the shoulders in the early part of the downswing serves to accelerate the club towards the ball and result in its maximum angular velocity close to the time of impact. (Burden *et al.*, 1998).

2.4.2 X-Factor

Differential rotation between the hip and shoulder rotations studied by several researchers has become better known as the 'X-Factor' (including McLean, 1992, 1993 and McTeigue *et al.*, 1994). McLean proposed that the differential between hip and shoulder turn at the top of the backswing was more important than the absolute shoulder turn (see Figure 2.5 for illustration of X-factor differentiation, 'α'), although this was demonstrated false in subsequent work. McLean demonstrated that that greater the absolute or relative X-factor, the higher a professional golfer was ranked on drive distance. The X-factor may be taken as the differential angle between the line joining the acromion processes and the line joining the left and right greater trochanter at the top of the backswing.

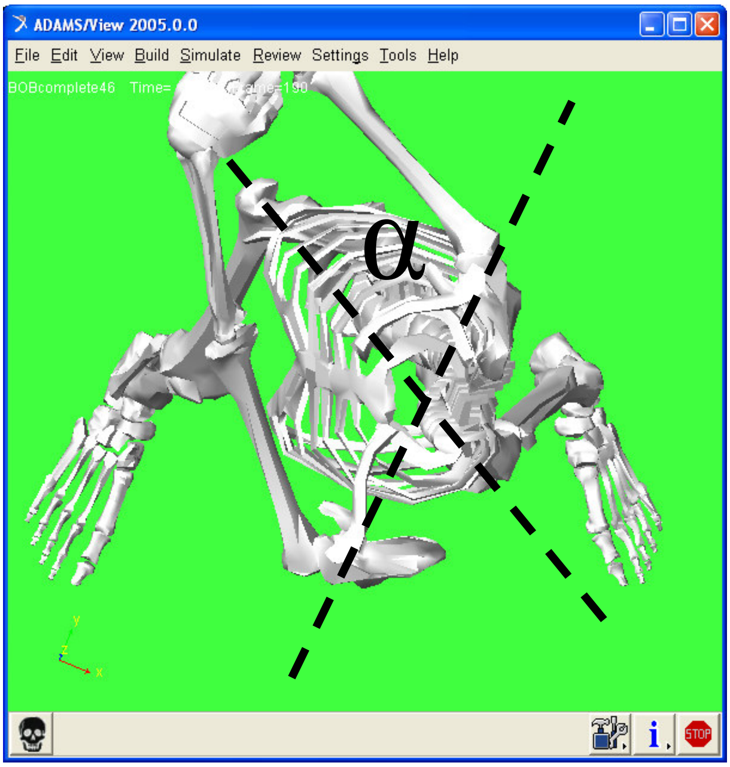

Figure 2.5 Model top view showing hip/shoulder angle differential (X-factor)

McTeigue *et al.* (1994) adopted a more rigorous scientific approach and quantified the X-factor further (McClean's initial article in Golf Magazine was based on collaborative work with McTeigue). One hundred and thirty one male golfers were recruited, incorporating 51 PGA Tour players, 46 Senior PGA Tour players, and 34 amateurs with a handicap range of between 5 and 36 and a mean of 17.5. A 'Swing Motion Trainer™' (SMT) housed a rate gyroscope and 6 potentiometers linked by lightweight rods and quantified the hip and shoulder turn differentiation.

Despite PGA Tour players displaying greater hip and upper body rotation angle differentiation, there was no clear correlation between specific torso position and excellence in driving distance or accuracy (fairways in regulation). Nonetheless, it was noted that the 10 PGA Tour players in the study that ranked in the top 50 in driving distance generated a mean 42% of their turn from the differential turn, compared to 35% for the rest of the study group (Table 2.2). However, differences were not deemed statistically significant. It was suggested that whilst the X-factor at the top of the backswing may have contributed to greater driving distance, the magnitude of the X-factor stretch seen in the early phase of the downswing possibly being of even greater importance to achieving optimum driving distance.

Further work by Cheetham *et al.* (2001) collected swing data using a 'SkillTec 3D-Golf™' system for 10 skilled (zero handicap or better including 8 professionals) and 9 less skilled (15 handicap or higher). The system which was strapped to the golfer worked on an electromagnetic sensing principle using transmitters and sensors placed at anatomical landmarks to compute position and orientation of each sensor in real time. Each golfer performed shots in a laboratory setting using a 5 iron. It was found that, on average, a direct contrast of the X-Factor means (hip/shoulder angle differential) at the top of the backswing showed no statistically significant differences between highly skilled and less skilled golfers. Less skilled golfers demonstrated a mean differential of 44°, with the highly skilled group showing a mean differential of 48°. In addition, Cheetham *et al.* studied the variation between hip and shoulder angle differential at the top of the backswing, and the apparent greater differential exhibited early in the downswing. The highly skilled golfers showed a 19% increase in the X-Factor due to the stretch at the beginning of the downswing and the less skilled golfers only a 13%

increase. For most golfers, immediately prior to the transition from the backswing to the downswing, the pelvis decelerates and changes direction to rotate forward whilst the trunk continues to rotate backwards. This early release of the hips towards the direction of the target was shown to increase the X-Factor significantly. It was noted that the X-Factor stretch facilitates force production and greater clubhead velocity at impact.

Table 2.2 Top of Backswing rotation angles

Subject Group	Rotation Angles (˚) $\mu \pm \sigma$ Upper Body	Hips	Differential (X-Factor ˚)
PGA Tour	87 ± 3	55 ± 3	32
Senior PGA Tour	78 ± 4	49 ± 3	29
Amateur	87 ± 4	53 ± 4	34

(McTeigue *et al.*, 1994, pp53)

The muscle stretch initiated by the early hip downward movement coupled with continuing shoulder backward turn is termed stretch reflex, or the stretch shortening cycle (SSC) and has been extensively investigated with regard jumps and rotational movement in sports (including Bobbert and Casius, 2005; Bobbert *et al.*, 1996, 1986; Bobbert and Van Ingen Schenau, 1988; Chalmers, 2004, Grey *et al.*, 2001). Chapman, 1985 and Komi, 1984 noted that the average and total mechanical work that a muscle can produce during a concentric contraction is enhanced if it is immediately preceded by an active pre-stretch (eccentric contraction). Enhancement in mechanical work output during the concentric phase associated with an active pre-stretch, in comparison to a maximum pre-isometric contraction, may be dependent on a number of eccentric loading strategies. Thus enhancement increases with:

i. Increases in eccentric loading.
ii. Increases in speed of stretching and shortening.
iii. Increases in the length to which the muscle is stretched .
iv. Decreases in amplitude of the stretch (independent of velocity of stretch).
v. Decreases in coupling time (eccentric to concentric contraction period).

The utilisation of an active pre-stretch enhanced force development during the concentric phase (CC phase) allows faster contractions at all force levels and a greater magnitude of mechanical work to be performed. Contraction enhancement increases with the speed of muscle stretch and shortening, and the length to which the muscle is stretched, whilst it decreases with long duration between stretching and shortening (coupling time). These enhancements are critically important because the SSC forms a typical muscular action, both in sporting and everyday movement.

Essential contributions to the enhancement of maximum work in SSC:

1. Storage and reutilisation of elastic energy

During countermovement, active muscles are pre-stretched and energy absorbed, part of which is temporarily stored in series elastic elements and later reutilised in the phase where the muscles act concentrically. This mechanism is sometimes referred to as "elastic potentiation" (Bosco *et al.*, 1981; Komi, 1992). Many researchers asserted that this helps to enhance the maximum work produced during the concentric phase (for example Asmussen and Bonde-Petersom, 1974a; Hull and Hawkins, 1990; Komi and Bosco, 1978).

2. Potentiation of the contractile machinery

It is well documented that the force produced by tetanised isolated muscle may be enhanced by a stretch to a value of up to twice the maximum isometric force (Ettema *et al.*, 1990; de Hann *et al.*, 1989). This enhancement, also called potentiation (Hill, 1970), has been shown to increase with the speed of stretch (Edman *et al.*, 1978, 1982) and to decrease with the amount of time elapsed after the stretch (Cavagna *et al.*, 1968; Edman *et al.*, 1978, 1982). If the muscle is quickly released after the stretch, it is able to shorten isotonically against its maximum isometric force. Thus, the capacity of the contractile machinery to do work is also enhanced.

3. Stretch reflex (spinal reflexes)

Movement, or motor control, is regulated by the central nervous system (CNS) utilising various forms of sensory feedback available from proprioceptors. These receptors contribute to a person's awareness of their body and its movements; this awareness has been termed kinesthetics. The proprioceptors are the muscle receptors which include the Golgi tendon organ (GTO) and muscle spindle (MS). The proprioceptive reflex in motor skills are generally controlled by the MS and GTO, their effects being facilitation, reinforcement or inhibition of muscle contractions (Lundin, 1985). The muscle spindles are widely distributed throughout muscle tissue. Each spindle consists of 5 to 9 intrafusal muscle fibres (IF), which do not contribute to the force of contraction such as the extrafusal fibres (EF) and are responsible for the development of external tension. The IFs are oriented parallel to the EFs within the muscle tissue. Due to their position within muscle tissue, an externally applied stretch results in a distension of the IF as well as the EF. The stretching of the IF evokes an afferent or sensory discharge to the spinal cord which causes a motor response, whereby the stretched muscle begins to contract with a corresponding inhibition of the antagonist muscle. This process is called the myostatic (or stretch reflex), which aims to control movement and maintain posture. The strength of a response by the MS to stretch is determined by the rate of the stretch; the greater and more rapidly a load is applied to a muscle, the greater the firing frequency of the MS with a corresponding stronger muscle contraction (Lundin, 1985).

4. Pre-stretch

Pre-stretch allows muscles time to develop a high level of active state and force before starting to shorten. In leg extension tasks, it may take 300-500ms before 90% of the maximal force is reached. If the concentric contraction starts as soon as the force begins to rise, part of the shortening distance of the muscle-tendon complexes travelled at sub-maximal force, and thus the work produced is sub-maximal (van Ingen Schenau *et al.*, 1997a). It is well documented that the force produced by the tetanised isolated muscle may be enhanced by a stretch to a value of up to twice the maximum isometric force (for example Ettema *et al.*, 1990; de Hann *et al.*, 1989).

Thus, the observations by McLean (1993), McTeigue *et al.* (1994) and Cheetham *et al.* (2001) that increasing peak hip/shoulder differential at the region of the top of the backswing has sound physiological theory supporting it.

It should be noted that the use of the acromion process, as the aforementioned studies utilised, should be treated with caution. Differences in reconstructed shoulder complex angle can be attributed to marker error caused by movement of the scapula. Stockhill & Bartlett (1996) warned of the dangers associated with using acromion process markers to calculate shoulder alignment during nine different shoulder positons. Subjects were secured to a chair with the aim of allowing maximum glenohumeral joint and scapular movements, while preventing spinal twist below the seventh thoracic vertebrae. Results showed that three-dimensional digitisation of the acromion process contained errors up to 30°. However, Elliot *et al.* (2002) in their investigation of shoulder alignment during cricket fast bowling found a mean interclass correlation coefficient of 0.97 between the projected transverse plane three-dimensional shoulder and thorax alignments when acromion process markers were used. They concluded that thorax alignment, as was investigated in the current study for the golf swing (X-factor acromion processes-pelvis differential), may be reasonably estimated using a three-dimensional reconstruction of a line joining the acromion processes.

2.4.3 Neuromuscular input to consistency

There are two current approaches most commonly implemented to understand motor control mechanisms. One looks at understanding what specific neural mechanisms are responsible for motor behaviour. Alternative approaches involve assessment of kinematics and variables used to describe the behaviour of dynamical systems theory[5] (Glazier *et al.*, 2003). Alternative approaches have been investigated to a greater extent, particularly in the sports sciences, however, underlying mechanisms to movement patterns has historically received little attention, rather in science it is more straightforward to study the obvious, descriptive characteristics, such as temporal and state space and exhibited forces. It is more common to investigate what is happening than to delve into the mechanisms of how something happens. Obvious conclusions are commonly drawn, such that ‘people who exhibit high muscular strength tend to look like they have big muscles, therefore, big muscles must be the determinant of muscular strength’. However, this kind of statement is incorrect in that research has told us that there exists practically no relationship between movement velocity and maximal strength (including Smith, 1970; Lagasse, 1979). The relationship between muscular force and muscle size has been shown to often be quite poor, with correlations as low as r = 0.3 (Young *et al.*, 1985, in Kamen, 2004).

[5] Dynamical systems- movement patterns emerge through generic processes of self-organisation found in physical and biological systems (respiratory, circulatory, nervous, skeletomuscular).

Knight (2004), rather than take the perspective of golf analysis to be simply descriptive kinematics in nature and performed until the swing is invariant, presented a paper whereby they take the perspective that variability is inherent in the game and the golf swing.

> *"Based on dynamical systems and motor control schema perspectives, it is argued that golfers can learn a more reliable swing by exploring swing parameters and focusing on higher order control principles that reduce the vast number of degrees of freedom."*
>
> (Knight, 2004, pp9)

It is thought that the effective golf swing is sought in the reckoning that if the aim is reduced variability in ball contact characteristics throughout the practice and learning phase, the resulting kinematics that creates these conditions will follow. The ability to develop an effective golf swing is based on minimising variability in the outcome performance, but the stability of the swing rests in the ability to solve this complex motor problem (managing redundant degrees-of-freedom) rather than in a single solution. Anecdotal and scientific literature is replete with references to the relationship between muscular strength and various muscle characteristics, such as contractile characteristics, muscle size, myosin adenosine triphosphatase enzymatic concentrations and other muscular factors. However, it is now evident that a number of neural factors are also involved in the expression of large muscular forces. Evidence of this concerns the observation that muscular strength increases rapidly following just one or two training sessions during which muscle fibre size has not changed (no hypertrophy). 15% increases in just a few days have been reported (for example by Kroll, 1965; Kamen, 1983; Schenck and Forward, 1965). Therefore, the control and coordination of movement appears to matter more in skilled exercise such as the golf swing, than does muscle size. Whilst similarly skilled golfers differing in muscular strength would be expected to develop different levels of hub and clubhead velocity at impact, thus different drive lengths, variability and maintenance of accuracy should be of foremost importance and the correct technique may aid further drive distance than would increases in muscle size and strength.

In order to understand the nature of human movement and thus develop an appropriate research methodology, it is important to first understand some of the more important factors that influence and affect behavioural, in this case the golf swing, observations. Such factors are: movement constraints, human variability, response patterns, and aggregation. Primarily, Bernstein (1967) pioneered the proponents of the constraints that exist and influence human movement. These constraints included biomechanical, morphological and environmental factors and interaction of all three as they affect all human movement outcomes. Higgins (1977) defined biomechanical constraints as limitations imposed on the human system by physical laws, i.e. gravity, friction. Morphological or anatomical constraints are those limitations imposed on the system as a result of the physical structure and psychological makeup of the individual. Environmental constraints are considered the result of extraneous factors that affect performance, including personal arousal, crowd response, lighting and temperature. These all affect intrinsic responses.

Operating over all of these constraints is the objective of the movement, termed the task constraint. It is this constraint, in conjunction with experiences and memory that most directly dictates the responses of the individual. That is, the task constraint refers specifically to the goal of the movement, namely the appropriate clubhead-ball impact. If one is trying to run fast then speed is optimised, versus running endurance. If one is trying to move a large, heavy weight, then strength is optimised, versus fine motor control of the phalanges. In short, the constraining nature of the task to be performed dictates the contributions of the remaining three constraints and subsequently produces a movement pattern that can be repetitive or variable, given the experience and prior knowledge of the performer. The system is functionally pliable (e.g. volition, learning, perception, growth and development) are possible within the bounds of the imposed constraints, allowing for a seemingly infinite number of movement outcomes or solutions to any movement task. Bates (1996) suggested that although the system has a considerable number of degrees-of-freedom, the number of functional degrees-of-freedom (choices) is “seemingly infinite”.

Colonel John Stapp (1971) described man as an obstinate and irregular object. “*This fifty litre rawhide bag of gas, juices, jellies, gristle, and threads movably suspended on* *more than 200 bones presided over by a cranium, seldom predictable and worst of all living, presents a challenge to discourage a computer into incoherence*"

(pp115)

The result of this structural complexity is an even more complex functional system that is inherently variable. Newell and Corcos (1993) stated that variability is inherent within and between all biological systems and is the result of interactions among the structural and functional characteristics of the system and the constraints imposed on motion. Highly skilled acts are characterised more by the consistency of their output or results than by the consistency of the muscular contractions needed to achieve them.

Variation in the structure or function of biological systems within an individual, interacting with the constraints provided by the task, the environment, and the individual's psychological state at the time of movement execution, contributes to movement variability (Higgins, 1977; James & Bates, 1997). Variability is believed to be an emergent property of the self-organising behaviour of the non-linear dynamical properties within the neuromotor system (Turvey, 1990). The biological variability present within the neuromotor system is believed to be a function of both the deterministic evolutionary processes of the movement and error.

Concerning the golf swing, it would be natural to assume, following the discussions of those researchers that have been mentioned previously, that the biomechanical analyses said to be open to measures of error due to variability of movement will include variation in the swing of even highly skilled golfers both within- and between-subjects.

2.5 Anthropometric considerations

Brozek first developed techniques for assessing body composition in 1956 and his techniques remain to this day the most popular method for studying nutritional changes and dietary therapy in clinical studies (Bastow, 1982). Additionally, modern surface anthropometry arose from the late nineteenth-century via anthropology, which was concerned with skeletal classification and description, in the main to characterise racial differences. Current anthropometric practices, such as landmarking follow the same principles and is most often used to determine bone lengths in individuals and/or populations (for example Zhang *et al.*, 2004; Kasarskis *et al.*, 1997). However, landmarking as a method via which to infer segment length is not without inaccuracies despite remaining the most popular method. The International Society for the Advancement of Kinanthropometry (ISAK) highlights the problems associated with bony landmarks that in many individuals are common places for fatty deposits leading to problems in identification of the bony landmark for the investigator. The trochanterion landmark is one such landmark. It is extremely hard to locate the superior point on the greater trochanter (hip) on a living human, because of various muscle attachments and common high levels of subcutaneous adipose tissue (Olds, 2004), yet this landmark gives the best estimate of femur length and remains to be used.

Godoy *et al.* (2005) used physical stature, weight, and body mass index (BMI) to assess anthropometric variability in the USA from 1971 to 2002 (four pools studied during 1971-1975, 1976-1980, 1988-1994 and 1999-2002, using the same selection criteria), utilising measurements determined from bony landmarks. The landmarking that was used provided good data with very low levels of variability. In sports-related studies, Russell *et al.* (1998) used anthropometric, as well as metabolic and strength variables to predict 2000m rowing performance in elite schoolboys. For 19 elite schoolboy rowers, anthropometric variables of standing height, body mass, and skinfold measurements were recorded to calculate BMI. Body mass in particular, was shown to correlate well ($r = -0.41$, $p<0.05$) with 2000m performance time.

Lesh *et al.* (1979) and Capozzo *et al.* (1988) described the biological errors that are apparent when analysing human body segment movement using a surface marker arrangement to represent joint centres and segment centres of mass (COM). An array of at least three markers per segment is needed for the definition of a segment embedded reference frame that represents the pose of the segment. Due to skin movement, the marker array displaces and rotates relative to the underlying bone. Skin motion is currently considered the bounding error source in evaluation of skeletal motion by opto-electric systems (e.g. MAC™) recording markers of the skin (Holden *et al.*, 1997; Reinschmidt *et al.*, 1997, 1997a). Holden *et al.* noted differences between bone-pin and surface marker results of up to 10mm displacement and 8° rotational error. However, Alexander and Andriacchi (2001) state that in most cases only large motions such as flexion-extension have acceptable error limits with skin-based marker systems, and whilst the use of bone-pin marker arrangements result in more accurate representation of the segment, this approach is necessarily limited. A balance should be struck between the acceptable error limits associated with surface marker arrangements, and the imposition perceived by the subject under investigation on the motion to be analysed.

The need for invasive methods (bone-pin markers) for biomechanical analyses in the assessment of basic joint function varies with the soft tissue situation. Where a thin soft tissue layer is firmly attached to the underlying bone (e.g. anteromedial surface of the tibia), passive skin markers reflect the movements of the underlying bone comparatively well. However, where soft tissues are thick (hip) or tend to move in relation to the bone (over the scapula) then skin markers will only reflect skin movement. Nonetheless, this also causes problems with placement and recording of motion using pin markers in that excessive soft tissue impingement (hip) may influence recorded motion, and stretching of the skin (scapula) may reduce range of motion and decrease comfort levels for the subject (Lundberg, 1996). The mere presence of testing equipment on the golfer was the concern for Egret *et al.* (2004) who investigated the effect of electromyographic equipment on golf swing kinematics, under the premise that experimental procedures often involve cumbersome equipment which is often restrictive and may hinder golfer's freedom of movement. The study indicated that the attachment of surface electrodes induces changes in muscle activity pattern, a result of reduction in joint rotation angles thus range of movement. Additionally, clubhead velocity decreased with the presence of surface EMG electrodes, from 42.2 ± 4.8 ms^{-1} to 39.5 ± 4.7 ms^{-1}.

2.6 Muscle function during the golf swing (Electromyography)

The synergistic action of muscles most greatly used in the action of performing a golf swing has been the focus of several electromyographic (EMG) studies. Most literature has focused on analysis of the shoulder and back (see Tables 2.3 and 2.4) with little attention paid to the lower extremity or forearms.

Table 2.3 Summary of golf EMG studies and the muscles investigated

Author(s)	Muscles studied
Bechler *et al.* (1995)	7 hip and knee muscles of both legs
Bradley & Tiborne (1991)	Shoulder muscles
Bulbulian *et al.* (2001)	Lumbar, external oblique, latissimus dorsi and right pectoral bilaterally
Glazebrook *et al.* (1994)	Flexor and extensor muscles of the forearm
Jobe *et al.* (1986)	Supraspinatus, subscapularis, infraspinatus, latissimus dorsi, pectoralis major, anterior deltoid, middle deltoid and right posterior deltoid
Jobe *et al.* (1989)	Pectoralis major, latissimus dorsi, supraspinatus, infraspinatus, subscapularis, anterior, middle and posterior deltoids
Kao *et al.* (1995)	Levator scapulae, trapezius, seratus anterior, rhomboids bilaterally
Lim (1998)	Rectus abdominus, external oblique, internal oblique and erector spinae
Moynes *et al.* (1986)	EMG review
Pink *et al.* (1990)	Shoulder muscles
Pink *et al.* (1993)	Abdominal oblique and erector spinae muscles bilaterally
Watkins *et al.* (1996)	Abdominal oblique, gluteus maximus, erector spinae, upper rectus abdominis and lower rectus abdominis bilaterally

Adapted from McHardy and Pollard (2005)

The researchers Pink, Perry and Jobe have worked extensively in this area, not only acting as lead authors in their respective papers (Jobe, Moynes and Antonelli, 1986; Jobe; Pink, Jobe and Perry, 1990; Pink, Perry and Jobe, 1993) but as contributing authors in several other papers (Watkins, Uppal, Perry, Pink and Dinsay, 1996; Bechler, Jobe, Pink, Perry and Ruwe, 1995 and Kao, Pink, Jobe and Perry, 1995). As such, methods used were very similar, recruiting 15-23 male golfers with handicaps of 5 or less (Kao *et al.*, 1995 and Pink *et al.*, 1993) or 7-13 professional male and female golfers, all right-handed.

Table 2.4 Summary of the muscles and muscle regions investigated during EMG studies

Upper body	Trunk	Lower body
Deltoids	Abdominal obliques	Adductor magnus
Levator scapulae	Erector spinae	Long head biceps femoris
Subscapularis	Latissimus dorsi	Semimembranosus
Supraspinatus	Rectus abdominis	Vastus lateralis
Trapezius	Rhomboids	
	Serratus anterior	

Adapted from McHardy and Pollard (2005)

Combining data for percent MMT (maximal muscle strength test) from Bechler *et al.* (1995) and from Pink *et al.* (1990) (Table 2.5) it is evident that greatest work is being carried out by the legs early in the downswing whilst the muscles of the arms, shoulders and upper trunk work closest to maximal late in the downswing immediately prior to impact (for professional golfers and golfers with a handicap less than five).

Variations in the golf swing are the result of variations in muscle activation patterns, not only as a function of MMT as these studies have examined, but by firing patterns and the coupling of stabilising muscles alongside the prime movers which are often difficult to examine using EMG. Musculoskeletal modelling is one way in which to more accurately investigate the problem.

Table 2.5 Example of mean (± s.d.) EMG (% MMT) activity at different swing phases

Muscle	Takeaway	Early downswing	Late downswing	Early follow-through	Late follow-through
Right leg (trail)					
Adductor magnus	17 ± 17	36 ± 29	30 ± 23	22 ± 19	17 ± 14
Upper glut max	20 ± 14	100 ± 55	28 ± 49	13 ± 18	11 ± 10
Lower glut max	16 ± 13	98 ± 43	27 ± 28	12 ± 13	7 ± 6
Glut med	21 ± 10	74 ± 36	51 ± 36	59 ± 37	22 ± 20
Bicep femoris (LH)	27 ± 27	78 ± 35	16 ± 21	7 ± 11	10 ± 11
Semimembranosus	28 ± 14	67 ± 37	17 ± 21	17 ± 25	7 ± 11
Vastus lateralis	25 ± 25	39 ± 49	40 ± 36	41 ± 32	40 ± 25
Left leg (lead)					
Adductor magnus	8 ± 8	63 ± 22	43 ± 25	36 ± 12	35 ± 19
Upper glut max	9± 9	50 ± 47	58 ± 61	47 ± 59	21 ± 15
Lower glut max	7 ± 4	50 ± 42	58 ± 63	39 ± 28	16 ± 31
Glut med	7 ± 8	36 ± 20	32 ± 24	20 ± 12	31 ± 26
Bicep femoris (LH)	23 ± 12	60 ± 43	83 ± 58	79 ± 67	41 ± 38
Semimembranosus	5 ± 4	39 ± 17	51 ± 31	45 ± 24	42 ± 24
Vastus lateralis	14 ± 13	88 ± 40	58 ± 50	59 ± 41	42 ± 25
Trunk/shoulder					
R supraspinatus	25 ± 20	14 ± 14	12 ± 14	7 ± 5	7 ± 5
L supraspinatus	21 ± 12	21 ± 15	18 ± 11	28 ± 20	28 ± 14
R infraspinatus	27 ± 24	13 ± 16	7 ± 8	12 ± 13	9 ± 10
L infraspinatus	14 ± 12	16 ± 13	27 ± 25	61 ± 32	40 ± 24
R subscapularis	16 ± 12	49 ± 31	68 ± 67	64 ± 87	56 ± 44
L subscapularis	33 ± 23	29 ± 24	41 ± 34	23 ± 27	35 ± 27
R latissimus dorsi	9 ± 7	50 ± 38	47 ± 44	39 ± 39	28 ± 19
L latissimus dorsi	17 ± 13	48 ± 25	31 ± 28	32 ± 33	18 ± 15
R pectoralis major	12 ± 9	64 ± 30	93 ± 55	74 ± 55	37 ± 35
L pectoralis major	21 ± 32	18 ± 14	93 ± 75	74 ± 74	39 ± 23
R anterior deltoid	5 ± 6	21 ± 23	10 ± 10	11 ± 15	8 ± 8
L anterior deltoid	13 ± 13	9 ± 9	10 ± 10	21 ± 25	28 ± 30
R middle deltoid	3 ± 3	2 ± 3	2 ± 5	6 ± 10	8 ± 8
L middle deltoid	3 ± 3	4 ± 6	2 ± 2	7 ± 9	5 ± 3
R posterior deltoid	17 ± 25	10 ± 15	9 ± 13	17 ± 16	11 ± 12
L posterior deltoid	5 ± 6	24 ± 20	11 ± 9	9 ± 9	9 ± 14

Adapted from Bechler *et al.*, 1995 and Pink *et al.*, 1990)

2.7 Variations in swing mechanics

James (1996) described the golf swing as an athletic movement involving the spine or trunk of the body as a link between the legs and arms, which connects to the golf club. With feet placed at shoulder width distance apart, the legs act as a platform around which the trunk can rotate. At address, ideally the body's position should be bent anterior at the hips. At the start of the swing the golfer rotates to the right (for a right-handed golfer) by coiling the trunk and turning the hips, shoulders and knees about the lower legs (James, 1996). Concurrently, the anterior aspect bend is maintained, body weight is transferred to the right foot and the head is kept steady. As the backswing progresses, the left arm is raised superior and swings across the trunk. On reaching the top of the backswing maximum elongation (eccentric contraction) of the lateral muscles of the trunk is obtained and swing direction is reversed by firstly initiating concentric contraction of the muscles of the pelvic region (hips) followed by rotation of the upper body (Burden *et al.*, 1998) and a shift of weight to the left side by moving the hips towards the flag whilst anterior aspect bend is maintained until the clubhead strikes the ball. Rotation continues to the left side during impact and follow-through and the spine progressively extends until a static reverse 'C' finish position us held with the majority of the body's weight on the left foot and balance maintained through the right metatarsals and phalanges (Cochran and Stobbs, 1996; Burden *et al.* 1998; Brampton, 1991; Owens and Bunker, 1992; Hume *et al.*, 2005).

Whilst the above description of the golf swing basically gives the actions required, no two golf swings are alike. There will always be differences in movement patterns between and within golfers, be that merely fractions of a degree or milliseconds (Bernstein, 1967). Swing timing is one aspect that appears to vary considerably.

> *"…the major downfall in actual competition (with its inherent stresses and pressures) is the failure to maintain proper timing."*
>
> (Libkuman *et al.*, 2002, pp78)

There remains little empirical literature concerning temporal aspects of the golf swing. Swing tempo refers to the overall speed of the swing and is inversely related to the overall duration of the swing (Jagacinski *et al.*, 1997). Recent research by Wallace *et al.* (2004) on driver shaft influences on posture and swing tempo in skilled golfers concluded that no matter what club was used, temporal ratios in terms of overall swing time were consistent, suggesting common relative phasing. They recruited 9 male skilled golfers (40.2 ± 12 yr, 1.80 ± 0.05 m, 83.7 ± 9.5 kg and 5.4 ± 2.8 handicap) who each performed 10 shots with each of 4 randomly assigned driving clubs (46″, 47″, 49″ and 52″) in an indoor testing facility. Drivers were specifically constructed for the study, matched for all physical properties except shaft length and swingweight, which naturally increased with driver length. Three dimensional coordinates of body and club motion were captured using a MAC™ 5 camera motion analysis system operating at 240Hz. It was found that total swing time increased statistically significantly with increasing club length (46″- 1.11 s, 47″- 1.14 s, 49″- 1.17 s, 52″- 1.23 s). However, the relative percentage times for the backswing (t_{bs}) and downswing (t_{ds}) were unaffected by club length (t_{ds} %: 46″- 26.4, 48″- 27.3, 49″- 25.9, 52″- 26.2). Wallace *et al.* also noted variation in stance width and feet-to-ball distance (increasing distances), right and left knee joint flexion angles at address and at impact, trunk inclination angles and left arm/trunk angle and hip and shoulder rotation angles at address, top of the backswing, and at impact. However, most results were statistically non-significant, shoulder rotation angle at impact, trunk inclination at each of the three discrete stages (address, top-of-backswing and impact) and feet-to-ball distance only proving significant, suggesting that overall, golfers attempt to maintain their normal body postural and swing characteristics when such variations as driver length are introduced.

Further research by Egret *et al.* (2003) suggested that for kinematic analysis of seven male elite golfers using a Vicon™ 5 camera motion analysis system operating at 50Hz, there were no significant changes in total swing time as club length varied. However the clubs used for their study were a driver, 5-iron and pitching-wedge rather than Wallace et al's. differing driver shaft lengths. Although, Egret *et al.* did report similar findings in that relative phase timings also did not alter significantly with club (shaft length). Egret *et al.* (2003) also reported that kinematics, for the golfers with a handicap of 0 to 3, were different depending of the clubs used. Stance width varied significantly across all clubs, and joint data (right knee joint flexion) varied significantly when other clubs data were compared to driver data.

In their study, Libkuman *et al.* (2002) investigated the influence of training in timing on performance accuracy in golf. 40 skilled golfers were recruited (female n = 6, male n = 34) to perform 60 shots in an indoors testing facility, 15 each with a driver, 5-iron, 7-iron and a 9-iron. Subjects were placed in either an experimental or control group, each completing pre- and post-tests, with those in the experimental group also involved in 10 hours of timing training between the tests. Training involved practice and tests using an Interactive Metronome® which relayed beats to headphones worn by the subject who subsequently were required to follow the beats by tapping on a foot pedal or triggering motion sensors in a hand glove. A 'Full Golf Swing Simulator™' measured clubhead and ball launch conditions and provided a simulation of each shot on a screen containing the fairway and flag view. Shot accuracy was the performance measure for pre- and post-tests and signified the final resting position of the ball from the flag- the smaller the distance the more accurate the shot. Results showed a correlation between improvement in metronome training tests times and shot accuracy. There was an improvement between pre- and post-test as a function of club and treatment group (Table 2.5). It was suggested that:

i. Timing training improved the golf swing by fine-tuning the timing properties (tempo and rhythm)
ii. Timing training made the coordination between participant's intention and voluntary movement more precise
iii. Improvement was an artefact of demand characteristics

However, accuracy for drives is not necessarily the displacement from the flag as Libkuman *et al.* defined it. The ball could be 50 yards lateral in the rough, and by this definition would appear to be a better shot than one where the ball lies 60 yards short of the flag but centre of the fairway. Table 2.6 presents a summary of the variation in temporal factors for the different stages of the golf swing as has been discussed.

Table 2.6 Summary of temporal aspect findings where club length was a controlled variable

Author (s)	Club	Total time (s)	Backswing time (s)	Downswing time (s)
Burden *et al.* (1998)	Own Driver	1.21 ± 0.14	0.95 ± 0.12	0.26 ± 0.05
Egret *et al.* (2003)	Own Driver	1.08 ± 0.04	0.81	0.26
	5-iron	1.09 ± 0.05	0.82	0.27
	PW	1.09 ± 0.04	0.81	0.2
Wallace *et al.* (2004)	Driver: 46″	1.11 ± 0.82	0.82 ± 0.16	0.29
	47″	1.14 ± 0.83	0.83 ± 0.16	0.31
	49″	1.17 ± 0.87	0.87 ± 0.18	0.30
	52″	1.23 ± 0.91	0.91 ± 0.18	0.32

It would seem that due to the contrasting results purported by various authors, that the effects of club length vary a great deal depending on the skill level of the golfers being studied. One way of removing this variable is for further theoretical investigation via modelling and computer simulation of the golf swing.

2.8 Biomechanical modelling & computer simulation

This section raises the importance of modelling of the human figure in general, and of the human body for sports applications in particular, and invokes the gap that remains to be filled concerning the understanding of human movement and interaction with a golf club during the swing. In theory, modelling consists of developing a representation of the properties of an object/phenomenon with respect to the goals of its analysis.

To date, much research has been carried out in the clinical setting to model the musculature and movement patterns of the upper limb (e.g. Maurel, 1998), whole-body anatomical modelling (e.g. Wilhelms and Van Gelder, 1997), dynamically modelling multi-body systems (e.g. Otten, 2003) and applied modelling studying the somersault rotation (for example King and Yeadon, 2004). Few researchers combine an experimental and theoretical approach, and fewer to date have applied biomechanical modelling and computer simulation to study the golfer. Nesbit *et al.* (1994) were first to undertake interactive modelling and computer simulation of the golfer and golf club, applying an experimental background to theoretical work utilising an early version of MSC/ADAMS^{TM} software. Further modelling and simulation research concerning the golfer and club interaction was conducted by McGuan (1996) who developed the

LifeMOD^{TM} toolkit now used in conjunction with ADAMS^{TM} engineering software to simulate biomechanical movement. McGuan developed a 12-segment human model combined with a 3 segment club model to study the correlation between club shaft stiffness and swing timing, combining image-based experimental work and theoretical modelling work.

Nesbit's first model (1994) represented as a rigid ellipsoid model defined using segment inertial parameters. The difficulty, though, is in developing a sufficiently detailed and accurate model that will represent the key features of the sports movement (Yeadon, 1994). In the case of human movement, the model should be able to represent such factors as bone characteristics, ligaments and tendons, gravitational influence, angular torque and acceleration, and musculature. Muscle recruitment issues have been a problem for biomechanists, with concerns surrounding the 'optimum' level of muscle innervation for a given movement, associated muscle firing, identification of support muscle groups for a given movement, complex multi-planar and muscle-group actions (Rasmussen *et al.*, 2003). The manner in which these problems are dealt with is an important consideration in the selection of the most appropriate modelling software package for the researcher.

Early simulations of movement based on the application of dynamic optimisation (forward dynamics) were limited mainly by the performance of the computers available at the time. With better computational power available now than in the early 1990's, large-scale models can be combined with dynamic optimisation theory to produce simulations that are an order of magnitude more complex than those performed just 10 years ago. The feasibility of using dynamic optimisation to produce realistic simulations of movement depends on three factors: (a) a robust computational algorithm is needed to converge to a solution of the dynamic optimisation problem; (b) high-performance, parallel computers are needed to solve the problem in a reasonable amount of time, and (c) very fast computer graphics workstations are needed to visualise the simulation in real time.

Computer and mathematical simulation can provide better understanding of movement patterns in terms or neuromusculoskeletal activity, but a purely theoretical investigation is open to question concerning its validity. The approach being adopted for the present study is a combination of experimental and theoretical modelling work, experimental data providing validation for the model's data. Whilst often used synomously, computer modelling and computer simulation differ markedly:

Computer modelling refers to the setting up of mathematical equations to describe the system of interest, the gathering of appropriate input data, and the incorporation of these equations and data into a computer program.

Computer simulation, however, is restricted to mean the use of a validated computer model to carry out 'experiments' under carefully controlled conditions, on the real-world system that has been modelled.

(Vaughan, 1984 pp373)

From the definitions it is clear that a computer simulation cannot take place without developing a computer model. However, it is quite possible that the activity of computer modelling can be performed without utilisation of computer simulation.

Although computer simulation is relatively well established as a research tool in fields such as medicine and engineering, its application to sport is of relatively recent origin. Some of the pioneers in the field have been Kahne and Salasin (1969), Miller (1973, '74, '79), Ramey (1973) and Ramey and Yang (1981). Computer simulation has only now advanced to the stage where it is readily accepted as a research tool in sports biomechanics. There traditionally exist two schools of thought concerning the work of the sports biomechanist. The first, ascribed by Hatze (1979) whereby traditional training of the sports biomechanist emphasises statistical methods and induction techniques, and mathematical simulation is the way forward for deductive modelling and predicting sports performance. On the other hand, Hay (1983) argues that there should lie a healthy balance between analysis and mathematical modelling, the sports biomechanist being able to explore human movement and provide a scientific basis in what is now the unknown. Such an approach might provide answers as to how the human body can be moved to best effect during the golf swing.

The vast majority of research in sports biomechanics for which computers have been used have dealt only with modelling. Fewer researchers have extended their computer models to the simulation stage. In theory, computer models work well, but in practice, actually isolating certain variables (for example pike dive, golf swing wrist action) can prove extremely difficult and attempting to adjust these variables whilst in the sports arena can be detrimental to performance. The combination of virtual and experimental testing can therefore help to provide a sound scientific backing to a proposed research question that can be put into practice.

The sections which follow in this chapter will discuss the advantages and disadvantages of virtual testing, the level of human representation that can realistically be achieved through computer simulation, and the important assumptions that should be made when developing multi-body systems for golf analysis. In addition, dynamics, both forward and inverse, will be discussed and the role they play in the simulations that will be performed as part of study 4 (Chapter 7).

2.9 Simulation studies - advantages and limitations

There are several advantages to a computer simulation approach to a research question. The first concerns the safety of the subject. The subject is saved from having to perform potentially dangerous experiments (for example multiple turn/twist dives or repeated strenuous movements) and the validity and reliability of the motion is maintained as the simulated athlete will not tire through repeated trials. Secondly, time can be saved once the model is constructed as many different simulations can be performed within a very short space of time depending on the computing power of the processor being used. Thirdly, there is the ability to accurately predict optimal performances (Hatze, 1979) due to the ease with which variables can be isolated and investigated, highlighting the best methods using the techniques of mathematical optimisation theory. Soong (1982) highlighted the fact that computer simulation removes the need for expensive physical models to be constructed for experimental testing. Despite these obvious advantages, there remain some important limitations to the effective use of computer simulation. Panjabi (1979) succinctly stated:

"*After all, a mathematical model is only a set of equations. Its link to reality is via the physical properties data of the system it is intended to model. Its success at simulation is not guaranteed but must be proven by suitable validation.*

(pp 238)

Hatze (1979 and 1983) also noted that a possible limitation of computer simulation is that an advanced knowledge of mathematics and computers is necessary. Inoue and Kai's (2002) mathematical model of the golf swing is one example. Because of the degree of specialisation required, relatively few researchers have the necessary training in both sports biomechanics and computer simulation. One of the greatest dangers is using the computer model as a "black box" without an understanding if its complexity, disadvantages or validity.

Finally, the interpretation of simulated results is often difficult for one of two reasons:

i. Published results of simulated human movement is often not aimed at a readership of sports coaches and athletes, but fellow biomechanists thus having little meaning for those it ultimately aims to assist.
ii. Physical execution of the movement produced by a simulation may prove difficult or impossible (Vaughan, 1984).

Table 2.7 summarises the advantages and disadvantages of computer simulation that have been discussed.

Table 2.7 Computer simulation merits and disadvantages

	Advantages		Disadvantages
1	Safety: no hazardous experiments for the athlete	1	Validation: often difficult without experimentation
2	Time: ability to perform many different simulations quickly	2	Specialised knowledge: advanced mathematical & computing skills needed
3	Optimal performance: may easily be predicted	3	Interpretation: results, and conditions often difficult to translate to practicality
4	Cost: redundancy of physical models		
5	Computing power: narrowing of gap between PCs and Silicon Graphics computing		

(Adapted from Vaughan, 1984, pp377)

2.9.1 Redundancy

The problem of redundancy in movement control is encountered when an attempt is made to solve the problem relating to how the central nervous system (CNS) determines the pattern of neural activity required in some five million descending motor fibres to control only one hundred to one hundred and fifty degrees of freedom (DOF) of movement. This may be likened to solving a set of simultaneous equations with many more unknowns than equations. The system is redundant because it has an infinite number of possible solutions (Neilson, 1993; Hatze, 2002). Redundancy of the human body is caused by the great number of joints and muscles and thus motor fibres innervating them. Each joint has one, two or three DOF. Therefore the total number of DOF of the human body is more than one hundred. Whilst this freedom enables the body to avoid obstacles and structural limitations, such as rotational joint angle limits, and enables skilful movement such as the golf swing, complicated algorithms are needed to control the system (Komura *et al.*, 1997, 2000). Constructing an algorithm to determine the activation of each muscle therefore entails guessing the motives behind the CNS's function. As humans are able to repeat movements with considerable precision, many researchers believe that control of muscle forces is based on some rational criterion (Rasmussen *et al.*, 2003).

The mathematical form of the redundancy (inverse dynamics) problem:

$$\text{Minimise} \quad G(\mathbf{f}^{(M)}) \qquad \text{(Equ. 4)}$$

$$\mathbf{f}$$

$$\text{Subject to} \quad \mathbf{Cf} = \mathbf{d} \qquad \text{(Equ. 5)}$$

$$f_i^{(M)} \geq 0, \qquad i \in \{1,\ldots,n^{(M)}\} \qquad \text{(Equ. 6)}$$

where G is the objective function of the recruitment strategy in terms of the muscle forces, $\mathbf{f}^{(M)}$, and minimised with respect to all unknown forces in the problem, $\mathbf{f}= [\mathbf{f}^{(M)\,T}\ \mathbf{f}^{(R)\,T}]^T$, i.e., muscles forces, $\mathbf{f}^{(M)}$), and joint reactions, $\mathbf{f}^{(R)}$. Equation (5) is the dynamic equilibrium equations which enter into the optimisation problem as constraints, **C** is the coefficient-matrix for the unknown forces, and the right-hand side, **d**, contains all known applied loads and inertia forces. The non-negativity constraints on muscle forces, (6), state that muscles can only pull, not push. Damsgaard *et al.* (2001) noted that solving this problem, with a minimum fatigue criterion can lead to a very high numerical efficiency for modelling movement.

To perform the golf swing, a model of a human may be constructed with a minimal number of muscle actuators and via a feed-forward inverse and forward dynamics approach the model may swing correctly. In this way, by rigidly stipulating anthropometric and physiological limits such as joint angle limits, muscle and tendon pre-stretch values and resting loads, muscle cross-sectional areas and maximal force outputs, the limited number of muscle actuators may produce the necessary joint torques to perform the swing. Using this optimised method (utilised for example by Pandy *et al.*, 1990; Panne, 1996; Davy and Audu, 1987; Srinivasan and Ruina, 2006; Li *et al.*, 2006; Hatze, 1976; Anderson and Pandy, 1999; Yamaguchi *et al.*, 1995; Kautz and Hull, 1995; Anderson *et al.*, 1996 and McGuan, 1996) movement may be accurately and reliably simulated, developing realistic joint torques and muscle force output despite not using all of the body's available muscles.

2.10 Segmental human modelling & application to golf

One of the most serious limitations of modelling the human body is the unavoidable trade-off between simplicity and accuracy. The level of representation of the human body that is required for a particular research question importantly creates a number of assumptions to be made. Beginning in the early 1960's, the manned space program provided impetus for the development of an 'inertial parameter' type of rigid body model in an attempt to anticipate reorientation problems which would have to be faced by orbital workers. Whilst these models have been refined considerably since the seven segment model proposed by Simons and Gardner (1960) (Figure 2.6), the majority of models since (incuding McCrank and Seger, 1964; Riddle and Kane, 1968; Whitsett, 1963 and Whitsett, 1964) have the following assumptions in common:

i. Body segments are considered to be rigid, of uniform density and simple geometric shape
ii. The rigid links rotate about fixed axes
iii. Tissue deformation and the asymmetrical location of internal organs are considered negligible

(Hanavan, 1966)

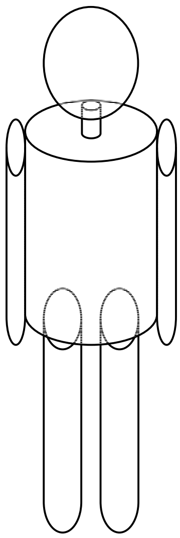

Figure 2.6 Inertial segment model

(Adapted from Simons and Gardner, 1960, in Miller, 1979, pp118)

Within this classification, the Hanavan 1966 model and its subsequent modifications have made the most significant contributions to date. These models have been used to portray the human body in simulations of springboard diving (Miller, 1973), kip-up[6] in gymnastics (Ghosh, 1974; Ghosh and Boykin, 1974), swimming (Gallenstein and Huston, 1973) and walking (Abdelnour *et al.*, 1975). In its original form, the 15 segments of the Hanavan model were defined by 25 anthropometric measurements of an individual including body weight, height and segment lengths and girths. Segment and total body centres of gravity and mass moments of inertia can be calculated mathematically utilising the computer program developed by Hanavan.

[6] Kip-up - From a lying position, the subject bends their knees, draws their legs into the chest, rolls back slightly, then kicks up to a standing position.

Recent work (Metzler *et al.*, 2002) has indicated that further modifications of the Hanavan model are required to improve the accuracy of the segmental moment of inertia predictions, but agree that the majority of present-day model calculations for segment inertia can still be based on Hanavan's model.

Yeadon *et al.* (1990) developed an 11 segment 17 degrees-of-freedom model of a gymnast performing an aerial somersault and was required to make the following assumptions about the computer simulated model:

i. Air resistance may be neglected
ii. The inertia values of the left and right limbs are equal
iii. The body segments are connected at a single point
iv. Adjacent segments are connected at a single point
v. The head, hands and feet do not move relative to their adjacent segments
vi. The flexion angles of the thighs are equal
vii. The left and right knee angles are equal

(pp87)

Yeadon *et al.* (1990) also added, *"In reality not one of the above assumptions is true. The extent to which they are reasonable assumptions for the model may be evaluated by how close the agreement is between the output angles of the model and the angles obtained from film data."*

(pp87)

What to include in a model of movement depends on the intended use of the model. Traditionally, structures contributing to the overall stiffness of a joint, including cartilage, menisci, ligaments, and capsule, are not usually included in multi-joint models. This level of detail does not seem necessary, especially if the goal is to explain muscle function. Cartilage and the menisci are rarely included due to the fact that these structures do no alter the forces transmitted by the joint; cartilage and menisci instead act to decrease the joint stresses by increasing the contact areas between bones (Shrive *et al.*, 1978).

In developing a large-scale musculoskeletal model, it is generally accepted that the following should be included:

i. model of the skeleton
ii. model of the muscle paths
iii. model of musculotendon actuation
iv. model of muscle excitation-contraction coupling
v. model of the goal of the motor task

The basic premise of engineering principles are that a system should be represented for investigation in such a way that it is neither over-simplified or disproportionately complex; that there is an understandable and accurate system being studied. Investigations that have been carried out from an engineering perspective in the field of golf have become more prevalent in the past few years due to the convergence of a broad spectrum of research disciplines, particularly biomechanics and engineering. Sprigings and Mackenzie (2002) examined two aspects of the golf swing (1) whether, in theory, a delayed release technique that used resistive wrist torque provided an advantage in clubhead speed; and (2) to identify the mechanical sources of power that are responsible for increasing clubhead speed. A two dimensional three-segment model (Figure 2.7) comprising torso, arm and golf club was used to model the downward phase of the golf swing. Muscle torque generators, constrained by the activation rates and force-velocity properties of human muscle, were inserted at the proximal end of each segment. After optimal simulation was performed, results indicated that there was a small advantage in employing the delayed release technique using resistive wrist torque. The main source of power delivered to the golf club originated from the passive joint forces created at the wrist joint during the swing.

Additional modelling work that has been carried out to investigate golf-related issues include Inoue and Kai (2002) who examined dynamics of the swing and wrist turn mechanism; Suzuki and Inooka (1999) who developed a mathematical golf-swing robot to emulate the skill and tactile sensations that a golfer can produce; Iwatsubo *et al.* (2002) who concluded that after comparison of two- and four-link models, four-link models better describe motion of the shoulder and elbow and a golfer's skill; and Pickering (1998) who provided a computational study of the double pendulum model of the golf swing. Pickering showed that using 3, 6 and 9 irons, placing the ball in line with the longitudinal axis of rotation results in a more downward strike at impact, desirable for shorter irons.

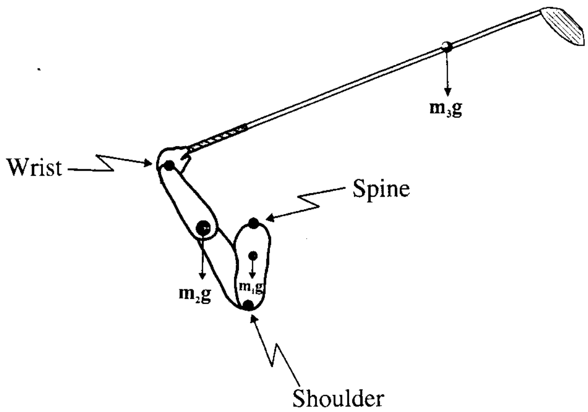

Fig 2.7 Two-dimensional model, with muscle torque generators inserted at the spine, shoulder, and wrist, used in the simulation of the golf swing.

(Sprigings and Mackenzie, 2002, pp24)

Brylawski (1994) combined computer and mathematical models to investigate the three dimensional deformation of the golf club during the downswing. Equations of motion were constructed using Lagrangian dynamics and mechanical properties of the shaft calculated. Combining experimental data from marker trajectories that were attached to the shaft during downswing, the equations of motion were used to determine the forces generated by the acceleration of the shaft and the effect of the shaft flexibility on the clubhead positioning. Had a full body model of the golf swing been developed as in Nesbit's investigation (Nesbit *et al.*, 1994, 1996; Nesbit and Ribadeneira, 2003; Nesbit, 2005), further experimental data to look at a wider range of shaft flexibility could have been avoided as the model could easily accommodate such changes. This point was iterated by Hocknell *et al.* (1999) who discussed the merits of computational over experimental analysis. It was stated that:

"In the pursuit of knowledge of the detailed mechanics occurring during impact, a validated finite element model is particularly useful... in the golf impact, it is particularly difficult to capture experimental data from points on the club head or

ball near the contact site. However, the range of measurements made elsewhere on the club head and ball suggest strongly that the behaviour of those areas for which there is no experimental data is also represented accurately in the finite element model."

(pp532)

2.10.1 Muscle

Research concerning muscle modelling has recently tended towards applied modelling on movement of selected parts of the body. This includes the whole upper torso, hand, shoulder, knee and lower limbs, to answer questions concerning muscle capacity to exert force on objects (Zajac, 1992); simulation of jumping and level ground walking (Pandy and Anderson, 2000); variations in simple and complex models for muscle function in walking (Pandy, 2003); and muscle coordination of maximum-speed pedalling (Raasch *et al.*, 1997) to name just a few studies. To date no studies have been published concerning modelling the musculature of the golfer. The majority of researchers also currently use computing power to simulate muscle and tendon-unit movement as opposed to purely theoretical and mathematical studies commonplace in the 1980's and early '90s.

However, much of the recent research published relies heavily on the clinical studies produced in the 80's and 90's that concentrate on surgical and anatomical considerations, to progress basic knowledge on muscle architecture (e.g. Lieber *et al.*, 1992; Jacobson *et al.*, 1992), muscle model designs (e.g. Wilmelms and Van Gelder, 1997), coordination of movement (e.g. Zajac, 1993), and energy considerations for muscle contraction (for example Bhargava *et al.*, 2004). Zajac has worked extensively on muscle co-ordination and architecture, reviewing musculotendon architecture and the relation between architectural parameters and the force, speed, and excursion capacity of musculotendon units. Zajac studied how muscles with equal mass can have different force, speed, and excursion capacities, and how the capacity for a muscle to exert force on an object (as golf club handle for example), is directly proportional to its moment arm and the speed and range over which the force is exerted in inversely proportional to the moment arm. Thus, there are implications for gripping a golf club, flexion of the arms, and timing for uncocking of the wrists for the effective transfer of speed and torque to the club and the overall swing.

Further work was also carried out investigating uni- and biarticular[7] muscles. Uniarticular muscles were found to generate the propulsive energy and biarticular muscles fine-tuning the coordination. Muscles were also found by Zajac (1993) to act to accelerate all joints and segments, even joints it does not span and segments to which it is not attached. This poses specific problems for the researcher involved in developing accurate models to simulate a given movement as in reality there may be many muscles acting some distance away from a said joint that combine to produce the movement. What the researcher should include and omit to create a model with a high degree of biofidelity is crucial to producing valid and reliable results.

2.10.2 Bone

Bone can be considered to provide the rigidity for each segment of a model, uniform in weight, proportional to volume and with tensile and compressive strength. In the present study, as in several others (including McGuan, 1996, 2001, 2002; Anderson and Pandy, 1999), the presence of bone is only such that inertial properties of the limbs, head and trunk are needed for computation. Alexander (2003), in his paper entitled "Modelling approaches in Biomechanics" addressed the area of bone modelling and assumptions that have to be made when investigating bony structures. For example, Alexander highlighted early research that modelled the lower limbs as one long rigid rod to investigate aerial movement in high jumping (Hubbard and Trinkle, 1985), and more recent work that dealt with epiphyses which were found to ossify separately from the main shaft of the bone, thus affecting muscle and tendon attachment to some degree.

More commonly in biomechanics research, development of skeletal models aid analysis following tracking motion of the spine. The absence, normally, of a large amount of soft tissue or fatty deposits around the spine, particularly in healthy subjects allows for more accurate tracking of the vertebrae. O'Sullivan *et al.* (2003) modelled biomechanical measurements of the spine during a rowing exercise using 18 international and national

[7] Biarticular muscles are muscles that work on two joints rather than just one, such as the hamstrings which both extend the hip and flex the knee.

standard rowers. Systematic changes in technique were easily detected, monitored, and modelling as a two dimensional system due to lack of rotational movement, rowing occurring mainly in a sagittal plane. Bone is modelled in many studies that combine experimental kinematic tracking to additionally provide anatomical landmarks on which to create virtual markers to represent the actual indwelling or surface markers used during experimentation (Mitchell *et al.*, 2003). This technique will form the basis of model validation for study 4.

2.10.3 Anthropometrics and scaling

Tables 2.8 and 2.9 illustrate mean weights of body segments and their ratio to total body weight, extracted from work by Dempster and Gaughran (1967). Such values provide the important information needed to calculate inertial values for body segments for healthy, average-sized individuals such as those used in the present study.

Table 2.8 Mean weights of male cadaver segments and ratio to total body weight

	Mean Weights (gm)	% of Total
Total body weight	61190 ± 8137	100
Head & trunk	34637 ± 5607	56.34 ± 2.45
Head & trunk minus shoulders	28077 ± 3994	46.02 ± 2.239
Head & neck	5119 ± 838	7.92 ± 0.85
Shoulders	3401 ± 843	5.27 ± 0.546
Thorax	7669 ± 2270	10.97 ± 1.521
Abdomino-pelvic headless trunk	16318 ± 2505	26.39 ± 2.908
Arm	1636 ± 350	2.64 ± 0.294
Forearm	947 ± 199	1.531 ± 0.166
Hand	378.3 ± 71.7	0.612 ± 0.058
Thigh	609.6 ± 985	10.008 ± 1.197
Shank	2852 ± 695	4.612 ± 0.534
Foot	884 ± 178	1.431 ± 0.142

(Adapted from Dempster and Gaughran, 1967, pp52)

Modelling work for the present study will initially use anthropometric values on databases presented within the ADAMS^{TM}/LifeMOD^{TM} software, 'GeBOD'. The database was developed by the 'Modeling and Analysis Branch' of the Air Force Aerospace Medical Research Laboratory and the University of Daytona Research Institute. It generates the masses and principal moments of inertia of the segments and the basic geometric shapes of the segments The regression equations which make up the database are based on three surveys of human body dimensions. The adult male data was taken from a survey of 2420 subjects from the United States of America. Biomechanical models are commonly published using scaled data based on large database information. However, if models are to be developed for single subjects, as discussed by Hatze, 2005; Kinugasa *et al.*, 2004; Bates, 1996, Bates *et al.*, 2004 and Farrally *et al.*, 2003) then more accurate methods of body representation are needed.

Table 2.9 Segment mass percentage of total body weight

	Skin & fascia	Muscle	Bone
Thigh	29.0 ± 3.31	59.6 ± 2.81	11.5 ± 1.78
Shank	22.2 ± 2.98	45.6 ± 2.85	32.3 ± 2.56
Foot	29.2 ± 4.30	20.3 ± 4.25	50.7 ± 7.35
Arm	26. 0± 3.85	56.8 ± 4.74	18.0 ± 1.61
Forearm	18.7 ± 4.25	53.2 ± 4.90	28.2 ± 3.99
Hand	28.4 ± 3.04	27.6 ± 2.98	44.0 ± 3.27
Shoulders (left side)	36.5 ± 3.34	53.9 ± 4.09	9.6 ± 3.76

(Adapted from Dempster and Gaughran, 1967, pp53 Table 6)

Delp *et al.* (1994) developed a computer model of the human lower extremity firstly by placing a cadaver on an anatomy bench and using an OPTOTRACK^{TM}/3010 digitising system with a camera residual of 1 mm, tracked using infrared emitting diodes a reference frame and coordinates for the anatomy studied. Scanning the geometry to be studied, be that human or equipment form has been performed using magnetic resonance imaging (MRI) (e.g. Bemben *et al.*, 2005; Fuller *et al.*, 1999) and computational fluid dynamics (CFD) which uses non-contact lasers (Hart *et al.*, 2004). The benefit of MRI is that not only are the geometry parameters identified very precisely, but the composition of the body segment or piece of equipment can be identified and dimensions given (fat/muscle/bone layers). However, MRI is not an option readily available to most biomechanists, the equipment proving expensive and the profiling time consuming.

Furthermore, Siston and Delp (2006) published work evaluating an algorithm developed to determine the hip joint centre. A pivoting algorithm based on vector addition was created based on experimental analysis using two rigid segments to represent a pelvis and femur. A 'Polaris^{TM}' optical tracking system operating at 30 Hz with a residual of 2mm tracked the reference frame needed to create the vectors. The algorithm was reported to be an accurate and fast technique to locate the hip centre, minimally affected by reasonable limits of motion and noisy motion data, but requiring additional work for evaluation in the clinical setting.

In the absence of an MRI or CFD scanner, the present study utilised the scaling algorithms provided by ADAMS^{TM}/LifeMOD^{TM} software to initially create a human model (based on the single subject's height, weight and age) followed by application of fifty anthropometric measurements detailing lengths, widths and circumferences of all body parts (see section 7.1.3. 'Model construction').

2.11 Optimisation of human movement

Connected multi-body systems exhibit markedly complex behaviour when driven by external and internal forces and torques. Reconstructing the internal forces and/or torques from the movements and known external forces is called 'inverse dynamics'. Motion capture data used in the kinematic study of human movement may be used as the known movements and external force/time histories to reconstruct such internal forces. In the present study body segments and joints of the golfers were tracked using reflective markers, this data acting as the known movement history from which the internal forces and torques could be calculated in the ADAMS^{TM}/LifeMOD^{TM} software.

Calculating the motion from known internal forces and/or torques and resulting reaction forces is called 'forward dynamics'. Such calculation is more efficiently carried out post- inverse dynamics calculation allowing for shorter calculation time through less estimation of initial forces and torques. Inverse dynamics calculations applied to a set of motion data from an event such as the golf swing can teach us how temporal patterns of joint torques were responsible for the observed motion. In forward dynamics calculations the user may attempt to create motion from such temporal patterns, which is often very difficult, because of the complex mechanical linkage along the chains forming the multi-body system. Whilst much of the inverse and forward dynamics calculations and orientation of data can be performed within modern software, it is useful to understand, predict and control the multi-body system using mathematical expressions so that the user may possess sufficient freedom and manipulation over the system. The Newton-Euler, Lagrangian and Featherstone approaches that are commonly used all have their advantages and disadvantages. All three are used mainly for the solution of forward dynamics problems and differ mainly by the degree-of-freedom they represent and the calculation time they need. Figure 2.8 illustrates the forward and inverse dynamics mathematical processes for simulation of human motion.

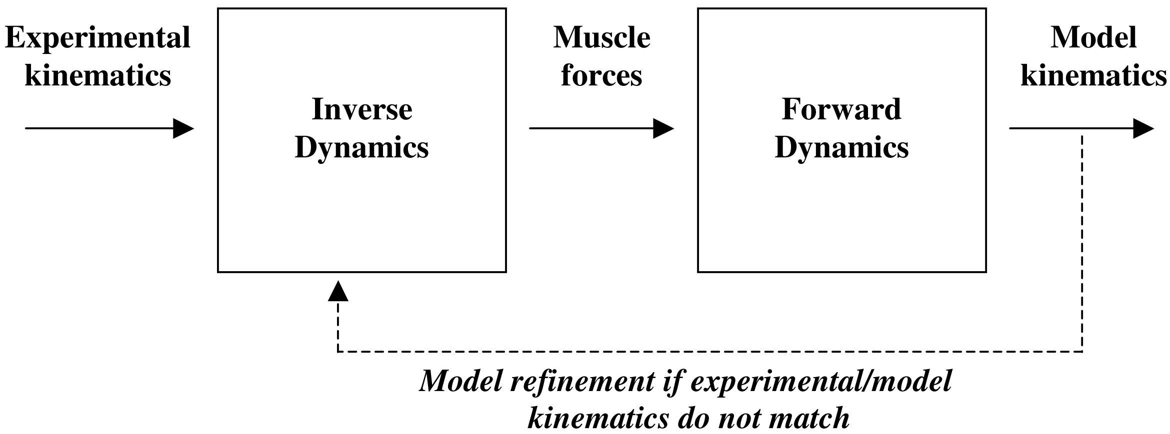

Figure 2.8 Inverse-forward dynamics approach

<u>Forward Dynamics</u>

The most relevant research conducted using forward, and inverse dynamics, was that by McGuan (1996). Discussed in section 2.8, McGuan developed a 15 segment model of the golfer and club, collected motion data consisting of three dimensional trajectories of markers placed on the body and club, and used ADAMS^{TM} software to calculate internal force-time histories of contractile elements (inverse dynamics). From this point, McGuan was able to manipulate swing timing and alter variable of components of the model, namely club shaft stiffness and perform further forward dynamics simulations to predict changes in swing patterns dependent on these variable changes.

Research applied to muscle function in walking by Pandy (2003) used a forward dynamics method to compare results obtained from both simple and complex muscle models. A simple model consisting of an inverted double pendulum explained only sagittal plane movement whereas the complex model developed which simulated muscle-actuation to a greater degree was able to more accurately describe the contributing components of level walking, particularly hip and pelvic movement. Using forward dynamics calculations Pandy was able to alter independent variables to investigate both gross and fine movement patterns using the two models. Similarly, Anderson and Pandy (1999, 2001; Pandy and Anderson, 2000) developed complex models (23 degree-of freedom mechanical linkage actuated by 54 muscles) to investigate muscle metabolic energy for walking and to investigate dynamic optimisation for vertical jumping. Crucially, they noted that the optimisation solution developed for jumping simulated accurately the muscle-coordination patterns evident when human subjects jump maximally.

Forward dynamics simulation has not only been utilised for applied research (Cole, 2003-runner’s gait; Nagano and Gerritsen, 1999- afferent feedback modelling of hopping) but extensively for clinical biomechanics and pure mathematics in areas of research concerning concepts of power transfer (Zajac *et al.*, 2002, 2003), simulation of anterior cruciate ligament forces during isokinetic dynamometry (Serpas *et al.*, 2002) and numerical simulation of human movement (Anderson *et al.*, 1995).

Otten (2003) described the importance and usefulness of forward dynamics in developing an effective human model:

> *“It is very instructive to try and control a model of a human with 15 segments in three dimensions by adjusting the joint moments of force... first of all it is hard to predict a change in moment of the force... Second, it is hard to predict the movements that result from such a change in moment of force in the rest of the body. Before long, you are adjusting moments of force everywhere... It may be very helpful to use*

a recording of movements of a subject and calculate the moments of force at the joints by inverse dynamics.

(pp1495)

Forward dynamics problems can also be formulated so that the solution is constrained to follow a given path. For example, in a gait simulation, the joint angles and the components of the ground reaction force may be treated as constraints that the solution must satisfy within a prescribed tolerance. The problem then is to find the muscle excitation histories that correspond to the measured patterns of body motions and ground forces. This approach has been used to simulate the lower-limb (Yamaguchi and Zajac, 1990; Fregly and Zajac, 1996; Neptune *et al.*, 2000; Davy & Audu, 1987; Neptune *et al.*, 1998) and upper-limb movements (Hannaford *et al.*, 1986) and is called tracking because the forward dynamic optimisation solution is required to track a set of limb motion and external force measurements obtained from a motion analysis experiment (Bryson and Ho, 1975). The benefit of adopting such an approach is such that by prescribing a path for the model to follow, the simulation is more likely to converge on a pattern of movement that is similar to what is observed in the natural environment. The nature of some movement patterns, for the example the golf swing, is such that trajectories of some of the degrees of freedom cannot be accurately measured due to rotational aspects of the joints and segments (yaw, pitch and roll). However, the tracking approach can be used to constrain the model to follow those movements that can be measured and to predict all the remaining coordinates within a frame of reference within which the studied motion has taken place (direct linear translation- Abdel-Aziz and Karara, 1971).

The main limitation of the tracking method, however, is that it compromises the predictive power of the forward dynamics approach; specifically the tracking method cannot be used to predict how changes in body structure affect tissue function and task performance. Ultimately, though, the combination of tracking as an experimental approach with computer simulation serves to provide an extremely useful starting point and framework for optimisation problems, allowing for inverse dynamics to be easily executed without estimation of body segment positions and movement therefore reducing calculation error.

Inverse Dynamics

As discussed, Otten (2003) noted the processes involved in both forward and inverse dynamics in the modelling of multi-body systems. The two were described in such a way that inverse dynamics calculations applied to a set of motion data from such an event can teach us how temporal patterns of joint torques were responsible for the observed motion. Forward dynamics calculations is an attempt to create motion from such temporal patterns, which is extremely difficult because of the complex mechanical linkage along the chains forming the multi-body system. As such, normally inverse dynamics calculations are performed firstly, creating a starting point for motion to be described by forward dynamics.

When inverse dynamics is used, it is usually in conjunction with forward dynamics and related to applied, experimental research where two dimensional or three dimensional motion has been analysed. Such an approach was adopted by de Zee *et al.* (2003) in the simulation of lifting. Their paper was entitled "Simulation of lifting using the better of both worlds: forward and inverse dynamics". The simulation was image-based (200 Hz video analysis) and two identical two dimensional musculoskeletal models of the leg and upper body were built using 'SIMM^{TM}' and 'AnyBody^{TM}' modelling software systems. SIMM^{TM} was used for a forward dynamics tracking optimisation, and AnyBody^{TM} used an inverse dynamics method and the video. It was concluded that firstly using an inverse dynamics approach to determine muscle activities almost halved the forward dynamics approach as a starting point for motion history was available. It was recommended that all complicated multi-body models utilise inverse dynamics before progressing to forward dynamics.

2.12 Validation of simulated results

In their letter to the editor of the Journal of Biomechanics, Panjabi (1979, pp238) (see Section 2.9) raised the issue of model validation following observations of invalidated or poorly validated models presented at a recent conference. A model can be considered as successfully validated if, in the limited simulated situations it provides, its predicted behaviour comes close to the experimental results. Generally, musculoskeletal biomechanical models are all validated in the same manner, that being comparison, statistically via correlational analysis, or graphical or tabular observation, with data produced under the same conditions during experimentation.

The methods most commonly employed are:

i. EMG can be used to measure electrical activity emitted by the muscles, comparing activation periods.
ii. Direct measurement of external forces (ground reaction forces or grip forces).
iii. Kinematic analysis, for comparison of linear and angular displacement and temporal patterns.

(Adapted from Rasmussen, 2005)

Following the development of their fifteen segment full body rigid model of a golfer and parametric club, Nesbit *et al.* (1996) simply provided graphical analysis of experimental force plate GRFs against analysis data, showing "verification of the model." Interpretation of the graph would seem to show a 4.5% difference in peak GRF. Similarly, in Pan *et al.*'s (2004) evaluation of a computer simulation model for human ambulation on stilts, 95% simultaneous confidence intervals were noted, whereby the model underestimated centre of mass time histories and coordinates. For the three subjects studied, it was concluded that the model was able to evaluate, with a 20% tolerance limit, stilt walking at 24″.

Rullkotter *et al.* (1999) validated their knee simulator via comparison of flexion-extension and adduction-abduction angles and time histories simulated and experimental data. Experimental data was collected for a single subject and compared to the ADAMS model output via graphical representation. It was stated:

> *"Experimental and virtual analyses compared well overall. Flexion-extension and abduction-adduction correlated well in magnitude and time-scale."*

(Rullkotter *et al.*, 1999, pp1)

Furthermore, in application of their lower extremity model, Thelen *et al.* (2003) simulated bicycle peddling and compared model data for pedal angle, tangential force and radial force about the pedal with data obtained experimentally in a previous study of ten male competitive cyclists (Neptune *et al.*, 1997). The simulated pedal and crank angles were within one standard deviation of experimental measurements throughout the peddling cycle, and simulated pedal forces were within one standard deviation of experimentally measured pedal forces for the majority of the crank cycle. However, it should be noted that the range for force measured/simulated was approximately 300N and RMS errors were 17N for the tangential pedal force and 37N for the radial pedal force (>12%). Piazza and Delp (2001) also compared simulated and experimentally derived forces, this time knee joint forces for their three-dimensional knee simulation. Medial-lateral net knee forces were shown to compare favourably with those of knee replacement patients (experimentally derived data) but net forces in the superior-inferior direction in the simulation were approximately 50% of experimentally measured values. However, they added that results were comparable to that achieved by Banks *et al.* (1997) for *in vivo* studies.

Anderson *et al.* (2005) developed a 10 segment, 23 degree-of-freedom linkage, scaling the model based on McConville *et al.*'s (1980) regression equations and applied 54 musculotendon actuators. The model was used to simulate human walking and validation of the model was conducted by comparing simulated and experimental for kinematics, GRFs and muscle excitations. Simulated joint angles were reported to lie within one standard deviation of experimental values, and graphical representation showed GRFs and muscle excitations for calf, quadriceps and gluteal muscles "compared favourably" (pp201).

It is clear from the aforementioned studies that there exists a considerable margin for error concerning published simulated data. As statistical analysis would purport, a confidence level of 95% should be achieved for authors to be able to claim that their model can produce as valid and reliable data that experimentation can.

2.13 Justification of the present study

This chapter critically reviewed the pertinent literature relating to the kinematics and kinetics of the golf swing and the few studies that have been conducted to model the golfer and club. It has become evident that research examining the effects of driving performance when using clubs of different shaft length is scarce.

Research to date in the biomechanics of golf has been largely experimental in nature, with both kinematic and kinetic data derived to ascertain the effects of club specifications on golf performance. The work in this thesis has extended this research to provide appropriate experimental data which has been used to drive simulation models of the golfer. Modelling work of this kind has been carried out for other sporting activities (such as gymnastics) but little has been done specifically in golf biomechanics and golf technology.

Of the studies that have been experimental in nature, for example Mizoguchi *et al.* (2002), Wallace *et al.* (2004), Nagao and Sawada (1973), Egret *et al.* (2003) and Werner and Greig (2000), several have inferred increased drive performance solely based on increases of either clubhead velocity or initial ball velocity. This fails to take into account other ball launch characteristics such as spin and trajectory which may be affected by the length of the club and which may have a significant effect on ball carry and shot accuracy. Furthermore, several of these studies have based their conclusions on experimental analysis of clubs of different shaft length including irons. In that shots performed with irons are commonly not struck with the intention of maximal carry distance as those stuck with a driver are, results derived from such studies are misleading.

The review of literature additionally highlighted the lack of research focusing on shot accuracy when using drivers of different shaft length. To date only two papers have investigated shot accuracy. However, both Werner and Greig (2000) and Iwatsubo and Nakajima (2006) conducted tests using a limited number of subjects, n = 4 and n = 2 respectively. In addition to subject numbers being low, recruitment of high handicapped golfers, which both studies used, serves to introduce greater levels of intra-subject variability which may skew results. The present study used more subjects and more highly skilled golfers to draw conclusions as to the effect of driver shaft length on shot accuracy. It has been noted that the studies that have investigated driver shot accuracy drew the conclusion that golfers were not able to adapt to using a club longer than their normal 45" driver therefore shots were less accurate. No attempt has been made by any study to examine the clubhead/ball impact characteristics to determine which component of initial ball flight may affect shot accuracy.

Attempts have been made, however, to characterise the kinematics of the golf swing when using drivers of different shaft length, but results have not conclusively ascertained how any changes in swing kinematics may alter shot performance. Egret at al. (2003) and Nagao and Sawada (1973) have characterised certain aspects of the golf swing including posture and timing, but for drivers and irons. Only Wallace *et al.* (2004) has examined in detail postural kinematics and temporal aspects of the golf swing, for skilled golfers, using drivers which differed in shaft length. This study provided a useful comparison with results from the low handicapped golfers examined in the present study. The present study did, however, also include investigation of aspects of the swing which have not been studied in relation to drivers of different shaft length. This included hub angular velocity and range of rotation (X-factor).

Finally, it is evident that the literature contains little material concerning investigation of the kinematics of the golf swing using full-body computer models, and none to date investigating the kinetics of the golf swing using musculoskeletal computer models. Mathematical modelling of the arms and the club has been carried out by Reyes and Mittendorf (1999), and a full-body rigid computer model has been developed by Nesbit *et al.* (1994) and further refined to study joint torque when using iron clubs (Nesbit, 2005, Nesbit *et al.*,1994, 1996; and Nesbit and Ribadeneira, 2003). The present study has taken this modelling approach significantly further, developing a large-scale rigid human model and parametric flexible driver model to investigate the kinematics of the golf swing. Additionally the human model included a large number of muscles to study the kinetics of the swing.

Previous models have utilised single-subject analysis on which to base results. The present study also utilised this type of analysis for the modelling work as part of study

4. Biomechanics researchers including Hatze (2005) and Farrally *et al.* (2003) have discussed in their papers the need for subject-specific investigation into human motion by means of computer models and movement simulation. They called for development of models that are anthropometrically tailored for individual subjects, therefore providing a better correlation between experimental and theoretical results. Statisticians including Bates (1996), Bates *et al.* (2004) and Kinugasa *et al.* (2004) have expressed confidence in conclusions drawn using the appropriate statistical techniques which may be applied to perform analyses on data collected during single-subject investigations. The model developed in study 4 used a highly skilled elite golfer deemed representative of category 1 golfers. Whilst results pertain solely to that golfer, the model can readily be tailored to accept motion data for any golfer's swing, answering the need in biomechanics, as Hatze (2005) discussed, for subject-specific investigations.

2.14 Summary

This chapter has discussed the literature relating to golf biomechanics and biomechanical modelling in relation to driver shaft length. Limitations to previous literature and gaps in this field of research have been highlighted in Section 2.13 'Justification of the present study'. It is apparent that a more comprehensive characterisation of the kinematics of the golf swing, for a number of skilled golfers was required. In addition, analysis of driving performance, that is ball carry and shot accuracy and the clubhead and ball launch conditions that produced the performance was merited. The literature also highlighted a need for further biomechanical modelling research relating to the golf swing.

CHAPTER 3

METHODOLOGICAL ISSUES

3.0 Introduction

Investigation of golf swing biomechanics associated with club parameter variations is presented in the four main studies within this research thesis (Chapters 4 to 7). However, the review of literature and in-depth consideration of the methods employed in previous studies have identified four methodological issues which require addressing prior to embarking on these main studies:

i. The selection of clubs used for testing;
ii. The effects of inter- and intra-subject variability;
iii. Effects of the testing environment and laboratory equipment on performance; and
iv. The selection of launch monitors

All four issues were experimentally researched and the results and their implications are discussed in the sections which follow. The conclusions drawn were used to determine appropriate experimental procedures to be employed in the four main studies.

Where appropriate, and in order to avoid replication, where any methods used in these preliminary studies follow experimental methods used during a main study, sufficient detail only will be provided in this chapter, but reference will be given to the corresponding main study.

3.1 Test club features and criteria

The main aim of the present study was to assemble test drivers comprising components that exhibited minimal physical property difference. Different clubs have distinct design characteristics which influence ball launch characteristics. Driver clubhead, shaft and grip were the three components considered for investigation. The main design features of drivers as was discussed by Harper *et al.* (2005) include club mass, length, shaft flex, face loft, lie angle and head size. Players' subjective perceptions of the characteristics, suitability and quality of the equipment will have a significant bearing on their club selection. A golfer will judge the quality of a swing from internal kinaesthetic and external auditory, tactile and visual systems during the swing (Roberts *et al.*, 2005;

Hedrick and Twig, 1994) which depend very much on the type of club selected and its physical characteristics.

The general concept when matching test clubs is that each club should have the same swing feel (Harper *et al.*, 2005). This is only achieved via careful selection of club components and assembly procedures, either by matching the club's first moment (swing weight), or by matching component characteristics. Figure 3.1 shows in flow-chart format, the basis for test club assembly.

Choose selected components

↓

Describe tests clubs when assembled

↓

Subject test clubs to experimental tests to identify the effects of selected club characteristics on shot performance

Figure 3.1 Flowchart showing the relationship between choice of test club components and their use in experimental procedures

However, the approach adopted here was to alter one feature, that is shaft length, and to examine shot characteristics and performance outcomes. The following sections detail selection of the club components used, static testing procedures employed, and the basic club assembly procedure.

3.1.1 Physical properties

Manufacturers place tolerances on club components in an attempt to maximise performance consistency and to minimise alterations required to assembled clubs to achieve a desired product. Titanium alloy driver clubheads typically have a mass of approximately 205g, with a manufacturing tolerance of ± 4g, with driver shafts varying in mass between 50g and 120g with a tolerance of ± 3g (Harper *et al.*, 2005). Additionally, grips also vary in mass between 30g and 65g with a tolerance of ± 3g, equating to an assembled drive overall mass of between 285g and 390g, with a ± 10g variation due to manufacturing tolerances and use of fitting splines[8]. Such manufacturing tolerances are considered small in clubs produced for the commercial market. However, in relation to experimental investigation of select club physical characteristics, such tolerances are considered large and attempts should be made to minimise this source of possible experimental error.

In Harper *et al.*'s (2005) study (see section 2.1.3) 30 golfers performed 10 shots with four drivers, shaft flex for which were correctly matched for swing speed, but with differing swingweight (C7, D0, D5 and E0). A significant relationship between swingweight and clubhead peak clubhead velocity was found, where an increase in swingweight of a club resulted in a reduction of peak clubhead velocity of 2.64 ms^{-1}. However, no significant difference was found between swingweight and clubface impact location, launch angle or backspin, suggesting the effect of swingweight on golf club control was negligible. Furthermore, the majority of golfers were only able to detect large changes in swingweight of five or more swingweight points. It was concluded that changes to golf weight distribution were found to have little effect on player performance, and that manufacturing tolerances for component masses appeared to offer sufficient control over club weight distribution, allowing for less stringent, therefore less expensive, manufacturing procedures.

3.1.2 Static testing

Component brands were selected based on perceived quality and their popular use by elite golfers. Fifteen shafts and 15 clubheads were purchased, all of which underwent static testing in the laboratory to determine their key properties prior to club assembly. Clubheads were tested for mass, volume, loft, lie and face area to identify 5 clubheads best matched for these properties. Similarly, the 15 shafts were statically tested for shaft mass, torque and frequency so that 5 closely matched shafts could be selected. Figure 3.2 illustrates the set-up used for testing shaft torque.

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[8] Filaments fitted to the hosel to ensure correct shaft/clubhead fit.

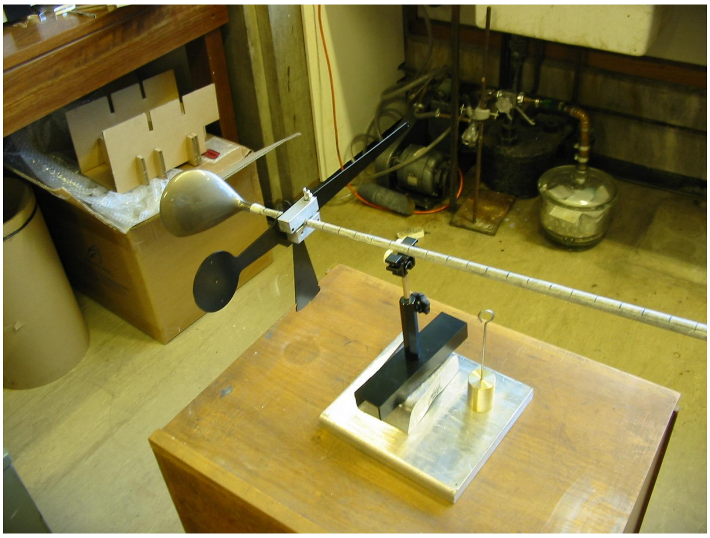


Figure 3.2 Measuring shaft torque

A standard club head was temporarily fitted to each shaft in turn for the purposes of the test. The butt end of the shaft was clamped in a Golfsmith's^{TM} frequency analyser, a support placed at a distance of 15 cm from the hosel and a weight clamp positioned 5cm from the hosel as illustrated. A protractor fixed to the weight clamp was used to determine angular displacement of the clamp when a mass of 50g was placed on the distal end of the clamp.

Figure 3.3 Measuring shaft frequency

Figure 3.3 illustrates the set-up used for determining shaft frequency. The Golfsmith's™ frequency analyser clamped the butt end of the shaft in place as shown. Masking tape was placed around the shaft and the tape marked around its circumference at 15 degrees intervals. A self-selected downward pressure was placed on the clubhead which, when released, allowed the clubhead to oscillate naturally. For each 15 degrees angular displacement, the test was performed 3 times and frequency values obtained from the analyser.

Tables 3.1 and 3.2 show physical properties of the main component measures obtained for 'matched[9]' clubs and for 'length[10]' clubs. Selection criteria and tolerance levels were refined for studies 3 and 4 demonstrated by smaller measure ranges. 'Matched' drivers were used for preliminary testing (see section 3.3 'Inter-subject variability').

Table 3.1 Studies 1 and 2 club physical property means (±SD)

Measure	Mean (± SD)
Club length ("/m)	48.50 ± 2.65 / 1.23 ± 0.07
Clubhead mass (g)	198.00 ± 1.41
Clubhead volume (cc)	255.00 ± 0
Clubhead loft (˚)	7.00 ± 0
Clubhead lie (˚)	60.00 ± 0.41
Clubhead face area (mm^2)	3164.25 ± 1.50
Shaft mass (g)	57.75 ± 3.77
Assembled club frequency (Hz)	245.75 ± 20.27
Swingweight (in/ou)	21.75 ± 1.98

[9] 'Matched' drivers – clubs assembled with closely matched physical properties

Table 3.2 Preliminary study 3 and studies 3 and 4 club physical property means (±SD)

Measure	Range	
	Matched drivers	Study 3 & 4 drivers
Club length ("/m)	46.00 ± 0 / 1.17 ± 0	48.00 ± 2.00 / 1.22 ± 0.05
Clubhead mass (g)	200.19 ± 0.28	200.16 ± 0.66
Clubhead volume (cc)	350.00 ± 0	350.00 ± 0
Clubhead loft (°)	9.00 ±0	9.00 ± 0
Clubhead lie (°)	62.33 ± 0.29	62.50 ± 0.50
Clubhead face area (mm^2)	3712.75 ± 34.83	3694.93 ± 7.70
Torsional stiffness (°)	2.80 ± 0	2.80 ± 0
Shaft mass (g)	63.00 ± 0	65.06 ± 2.30
Assembled club frequency (Hz)	375.13 ± 7.13	318.80 ± 16.48
Swingweight (in/ou)	228.67 ± 1.01	234.63 ± 7.60

3.1.3 Club assembly

Drivers were assembled by a skilled club assembly qualified PGA professional. Measures of loft, lie and overall mass were repeated during the assembly process to minimise clubs differences.

3.1.4 Conclusions

In total 12 clubs were assembled for the purposes of this study. Table 3.3 summarises study aims and details the main club properties used for each study. Club lengths represented average amateur golfer driver length, driver length at the limit imposed by the R&A Rules Ltd. of 48", and lengths exceeding the limit.

[10] 'Length' drivers – clubs assembled which were primarily different only for shaft length

Table 3.3 Summary of study aim and the main club properties for each study

Study	Main aims	Club properties	
		Shaft length (")	Clubhead volume (cc)
1 & 2	Effects of shaft length on swing kinematics and shot performance	46	255
		47	255
		49	255
		52	255
Preliminary study 3	Investigation of inter-subject variability	46	350
		46	350
		46	350
3 & 4	Effects of shaft length on shot performance, and golf swing simulation	46	350
		48	350
		50	350

3.2 Appropriate selection of launch monitors

There exist several systems in the current marketplace, commercially available and non-commercial, such as golf equipment manufacturers' own systems, designed to quantify the launch characteristics associated with clubhead and ball impact. The presentation of the clubhead to the ball positioned on the tee or ground surface and initial characteristics of flight of the ball immediately after impact are of particular concern to manufacturers. Determination of a golfer's clubhead velocity, clubhead dynamic loft and orientation at impact, and ball initial velocity, backspin and sidespin components, side angle and launch angle can aid assessment of shot performance using a particular club.

Issues relating to the use of a particular launch monitor include its availability, the test location, be that in the laboratory or on the golf course, the variables under scrutiny and the precision and accuracy desired. The majority of systems use image based analysis, or photogrammetry that allows extracting precise and reliable measurements from images (Gruen, 1997). High speed cameras capture several images during the moments immediately before and after impact and with known exposure rates and/or strobe flash sequencing velocities of the clubhead and ball. This permits orientation of the ball as it moves away and clubhead as it reaches the ball to be determined. Similarly, with the ball marked in a certain fashion, commonly with 2 black lines around its circumference, software algorithms can determine spin along a chosen axis. Other systems utilise light-gate technology where infrared sensors calculate similar measures based on the moving clubhead and ball altering light intensity surrounding the sensors.

Where possible, two launch monitors were used at any one time during tests conducted as part of this thesis in an effort to ensure test validity and reliability. One system, the Golftek^{TM} ProV launch monitor which utilised infrared sensors technology was used in the majority of the studies in this thesis. This was because the system was readily available, and it was designed such that it acted as the tee from which to hit shots meaning that other systems could easily be positioned around it. The Golftek^{TM} ProV launch monitor was used for main studies 1 and 4, and for preliminary study 3.4. Requiring a light source positioned directly above the system, the Golftek^{TM} ProV launch monitor could not be used outdoors, therefore was not utilised in the main studies 2 and 3. Table 3.4 gives a brief description of all 3 launch monitor systems used. Monitor 2 was a stereoscopic high-speed camera launch monitor. Monitor 3 was a single-camera system, also utilising automatic digitising software to track multiple images of the clubhead and ball. Monitor 2 was considered to be the most accurate and reliable system, thus was the ‘gold standard’. However, system 2 was not as readily available as system 1 therefore could not be used for all studies.

Table 3.4 Description and ID number given to the launch monitor systems used

Monitor ID	Description
1	Golftek^{TM} ProV utilising dual sets of infared sensors
2	Stereoscopic launch monitor
3	Launch monitor using digitised image analysis

The purpose of this preliminary study was to compare data output, for comparative purposes peak clubhead velocity, for the other systems against the Golftek^{TM} ProV launch monitor by means of correlational analysis and RMS. Ensuring that little deviation existed between measures obtained using different launch monitors allowed for comparison of data between studies conducted in different environments. Measures collected could therefore lead to valid conclusions. Tests performed proved the reliability of the systems used, that is the measuring procedure produced the same results for repeated trials, and the validity, that is the degree to which the launch monitors accurately reflected and assessed clubhead and ball launch conditions.

3.2.1 Data collection

For the purposes of this preliminary investigation (3.2), single-subject analysis was utilised. The same single-subject was used for the present study as was for preliminary study 3.4 and main study 4, and who was also part of the subject group studied during preliminary study 3.3 and main study 3. After performing his usual pre-game warm-up routine which included stretching and hitting 10 practice shots with their own driver, the subject was instructed to aim along a target line (Figure 3.4) into netting hanging 4.5m away. For each test set comparing system 2 and 3 against system 1, the golfer performed 40 trials. At least 30 seconds passed between each shot and 30 minutes between each test set to reduce any fatigue effect. After each shot was struck, an investigator wiped the clubface and ball with white spirit to ensure a clean contact surface was being used. Acceptance of a swing was based on data quality which meant complete data for all launch conditions by both systems, and positive subjective feedback from the subject.

Premium golf balls were used for the tests, each one marked along its circumference with a black line to aid calculation of spin rates from the digitised images captured by each system that used image analysis. A new ball was used for each set of 10 trials. The golfer teed the ball to a height with which he felt comfortable and this height (2.5″/0.0635m) remained the same throughout all 120 trials. Both irons and driver clubs were used for the tests, chosen in a random manner. Table 3.5 shows the clubs used for the individual tests. Tests comparing system 1 and system 2 utilised the subject’s own irons, and tests comparing systems 1 and 3 used drivers which were constructed for the main studies 1 and 2, thus were clubs with which the subject was unfamiliar.

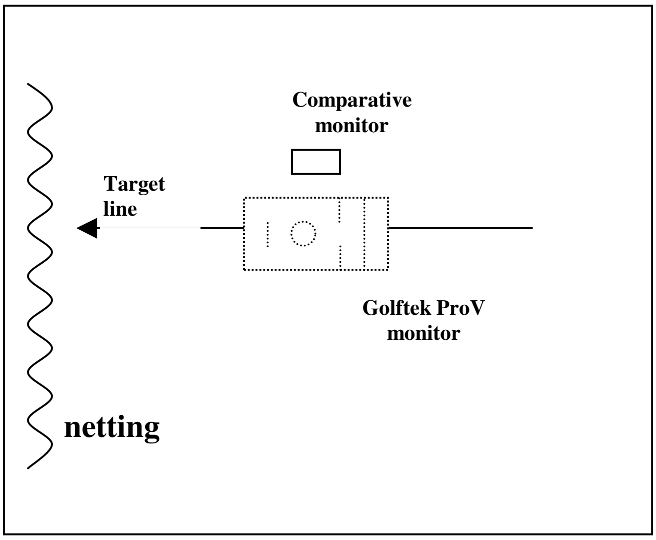


Figure 3.4 Laboratory test arrangement for launch monitor comparison

3.2.2 Data analysis

Descriptive statistics (mean ± standard deviation) were derived for and comparisons between pairs of launch monitors were carried out by performing a Pearson's test for correlation using the statistical package SPSS™ v 11.5.1. Correlation was deemed appropriate as it provides a good indication of the relationship of one set of data or measure with another. However, correlational analysis can mask absolute difference in the measured values between data sets. Thus, where Pearson's correlation was applied to similar data in the present study, and in other studies within this thesis, is was supplemented with calculation of the root mean square (RMS) of the difference between data sets studied.

Significant statistical results, for example a p-value of 0.001 (Table 3.5) have been presented in the test throughout this thesis as $p < 0.001$, corresponding to the format used in the Journal of Biomechanics (Rousanoglou *et al.*, 2006).

3.2.3 Correlational analysis

It can be seen in Table 3.5 that data measured by systems 1 and 2 most closely matched, indicated by a correlation coefficient of 0.913. Systems 1 and 3 were also reasonably well matched in terms of recorded clubhead velocity. RMS difference mirrors this trend, showing small variation of 1.10 ms^{-1} between measured clubhead velocity for systems 1 and 2, and marginally larger variation of 4.42 ms^{-1} for systems 1 and 3.

Table 3.5 Descriptive statistics and correlation coefficients for launch monitor comparisons

Monitors	Club tested	Clubhead velocity ($\bar{x} \pm \sigma$ ms^{-1})	Pearson's correlation 'r'	RMS difference (ms^{-1})
1 / 2	3-iron	41.1 ± 0.25 / 41.4 ± 0.72		
1 / 2	5-iron	40.0 ± 0.49 / 40.5 ± 0.89		
1 / 2	7-iron	39.0 ± 0.59 / 40.5 ± 0.89	0.913*	1.10
1 / 2	9-iron	36.7 ± 0.46 / 37.9 ± 0.62		
1 / 2	PW	37.2 ± 1.06 / 38.4 ± 1.11		
1 / 3	46″	42.7 ± 2.85 / 45.4 ± 3.45		
1 / 3	47″	43.8 ± 2.69 / 46.1 ± 2.90	0.871*	4.42
1 / 3	49″	43.8 ± 2.44 / 46.3 ± 2.69		
1 / 3	52″	44.0 ± 2.87 / 47.2 ± 2.76		

**Significant at the 0.001 level*

3.2.5 Conclusions

Results showed that a strong and statistically significant correlation existed between data obtained using launch monitors 1 and 2 and launch monitors 1 and 3. This would indicate that during tests where launch monitor 1, the Golftek^{TM} ProV, could not be used, closely matched data was provided using either launch monitor 2 or 3.

3.3 Inter-subject variability

Most published research into golf biomechanics utilised a relatively small number of subjects and often a small number of trials to represent the golf swing. Table 3.6 summarises a few key studies in golf biomechanics. However, handicap and skill level, varying conditions between trials considered pertinent when testing outdoors, golfers' ability to perform as they normally would under laboratory testing conditions and fatigue all produce variation in performance.

Table 3.6 Summary of number of subjects and trials per condition used in key golf biomechanics experimental analyses

Author (s)	No. of subjects	No. of trials (per condition)
Burden *et al.* (1998)	8	20
Egret *et al.* (2003)	7	6
Egret *et al.* (2005)	12	5
Gatt *et al.* (1998)	13	10
Lindsay *et al.* (2002)	44	3
Mitchell *et al.* (2003)	65	3
Mizoguchi *et al.* (2002)	13	5
Nesbit *et al.* (1994)	1	unspecified
Nesbit (2003)	4	"several"
Wallace *et al.* (1990)	2	10
Wallace *et al.* (2004)	9	10

Newell and Corcos (1993) stated that variability is inherent within and between all biological systems and is the result of interactions among the structural and functional characteristics of the system and the constraints imposed on motion. Biomechanical analyses said to be open to sources of error due to variability of movement, will include variation in the swing of even highly skilled golfers for/at both within-and between-subjects level.

Wallace *et al.* (1990) highlighted the deviation in shot performance between high and low handicapped golfers, for foot to ground pressure patterns. Two subjects were examined using two force platforms, one subject with a handicap of 6, the other of 24. The high handicapped golfer showed higher standard deviation between trails for 4 of the 6 measures which included top of backswing, mid downswing, contact, and follow through pressure. A one-factor ANOVA showed no significant difference between trials for either player. As such, if a condition such as shaft length variation is investigated, even within a small handicap range (category 1 golfers, up to 5 handicap) clubhead and ball launch characteristics and shot outcome may be markedly different. Furthermore, Fradkin *et al.*'s (2004) study (see Section 2.2.1) showed intra-subject variance of between 1.2 ms^{-1} and 4.1 ms^{-1} for clubhead velocity for the 10 shots that each golfer performed. Clubhead velocity also decreased as handicap and subject age increased.

Convenience sampling techniques were undertaken to provide test subjects for the studies in this thesis. This sampling method has also been used in previous studies, such as those given in Table 3.5, whilst also affording acceptable levels of experimental control, including:

- Matched skill level of subjects, thereby reducing inter- and intra-subject variability;
- Availability of subjects for repeat testing sessions thereby providing longitudinal data sets;
- A suitable sample size for each test to permit field testing to be conducted for all subjects on the same day thereby minimising environmental constraints.

Thus, 9 subjects of 5.4 ± 2.8 handicap were recruited for studies 1 and 2. Study 3 then recruited 6 golfers of a higher skill level (0.04 ± 2.28 handicap) in an attempt to further reduce both between and within subject error. Finally, study 4 (Chapter 7) utilised a single-subject for the development of a subject-specific musculoskeletal model for simulation of the golf swing.

3.3.1 Methods

This preliminary study addressing inter- and intra-subject variability utilised the same methods employed in study 3 (Chapter 6). To avoid replication only a brief outline of experimental procedures and equipment are discussed here. Further details can be found in Section 6.0.

Six elite golfers (0.1 ± 2.2 handicap, 22.1 ± 2.31yrs, 76.93 ± 9.45kg, 1.80 ± 0.04m) took part in the study. Testing was carried out on a purpose-built practice hole with a straight fairway cut 40 yards wide, 330 yards from tee to pin, with a raised tee box and visible flag on the green. Figure 3.5 illustrates the set-up used for testing.

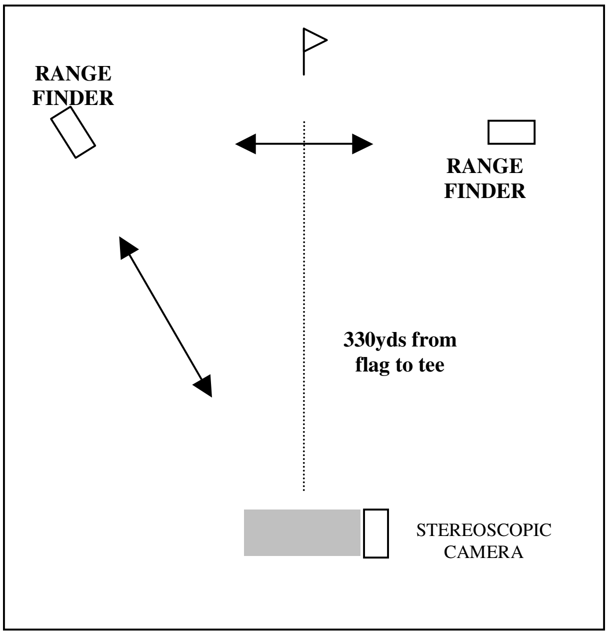


Figure 3.5 Schematic testing set-up

A stereoscopic high-speed camera positioned perpendicular to the intended direction of ball flight was used to record clubhead and ball launch conditions prior to and immediately after impact which included clubhead velocity, clubhead orientation, initial ball velocity, ball backspin and sidespin components, and ball launch angle, both elevation and sideangle. Two laser range finders were positioned approximately 250 yards from the tee such that using calibration coordinates and known distance from one laser to the other, and the second laser to the tee, ball carry position as identified by two ball spotters could be determined within a coordinate frame, giving both carry and dispersion from a fairway centre line. Personnel were in place so that for each shot, data were recorded for clubhead and ball launch conditions using the launch monitor, for anecdotal information at the tee relating to quality and direction of the shot, and from each of the laser range finders for ball carry and dispersion.

Section 3.1 detailed the process where club components were selected, and assembled to give the finished test clubs. To evaluate golfer skill and determine the level of variability, as indicated by the range or standard deviation of measures recorded, subjects were provided with test drivers. Three drivers were constructed, matched for all physical properties as closely as was possible based on acceptable tolerances discussed in Section 3.1. Table 3.7 shows selected characteristics for both the shafts and clubheads chosen as components of the assembled drivers. Section 3.1 Table 3.2 provides complete data.

Table 3.7 Matched club shaft and clubhead characteristics

Physical Characteristic	Club		
Club ID	5	6	13
Length (m/″)	1.168 / 46	1.168 / 46	1.168 / 46
Tip diameter (m)	3.5	3.5	3.5
Flex	X*	X*	X*
Torque (°)	2.8	2.8	2.8
Shaft Mass (g)	63.0	63.0	63.0
Loft (°)	9.0	9.0	9.0
Head Mass (kg)	199.97	200.10	200.50

**X- Denoted 'stiff' by manufacturer*

Data from a previous study (Egret *et al.*, 2003) determined that normal clubhead velocity for the skill level of the subjects recruited was in excess of 44.7 ms^{-1} (100mph) and less than 51.4 ms^{-1} (115mph). As such, as discussed in Section 2.1.2, the speed of a swing affects the amount of bending experienced by the shaft, therefore clubhead/ball impact characteristics, the magnitude of shaft deflection increasing as swing speed increases. Swing speed for the subjects recruited for this preliminary study suited a stiff shaft. Club length for subjects' own drivers ranged from 1.13m (44.5″) to 1.17m (46″) and matched drivers were constructed 46″ in length.

Subjects were informed as to the purpose and protocols of the study, and signed an informed consent to participate in the investigation. Each golfer performed their usual warm-up routine which involved stretching followed by 10 practice shots with their own driver. Three sets of 8 trials were performed by each golfer, using the randomly assigned matched drivers given the ID numbers 5, 6 and 13 (Table 3.7). Premium balls were used for the investigation.

3.3.2 Data analysis

Carry and dispersion and launch monitor data were amalgamated in tabular form using MS^{TM} Excel v9.0.3821 SR-1 and included anecdotal information obtained from the tee. Anecdotal information identified any of the 8 shots which were mis-hit or which subjects reported as being markedly inferior. As a result most sets of trials produced at least 6 acceptable shots. Descriptive statistics were calculated relating to the central tendency of the measures recorded, namely mean, standard deviation, and the standard deviation of the mean ($^{\sigma}/_{\sqrt{n}}$). Inter-subject variance was statistically analysed using a one-way ANOVA with a post-hoc LSD test applied to any measures that showed significant variance. ANOVA assumes that data has been sampled from populations that follow a Gaussian bell-shaped distribution. Biological data never follow a Gaussian distribution precisely, because a Gaussian distribution extends infinitely in both directions, so it includes both infinitely low negative numbers and infinitely high positive numbers. But many kinds of biological data, such as that collected in the present study, follow a bell-shaped distribution that is approximately Gaussian. Because ANOVA works well even if the distribution is only approximately Gaussian these tests are used in many fields. Graphical display in SPSS of the data collected in the present study confirmed that the distribution was normal. The post-hoc test that was selected, LSD, provided the simplest and most powerful means by which to clearly identify where any differences rested, in this case signifying inter-subject variability.

3.3.3 Results

Table 3.8 shows the mean and standard deviation for all subjects for clubhead velocity, ball carry and dispersion. Also shown is the standard deviation of the mean for dispersion. It can be seen that there existed significant difference in overall performance between subjects. Clubhead velocity at impact and ball carry showed significant differences between subjects for all clubs, whilst dispersion from the fairway centre was statistically significant only for club 13.

Table 3.8 Clubhead velocity and shot performance means (± s.d.) for matched drivers for all subjects

Club ID	Clubhead Velocity (ms^{-1})	Carry (yds)	Dispersion (yds)	$^{\sigma}/_{\sqrt{n}}$
5	48.52 ± 2.04*	241.23 ± 15.20*	-2.10 ± 16.24	6.63
6	48.74 ± 2.19*	240.86 ± 15.51*	5.17 ± 17.15	7.00
13	48.61 ± 1.92 *	242.70 ± 11.31*	5.25 ± 13.85*	5.23

\- = left of target line
*significant difference among subjects ($p \leq 0.05$)

Table 3.9 shows further descriptive statistics for launch characteristics recorded by the stereoscopic launch monitor for all trials for all subjects using each matched driver. Significant difference was demonstrated for measures of side angle, launch angle and backspin.

Table 3.9 Launch angles and spin rate means (± s.d.) for shots performed using matched drivers

Club ID	Side Angle (˚)	Sidespin (RPM)	Launch Angle (˚)	Backspin (RPM)
5	-0.44 ± 2.75	874.28 ± 859.34	8.63 ± 1.86*	2334.72 ± 1672.68*
6	0.00 ± 3.10*	156.90 ± 667.47	7.97 ± 1.98	2840.62 ± 1117.88*
13	-0.46 ± 2.15*	339.72 ± 735.01	8.66 ± 2.54*	2819.40 ± 593.51

\- = left (of target line)
*significant difference among subjects ($p \leq 0.05$)

Dispersion charts are shown for each driver for all subjects (Figures 3.6 to 3.8) and for individual subjects (Figures 3.9 to 3.14). Again, industry standard yards are the units used for graphical representation.

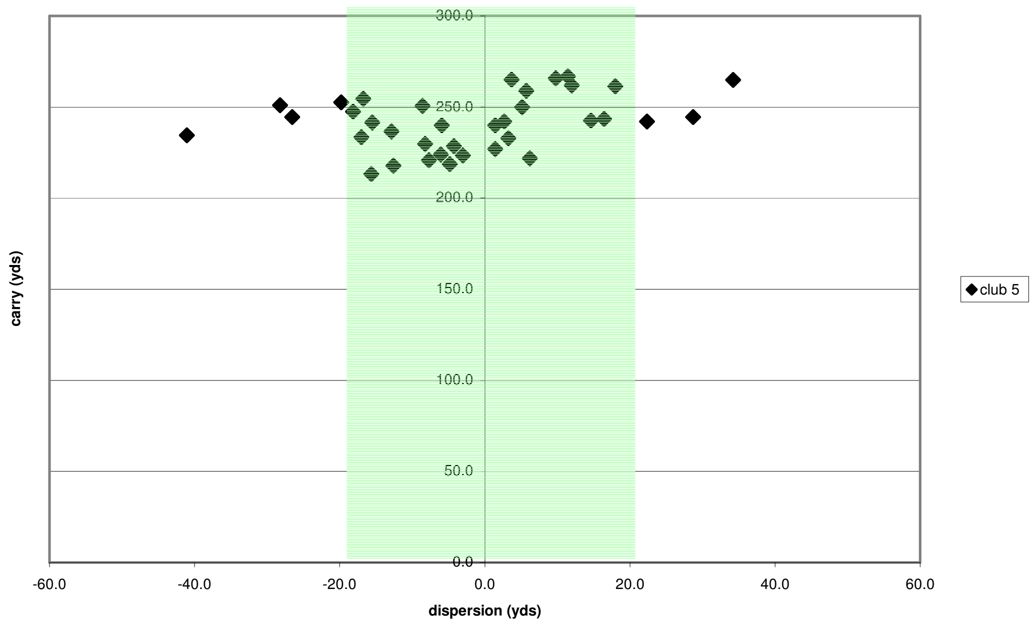


Figure 3.6 Scatterplot for all subjects using matched club 5

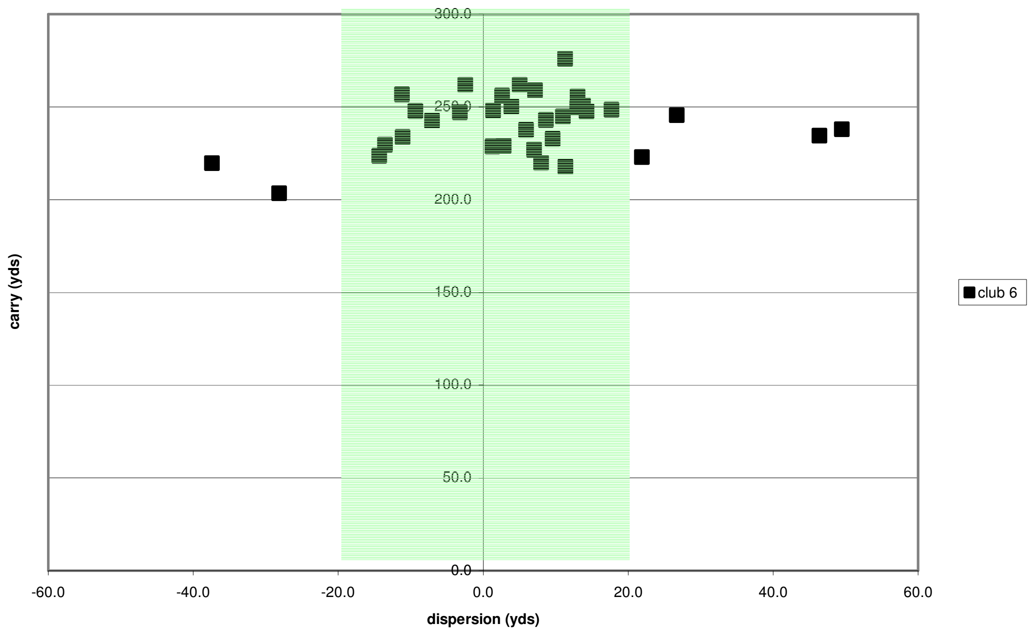


Figure 3.7 Scatterplot for all subjects using matched club 6

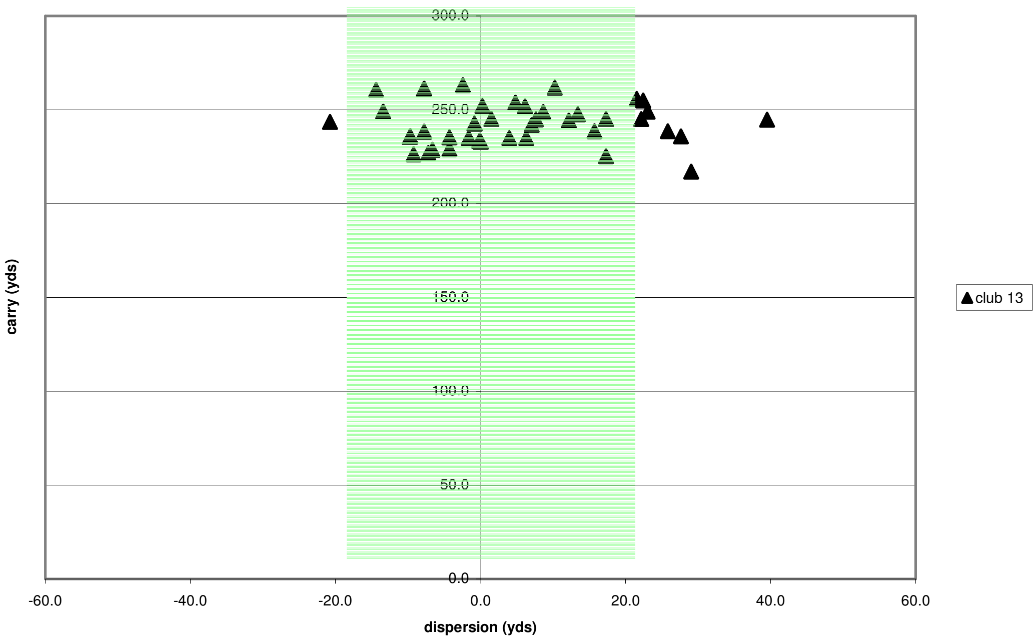


Figure 3.8 Scatterplot for all subjects using matched club 13

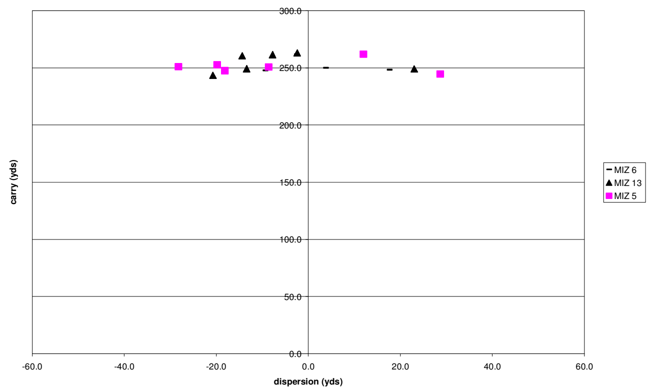


Figure 3.9 Scatterplot for subject #1 using matched drivers

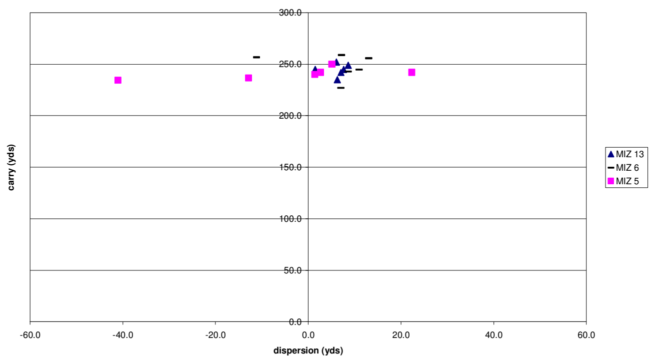


Figure 3.10 Scatterplot for subject #2 using matched drivers

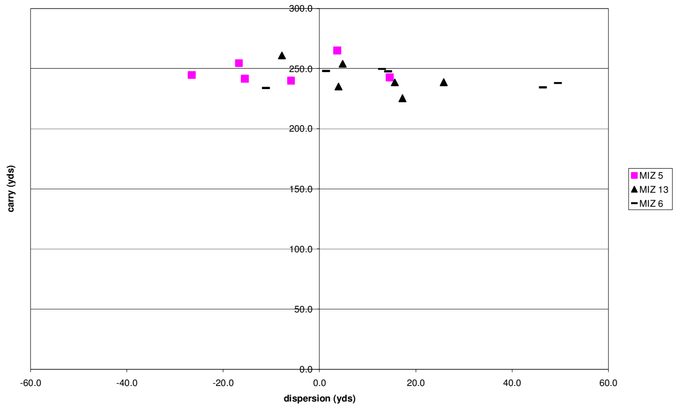


Figure 3.11 Scatterplot for subject #3 using matched drivers

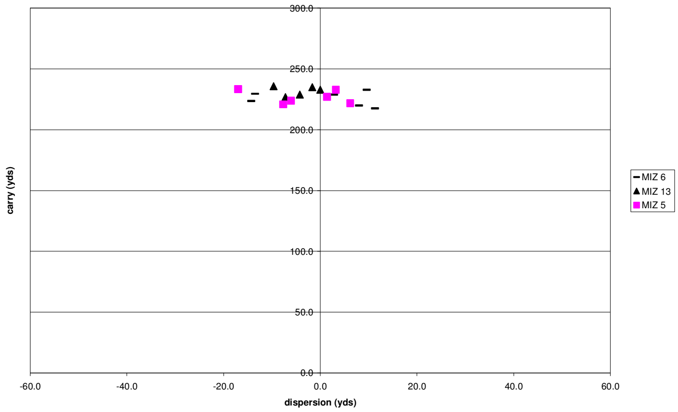


Figure 3.12 Scatterplot for subject #4 using matched drivers

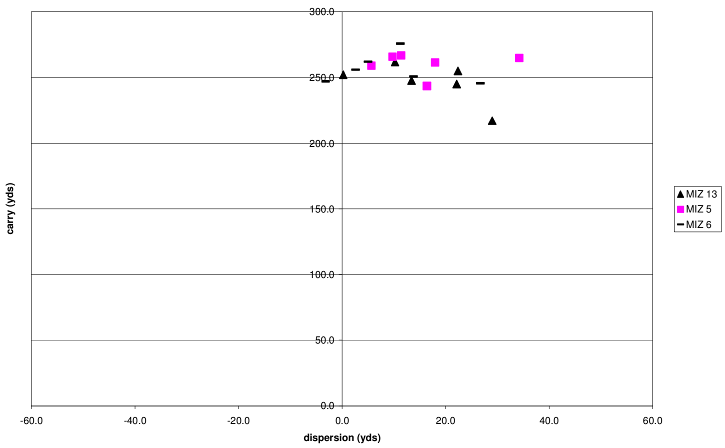


Figure 3.13 Scatterplot for subject #5 using matched drivers

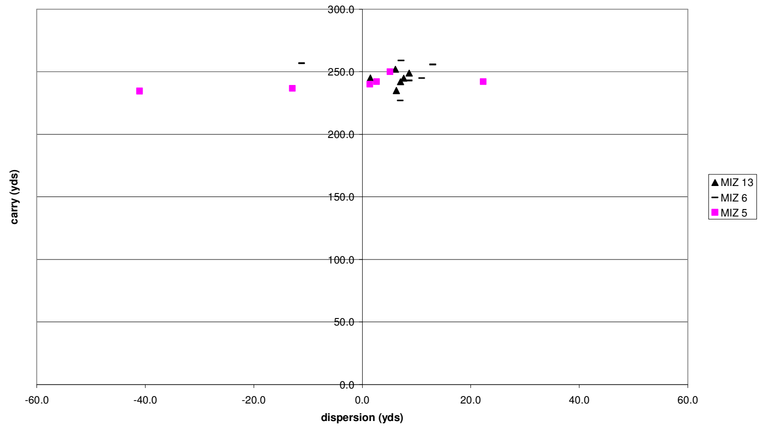


Figure 3.14 Scatterplot for subject #6 using matched drivers

Key ■ Club 5	— Club 6	▲ Club 13

In addition to individual scatterplots showing performance difference between subject (Figures 3.9 to 3.14), Table 3.10 presents descriptive data for clubhead velocity immediately prior to impact for each subject for each club. It can be seen that, in terms of mean clubhead velocity and standard deviation, there existed considerable difference in performance within the small group of elite golfers studied. Table 3.11 presents test scores for the one-way ANOVA and post-hoc LSD performed, showing significant inter-subject variability ($p<0.01$).

Furthermore, data showed considerable range in standard deviation of clubhead velocity for individual subjects from 0.24 ms^{-1} up to 0.96 ms^{-1} for sets of trials, indicating significant intra-subject variability, as the post-hoc LSD confirmed ($p<0.01$).

Table 3.10 Clubhead velocity at impact means (± s.d.) for matched drivers for individual subjects

Subject #	Club ID	Clubhead Velocity (ms^{-1})
1	5	50.48 ± 0.44*
2	5	49.09 ± 0.24*
3	5	49.28 ± 0.47*
4	5	44.52 ± 0.32*
5	5	50.08 ± 0.31*
6	5	46.98 ± 0.50*
1	6	50.66 ± 0.26*
2	6	49.44 ± 0.33*
3	6	49.75 ± 0.96*
4	6	45.03 ± 0.48*
5	6	50.81 ± 0.38*
6	6	47.04 ± 0.69*
1	13	50.72 ± 0.59*
2	13	48.86 ± 0.43*
3	13	49.22 ± 0.51*
4	13	45.04 ± 0.32*
5	13	50.62 ± 0.35*
6	13	47.27 ± 0.92*

*significant difference among subjects ($p \leq 0.01$)

Table 3.11 Statistical test results for subject effect

Test	Test statistics & variant subjects
1-way ANOVA	$F=177.73$, $p<0.01$
L.S.D.	1v3,4,5,6; 2v3,4,5; 3v4,5,6; 4v6; 5v6

3.3.4 Discussion

In recent years biomechanical studies have been carried out on single subjects, for example by Bates, 1996; Bates *et al.*, 2004; Kinugasa *et al.*, 2004 and Reboussin and Morgan, 1996. It has been reported, both in experimental and theoretical modelling journal papers, that it is unlikely that any two golfers will have an identical swing, and even that an individual golfer is unlikely to produce two identical swings in terms of kinematics. Also, naturally, intra-subject trial data will usually correlate better than inter-subject data. The huge number of degrees of freedom associated with whole body movements, and the larger number of motor control units and muscles involved in multi-joint movements mean that the method by which a golfer moves the driver clubhead from the address position to make appropriate impact with the ball will differ in three dimensional space. During the current study, the use of drivers with which the golfer was unfamiliar would have introduced some error into the normal swing path, but for the highly skilled golfers studied, this error is thought to be minimal. Results showed that, overall, there was little performance variation between subjects using drivers matched for physical properties. Nonetheless, some measures were deemed statistically significant and used as indicators of decreased accuracy for selection of a single, representative golfer.

Bernstein’s treatment of the problem of coordination may go some way to explaining the small variation in results seen in our testing of the matched clubs. Whilst the subjects tested were ‘good’ amateurs with a high level of skill, there will nonetheless be a period of time needed during which the golfer will use feedback, afferent, auditory, tactile in nature, to become accustomed to new drivers. It may be the case that a subject will constantly perform poorly with a particular club no matter how long a period they have to become accustomed to it. It may require days or weeks of practice with a club in order to familiarise oneself with it, in which case the small number of trials used in the present study (n=8) is only an indication of shot variability.

Finally, presentation of selected individual subject data enabled identification of a subject, subject number 1, that would be used for single-subject analysis for the modelling study in this thesis (Chapter 7 Study 4). A combination of relatively low intra-subject variability, driving performance deemed representative of the group of elite golfers studied, and ease of access to this particular subject aided this decision.

3.3.5 Conclusions

The aims of this preliminary study were to i) investigate the launch characteristics and driving performance of low-handicap golfers using identical drivers for assessment of inter-subject variability; and ii) to choose a subject to represent this group of elite golfers to act as a single-subject from which to collect kinematic motion data to drive the model developed in Study 4 (Chapter 7). Subject number 1 was selected based on the rationale:

i. Driving performance was representative of the group as a whole;
ii. Exhibited a high degree of accuracy and repeatability.

3.4 Effect of skin markers on golf driving performance

Golf is a very popular sport with purses for professional tournaments increasing (Shamanske, 2000) and the market for tools being used to analyse the golf swing, such as ball launch monitors and three dimensional optical tracking systems, growing proportionately with the increase in research and development investment by club manufacturers and biomechanics companies. Nevertheless, no study to date has reported if and how the use of surface markers used in three dimensional optical tracking methods to study swing kinematics would affect subject movement. Notably, however, Egret *et al.* (2004) studied the use of electromyographic equipment during the golf swing and concluded that the equipment significantly influenced the kinematic pattern of the golf swing. The present study therefore sought to deduce whether surface markers have an effect on golf swing performance for tests carried out in a laboratory setting.

The use of passive reflective markers, be that surface markers or bone-pin markers, allows the biomechanics investigator to analyse the kinematics of movement. No research to date has been carried out using bone-pin markers to analyse the golf swing. Therefore some of the literature discussed in this section refers to previous literature that performed clinical movement analysis such as the description of gait. For application to most sports, surface markers have been the preferred method due to their relative unobtrusiveness compared to bone-pin markers, for high-speed movement such as the golf swing (for example Alexander and Andriacchi, 2001; Karlsson and Tranberg, 1999). Researchers have previously concentrated their methodological analyses on such factors as the type of marker used, either wand or skin marker (Kirtley, 2002), the diameter of the sphere of the marker and the reflective material used to cover markers (Abuzzahab *et al.*, 1995), signalling noise and interference during processing (Bartlett, 1997), landmark identification (Cappozzo *et al.*, 1997), and skin movement artefact during movement (for example Holden *et al.*, 1997; Reinschmidt *et al.*, 1997, 1997a). These artefacts have been the main focus of both clinical and applied methodological research and is caused by movement of the skin and subcutaneous fat when calculating underlying bone motion that the skin marker is meant to represent. Whilst still a concern in the present study, the golf swing is a movement that is closed-chain, non-impact and does not cause excessive unwanted movement of skin and wand markers that can often be observed in kinematic analysis of running, gait and plyometric exercise when using skin markers. It is therefore concluded that the golf swing lends itself well to kinematic analysis using skin surface markers.

3.4.1 Methods

Single-subject analysis was carried out for the current study (Bates, 1996; Bates *et al.*, 2004; Kinugasa, 2004). The single subject recruited was a healthy male right-handed amateur golfer (+1 handicap, 25 yrs, 1.80m, 91.3kg). Golf shots had to be performed with and without markers attached to the body, therefore a kinematic analysis of movement using an optical multiple camera system to track marker three dimensional trajectory was not appropriate. Performance for each shot was therefore determined through analysis of clubhead and ball impact characteristics as measured using a commercially available launch monitor. The launch monitor incorporated the tee from which the ball was struck. The subject selected their own tee height as they normally would in competition. The subject was positioned on an artificial grass surface wearing golf spikes as they normally would on a golf course (Figure 3.15).

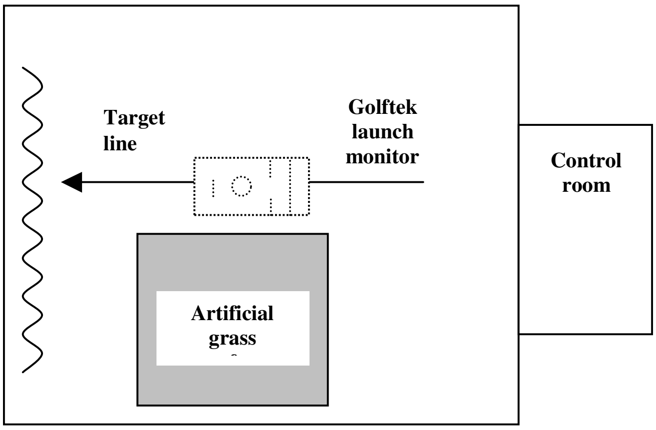


Figure 3.15 Launch monitor set-up in the laboratory

The only other clothing worn were a pair of lycra ‘cycle shorts’. Thirty four surface markers were attached to the subject as shown in figure 3.16. Humeral and radial markers were positioned on 2½″ wands and femoral and tibial markers were positioned on 4″ wands (figure 3.17).

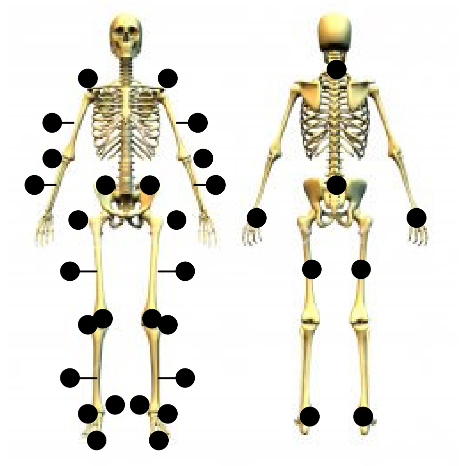


Figure 3.16 34 marker arrangement

Eight markers described arm motion and were ½″ in diameter, the remaining 26 markers were ¾″ in diameter. The marker arrangement was an adaptation of Mitchell *et al.*’s (2003) 26 marker arrangement used to study shoulder motion during the golf swing. Markers described the following anatomical landmarks: acromion, epicondyle, wrist centre, C4, anterior superior iliac spine, sacrum, greater trochantor, lateral epicondyle, anterior epicondyle, medial malleolus, lateral malleolus, 2nd metatarsal head, heel, and the geometric centre of mass (COM) of the upper and lower arms, and upper and lower legs. An additional marker was placed on the golf club shaft 10″ from the centre of the right wrist marker. The shaft marker in this case was used to replicate the marker set-up used for study 1 in this thesis and which would also be used for study 4. The shaft marker is normally used to aid digitised calculation of the wrist angle during the golf swing.

Figure 3.17 Femoral and tibial wand marker arrangement

The subject warmed up as he normally would before playing a round of golf. Using his own driver the subject was instructed to hit 8 shots along a target line marked on the floor into netting 4.5m away. Anecdotal information relating to the quality of each shot by the golfer was recorded and a trial was deemed acceptable when positive anecdotal information was provided and the launch monitor recorded a full set of launch conditions. Markers were then removed and the procedure repeated for 8 trials without markers attached to the subject.

Data recorded by the launch monitor included clubhead speed prior to impact, ballspeed immediately after impact, clubhead orientation, tempo and ball launch angle. Data were analysed using a Wilcoxon signed-ranks test to determine significant differences ($p<0.05$) between clubhead and ball impact data with and without markers. The prerequisite for parametric statistical analyses, that is the assumption of independence, used in group research designs is often not met in single-subject studies. Therefore, conventional statistical analyses used in group research designs, including *t* and *F* tests may not be applied in single-subject designs. Bates (1996) suggested that non-parametric tests are more powerful in single-subject studies, and the Wilcoxon signed-ranks test was best applied in the current study given that two paired groups (with and without markers) were analysed.

3.4.2 Results

Data for both conditions, with and without surface markers fixed on the subject, are shown in Table 3.12.

3.4.2.1 Launch characteristics

Significant differences ($z = -2.521$, $p < 0.05$) were noted for ballspeed when shots were hit with and without markers attached to the body. Shots hit without markers averaged 2.92 ms^{-1} slower ball velocity (-4.19%). Difference in clubhead speed did not prove significant with only 0.56ms^{-1} difference between the two conditions.

Table 3.12 Data recorded by the launch monitor during the golf swing with and without surface markers fixed on the subject

Measure	With markers	Without markers
Clubhead speed (ms^{-1})	49.96 ± 0.67	49.40 ± 1.07
Ballspeed (ms^{-1})	69.62 ± 0.85	66.70 ± 0.93*
Clubhead orientation (˚)	1.25 ± 3.24	3.00 ± 0.93
Tempo (s)	0.82 ± 0.01	0.81 ± 0.02
Backspin (rev/min)	2676.5 ± 312.2	3263.6 ± 672.1*
Sidespin (rev/min)	-493.1 ± 423.1	189.0 ± 701.5*
Ball launch angle (˚)	11.13 ± 2.12	10.63 ± 1.88

** Significant at the 0.05 level*

Both ball backspin and the sidespin component showed significant differences ($z = -2.38$, $p < 0.05$). Backspin increased by an average 587.1 rev/min when shots were performed without markers attached. In addition, with markers attached, ball sidespin component was -493.1 ± 423.1 rev/min (left, or anti-clockwise), but changed to an average 189.0 ± 701.5 rev/min (right/clockwise) when markers were removed. The angle at which the ball left the tee in relation to the horizontal decreased from 11.13 ± 2.12° to 10.63 ± 1.88° when markers were removed from the subject. This was coupled with an increase of an average 1.75° (open) clubface orientation angle presented to the ball.

3.4.2.2 Temporal data

Using a significance level of 0.05, swing tempo did not show significant difference between the two conditions. A tempo decrease of 0.01 was shown when markers were removed from the subject.

3.4.4 Discussion

The present study showed that attachment of passive reflective skin markers, that would normally be used to study the kinematics of the golf swing via optical three dimensional systems, induces changes in the swing as inferred by a change in ball launch characteristics. The attachment of markers to the subject showed that ballspeed increased significantly. This may be due to over-compensation by the subject to produce good shots whilst encumbered with the array of markers. However, there was no measure of shot accuracy for shots performed during this preliminary study in the laboratory. It could be that shots performed without markers in the present study are carried out with more control and accuracy, thereby slower, but more representative of shots performed normally on the golf course. Concurrently, shots performed with markers attached showed an increase in clubhead velocity prior to impact, albeit not a significant increase. The significance of difference in ball velocity may be compounded by several factors that are not present at the time measures of clubhead speed are obtained; that is clubhead orientation, ball spin and ball launch angle. Each of these components are known to impact on ballspeed after impact. Thus, if the subject is better able to control the redundant degrees of freedom (Bernstein, 1967) present in the skill of executing the golf swing, and which degrees of freedom are not as well controlled when markers are attached to the body, the components of ballspin, clubface orientation and ball launch angle may also be more representative of conditions seen on the golf course.

Clubface orientation increased by an average 1.75° when markers were removed, to produce a more open clubface. Anecdotal information offered by the subject indicated that the markers they were most concerned with were those arranged on the arms and on the femur. This may have caused the subject to swing their arms more rigidly to avoid the wand marker on the right femur and perform less wrist cock/uncock action which may account for the clubface orientation to be in a more closed position when markers were attached.

Sidespin, or non-horizontal component of the ball was shown to orientate left, or anti-clockwise for shots performed with markers attached. Significantly, the magnitude of these shots were greater than that for swings performed without markers (by 304.1 rev/min), and in an opposite direction. This would indicate that those shots performed with markers attached may have been less accurate, producing a more excessive right-to-left 'hook' shape.

The final variables for consideration, backspin, launch angle and tempo, may be discussed together as they are considered to have a combined effect on the flight of the ball. In driving for distance, low backspin and a relatively high launch angle are considered necessary. However, backspin was shown to be significantly lower ($p = 0.017$) in the present study for shots with markers (2676.5 ± 312.2 rev/min) than shots performed without markers (3263.6 ± 672.1 rev/min). Similarly, an opposite result than was expected was found as ball launch angle decreased by an average 0.5° when markers were removed. These findings may be explained in accordance with the decrease in ballspeed exhibited when markers were removed, that the subject was better able to control their shots, thus driving more for accuracy and repeatability than for distance. Furthermore, the small increase in tempo (0.01) for shots hit with markers attached would ordinarily indicate a slower swing speed, but only if swing kinematics remained constant between trials with markers and trials without. That swing speed (ballspeed) was shown to increase with markers attached, this would signal a change in swing kinematics, possibly a deeper backswing, thereby increasing the possibility of error associated with the swing.

3.4.5 Conclusions

The presence of passive reflective surface markers had a significant effect in terms of ballspeed (4.19%), backspin (18.0%) and sidespin (61.7%) components of ball flight, thus modifying the performance of shots hit with a driver. However, a greater number of the performance measures recorded, including clubhead velocity at impact, clubhead orientation, swing tempo, and ball launch angle, were relatively unaffected by the presence of skin markers. As impact is not simulated in the model developed and discussed later in this thesis, clubhead velocity being the main measure of shot performance output by the model, the fact that markers did not significantly affect shot performance in the present study is a reassuring find, rendering laboratory-obtained kinematic data valid.

3.5 Summary

The preliminary studies included in this chapter address issues relating to test club features and criteria, appropriate selection of launch monitors, inter- and intra-subject variability, and the effect of skin markers on golf driving performance. Test clubs were assembled with closely matched components. However, swingweight was not matched for drivers that varied by shaft length, thus club's first moment of inertia was allowed to increase as shaft length increased. The clubhead and ball launch monitors which were selected were shown to produce data that correlated strongly, providing reliable launch condition data. Inter- and intra-subject variability for clubhead velocity immediately prior to impact was found to be significant, even with the elite group of golfers (<5 handicap) studied here. As such, and with knowledge that the golf swing varies between every golfer (Newell and Corcos, 1993), the use of single-subject analysis for Study 4 may be justified, despite its apparent limitations concerning statistical analyses (Bates, 1996; Bates *et al.*, 2004; Kinugasa *et al.*, 2004 and Reboussin and Morgan, 1996). Finally, skin markers were found not to significantly affect the majority of performance measures commonly recorded during biomechanical analyses of the golf swing. Thus, it can be concluded that testing performed in the laboratory with markers attached to the skin of golfers is a valid representation of the golf swing.

CHAPTER 4

STUDY 1:

Kinematic analysis of the golf swing for low-medium handicapped golfers using drivers of different shaft length

4.0 Introduction

The review of literature highlighted the lack of research which fundamentally described movement patterns during the golf swing for golfers using drivers of different shaft length. A limited number of studies, for example Nagao and Sawada, 1973 and Egret *et al.*, 2003 examined the kinematics of the golf swing for golfers using different clubs, including a driver, 5-iron and 9-iron. Other studies examined clubhead velocity and ground reaction forces during the golf swing for drivers varying in shaft length (Mizoguchi *et al.*, 2002) and driver shaft length influences on tempo and posture (Wallace *et al.*, 2004). However, none to date have holistically addressed the kinematics of the golf swing, to include characterisation of posture, hip and shoulder angular velocity, and investigation of temporal characteristics for low-medium handicapped golfers using drivers of different lengths.

The aims of the present study (Study 1) were:

i. To evaluate the effect of driver shaft length on posture at address, the top of the backswing and at impact for low-medium handicapped golfers.

ii. To determine the effects of driver shaft length on hip and shoulder angular velocity for low-medium handicapped golfers.

iii. To evaluate the effect of driver shaft length on swing timing for low-medium handicapped golfers.

4.1 Methods

Details of equipment, subjects and testing procedures employed in addressing the aims of the present study are presented in the following sections.

4.1.1 Equipment

Four driving clubs were constructed with shaft lengths of 46″, 47″, 49″ and 52″. These clubs were the same as were used for study 2. Table 4.1 shows the physical characteristics of the clubs (see section 3.1.2 for component ranges). All other club parameters were, insofar as was possible, matched. Driver lengths were selected based on club parameters commonly used in the professional game, and shaft lengths below the limit of 48″ imposed by the governing bodies of golf, above the limit, and significantly greater than the limit.

Table 4.1 Test club parameters

Measure	R	L	XL	XXL
Shaft Length (m/″)	1.143 / 46	1.194 / 47	1.245 / 49	1.301 / 52
Clubhead CT (ms)	243.1	233.8	243.5	244.5
Clubhead volume (cc)	255	255	255	255
Clubhead mass (kg)	0.197	0.197	0.200	0.198
Clubhead loft (˚)	7.0	7.0	7.0	7.0
Clubhead lie (˚)	59.5	60.0	60.0	60.5
Clubhead face area (m^2)	0.003165	0.003165	0.003165	0.003162
Cut Shaft mass (kg)	0.053	0.057	0.059	0.062
Assembled club frequency (Hz)	266	253	246	218
Swingweight (in/ou)	19.7	20.7	22.4	24.2
Swingweight (Lorythmic)	D0.0	D7.0	E8.0	F9.0

Kinematics for each swing were recorded using the three dimensional 5-camera MAC™ Falcon Analogue motion analysis system operating at 240Hz. Figure 4.1 illustrates schematically the laboratory set-up used for kinematic analysis. An analogue camera system was used to provide a high resolution of image for the field of view that was required for movement in a large calibrated volume. The use of analogue cameras over digital at this range (3 to 4m) meant that image size and resolution (640 x 240 pixels) was maintained and markers were not distorted allowing for automated three-dimensional tracking. The C-mount lenses used worked with the 630nm ring-light strobe comprising 237 LED's per ring-light. The Falcon system allows for up to 28 cameras to be synchronised and used to track motion, but due to the relatively small calibrated volume needed for the golf swing, 5 cameras were sufficient to ensure all markers were visible by at least 2 cameras at any point in time during the golf swing.

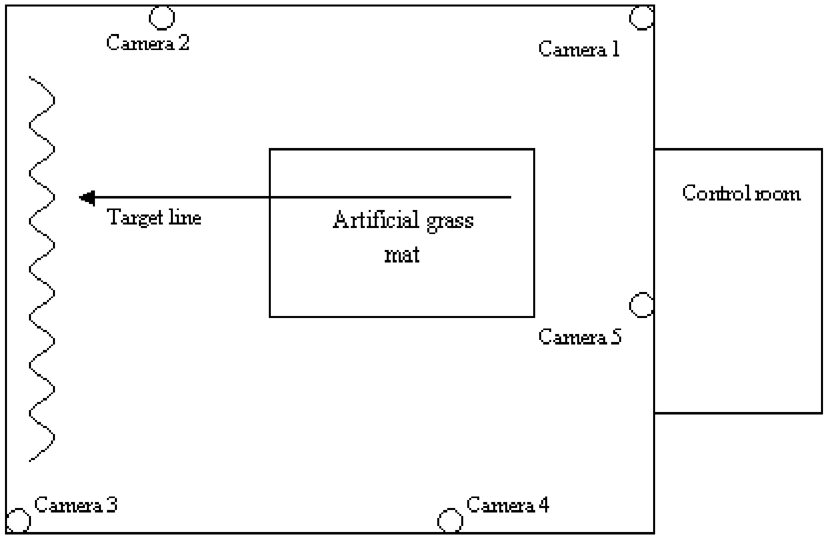


Figure 4.1 Laboratory set-up and calibration frame orientation

Arrangement of the cameras in the laboratory, which was approximately 12m by 8m, followed the method described by Gazzani (1993) which allowed for 'free-positioning' of cameras within a space of known dimensions, adhering to the principle of direct linear transformation (DLT) pioneered by Abdel-Aziz and Karara in 1971. This suggests that transformation of image to object coordinates is affected by camera calibration involving eleven or more parameters for each camera, including camera-to-camera distance, angle, elevation, lens type, camera-to-object origin distance and coordinates. Cameras were fixed to the vertical via bolts drilled through concrete wall to minimise risk of extraneous vibration. Setup and image verification was carried out as instructed by the MAC™ Falcon instruction manual available from Motion Analysis Corporation. Calibration of the system is described later in section 4.1.1.

An adaptation of Mitchell et al's (2003) 26 marker setup[11] was used to describe the motion of the golf swing. Reflective passive surface markers were used, 8 of which described arm motion and were ½″ in diameter. The remaining 18 markers used were ¾″ in diameter. Smaller markers were used to track arm movement due to the greater relative angular velocity of the arm lever during the golf swing, thus common difficulty in determining the joint centre of rotation of the wrist and elbow, and the centre of mass

[11] 26 marker model- proposed by Mitchell *et al.* (2003) to characterise shoulder motion during the driving swing for male recreational golfers tracked using a 6-camera MAC™ system.

of the upper arm and forearm. Figure 4.2 shows a not-to-scale diagram of the positioning of the 26 surface markers.

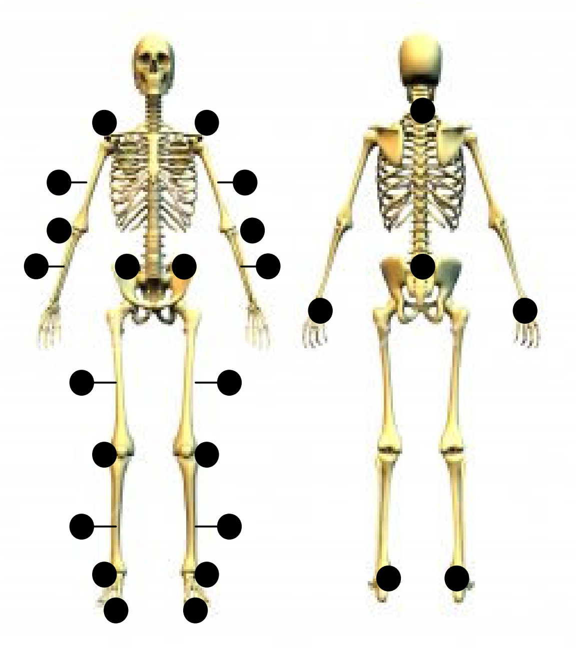


Figure 4.2 Diagram showing positioning of the 26 main passive surface markers

Segments were described using wand markers. These were tibial, femoral, humeral and radial wands as shown. This method allowed for greater precision in tracking rotational movement commonly associated with the golf swing known as yaw, pitch and roll. Additional manual calculation of Euler angle is also possible through the use of wand markers, therefore as an additional data processing tool the use of wands is beneficial were automated digitisation may fail. Wands 4″ (0.1016m) in length were used for the lower extremity whilst 2½″ (0.0635m) wands were used on the upper extremity to:

i. Reduce marker vibration, thus noise during the high velocity movement of the arms during the swing, and
ii. To aid comfort such that the subject may swing as naturally as possible. Long wand markers attached to the arms tend to feel more cumbersome for the golfer.

Wand markers were attached using rigid metal t-bar wands and fastened to the skin using double sided tape and taught elastic covered in inelastic non-allergenic tape (Figure 4.3).

Figure 4.3 Radial ½″ diameter reflective marker on 2½″ rigid metal wand

Sixteen body segments were identified as components of the marker model derived. These were: shoulder breadth, Left (L) and right (R) upper arms, L and R lower arms, L and R hands, upper torso, lower torso, pelvis, L and R upper legs, L and R lower legs, L and R feet. Each segment except the hands and feet used an array of 3 markers to describe the segment reference frame. Tables 4.2 to 4.7 detail the anatomical reference positions used for marker placement to describe the respective joint centres and body segment centres of mass.

Table 4.2 Torso markers

ID	Segment	Description
T4	Thoracic 4th	Spinous process of the 4th thoracic vertebrae

Table 4.3 Right Arm Markers

ID	Segment	Description
RSHO	Right Shoulder	Flat portion of the acromion
RHUW	Right Humeral Wand	A 2.5 inch wand placed on the upper arm ½ way between the elbow and shoulder. Laterally in anatomical ref position. Should be placed symmetrically with LHUW
REPI	Right Epicondyle	Placed on lateral epicondyle approximating elbow joint axis
RFOW	Right Forearm Wand	A 2.5 inch wand placed on the lower arm ½ way between the elbow and the wrist, along radial line. Should be placed symmetrically with LROW
RWRI	Right Wrist	Right wrist lateral centre

Table 4.4 Left arm markers

ID	Segment	Description
LSHO	Left Shoulder	Flat portion of the acromion
LHUW	Left Humeral Wand	A 2.5 inch wand placed on the upper arm ½ way between the elbow and shoulder. Laterally in anatomical ref position. Should be placed symmetrically with RHUW
LEPI	Left Epicondyle	Placed on lateral epicondyle approximating elbow joint axis
LFOW	Left Forearm Wand	A 2.5 inch wand placed on the lower arm ½ way between the elbow and the wrist, along radial line. Should be placed symmetrically with RROW
LWRI	Left Wrist	Left wrist lateral centre

Table 4.5 Pelvis

ID	Segment	Description
LASIS	L ASIS	Placed directly over the left anterior superior iliac spine
RASIS	R ASIS	Placed directly over the right anterior superior iliac spine
SACRU	Sacrum	Placed mid-way between the posterior superior iliac spines (PSIS).

Table 4.6 Foot Markers

ID	Segment	Description
L2MET	Left Metatarsal Head	Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
R2MET	Right metatarsal Head	Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
RHEEL	Right Heel	Placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker
LHEEL	Left Heel	Placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker

Table 4.7 Leg Markers

ID	Segment	Description
RFEMC	R Fem. Epicondyle	Placed on the lateral epicondyle of the right knee
LFEMC	L Fem. Epicondyle	Placed on the lateral epicondyle of the left knee
RFEMW	R Fem. Wand	A 4 inch wand is placed on the right thigh, viewed in the anatomical ref position, ½ way between lateral epicondyle of right knee and greater trochanter. Just below the swing of the hand
LFEMW	L Fem. Wand	A 4 inch wand is placed on the left thigh, viewed in the anatomical ref position, ½ way between lateral epicondyle of left knee and greater trochanter. Just below the swing of the hand
LLATM	Left Malleolus	Placed on the lateral malleolus along an imaginary line that passes through the transmalleolar axis
RLATM	Right Malleolus	Placed on the lateral malleolus along an imaginary line that passes through the transmalleolar axis
LTIBW	Left Tibial Wand	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. 4 inch wand
RTIBW	Right tibial wand	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. 4 inch wand

Table 4.8 Golf Shaft marker

ID	Segment	Description
SHFT	Golf Shaft Marker	Marker placed on the golf shaft 10 inches from the centre of the right hand. Frontal plane

In addition to the 26 body markers and 1 club marker (Table 4.8) that has been described, the MAC^{TM} computer rigid lever model that was constructed to represent the subject included a further 20 markers. Such markers aided calibration of the local coordinate frame, that is positioning of a marker with respect to each other marker. Additional markers that were used are described in Table 4.9. Those markers that were not clones and were attached to the subject are shown in Figure 4.4.

Table 4.9 Additional markers used to model the golf swing in MAC™ software

Tee	Left medial malleolus
Tee 1	Right medial malleolus
Tee 2	Left ankle_jc
Tee 3	Right ankle_jc
Left greater trochanter	Left knee clone
Right greater trochanter	Right knee clone
Left thigh (posterior)	Right acromion clone
Right thigh (posterior)	Left acromion clone
Left inferior patella	L5 clone
Right inferior patella	Navel

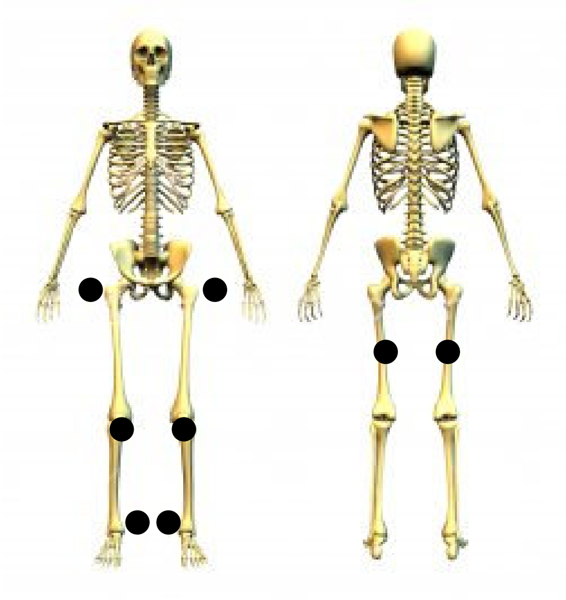


Figure 4.4 Additional visible surface markers

The volume within which the subject performed the golf swing was calibrated as per instructions detailed in MAC™'s Falcon Analogue system manual. Cameras were fixed and instrumented as described in Section 4.1.1. A 3′ by 2′ (0.91m x 0.61m) calibration frame was placed on the artificial grass mat approximately in the centre of the region where motion would take place. The rigid metal frame was fitted with eight 1½″ and two ¾″ passive reflective markers as shown in Figure 4.5. The cube itself was covered in matt black paint ensuring that light did not significantly reflect off the metal, providing contrast between the frame and the markers. Markers were permanently attached to the metal frame. Figure 4.6 shows a schematic of the orientation of the calibration frame in the laboratory. The calibration frame was set at an angle to the intended direction of golf shots to maximise the number of cameras that were able to obtain a clear view of each calibration marker. The calibration frame was placed where the golfers' body was positioned, but oriented in such a way that the cameras would have a non-obstructed view of all 8 control points. The Z-axis acted vertically. Calibration followed the methodological basis described by Gazzani (1993) which was a derivation of the DLT method.

Figure 4.5 Calibration cube

To ensure that the cameras were correctly calibrated, the frame was then removed and a t-bar fitted with three ½″ reflective markers was moved at speed by hand in different directions within the intended calibrated volume. The CPU linked to the cameras subsequently displayed the changing tri-axis co-ordinates of the markers on the t-bar. Maximum residual error was 0.0787″ (2mm) for each camera.

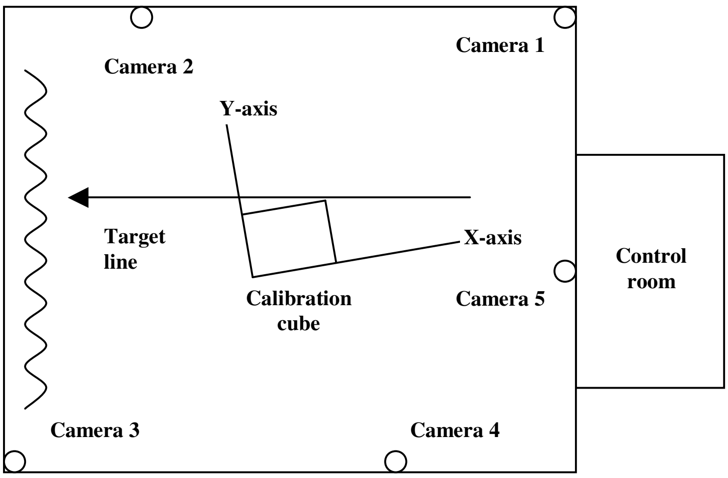


Figure 4.6 Orientation of calibration frame within the laboratory

4.1.2 Subjects & test protocols

Nine male, right-handed subjects took part in the study (40.2±12yr, 83.7±9.5kg, 5.4±2.8 handicap). Each subject was informed of the objectives of the study, completed a set of health history and golf history questionnaires, and signed an informed consent. Subjects were permitted a 10 minute warm-up period followed by 10 practice shots hit with their own driver. Subjects were then required to strike a series of 8 shots into an indoor net marked with a target line with each of the four randomly assigned drivers. Thus each subject performed 32 trials in total.

Subjects were instrumented with all 34 spherical markers placed over the selected anatomical landmarks. To assist in identifying specific events in the golf swing, an additional marker was placed on the club shaft as described in Section 4.1.1. A new premium golf ball was used as each golfer changed clubs. Subjects hit a maximum of 8 shots with each driver starting with their own driver, and then with each of the randomly assigned 'length drivers'. For each shot the MAC™ system tracked 3 seconds of motion including 1 second prior to beginning the swing, until approximately 0.5s after the swing ended, and an investigator recorded any anecdotal information relating to the quality of the shot offered by the subject. The subject was instructed to aim along a target line into netting hanging 4.5m away. After each shot was struck an investigator wiped clean the clubface and ball with white spirit to ensure a clean contact surface was being used. Testing was considered complete when at least 8 acceptable swings had been recorded for each driver. Acceptance of a swing was based on data quality, with reference to complete 3D data, and feedback from the subject.

4.1.3 Data collection & processing

Reconstructed co-ordinates of the markers, which inferred joint centre of axis and segment COM, were transferred from MAC™'s capture software EvaRT™ to KinTrak™. Data was smoothed using a low-pass Butterworth filter at 12Hz. This removed significant high-level noise within the motion spectrum resulting in smoother data with which to perform an analysis. Random noise was assumed here to be 'white' thus having a flat power spectrum and is not correlated between samples (trials). Movement signal on the other hand was mostly low frequency. Therefore by applying a mathematical filter to the data, high frequency noise was removed leaving meaningful low frequency movement data. It is widely accepted that the application of cut-off frequencies across all marker data is acceptable (Bobbert et al, 1996) and assumes that the frequency content of the true signal and the noise are the same for each joint marker/ subject combination. The efficacy of any data filtering is strongly dependent on the selection of an appropriate cut-off frequency and is based on the premise that whilst the true signal and the noise signal occur over a wide band-width of the frequency spectrum, the ratio of the signal to noise deteriorates at increasing frequencies (Figure 4.7).

Studies reported in biomechanics literature have tended to use a cut-off frequency of 6 Hz for filtering general slow motion such as walking and jumping. Raw data collected during the current study was examined, both trial-to-trial, and within each trial for marker-to-marker. It was concluded that there was not significant variability between marker data frequency therefore a uniform filter could be applied to the whole body data set. Also, the range of the noise frequency was such that a 6Hz filter would not sufficiently smooth the relative high speed motion of the golf swing and that a 12Hz filter would be needed (Mitchell et al, 2003).

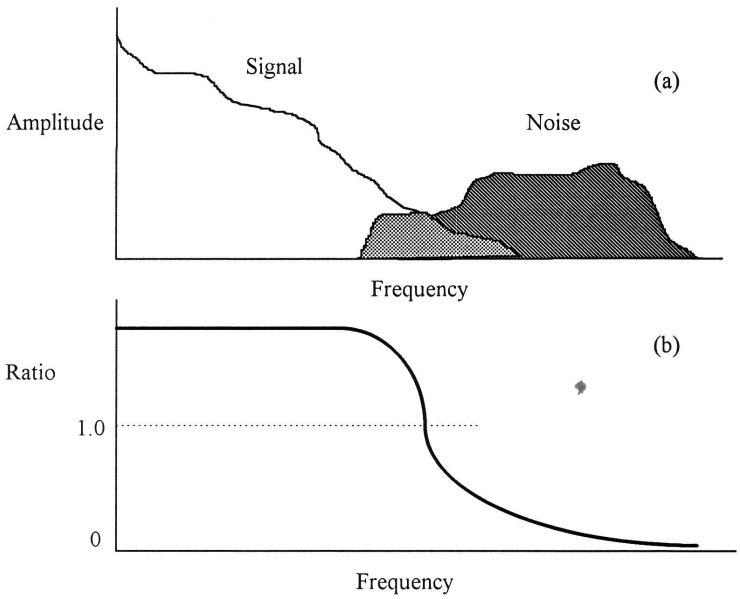


Figure 4.7 (a) Hypothetical frequency spectrum of a waveform consisting of the true signal and the unwanted higher frequency noise. (b) Ratio of signal-to-noise.

The 3D marker model that was constructed in EvaRT™ prior to data collection was tailored to the height and mass of the subject tested. The use of three markers per body segment allowed for reconstruction of the inertial component of each segment to the overall movement, based on cadaveric studies and known mass percentage of body parts. The tailoring of each model to the specific subject being studied is necessary to provide reliable and valid representation of the motion being studied.

4.1.4 Variable selection & calculations

Kinematic variables were evaluated in terms of magnitude and coordination. The variables selected for analysis of magnitude can be sub-divided into four main areas:

i. Posture at address (ADD)- body segment orientation of lower and upper extremities and posture relative to the tee.
ii. Posture at the top of the backswing (TOB)- upper extremity body segment orientation and relation to club position.
iii. Posture at impact (IMP)- upper and lower extremity body segment orientation.
iv. Angular velocity of the hips and shoulders throughout the swing.

Parameters for measurement and discussion within this study were limited to those deemed most relevant for identification of the effects of increasing shaft length. Variables were selected based on analyses presented in previous golf biomechanics literature, and more pertinently, kinematic studies into the effects of driver shaft length. Kinematics presented for each of the three areas were as follows:

i. <u>Posture at address (ADD)-</u> characterisation of initial posture. Measures analysed were: right and left knee angles in the frontal plane, right tibia (shank) angle in the sagittal plane, back inclination in the sagittal plane, left arm-trunk angle in the sagittal plane, left arm-club angle in the sagittal plane, shoulder rotation angle in the horizontal plane, hip rotation angle in the horizontal plane, stance width and foot-to-tee distance.
ii. <u>Posture at the top of the backswing (TOB)-</u> characterisation of body orientation at the moment the hands initiates the downswing. This included back inclination

in the sagittal plane, left arm-trunk angle in the sagittal plane, shoulder rotation angle in the horizontal plane and hip horizontal angle in the sagittal plane.

iii. Posture at impact (IMP)- characterisation of body posture at the moment of impact. This included right and left knee angles in the frontal plane, right tibia (shank) angle in the sagittal plane, back inclination in the sagittal plane, left arm-trunk angle in the sagittal plane, shoulder rotation angle in the horizontal plane and hip rotation angle in the horizontal plane.

iv. Angular velocity of the hips and shoulders throughout the swing- Peak hip and shoulder angular velocity, and representation of mean velocity for the duration of the swing.

Figures 4.8 to 4.16 represent a selection of the variables and detail the planes from which angles were calculated, based on three dimensional coordinate data of local body markers.

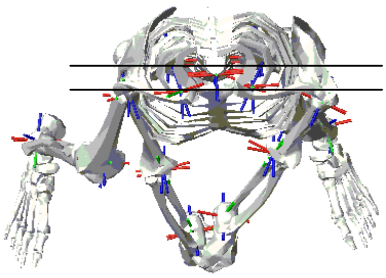


Figure 4.8
Hip/shoulder reference at ADD

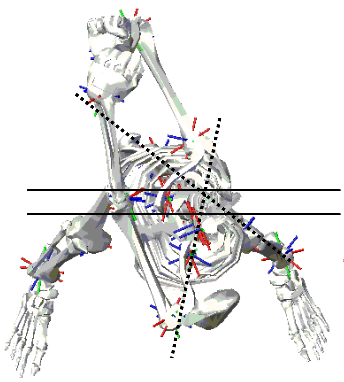


Figure 4.9
Hip/shoulder orientation and reference at TOB

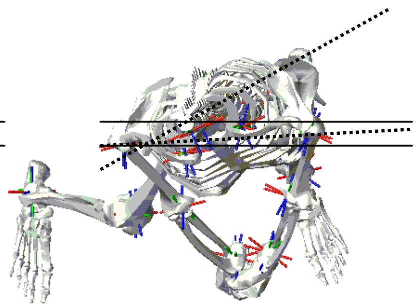


Figure 4.10
Hip/shoulder orientation and reference at IMP

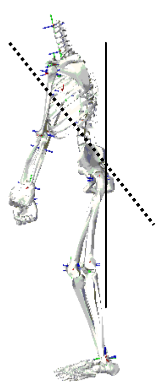


Figure 4.11
Back inclination and reference at ADD

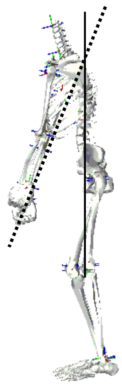


Figure 4.12
Left arm-trunk orientation and reference at ADD

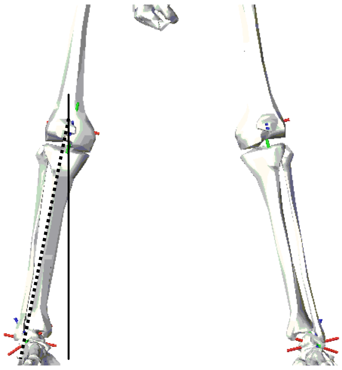


Figure 4.13
Right knee orientation and reference at ADD

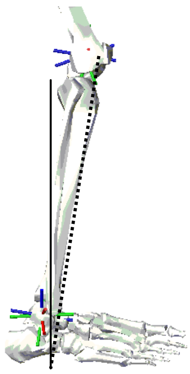


Figure 4.14
Right shank orientation and reference at ADD

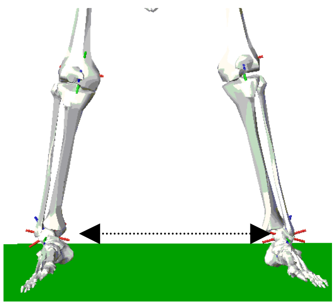


Figure 4.15
Stance width at ADD

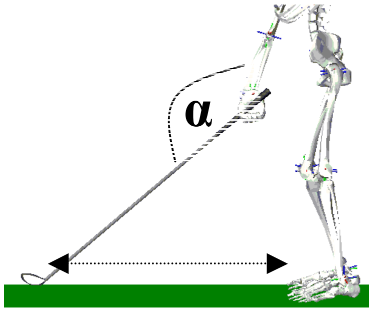


Figure 4.16
Foot-tee distance at ADD and L arm-club angle (α)

The variables selected for analysis of coordination concerned timing of the swing, to include:

- Total swing time
- Backswing time
- Downswing time
- Downswing time relative to total time (%)

For all variables, KinTrak™ processing was carried out for the best 3 of the 8 trials each golfer performed using each of the 4 drivers. It was common for frames to be 'missing' from the raw three-dimensional coordinate data recorded for each marker by the camera system. In keeping with previously published research, and allowing for missed frames for some trials, three processed trials per golfer per driver was deemed appropriate within the time constraints imposed by PhD study.

4.1.5 Data analysis

Data was reduced using Kintrak™ software for the variables highlighted in Section 4.1.4. Differences between the four club conditions were tested for statistical significance using a one-way Analysis of variance (ANOVA) where the level of statistical significance was set at $p = 0.05$. Where a statistical difference was observed, a post-hoc LSD test was used to determine where the differences rest. Analysis was performed using SPSS™ statistical analysis software. Descriptive statistics and percentage variation for postural kinematic data were calculated using MS™ Excel.

4.2 Results

Results are firstly presented for posture and angular kinematics, then for temporal measures.

4.2.1 Posture and angular motion

Tables in this section detail the mean (± SD) values and the results of statistical analyses. Table 4.10 shows mean postural orientation for each of the three discrete events in the golf swing, for all clubs. Shown also is the percentage difference of the

52″ driver from the orientation recorded for the 46″ driver. Applying a one-way ANOVA, it was found that no measure varied significantly between club lengths.

Table 4.10 Select whole body kinematics at address, top-of-backswing and impact for low-handicap golfers using drivers of different shaft length

Position	Measure	46″		47″		49″		52″		46″ - 52″
		$\overline{x}$	±SD	$\overline{x}$	± SD	$\overline{x}$	± SD	$\overline{x}$	± SD	± %
ADD	R Knee (°)	27.0	6.6	28.6	10.2	26.7	7.2	26.2	7.8	-2.8
	L Knee (°)	28.4	14.8	29.0	16.8	27.9	15.1	27.0	13.6	-5.2
	R Shank (°)	98.5	3.4	98.6	3.9	98.7	4.6	99.0	3.9	+0.5
	Back Inclination (°)	71.8	5.6	73.0	5.9	74.7	7.2	75.6	6.4	+5.2
	L Arm-Trunk (°)	38.7	4.6	38.8	4.9	38.3	4.6	38.8	4.5	+0.3
	Shoulder Rot (°)	-8.5	4.1	-8.7	5.5	-8.8	5.3	-8.9	5.8	+4.2
	Hip Rot (°)	-7.0	6.4	-7.3	5.7	-8.0	5.8	-7.2	5.7	+2.8
	L Arm-Club (°)	132.9	8.5	132.9	8.7	131.9	7.6	131.9	7.8	-0.7
	Stance Width (mm)	543.7	69.1	547.4	66.6	546.4	69.0	554.8	58.7	+2.1
	Foot-Tee (mm)	906.1	279.7	930.7	297.7	971.6	338.4	1067.5	365.2	+17.8
TOB	Shoulder Rot (°)	95.2	6.6	95.7	6.8	95.6	6.6	97.2	6.6	+2.1
	Hip Rot (°)	42.3	7.7	42.3	8.3	42.3	7.5	44.1	7.4	+4.3
	Back Inclination (°)	75.1	6.6	76.2	6.8	77.5	7.4	78.8	6.9	+5.0
	L Arm-Trunk (°)	85.4	3.67	84.9	3.8	84.5	3.5	84.4	3.8	-1.2
IMP	R Knee (°)	43.6	33.6	44.2	35.6	41.7	33.6	41.8	34.2	-4.3
	L Knee (°)	37.2	41.3	37.5	41.8	36.8	41.9	36.9	41.1	-0.9
	Back Inclination (°)	79.1	7.00	80.0	7.6	81.7	8.3	82.7	7.8	+4.6
	R Shank (°)	80.6	10.6	82.3	7.3	81.5	8.3	80.1	7.1	-0.6
	L Arm-Trunk (°)	38.0	4.4	37.9	4.6	37.9	4.2	39.2	4.8	+3.1
	Shoulder Rot (°)	-13.5	8.6	-13.7	9.1	-14.6	8.7	-17.4	9.9	+28.3
	Hip Rot (°)	-37.8	12.7	-36.8	13.4	-36.9	14.0	-37.6	14.1	-0.7

Mean angular data prefixed by ’-‘ indicates a closed orientation (towards the flag)

At address, the greatest variation, as indicated by percentage change between 46″ and 52″ driver results, concerned left knee angle (-5.22%), back inclination (+5.24%), shoulder rotation (+4.15%) and foot-to-tee distance (+17.81%).

At the top of the backswing absolute hip rotation (+4.27%) and back inclination (+5.01%) angles increased by the greatest amount. It is worth noting that the magnitude of shoulder rotation remained relatively unchanged as driver length increased.

Posture at impact again produced no significant differences in angular measures as driver length increased. However right knee angle (-4.29%), back inclination (+4.63%) and shoulder rotation (+28.32%) varied greatest in magnitude. The angle of shoulder rotation at the moment of impact varied from 13.52° closed for the 46" driver to 17.35° closed for the 52" driver which. The interaction of back inclination ($F = 0.642$, $p = 0.593$), stance width ($F = 0.047$, $p = 0.986$), foot-tee orientation ($F = 0.438$, $p = 0.728$) and hip and shoulder rotation ($F = 0.009$, $p = 0.999$) was evident through marked variation at address, top-of-backswing and impact, particularly comparing 46″ and 52″ clubs.

Additionally, Appendix 11.0 details inter-subject differences for the same measures, showing mean values for each subject for each club. One-way ANOVA and post-hoc LSD tests showed no significant differences between all these low-medium handicapped subjects for all measures.

Three-dimensional coordinate data for one trial for a single subject presenting minimal intra-subject variation, subject 6, has been plotted for various anatomical landmarks as a representation in posture change at address (Figure 4.17). This graphical representation confirms overall maintenance in kinematics when using clubs of different shaft length, with small changes in shoulder, back and knee angles. Additionally, back inclination, hip and shoulder rotation angles are represented, for the same single subject, for the whole swing in Figures 4.18 to 4.20. The events of address, top of the backswing and impact are also indicated.

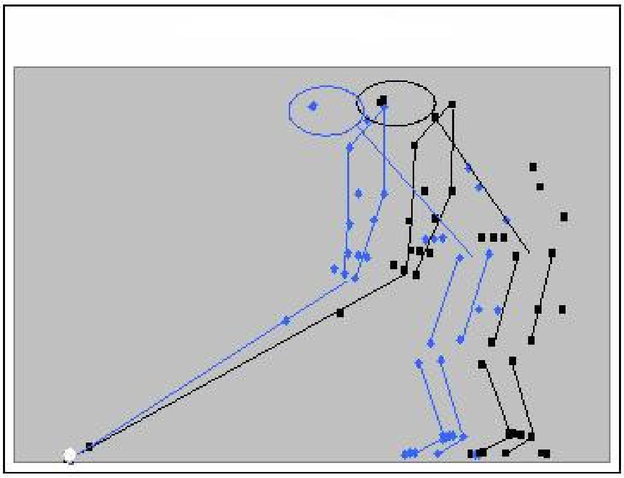
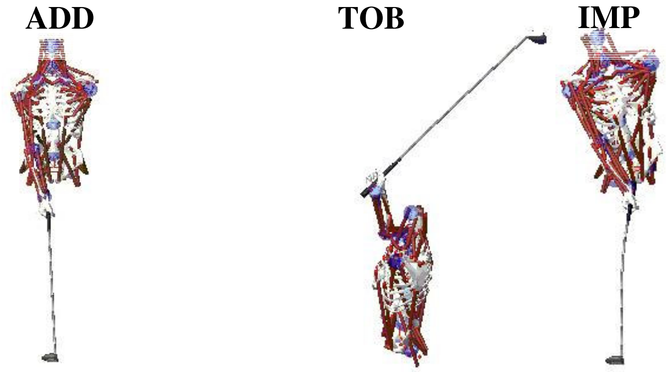


Figure 4.17 Representative posture at address for a 46″ and 52″ driver

Following initial findings from our study concerning the apparent trend for dynamics systems theory (Glazer *et al.*, 2003), and absolute differences in hip and shoulder orientation, kinematics were explored for shoulder and hip rotational velocities. Peak hip and shoulder velocity for all driver lengths are detailed in Table 4.11. There was an overall reduction in peak shoulder (0.1 rads^{-1}) and hip (0.29 rads^{-1}) angular velocity associated with an increase in driver shaft length. However, a one-way ANOVA showed that data did not vary significantly.

Table 4.11 Peak hip & shoulder velocity (from address to impact)

	Mean Peak Angular Velocity (rads^{-1} ±σ)	
Club	Shoulders	Hips
46"	10.24 ± 0.12	7.59 ± 1.06
47"	10.46 ± 0.16	7.50 ± 0.49
49"	10.21 ± 0.16	7.36 ± 0.69
52"	10.14 ± 0.09	7.30 ± 0.48



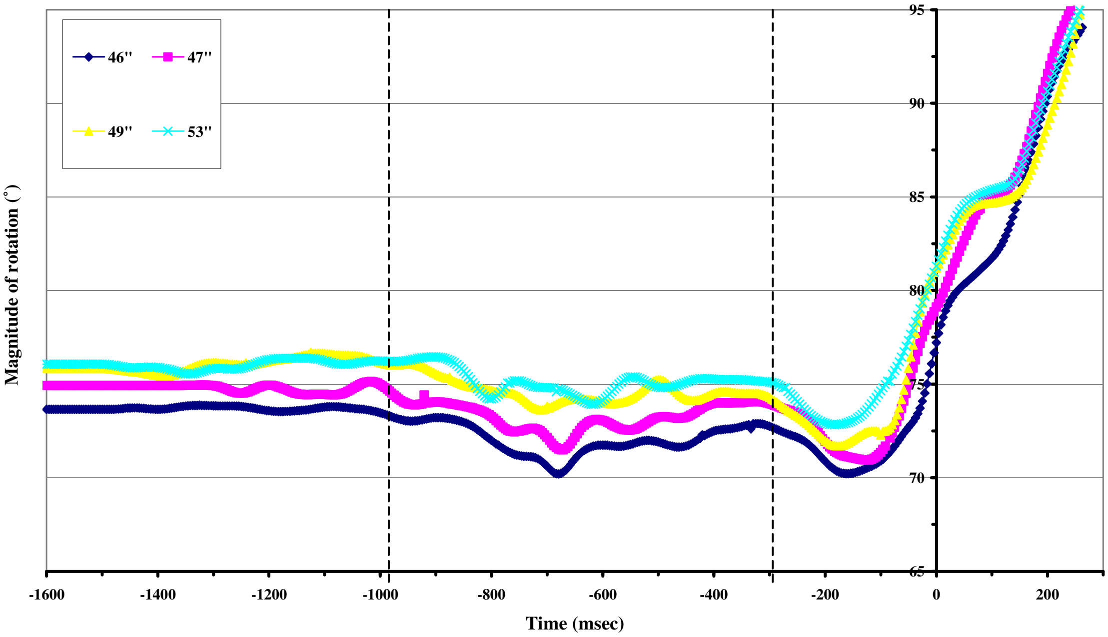


Figure 4.18 Representative back angle (inclination from pelvic transverse plane) for a 46″, 47″, 49″ and a 52″ driver.

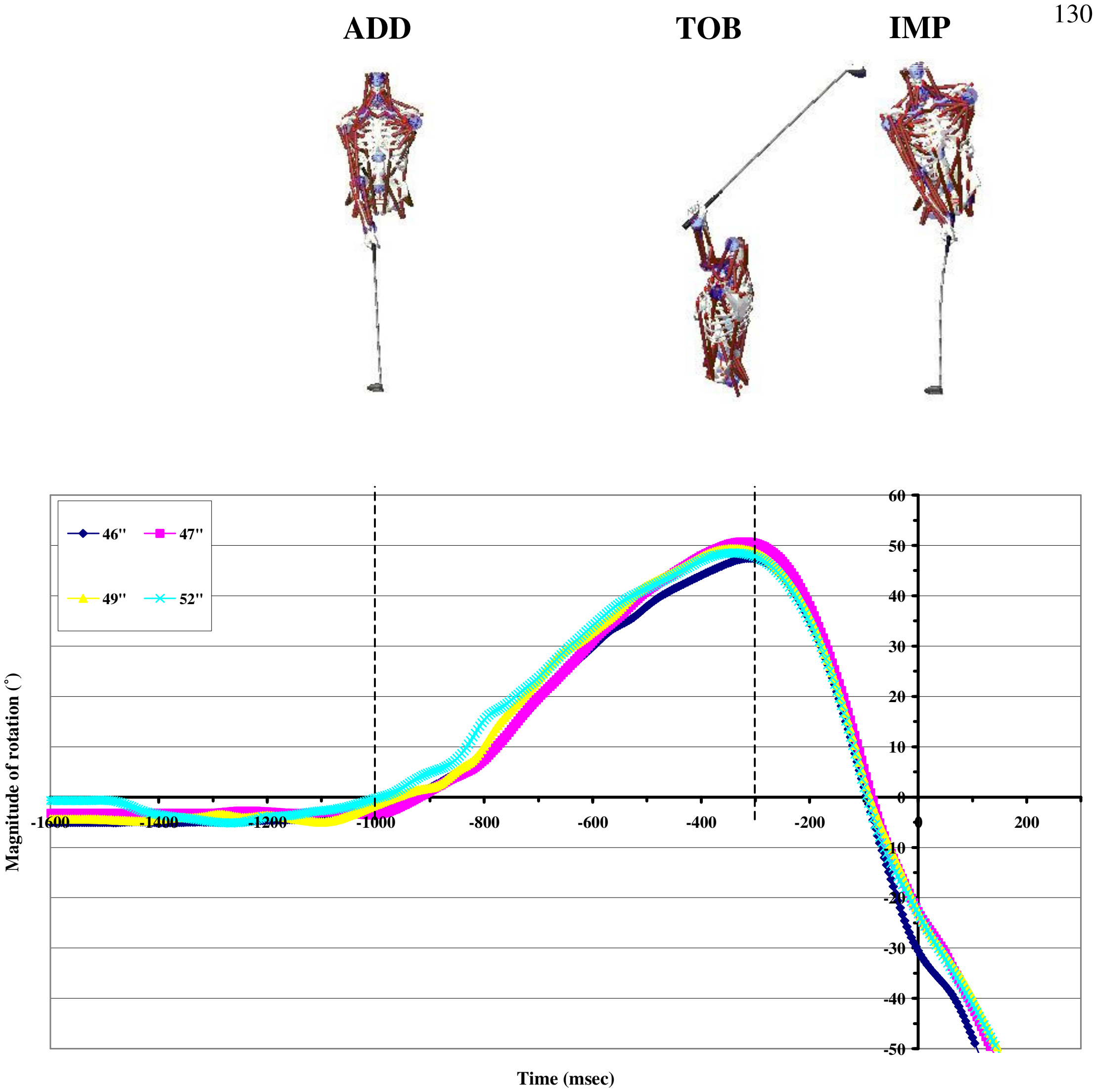


Figure 4.19 Representative hip rotation for a 46″, 47″, 49″ and a 52″ driver.

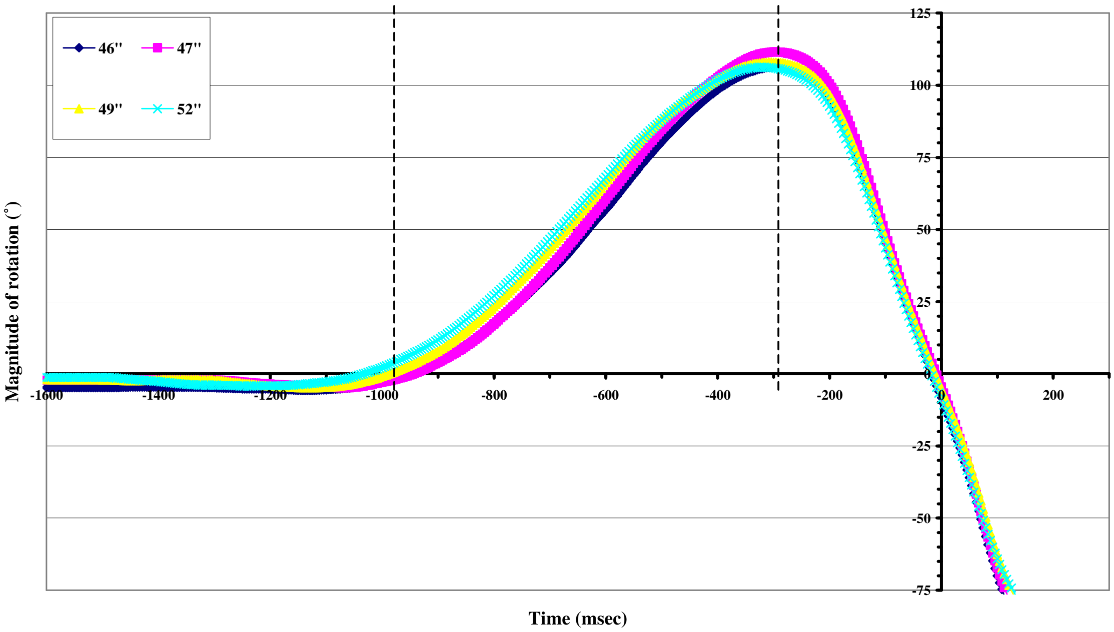


Figure 4.20 Representative shoulder rotation for a 46″, 47″, 49″ and a 52″ driver.

Further representative hip and shoulder peak angular velocity graphs are shown (figures 4.21 and 4.22). It can be seen that most golfers were able to rotate the hub, that is the shoulders and hips, as fast or faster when using a 47″ driver than a 46″ driver.

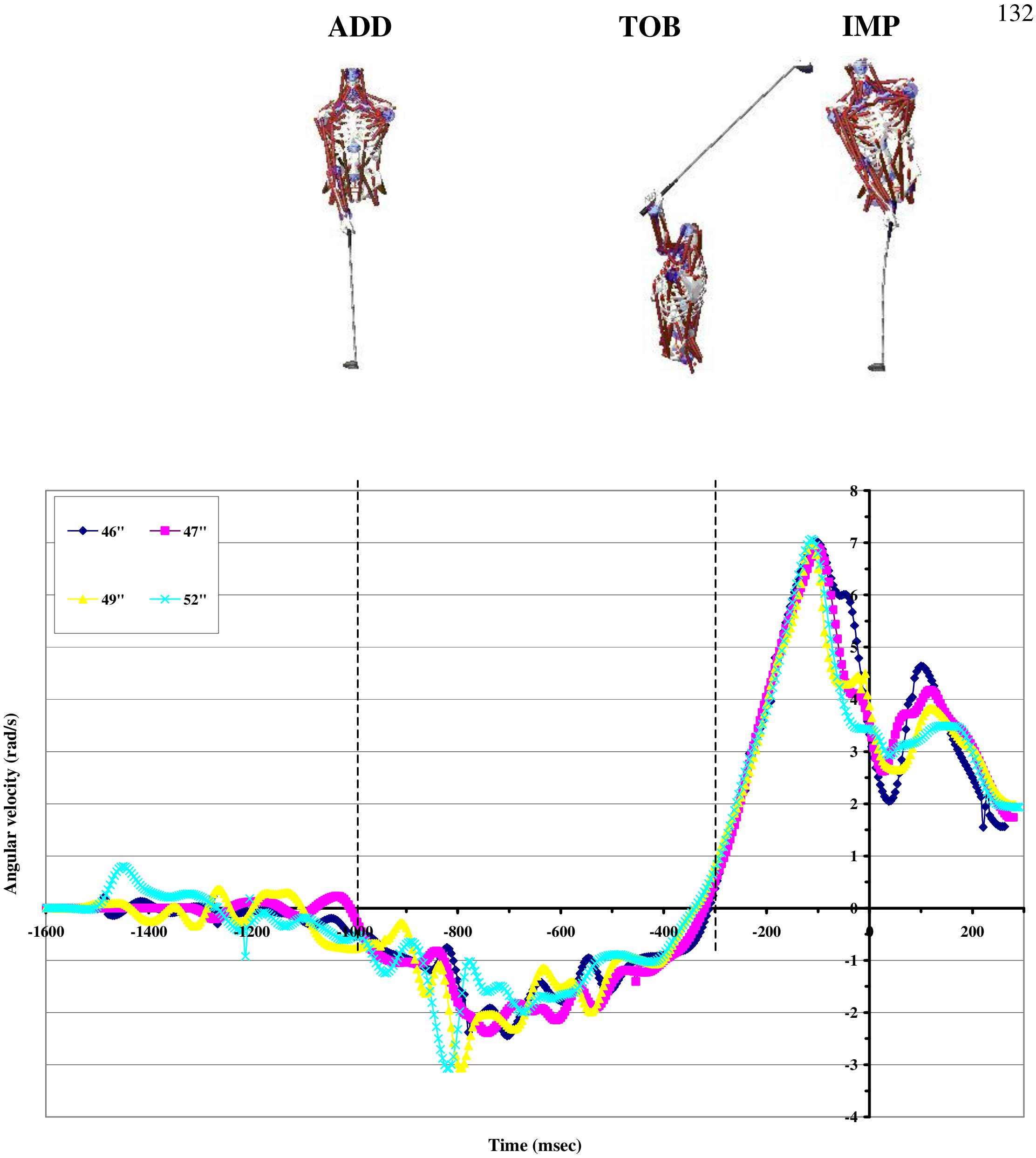


Figure 4.21 Representative hip angular velocity for a 46″, 47″, 49″ and a 52″ driver.

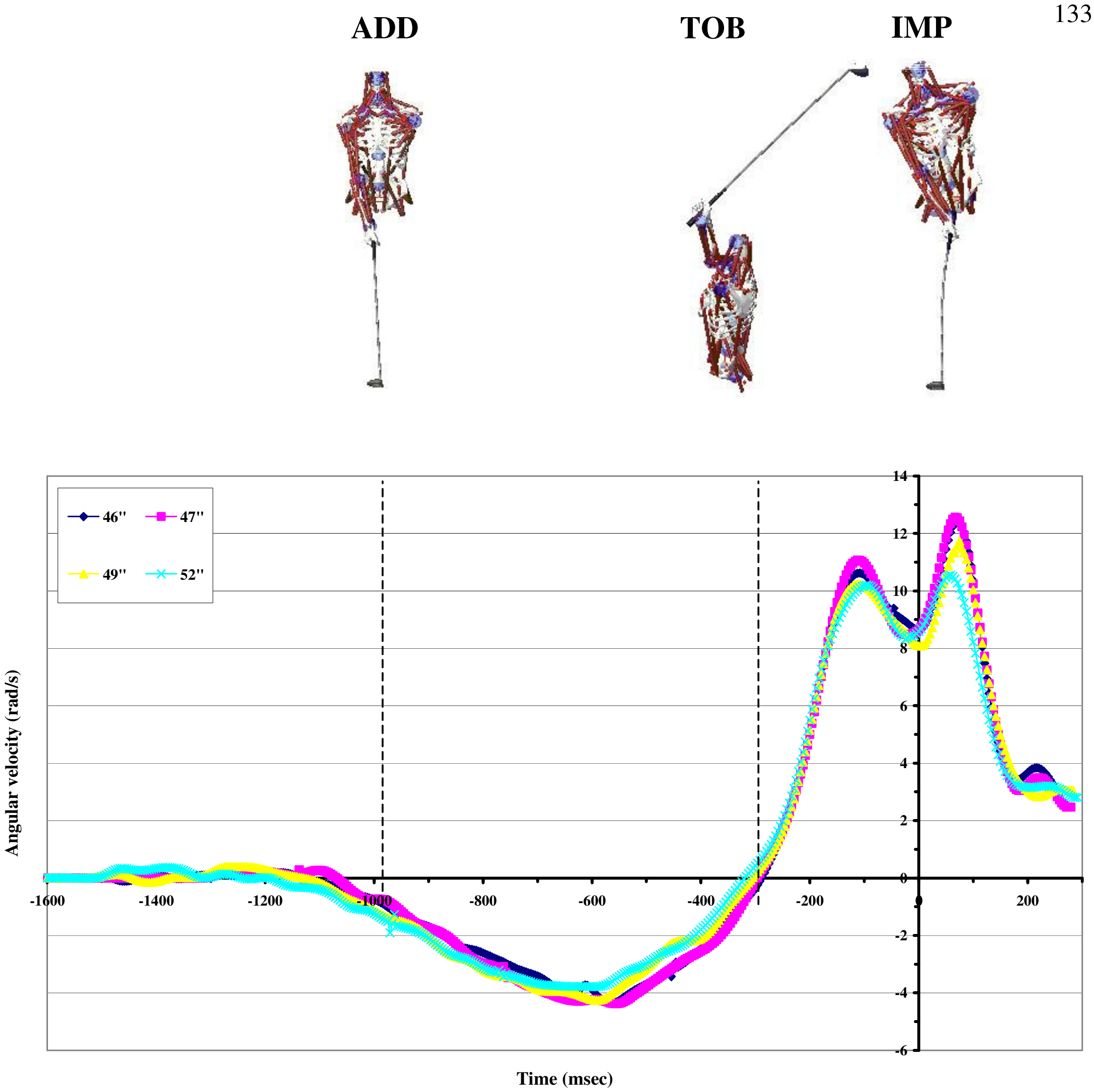


Figure 4.22 Representative shoulder angular velocity for a 46″, 47″, 49″ and a 52″ driver.

4.2.2 Temporal factors

Table 4.12 summarises the mean (± SD) values and statistical analyses for variables that depict swing timing. Total swing time, backswing time and downswing time all indicated a longer duration of swing phase as club length increases. Statistical analyses show significant variance between swing phase for the 46″ and 52″ and 47″ and 52″ driver for total swing time, 46″ and 52″ driver for backswing time and 46″ and 52″ and 47″ and 52″ driver for downswing time. However, the relative percentage time for the downswing (t_{ds}) as a factor of total time remained unaffected by club length.

Table 4.12 Total swing time (t_{tot}), backswing time (t_{bs}) and downswing time (t_{ds}) mean (±s.d.) for all club lengths

Club (″/m)	t_{tot} * (s)	t_{bs} ** (s)	t_{ds} *** (s)	t_{ds} [% of t_{tot}]
46 / 1.168	1.110 ± 0.163	0.813 ± 0.153	0.298 ± 0.047	26.847
47 / 1.194	1.126 ± 0.171	0.830 ± 0.160	0.304 ± 0.097	26.998
49 / 1.245	1.176 ± 0.197	0.863 ± 0.176	0.313 ± 0.051	26.616
52 / 1.321	1.232 ± 0.185	0.905 ± 0.171	0.327 ± 0.048	26.542

* F= 2.52, $p<0.05$ – 46″vs52″, 47″vs52″
** F= 1.65, $p<0.05$ – 46″vs52″
*** F= 2.37, $p<0.05$ – 46″vs52″, 47″vs52″

Additionally, Table 4.13 details inter-subject differences for the same measures, showing mean (± SD) values for each subject. Subject 6 shows relatively small variation (as indicated by standard deviation, whilst subject number 1 shows high intra-subject variation. One-way ANOVA and post-hoc LSD results are presented showing significant differences between all these low-medium handicapped subjects for all measures.

Table 4.13 Total swing time (t_{tot}), backswing time (t_{bs}) and downswing time (t_{ds}) mean (±s.d.) for all trials by individual subjects

Club (″/m)	Subject	t_{tot} * (s)	t_{bs} ** (s)	t_{ds} *** (s)	t_{ds} [% of t_{tot}]
46 / 1.168	1	1.35 ± 0.03	1.05 ± 0.02	0.30 ± 0.02	21.90
	2	0.86 ± 0.01	0.58 ± 0.00	0.28 ± 0.00	32.61
	3	0.96 ± 0.03	0.71 ± 0.02	0.25 ± 0.01	25.38
	4	1.29 ± 0.03	0.91 ± 0.02	0.38 ± 0.01	29.30
	5	1.01 ± 0.03	0.65 ± 0.02	0.35 ± 0.01	35.17
	6	0.99 ± 0.01	0.70 ± 0.01	0.28 ± 0.01	28.58
	7	1.12 ± 0.04	0.85 ± 0.04	0.27 ± 0.00	23.95
	8	1.23 ± 0.04	0.90 ± 0.03	0.33 ± 0.00	27.11
	9	1.19 ± 0.02	0.95 ± 0.02	0.24 ± 0.00	20.28
47 / 1.194	1	1.36 ± 0.13	1.07 ± 0.12	0.28 ± 0.02	20.79
	2	0.84 ± 0.01	0.57 ± 0.01	0.27 ± 0.00	32.09
	3	0.98 ± 0.04	0.73 ± 0.04	0.25 ± 0.01	25.46
	4	1.31 ± 0.02	0.94 ± 0.02	0.37 ± 0.02	28.27
	5	1.06 ± 0.02	0.70 ± 0.04	0.36 ± 0.01	34.23
	6	0.98 ± 0.01	0.70 ± 0.01	0.28 ± 0.00	28.43
	7	1.16 ± 0.01	0.88 ± 0.01	0.28 ± 0.01	23.79
	8	1.27 ± 0.05	0.93 ± 0.05	0.34 ± 0.01	26.53
	9	1.19 ± 0.03	0.94 ± 0.02	0.25 ± 0.01	20.73
49 / 1.245	1	1.50 ± 0.10	1.17 ± 0.06	0.34 ± 0.04	23.33
	2	0.86 ± 0.01	0.59 ± 0.01	0.27 ± 0.00	31.70
	3	1.01 ± 0.03	0.76 ± 0.03	0.26 ± 0.00	25.20
	4	1.39 ± 0.02	0.99 ± 0.01	0.40 ± 0.00	28.47
	5	1.09 ± 0.02	0.71 ± 0.01	0.38 ± 0.01	34.85
	6	1.01 ± 0.01	0.72 ± 0.01	0.29 ± 0.01	28.75
	7	1.19 ± 0.01	0.89 ± 0.01	0.30 ± 0.00	24.92
	8	1.28 ± 0.03	0.95 ± 0.03	0.33 ± 0.01	25.97
	9	1.25 ± 0.06	0.99 ± 0.06	0.26 ± 0.01	20.48

* F = 95.041, p<0.05 – 34 of 36 inter-subject post-hoc LSD comparisons (not 3vs6, 7vs9)
** F= 131.593, p<0.05 – 33 of 36 inter-subject post-hoc LSD comparisons (not 4vs9, 5vs6, 7vs8)
*** F= 86.853, p<0.05 – 31 of 36 inter-subject post-hoc LSD comparisons (not 2vs6, 2vs7, 3vs9, 4vs5, 6vs7)

Table 4.13 contd. Total swing time (t_{tot}), backswing time (t_{bs}) and downswing time (t_{ds}) mean (±s.d.) for all trials by individual subjects

Club (″/m)	Subject	t_{tot} * (s)	t_{bs} ** (s)	t_{ds} *** (s)	t_{ds} [% of t_{tot}]
52 / 1.321	1	1.49 ± 0.04	1.17 ± 0.04	0.32 ± 0.00	21.61
	2	0.92 ± 0.01	0.63 ± 0.01	0.29 ± 0.01	31.64
	3	1.07 ± 0.01	0.80 ± 0.01	0.27 ± 0.00	25.05
	4	1.43 ± 0.03	1.03 ± 0.02	0.41 ± 0.01	28.30
	5	1.14 ± 0.02	0.75 ± 0.01	0.39 ± 0.02	34.49
	6	1.07 ± 0.01	0.78 ± 0.01	0.30 ± 0.00	27.80
	7	1.32 ± 0.07	0.99 ± 0.06	0.32 ± 0.00	24.58
	8	1.30 ± 0.05	0.94 ± 0.06	0.36 ± 0.02	27.43
	9	1.35 ± 0.02	1.06 ± 0.02	0.28 ± 0.00	21.04

* $F = 95.041$, $p<0.05$ – 34 of 36 inter-subject post-hoc LSD comparisons (not 3vs6, 7vs9)
** $F = 131.593$, $p<0.05$ – 33 of 36 inter-subject post-hoc LSD comparisons (not 4vs9, 5vs6, 7vs8)
*** $F = 86.853$, $p<0.05$ – 31 of 36 inter-subject post-hoc LSD comparisons (not 2vs6, 2vs7, 3vs9, 4vs5, 6vs7)

4.3 Discussion

The kinematics of the golf swing has received considerable attention by a number of researchers. Lindsay *et al.* (2002) examined trunk range of motion (ROM) for shots with a 7-iron and a driver highlighting the greater stress placed on the lower back during increased back inclination associated with using shorter clubs. Burden *et al.* (1998) examined trunk motion during the golf swing. They studied the co-ordination and timing of the hip and shoulder rotations for drive shots, concluding that hub velocity may be increased if adhering to a specific sequential pattern of hip and shoulder movement. Furthermore, Egret *et al.* (2003) investigated the kinematic patterns of different golf swings using a driver, five-iron and pitching-wedge. They concluded that skilled, low-handicap golfers were able to produce identical timing for each club, but the kinematics and clubhead speed that comprised each shot varied.

Findings pertaining to variations of kinematic swing patterns for varying club length for golfers of low-medium handicap alone agreed in the main with previous findings by Egret *et al.* (2003), Burden *et al.* (1998), Adlington (1996), and Lindsay *et al.* (2002). Egret *et al.* and Wallace *et al.* (2004) suggested that timing remained identical across a range of clubs differing by shaft length. Our results showed that kinematics and timing varied minimally. Hub rotation was found to be one of the few marked variations due to driver shaft length. The change in hub movement patterns in the present study could relate to the sequential timing of the hub discussed by Burden at al. wherein the shoulders and hips rotate in such a manner that they conform to the 'summation of speed' principle and develop a stretch-shortening cycle (SSC) across the external obliques and latissimus dorsi on one side of the body, the left side for right-handed golfers.

4.3.1 Effect of club length on positional variation

Richards *et al.* (1985) showed that the golf swing should be identical for all clubs and the only variation exhibited related to swing speed. Furthermore, Budney and Bellow (1982) reported that the golf swing was identical for clubs such as 'woods' and irons. Iron clubs were not examined in the present study, nonetheless, the premise behind such research is that the clubs varied in length.

Results are in broad agreement with those purported by Egret *et al.* (2003) and Burden *et al.* (1998) for their observations with drivers. There were no significant differences in lower extremity joint angles (knee and shank angles) in the present study, and little absolute variation apparent (Table 4.10). Lower limb angular pattern was consistent despite a significant increase in driver length. Relative stance did differ, however, to accommodate the increase in shaft length, as was evident via a 2.05% (11.1mm) increase in stance width and 17.81% (161.4mm) increase in foot-to-tee distance respectively when comparing 46" and 52" drivers. That foot-to-tee distance increased is as expected when using a longer lever in attempting to maintain the golfer's usual ankle and knee angular displacement. It would appear that the golfer would prefer to stand further away from the ball when using a longer club, than to alter knee internal angle thus stand more upright. It is apparent though, that whilst not statistically significant, back inclination increased, trunk became more upright, by 5.24% (3.76º) at address, 5.01% (3.76º) at the top of the backswing and 4.63% (3.66º) at impact. Reluctance to straighten the legs by increasing knee joint angle as driver shaft length increased was compensated for both by increased stance width and back inclination.

The angle between the arms and the trunk, as measured in the present study as ‘L arm-trunk’ additionally remained constant indicating that golfers preferred to maintain their usual hand/grip height in relation to their body despite increases in club length. The subjects in the present study also maintained the arm-club angle (L arm-club, or offset angle), therefore shots performed with longer drivers were not performed with a greater or narrower turn than was normal. Offset angle is necessary to allow left forearm supination in the latter part of the downswing, an action which has been reported by Cochran and Stobbs (1968) as imparting extra speed to the clubhead.

Shoulder rotation angles were in broad agreement with those noted by Burden at al. (1998). It was found that club length had no significant effect on hip or shoulder angles at address, top of the backswing, or at impact. However, absolute difference for shoulder rotation at impact was large in magnitude, adopting a more closed position for trials with long drivers. Neal and Dalgleish (2000) reported following tests on a golfer using a club 2" (50mm) shorter than was optimal, optimal relating to maximum drive distance, for that golfer caused: 4º shoulders and 3º hips less rotation at the top of the backswing; 4º shoulder and 3º hips less open posture at impact affecting clearance of the hitting region and production of angular velocity of the hub and 8º less back inclination.

Differential between hips and shoulders absolute rotation at the top of the backswing has received much attention, by biomechanical research and in the press over the past decade. To generate power during the swing, elite-level golfers will attempt to maximise their shoulder turn relative to their hip turn (Burden at al., 1998; McLean and Andrisani, 1997). Cheetham *et al.* (2001), McLean (1992, 1993) and McTeigue *et al.* (1994) reported increased drive distance and force production with increased hip-shoulder differential, or X-factor. Table 4.14 summaries results shown in Table 4.10, highlighting the maintenance of this differential across the range of club lengths tested. Increased drive distance, if reported for long-shafted drivers, therefore cannot be attributed to increased X-factor. It is possible that the golfers examined in the present study, with an average handicap of 5.4, were not skilled enough to be able to adapt to using longer-shafted drivers. More highly skilled golfers, as were recruited for studies 3 and 4, were better able to utilise increased club mass associated with a longer driver to increase the X-factor, or the peak hip/shoulder differential, the ‘X-factor 2’.

Table 4.14 X-factor

Club	Hip-shoulder differential (°) ‘X-factor’
46	52.91
47	53.46
49	53.28
52	53.09

The rotation of the hips in relation to the shoulders induces tension in the external oblique and latissimus dorsi muscles. This is known as ‘stretch-reflex’, due to the stretch-shortening cycle (SSC). As the trunk rotates to a closed position at the top of the backswing a countermovement occurs immediately prior to downswing. The main effects of this is to create a tension in the agonist muscle and to marginally slow contraction of the main force generating muscles involved in downswing movement, such as the obliques, rectus abdominus, gluteals, quadriceps and posterior deltoids, to a speed where the individual can generate maximum force in each muscle (Maddalozzo, 1987).

Results agree with that reported by Wallace *et al.* (2004), that subjects accommodated longer length clubs by altering their positions relative to the ball and not by standing more upright. Golfers seem to attempt to maintain their normal body posture and swing patterns when using drivers different in length than that normally used.

4.3.2 Effect of club length on angular velocity

Nagao and Sawada (1973) claimed that arm rotational velocity increased as club length increased. However, results reported in Section 4.2.1 (Table 4.11, Figures 4.21 and 4.22) show that both peak hip and shoulder angular velocity decreased as club length increases. Peak hip angular velocity decreased uniformly from 7.59 rad s^{-1} for the 46" driver to 7.30 rad s^{-1} for the 52" driver. Peak shoulder angular velocity also decreased overall as club length increased, showing only a small increase in velocity from trials for 46" (10.24 rad s^{-1}) to 47" (10.46 rad s^{-1}) drivers before decreasing to 10.14rads^{-1} for the longest driver. Application of a 1-way ANOVA showed that angular velocity did not vary significantly as driver shaft length increased.

As discussed, stance width increased as driver shaft length increased. Increased stance width develops rotation such that the moment of inertia about the vertical axis increases therefore decreasing angular velocity about this axis. Feet position was further from the axis centre of rotation of the hub when longer clubs were used, and whilst this may benefit transfer of power from the foot plant (Wallace *et al.*, 1990), it is off-set by increased radius of gyration of the lower extremity thus making it more difficult to rotate at the same velocity as when using a shorter driver.

Additionally, reasons for the reduction in hip and shoulders angular velocity may lie in the basic physical principles of a rotating rigid lever. Increased mass of a driver with a longer shaft than is normal, as is the case in the present study, means that a greater coupled moment must be applied, or rotational torque about the wrists and hub. This is needed to overcome increased club inertia when initiating the downswing. The club will not turn around its principal axis as easily as if a shorter club was used, as indicated through Equation 7:

$$T = I.\alpha \qquad \text{(Equ. 7)}$$

Where the torque (T) is determined by the moment of inertia (I) times the angular acceleration of the object (α). Torque is the time-derivative of angular momentum, and angular momentum of a rigid body can be written in terms of its moment of inertia and its angular velocity. Thus, if the moment of inertia is constant, $T = I.\alpha$.

However, if a longer shafted club is altered such that its overall mass is reduced to match that of a shorter driver, as in the process of swingweighting, inevitably physical characteristics such as clubhead mass and shaft flexibility will be altered. This in turn affects dynamic loft, impact efficiency and thus performance measures of drive distance and accuracy. To produce equivalent peak hub angular velocity across all club lengths, it should be expected that increased force is needed from the muscles to deliver greater torque to the club grip. Further testing with a golf robot, or with more massive, stronger or taller golfers would be needed, coupled with measures of ball launch characteristics and drive distance and accuracy (studies 2, 3 and 4) are needed to investigate the force applied to longer clubs.

4.3.3 Effect of club length on timing

Timing of the golf swing is a crucial factor in good contact being made with the ball. Egret *et al.* (2003) noted that the timing for all shots by golfers using a driver, five-iron and pitching wedge was identical. Thus each golfer, whether he uses a club with a very long shaft, or his own driver, will select a depth of rotation that will develop the most appropriate force for the swing. It was shown that peak hip and shoulder angular velocity decreased as club length increased. This may be further explained by the idea proposed by Hill (1953) that muscle fibres fire maximally under contraction at a particular rate, varying greatly by muscle and by individual. Hub velocity may have decreased therefore, to aid in force production by those muscles with attachments around the lumbar and thoracic area. Increased force production is desirable, if able, to overcome increased inertia, particularly the second moment of inertia of the assembled driver, associated with longer drivers.

The stretch-shortening cycle (SSC) demonstrated by our subjects is also in agreement with Burden *et al.* (1998) in their explanation of the summation of speed principle. This sequential pattern of hip and shoulder rotation is hypothesised to result in a greater torque being applied to the club. This is needed to maintain correct timing when using long-shafted clubs. That results for the present study indicate maintenance of tempo across use of all four clubs, indicated via downswing time (t_{ds}) as a percentage of total swing time (t_{tot})[12] remained very similar. Absolute time did increase for all measures, by 0.09s, 0.03s and 0.12s for backswing, downswing and total swing time respectively when comparing 52″ driver data to 46″ driver data.

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[12] Total swing time (t_{tot})- in the present study represented as backswing time plus downswing time.

Timing, tempo and rhythm are terms that are commonly used to describe the skill of swinging a golf club. Whilst timing is a general term, tempo often refers to the overall speed of the swing and is inversely related to the overall duration of the swing. Rhythm, in contrast, refers to the pattern of speeding up and slowing down the clubhead at different points in the swing (Nicklaus, 1974; Merrins, 1979). In terms of rhythm, results from the present study do show variation in rhythm when using driver of different shaft length. Table 4.15 summaries results already shown in Table 4.12. It is apparent that as club length increases, sequence timing increases, denoted by an increase in the duration of backswing and downswing when comparing a 46″ driver to a 47″ driver, 47″ to a 49″ and 49″ to a 52″. Thus rhythm slows as club length increases. Jagacinski *et al.* (1997) suggested that changing one's tempo may disrupt rhythm, that the two are not independent. However, results here indicate that golfers attempt to maintain tempo, the overall speed of the swing and ratio between backswing and downswing, but that rhythm and portions of the swing slow as longer clubs are used.

Table 4.15 Rhythm variation for different club lengths

Clubs compared (″)	Δt_{bs} (s)	Δt_{ds} (s)
46 - 47	0.017	0.006
47 – 49	0.033	0.009
49 - 52	0.042	0.014

One possible reason for slowing rhythm and overall timing of the swing when using long-shafted driver is that the dynamics of the golf swing are inherently unstable. Unstable processes exhibit patterns of divergence. Small differences in movement, the golf swing in this case, tend to be amplified. If the backswing is initially slow, as a result of overcoming increased mass and inertia of the longer drivers, then this is amplified throughout the backswing, and similarly the downswing.

Differences proved highly significant for 34 of the 36 inter-subject comparisons (Table 4.13) for all timing measures. Golfer skill level for the present study was 5.4 ± 2.8 handicap. The 9 subjects exhibited a range of 0.13s for total swing time. It may be concluded that this level of skill is not high enough to ensure isolation of outcome measures such that results reported depend solely on the effect of club length and not significant variation in performance between trials by a golfer(s).

4.4 Summary

Within the range of movement strategies employed in this study, the findings of study 1 can be summarised as:

i. Golfers attempt to maintain their normal body postural positions and swing characteristics when using drivers of different shaft length. Only small variations in stance width (increase) and foot-to-tee distance (increase), back inclination (more upright) and shoulder rotation angle (more closed at impact) are apparent when using drivers longer than 46″ in length.

ii. Hip/shoulder differential angle (X-factor) did not vary when drivers of different length are used.

iii. Peak hip angular velocity decreases when longer drivers were used.

iv. Peak shoulder angular velocity decreases as longer drivers were used.

v. Swing tempo remained unaffected when longer drivers were used, however, backswing, downswing and total swing time increase in duration and rhythm slowed for longer shafted drivers.

vi. For the group of subjects used, significant inter-subject variation was found for swing timing. No significant intra-individual variation due to club length was observed.

CHAPTER 5

STUDY 2:

Analysis of driving performance and accuracy for shots performed on the range and in the laboratory using clubs of different shaft length

5.0 Introduction

Study 1 (Chapter 4) was concerned only the kinematics of the golf swing, examining variations in the swing when drivers of different shaft length were used. It did not examine clubhead or ball launch characteristics at impact, nor did it assess the end result of the golf shot, that is performance in terms of drive distance and shot accuracy. After examination of the biomechanical component of the golf drive, measures of performance were the next logical step to further investigate the effects of drive performance when using clubs of different shaft length.

The aims of study 2 were to:

i. Investigate the effect of driver shaft length on shot performance for shots performed in an outdoor setting.

ii. Evaluate the effect of test environment on golf driving performance using drivers of different shaft length by means of impact characteristics.

Pilot study Section 3.4 highlighted variation in ballspeed (4.19%), ball backspin (18.0%) and sidespin (61.7%) when experimental conditions were altered with respect to adding skin markers to a subject. Testing associated with aim 2 in the present study further examined the effects of changing test conditions by way of environmental factors. It was anticipated that changing the test environment to one based outdoors on the range, in conditions more akin to that encountered during golf play, would have no significant effect on driving performance. Thus, results obtained from tests conducted in the laboratory could be considered valid.

Recent research in driving performance has focused mainly on shot distance and the clubhead speeds achieved via either experimental studies or mathematical models using golf clubs of different shaft length. Few researchers have paid attention to driving accuracy, most concerned with driving performance in terms of the ability to increase clubhead or ball speed (Egret *et al.*, 2003; Mizoguchi and Hashiba, 2002). Early reference was made to the implications of increasing driver shaft length by Cochran and Stobbs (1968). They concluded that via application of physical principles an increase in driving distance through increased shaft length would be expected, but with an associated diminution in accuracy. This diminution in accuracy is the subject of the present study. Werner and Greig (2000) importantly investigated the launch conditions that contribute to various hit patterns (dispersion). They utilised measurements of clubhead speed, combined with general mathematical non-collinear models of the clubhead and part of the shaft. It was concluded that an optimum club length for drive distance was 50.3″, although clubs of 49″ in length or more produced a wider spread of hit pattern. It was also noted that the extra carry produced by the 50.3″ driver was independent of golfer skill level or size, and could be deemed too small a gain to warrant risking a larger hit pattern.

A crucial factor missing from much of the published research available is that concerning driving accuracy and performance away from the laboratory setting- an environment that lacks many of the cognitive cues that are present on the range in open play. A large proportion of experimental work seems to be based in the laboratory, for obvious reasons of variable control. Few studies seem to have been carried out in the field setting, and apparently none, to date, examining correlations between lab-based and field-based results. The present study will incorporate results from both these environments and present differences, if any, of ballspeeds at impact.

5.1 Methods

Details of the subjects and the testing procedures employed in addressing the aims of the present study are discussed in the following sections.

5.1.1 Equipment

The same driving clubs of length 46″, 47″, 49″ and 52″ as were used for study 1 (Chapter 4) were utilised for the present study (see Section 4.1.1). Launch conditions were monitored by a stereoscopic high-speed camera aligned perpendicular to the tee. The monitor utilised digitised image analysis (digital photogrammetry) to determine an array ball launch characteristics including ball velocity immediately after impact, ball spin and trajectory of flight. This particular monitor (monitor number 3, see Section 3.2) more reliably calculated ball velocity from images taken of clubhead/ball impact than clubhead velocity. Whilst only a presumption and which has not been further examined, it is thought reflection of light from the clubhead toe and shaft more frequently caused unreliable values, or no values, to be produced. Thus, to prevent a large number of trials being needed in order to obtain 8 full data sets for launch characteristics which would have introduced elements of fatigue, ball velocity was chosen as the measure of indoor/outdoor shot performance for launch characteristics for the present study. Details of determination of ballspeed by the launch monitor are presented in Section 5.1.3.

5.1.2 Subjects and test protocols

Five male, right-handed subjects took part in the study (36.8±3.3yr, 79.2±4.9kg, 1.78±0.05m, 5.1±2.0 handicap). These were subjects recruited from study 1 who demonstrated least intra-subject variability (temporal consideration, Table 4.13). Selection of these five subjects served to reduce average handicap, age and body mass for the test cohort. Each subject was informed of the objectives of the study, completed a set of health history and golf history questionnaires, and signed an informed consent form.

Each subject was allowed a warm-up period for general flexibility (Fradkin *et al.*, 2004) and mobility followed by 10 practice shots hit with their own driver. Subjects were then required to strike a series of 8 shots into an indoor net marked with a target line with each of the four randomly assigned drivers. After each shot was struck, an investigator wiped clean the clubface and ball with white spirit to ensure a clean contact surface was being used. Subjects were not instructed as how to hit each shot. The launch monitor recorded data for the following launch conditions: clubhead velocity, clubface impact position, orientation, swingpath, tempo, hit factor (SHF) and ballspeed, ball launch angle and back and sidespin components. Consideration was given to each of these outcome variables in order to deem the shot a ‘good’ shot, but analyses concerned only ballspeed immediately after impact. ‘Bad’ shots were those that the golfer felt were particularly poor therefore not representative of their ability, or those for which the monitor calculated ball velocity ±15 ms^{-1} from what was normal for that subject. Figure 5.1 shows the indoor testing setup.

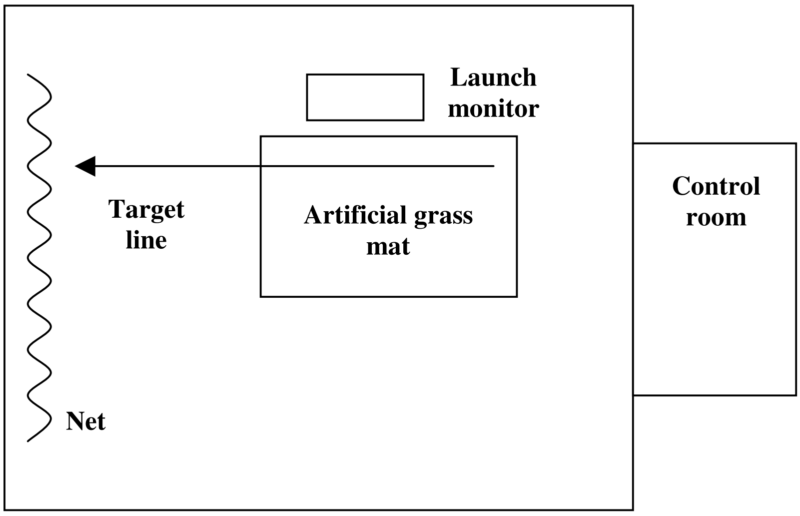


Figure 5.1 Schematic diagram of indoor testing setup

Three people were in the vicinity of the golfer- one investigator was present in the laboratory to record anecdotal information offered by the golfer and to retrieve balls, and two investigators studied ball launch data from the control room.

Following indoor testing and 30 minutes subsequent to, a similar tee set-up recorded launch conditions for the same range of shots performed in an outdoor environment. The outdoor facility was a practice hole with defined tee area, visible straight fairway and flag. Again, subjects were not instructed on how to approach their drives, but were informed the pin was 330 yards from the tee and the straight fairway was cut 40 yards wide. The fairway was ‘medium cut’ (1.5″). Ball carry position was additionally recorded via a triangulation system using two laser range-finders determining orientation and displacement of the ball from the tee. It should be noted that carry was assumed as the measure of drive distance, in doing so controlling variables such as fairway roll variation through turf hardness, and spin variations placed on the ball by the golfer causing different rolls. Two ball spotters worked to accurately locate the first landing point of each shot. Figure 5.2 illustrates schematically the set-up used for outdoor testing.

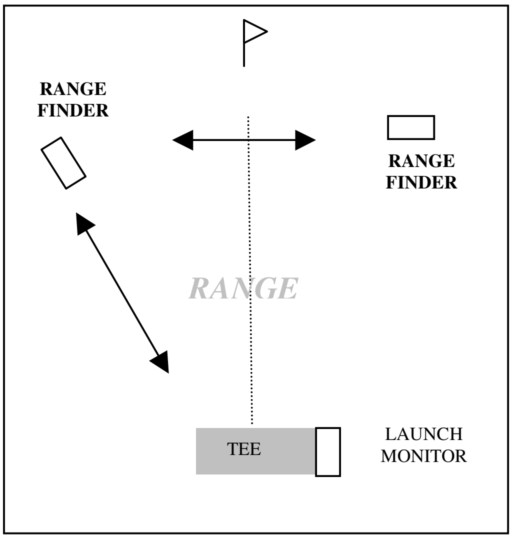


Figure 5.2 Schematic diagram of outdoor testing setup

5.1.3 Data collection and processing

Determination of ball velocity

A linear interpolation between frames of video data was used to identify the specific time and location of the ball as it moved away from the point of impact. The ball launch monitor tracked movement within its field of view, optimally capturing images midpoint between the camera lenses. Lens centres were spaced 0.1m apart and the required exposure time by the strobed lights which illuminated the ball is based on average ballspeed by a golfer/group of similarly skilled golfers.

Test shots performed by a few randomly-selected golfers showed an approximate average ballspeed of 65ms^{-1} using a range of club lengths, therefore the delay between individual camera images was based on this velocity and the equation:

$$\text{Time delay} = \frac{x}{v} \qquad \text{(Equ. 8)}$$

$$= 0.1 / 65$$

$$=0.001538 \text{ s}$$

Thus camera frequency was:

$$f = \frac{1}{x/v} \qquad \text{(Equ. 9)}$$

$$= 1 / \{0.1 / 65\}$$

$$= 650 \text{ Hz}$$

The tee area was calibrated such that tracking of the hosel, clubhead and ball was automatic. The premium golf ball was marked with a black line around its circumference. This allowed determination of the spin of the ball- both side and back spin, as it moved away from the tee. The global y-coordinate of impact (along the target direction) was assumed to be equal to the y-coordinate of the centre of the ball minus the radius of the ball (21.335mm). The global geometry of the ball as it moved away from impact was also tracked in the tri-axis x, y and z planes to allow for matching of initial ball trajectory with final ball position to highlight any irregular launch monitor measurements. The known quantity of frame rate, calibrated field of view, tee/ball origin and ball diameter allowed for the launch monitor software to determine ball velocity between frames and as a mean initial velocity at impact (ms^{-1}).

Determination of carry and dispersion

Figure 5.2 shows the positions of two laser devices that enabled ball carry and dispersion from the fairway centre to be determined. Each laser made use of an internal compass to provide units of measurement. One laser was calibrated using the tee as its point of origin. This laser therefore gave readings of distance (in yards) and bearing (in degrees) of the spot where the ball first landed from the tee. The second laser was calibrated with reference to a point on the first laser. Therefore the second laser gave a measurement of distance and bearing of the ball from the first laser. Via simple trigonometry the carry and dispersion (from a centre line marked on the fairway) of each shot was able to be calculated. Figure 5.3 shows an example of the position and bearing of 2 golf shots determined using laser range finder ‘1’ and ‘2’.

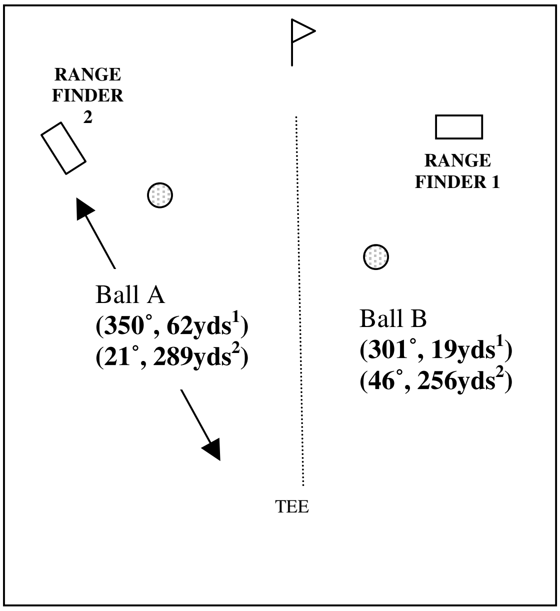


Figure 5.3 Example of position and bearing of 2 golf shots determined using 2 laser range finders.

Data for ball position and launch conditions were combined using Microsoft™ Excel.

5.1.4 Variable selection

Three variables were under consideration in the present study.

i. Carry- a measure of drive performance as ball flight distance measured for shots hit using drivers of different shaft length

ii. Dispersion- a measure of accuracy as the distance of the initial ball landing from the fairway centre line for shots hits using drivers of different shaft length

iii. Ball Velocity- a performance measure that can be recorded both indoors and out, for the investigation of variance or otherwise of shots struck in these two environments using drivers of different shaft length

For launch conditions (ball velocity) and drive performance (carry and dispersion) 8 trials per club were analysed. A maximum of 10 trials per club were performed where occasionally a very poor shot was hit and discarded. This resulted in 6 shots being required in addition to the planned 160 (8 trials x 4 clubs x 5 subjects).

5.1.5 Data analysis

Data were reduced for mean, standard deviation and standard deviation of the mean ($^{\sigma}/_{\sqrt{n}}$) where appropriate using Excel. Results are presented in tabular and graphical format for both ballspeed indoors and on the range, and for carry and dispersion on the range. Scatterplot graphs for ball position were plotted for each club, illustrating the variation, if any, of carry and dispersion.

Statistical analyses were carried out for ball position using SPSS™. A one-way analysis of variance (ANOVA) was applied to launch condition data to determine whether club length had a significant effect on ball velocity. Furthermore, a one-way analysis of variance (ANOVA) tested for ball velocity difference between the two testing environment conditions.

A one-way ANOVA was applied to test for between and within subject trials variance for carry and dispersion due to club length. Where a statistically significant difference was observed a post-hoc LSD (least squared difference) test was used to determine where the differences rest. In addition, to test for subject and/or trial and club effect on carry and dispersion, a UNIVARIATE test was applied with a follow-up post-hoc LSD identifying where differences rest.

5.2 Results

The results are sectionalised into two areas of drive performance:

i. Shot performance by driver length for <u>test environment</u>
ii. Shot performance by driver length for <u>carry and dispersion</u>

5.2.1 Test environment

Table 5.1 shows the mean, standard deviation and percentage change in ballspeed at impact for both indoor and outdoor drive testing. Ball velocity was found to generally increase as club length increased for both environments, demonstrating the repeatable nature of the tests. Variation for 46″-47″, 47″-49″ and 49″-52″ drivers indoors were +1.76ms^{-1}, -0.28ms^{-1} and +0.42ms^{-1} respectively, similar to ball velocity changes for 46″-47″, 47″-49″ and 49″-52″ drivers, +2.06ms^{-1}, -0.67ms^{-1} and +0.82ms^{-1} respectively tested on the range.

Table 5.1 Ball velocity mean (±SD) and % change between indoor and outdoor values for all subjects tested for all clubs

Club	Ball velocity (ms^{-1})		
	Outdoor	Indoor*	±%
46″	63.78 ± 5.16	66.98 ± 5.67	+5.02
47″	65.54 ± 5.01	69.04 ± 6.11	+5.34
49″	65.26 ± 4.51	68.37 ± 5.24	+4.77
52″	65.68 ± 4.88	69.19 ± 5.75	+5.34

* F=2.677, p<0.05

Shots performed in the laboratory showed an average 3.33 ± 0.81ms^{-1}, or 5.12% increase in ballspeed at impact for all subjects, compared with equivalent shots performed on the range. A one-way ANOVA showed that ball velocity differed significantly ($F = 2.677$, $p < 0.05$) due to driver shaft length during tests performed in the laboratory. Ball velocity did not differ significantly due to driver shaft length during tests performed in an outdoor setting ($F = 2.572$, $p = 0.054$).

Figures 5.4 and 5.5 graphically show ball speeds at impact for tests carried-out in each environment. Figure 5.4 illustrates the overall trend for each club for tests on all subjects. As Table 5.1 showed, tests performed in the laboratory setting demonstrated higher ball velocity (NS).

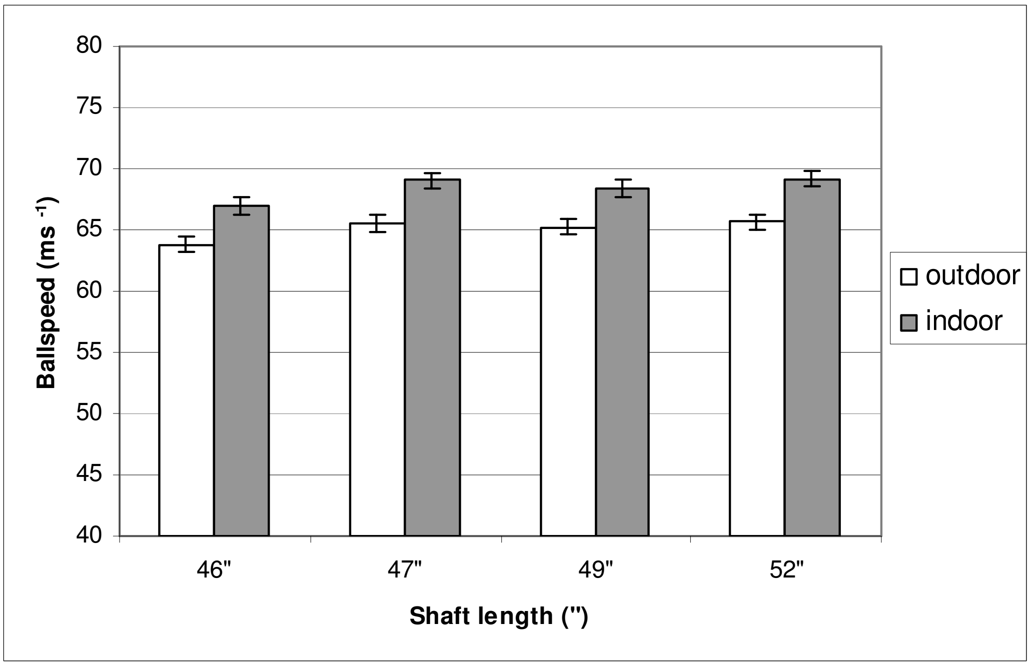


Figure 5.4 Comparison of mean (±s.d.) indoor and outdoor ball velocity at impact for club length

Furthermore, Figure 5.5 illustrates that each subject demonstrated higher ball velocity at impact during indoor testing; showing that overall higher ball velocity was not as the result of series mean calculation.

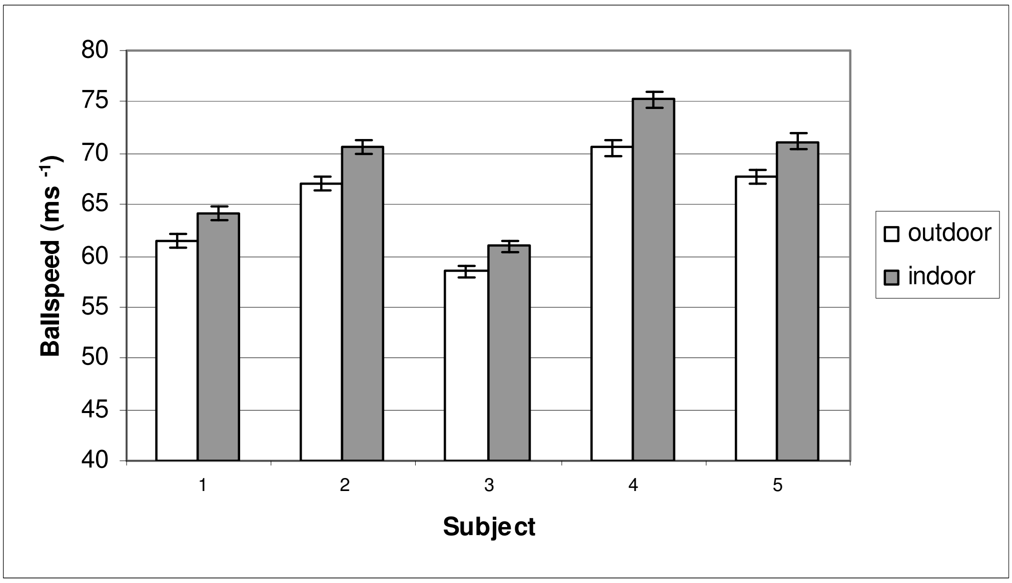


Figure 5.5 Comparison of mean (±s.d.) indoor and outdoor ball velocity at impact for individual subjects

5.2.2 Carry and dispersion

Table 5.2 shows carry and dispersion average, standard deviation and standard error, for all subjects and for all four clubs. The results show that, for outdoor testing, whilst the longest club produced the highest average carry (233.66 yards), accuracy was significantly reduced as inferred by increased standard error for dispersion ($^{\sigma}/_{\sqrt{n}}$). The shortest club, 46″, which was still 1″ longer than the subjects' own average club length, produced the least carry (219.57 yards), some 14.09 yards less than with the 52″ driver, but proved to be more accurate in terms of average displacement from the fairway centre. In addition, the 47″ club produced a significantly higher carry than the 46″ club, coupled with a higher average dispersion but lower standard deviation of the mean, that is, the general spread of shots produced using this longer driver was contained within a smaller area.

It is apparent that shots performed using the 47″ and 49″ drivers tended to land to the left of the fairway centre line, indicated by the '-' symbol in Table 5.2. This placement left of the centre line is greater in magnitude than average placement of the ball to the right of the fairway centre by the 46″ and 52″ drivers. Therefore, it would appear, however small, that shaft length and associated flexibility, has an effect on ball placement both in terms of positioning and of the spread of shots denoted by accuracy (standard deviation of the mean).

Table 5.2 Descriptive statistics for shot performance using drivers of different shaft length

Club	Carry (yards)*	Dispersion (yards)	$^{\sigma}/_{\sqrt{n}}$
46″	219.57 ± 17.93	0.21 ± 11.71	5.24
47″	225.33 ± 15.49	-1.36 ± 11.64	5.21
49″	226.59 ± 10.54	-3.90 ± 11.92	5.33
52″	233.66 ± 14.54	0.51 ± 15.57	6.96

Shots left of the target line are denoted by the '-ve' symbol under the dispersion column

*F= 6.92, p<0.001

Post-Hoc Carry: F= 6.92, p<0.05- 46″v47″, 47″v49″, 49″v52″, 47″v52″, 49″v52″

Post-Hoc Dispersion: F= 2.50, p<0.05- 46″v49″, 49″v52″

A UNIVARIATE statistical test indicated that apart from club length, no other factor had a significant effect on shot outcome (carry and dispersion). There was no statistically significant difference between trials within and between subjects, and no statistically significant difference between performance by different subjects. Importantly, this indicates that the group performed similarly as a whole, no subjects skewing the results which can often be the case with small subject numbers. Figure 5.6 is a scatterplot of all trials by every subject and shows the range of shot performance.

In addition, Figures 5.7 to 5.10 graphically represent shot placement for each of the 4 club lengths. Summarising data presented in Table 5.2, it is clear that shots appear longer and more scattered for drives performed with the 52″ driver.

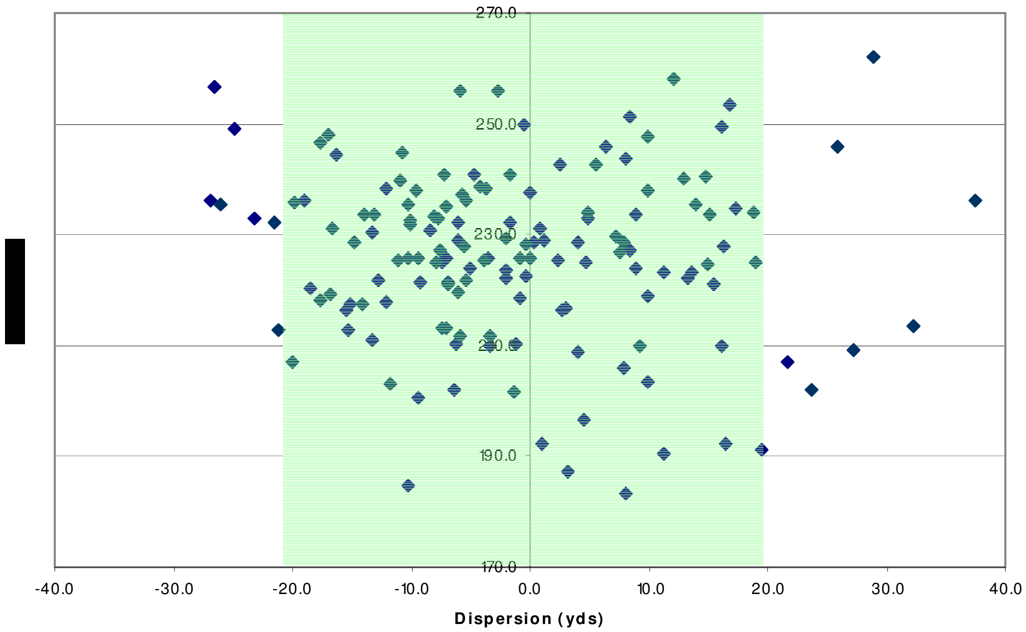


Figure 5.6 Data for all subjects for all clubs showing spread of performance for drivers ranging in length by 6".

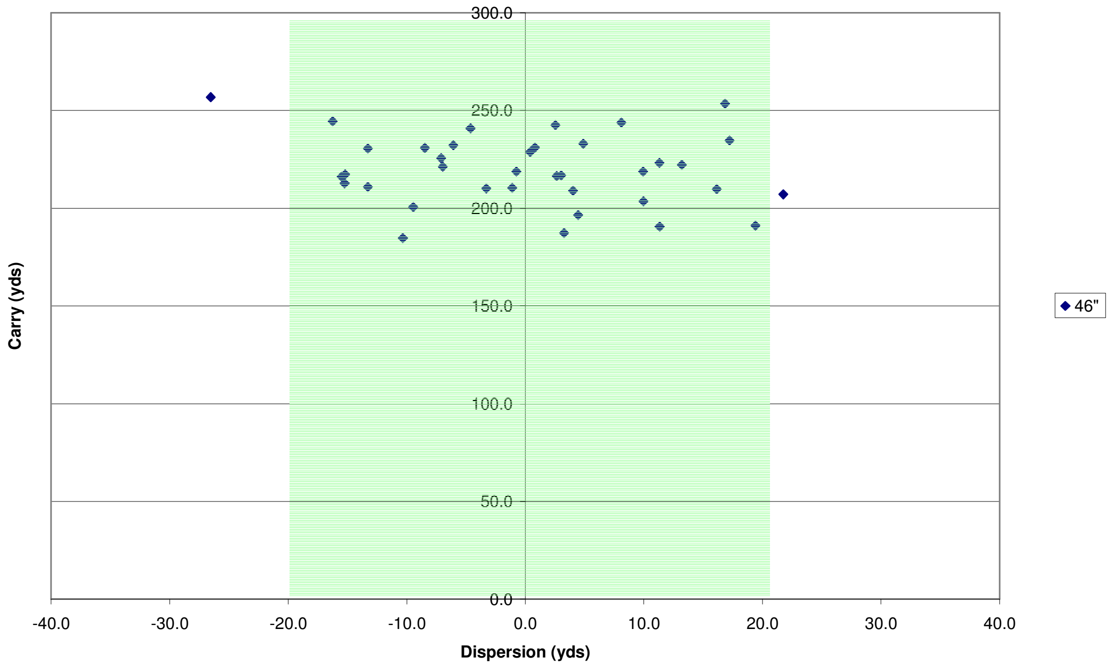


Figure 5.7 Scatterplot for all subjects using a 46″ driver.

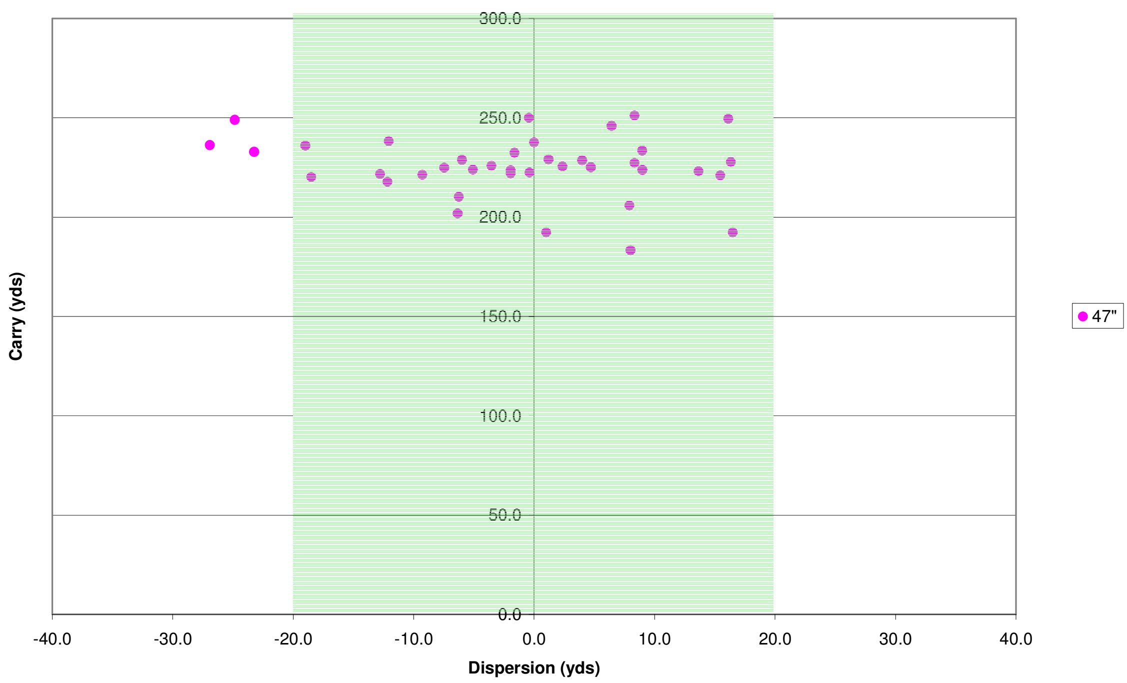


Figure 5.8 Scatterplot for all subjects using a 47″ driver.

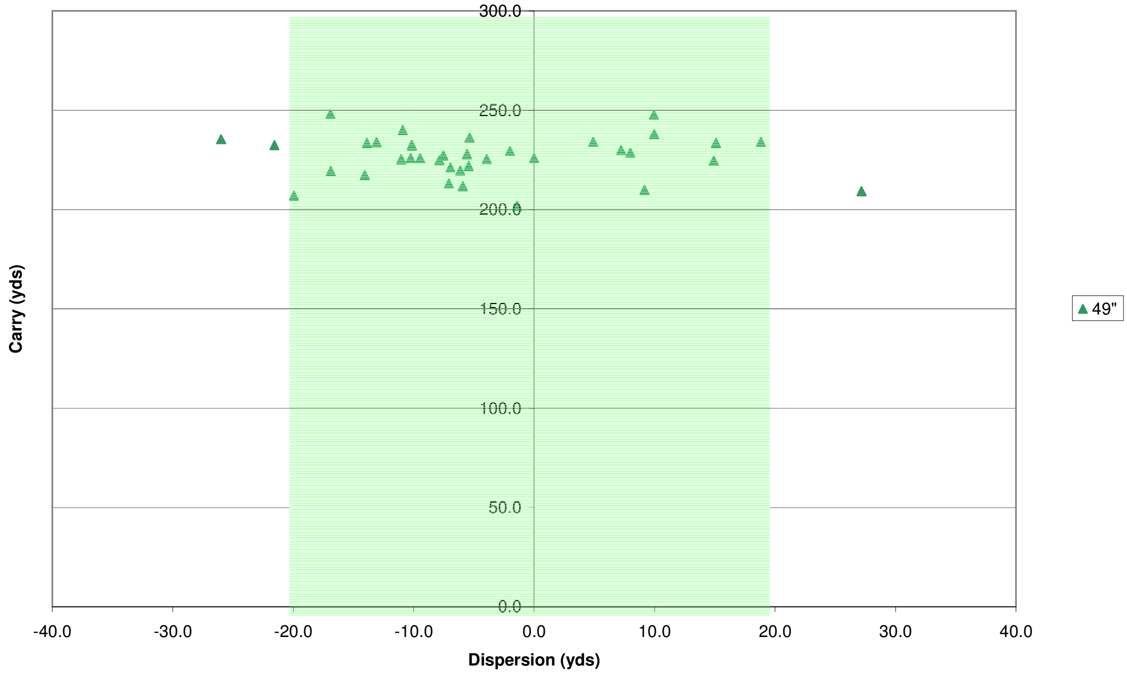


Figure 5.9 Scatterplot for all subjects using a 49″ driver.

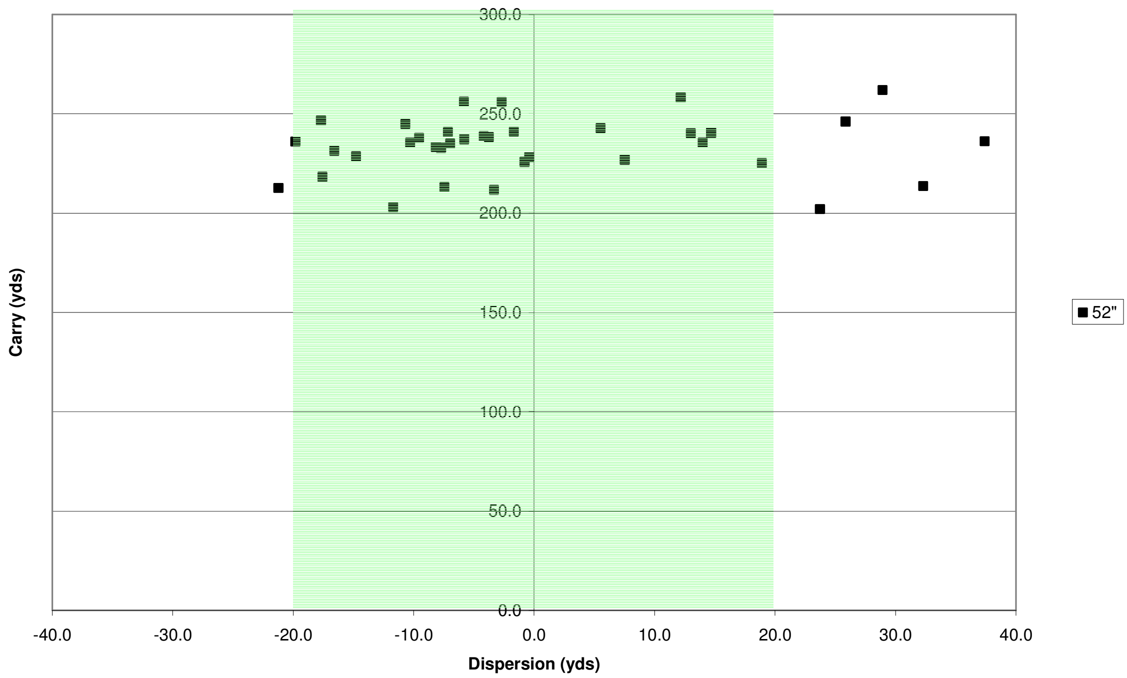


Figure 5.10 Scatterplot for all subjects using a 52″ driver.

5.3 Discussion

Results will be discussed in the same manner in which they were presented in Section 5.2, dealing first with the effect of the test environment then shot performance in terms of carry and dispersion for different club lengths.

5.3.1 Effect of testing environment on shot performance

The first point of discussion is that concerning the apparent variation between testing launch conditions in an outdoor and a laboratory environment. Equipment/personnel on the tee box were as unobtrusive as possible, and golfers knew to aim at the flag which was sufficient distance away so that they would not be able to reach it in a single shot, thus encouraging maximal driving effort. This environment, as such with the added wind (average 1 to 5 kph, “Light air” on the Beaufort scale, right to left for shots being played) and target factors, was as close to controlled, real conditions as could be achieved. The laboratory set-up, on the other hand, was more rigorously controlled in terms of environmental variables. The subjects were instructed to aim for the target line on the netting 4 metres in front of them. However, there was no accurate method, apart from indicative ball sidespin and horizontal launch angle, of telling how much dispersion each shot produced. It could be assumed that subjects neglected accuracy in favour of adding power to their swing such that they had no fear of sending the ball wide. The degrees of freedom associated with shots performed in the laboratory could be thought to be greater than those associated with shots in open play (Knight, 2004). Shots on the range may be more tightly controlled in terms of body kinematics as the central hub and the distal segments work together to produce repeatable skills. Knight also discusses ‘attractors’- those variables that affect control of the golf swing, which include, skill level, experience, environmental factors, and desired shot effect (hook/draw). These (hypothetical) constraints on each shot will change according to the environment in which the skill takes place, thus shots performed in the laboratory are devoid of shots effect attractors, and to some extent accuracy constraints. The net result could be to produce varied but high-powered swings as our findings showed.

Shots performed in the laboratory were on average $3.33 \pm 0.81ms^{-1}$ faster than shots performed on the range, which was a 5.12 % increase in ballspeed at impact for all subjects. Whilst no significant difference was found for ball velocity for shots performed in the laboratory and on the range, increase in ball velocity due to increasing club length is a contributing factor to the significant increase in carry distance. Table 5.4 summaries results previously detailed in Tables 5.1 and 5.2. It shows that an increase in ball velocity of 1.90 ms^{-1} contributed to an increase in 14.09 yards carry distance when using a 52″ driver compared with a 46″ driver.

Table 5.3 Summary of variation of ball velocity and carry on the range for different club lengths

Clubs compared (″)	Outdoor ball velocity (ms^{-1})	Carry (yards)
46-47	+1.76	+5.76
46-49	+1.48	+7.02
46-52	+1.90	+14.09

On average, each increase in club length of one inch, increased outdoor ball velocity by 0.32 ms^{-1} (0.37 ms^{-1} for indoors shots) and carry by 2.35 yards.

Reyes and Mittendorf (1999) predicted via their mathematical model that clubhead velocity produced using a 51" driver would be 1.34 ms^{-1} (3 mph) faster than shots performed using a 47" driver. As previously discussed, clubhead velocity was not recorded, however, using Equation 10, clubhead velocity can be calculated from ball velocity for a uniform impact.

$$V = \left\{\frac{v(M+m)}{1+e}\right\} \Big/ m \qquad \text{(Equ. 10)}$$

Where:

V = clubhead velocity

v = ball velocity (0.14ms^{-1} difference between 47" and 49" in the present study)

M =clubhead mass (average 0.1975 kg)

m = ball mass (Premium ball 0.0459kg)

e = C.O.R. (commonly represented by 0.8225 for modern driver impacts)

Therefore, $0.14ms^{-1}$ difference between 47" and 52" driver ball velocity (indoors) represents $0.1ms^{-1}$ clubhead velocity difference in the present study. This is significantly less than the reported 1.34 ms^{-1} by Reyes and Mittendorf (1999). However, the most significant increase in ball velocity for tests conducted for the present study occur for the 1" driver shaft length increase from 46" to 47" (1.76 ms^{-1}). Using equation (10) this equates to 1.19 ms^{-1} clubhead velocity.

Dynamic testing via the present study shows the margin between data produced experimentally, in conditions akin to actual competition, and that predicted mathematically. Section 5.0 raised the question whether in reality golfers would be able to maintain, or produce the greater levels of torque needed to execute their swing successfully and extract the predicted performance gains from a longer driver. Present study data confirms this doubt, that low-medium handicapped golfers (5.1 ± 2.0 handicap) are unable to utilise longer drivers as predicted via mathematical models.

It should be noted that Reyes and Mittendorf (1999) based their model data on the performance exhibited by a professional golfer who was a long-drive champion and competed in the 1997 season (prior to club length limit ruling) with a 51" driver. Therefore their data was for a more highly skilled golfer and a golfer accustomed to using longer than normal drivers. In addition, their model data showed that greatest carry distance could be achieved by this golfer using a 60" driver (with lighter clubhead mass). On the other hand, subjects in the present study were less skilled (5.1 ± 2.0 handicap) and their average driver length was 45". Golfers in the present study exhibited greatest ball velocity and carry gains using a driver length (47") lower in the range and in Reyes and Mittendorf's (1999) study for driver lengths higher up in the tested shaft length range. Whilst no measure of accuracy was predicted for the 60" driver, it may be possible that greater gains in drive length are possible by all golfers once they complete a significant learning period of using drivers longer than their own. Over time, a low-medium handicapped golfer may be able to use a 48" driver effectively, with a high degree of accuracy and with further gains in drive distance.

Psychological considerations

It could be suggested that subjects will sacrifice accuracy over power for shots performed in the laboratory setting. The main reason for this would seem to concern a few psychological factors. Zajonic (1965) proposed a model in which the presence of an audience has an effect of increasing arousal (drive) in the performing athlete. Since increased arousal facilitates the elicitation of the dominant response, the presence of an audience will enhance the performance of a skilled individual. Whilst testing both on the range and in the laboratory provides an audience for the golfer, it is fair to say that the intimacy of the environment in the laboratory is somewhat greater than on the range. Cox (1994) discusses this intimacy effect, as does Schwartz and Barsky (1977), stating that audience size and intimacy is related to performance levels. Home-played team sports performance demonstrated a greater winning percentage. Another point to note is that golfers tested in the laboratory may better be able to provide focused attention on the necessary cues needed to perform well. Easterbrook (1959) proposed the cue utilisation theory which suggests that there is an optimum level of arousal needed in order to utilise the necessary cues (task relevant) to perform well. Too low an arousal and too many negative cues will be acted upon by the golfer; too high arousal and too few positive cues will be acted upon as focus is too narrow. In essence, what this means is that either,

i. The laboratory setting is the ideal environment in which to perform well, driving fast and with accuracy, with the right level of arousal and focus by the golfer, or
ii. The laboratory setting is too intimate and accuracy is sacrificed for increased power in the drives, thus increasing ballspeed, as we found.

It is possible that the skilled golfers tested in the present study optimised their swings on the range, attempting to overcome problems such as wind, and fear of a miss-hit. This may lead to a reduction of power output from any number of individual, or combined movements (e.g. grip torque, hip/shoulder rotational velocity, lumbar torque). Physiologically, the force-velocity relationship of any muscle indicates that there is a certain velocity at which a muscle will produce peak power output. The slowing of certain gross movements may be the result of the optimal firing of stabilising muscles adding fine motor control to the swing as a whole. Without a measure of accuracy for shots performed in the laboratory, however, there is no definitive way of knowing how 'less accurate' shots there may be, if at all. Ultimately, golf is performed on the range and testing performed in that environment provides more meaningful results. The following section will discuss performance on the range.

5.3.2 Effect of shaft length on carry and dispersion

Shots performed with drivers of different shaft length differed significantly in both carry and dispersion. Shots performed with the longest driver, 52″, produced the longest carry (233.66 ± 14.54 yards) which was 14.09 yards longer than average carry produced using a 46″ driver. Drivers of 46″ are commonly used in the professional game. Each additional inch of driver shaft length developed on average 2.35 yards extra drive distance. However, as carry distance increased, the spread of shots (inferred by standard deviation of the mean) on the fairway increased as driver shaft length increased. The scatter pattern of shots hit using a 52″ driver increased in width by an average 3.86 yards over that of a 46″ driver. However, the scatter pattern of shots hit using a 47″ driver was smaller (by 0.07 yards) when compared to shots hit using the 46″ driver. That dispersion of shots was somewhat less when using this length of driver, golfers seemed able to cope with a driver 47″ in length, developing 1.76ms^{-1} greater ballspeed at impact and 3.86 yards carry distance. A driver shaft length of 47″ is within the 48″ club length limit imposed by the governing bodies of golf. Providing a golfer can demonstrate an ability to maintain accuracy whilst using a longer lever with which to propel the golf ball towards the hole as has been the case in the present study, it should be considered that the golfer's game will benefit.

Generally, though, across the whole 6″ range of shaft lengths investigated, accuracy was shown to decrease as club length increased, coupled with significant increases in carry distance.

Results were shown to generally agree with that of Werner and Greig (2000) that increases in shaft length resulted in increased drive distance and also decreased accuracy. However, the present study indicates that decreases in accuracy are to be found when using clubs longer than 47″ in length as opposed to the maximum 49″ they suggested. In addition, results agree with Werner and Greig that the extra carry produced by excessively long drivers is too small to warrant risking a larger hit pattern.

Accuracy determinants and theories

In order to understand the nature of human movement, and thus develop an appropriate research methodology, it is important to first understand some of the more important factors that influence and affect behavioural, in this case the golf swing, observations. Such factors are: movement constraints, human variability, response patterns, and aggregation. Primarily, Bernstein (1967) pioneered the proponents of the constraints that exist and influence human movement. These constraints included biomechanical, morphological and environmental factors and interaction of all three as they affect all human movement outcomes. Higgins (1977) defined biomechanical constraints as limitations imposed on the human system by physical laws, i.e. gravity, friction. Morphological or anatomical constraints are those limitations imposed on the system as a result of the physical structure and psychological makeup of the individual. Environmental constraints are the result of extraneous factors that affect performance, including personal arousal, crowd response, lighting, temperature etc. These all affect intrinsic responses.

Operating over all of these constraints is the objective of the movement, termed the task constraint. It is this constraint, in conjunction with experiences and memory, that most directly dictates the responses of the individual. That is, the task constraint refers specifically to the goal of the movement, namely the appropriate clubhead-ball impact. Bates (1996) suggested that although the system has a considerable number of degrees of freedom, the number of functional degrees of freedom (choices) is “seemingly infinite”. The result of human structural complexity is an even more complex functional system that is inherently variable. Newell and Corcos (1993) stated that variability is inherent within and between all biological systems and is the result of interactions among the structural and functional characteristics of the system and the constraints imposed on motion. Given a longer lever with which to execute a movement which an elite golfer is accustomed to performing, it is expected that there will exist greater variation in the degree of control of the distal end of the club (clubhead) which is now farther from the hub and final control point (hands). However, golfers, be that elite or higher handicapped, demonstrate the golf swing as a skill very repeatable in nature. Highly skilled acts are characterised more by the consistency of their output or results than by the consistency of the muscular contractions needed to achieve them.

Whilst statistically significant variation in carry and dispersion was observed for shots performed with different length drivers, absolute variation in accuracy across the whole range of shaft lengths was actually very small. The 'normal' 46″ driver produced one standard deviation (spread of shots for 68.26% of all shots) which equated to a range of 11.71 yards. Spread for the 49″ driver was still within 12.00 yards, yet a club length 3 to 5 inches (76.2mm to 127mm) longer than accustomed. Only the 52″ driver, some 4 inches (101.6mm) longer than the club length limit produced marked increase in deviation (accuracy) to 15.57 yards. With the test fairway cut 20 yards wide either side of the centre line (and many competition and club fairways even narrower than 40 yards), outside of 68.26% of all shots, initial ball fairway position is approaching the edge of the fairway.

This variability in data, that is drive accuracy, is pervasive throughout the multiple levels of movement organisation and occurs both within and between individuals. It exists because of the many complex systems and constraints that must interact in order to produce movement and is a direct result of the degree-of-freedom coordination problem expressed by Bernstein. Variation in the structure or function of biological systems within an individual, interacting with the constraints provided by the task, the environment, and the individual's psychological state at the time of movement execution, contributes to movement variability (Higgins, 1977; James and Bates, 1997). Variability is believed to be an emergent property of the self-organising behaviour of the non-linear dynamical properties within the neuromotor system (Turvey, 1990). The biological variability present within the neuromotor system is believed to be a function of both the deterministic evolutionary processes of the movement and error.

It would be natural to assume, following the discussions of those researchers who have been mentioned, that the biomechanical analyses said to be open to measures of error due to variability of movement will include variation in the swing of even highly skilled golfers both inter- and intra-subject. Using five low-medium handicapped golfers

(5.1±2.0 handicap), data was collected that was reliable in nature, that is without a large number of extraneous measurement errors or deviation from the mean, both inter- and intra-subject in nature, and showing a relatively small standard deviation that demonstrated trends for performance variations using the different club lengths.

Reduction in accuracy associated with using longer drivers may have been related to such factors as increases in dynamic loft as a result of increased flexibility of the lower part of the shaft providing movement of the clubhead (laterally as well as vertically) immediately prior to impact which the golfer may not be accustomed to. Variation in clubhead positioning when addressing the ball at impact causes different spin coefficients for the ball during flight which may alter final ball placement. Alternatively, a golfer may struggle to impart the necessary increased torque to the grip of a club with a longer shaft, thus sacrificing control over the need to maintain hub angular velocity. With decreased accuracy, though, appears to be increased drive distance when using long-shafted drivers. This may stem from increased acceleration of the clubhead in the latter part of the downswing as it 'catches-up' with the upper half of the more flexible longer shaft. Whilst all fitted with stiff graded shafts in the present study, shaft frequency decreases as shaft length increases (see Table 4.1) increasing the wavelength of oscillation of the distal end of the club creating a larger deviation between the upper part of the club which moves more or less linearly with the hands, and the clubhead, which naturally lags behind the hands during the downswing. However, shaft torque and the action of gravitational acceleration of the clubhead will close this gap by the time impact takes place- the greater the differential between the clubhead and the hands, the greater the acceleration of the clubhead in the latter stages of the downswing thus creating lead deflection and higher clubhead and ballspeeds at impact (Table 5.1) equating to greater drive distances.

5.4 Summary

The main aim of the present study was to investigate the effect of driver shaft length on shot performance (ball carry and dispersion from fairway centre) for shots performed in an outdoor setting for low-medium handicap golfers using drivers of different shaft length. In addition, dynamic testing environment was studied by replicating the experimental setup for both laboratory and on-course analysis.

Shots performed with drivers of different shaft length produced significant differences in both carry and dispersion. In terms of performance using the length clubs, the longest driver, 50″, produced the longest carry (233.66 ± 14.54 yards) which was 14.09 yards longer than average carry produced using a 'normal' 46″ driver. Each additional inch of driver shaft length developed on average 2.35 yards extra drive distance. However, the spread of shots (inferred by standard deviation of the mean) on the fairway generally increased as driver shaft length increased. The scatter pattern of shots hit using a 52″ driver increased by an average 3.86 yards over that of a 46″ driver, and the scatter pattern of shots hit using a 47″ driver was smaller (by 0.07 yards) when compared to shot hit using the 46″ driver. Golfers seemed able to cope with a driver 47″ in length, developing 1.76ms^{-1} greater ball velocity at impact and 3.86 yards carry distance. Generally, though, accuracy was shown to decrease as club length increased, coupled with significant increases in carry distance. Overall, best performance seems to have been achieved using the 47″ driver with significant increases in carry distance, and an increase, albeit statistically non-significant, in accuracy. Results were shown to generally agree with that of Werner and Greig (2000) that increases in shaft length resulted in increased drive distance and also decreases in accuracy. However, the present study indicates that decreases in accuracy are to be found when using clubs longer that 47″ in length as opposed to the maximum 49″ they suggested. Results for the present study also agree with predictions made by Cochran and Stobbs (1968) that an increase in driver shaft length brings about an increase in drive distance but with associated diminution in accuracy.

Furthermore, shots performed in the laboratory were, on average, 3.33 ± 0.81ms^{-1}, or 5.12% faster in relation to ball velocity at impact. Statistical analysis deemed this increase non-significant, therefore confidence may be placed on test results conducted on the range or in the laboratory that data produced is valid and reliable. Although, this may have implications when comparing new driver performance against any literature for statistics of on-course driving performance by another driver.

CHAPTER 6

STUDY 3:

Analysis of driving performance for elite golfers using driver of different shaft length

6.0 Introduction

Study 2 (Chapter 5) investigated the overall performance on the range for low-medium handicapped golfers using drivers of different shaft length. Measures of ballspeed, carry and dispersion were analysed. Further to this, the present study (study 3) investigated the effects of ball launch characteristics on shot performance by elite level golfers (category 1, <5 handicap), again using drivers of different shaft length. Golfers of a lower handicap were recruited in order to reduce the subject-effect on shot performance exhibited in studies 1 and 2. New driving clubs were constructed, more closely matched in terms of physical properties than in the first 2 studies, and uniformly ranging in shaft length, below (46″), above (50″) and at the limit (48″) imposed by the governing bodies of golf.

As previously stated, few researchers have paid attention to driving accuracy, most research concerned with driving performance in terms of the ability to increase clubhead or ball speed (Egret *et al.*, 2003; Mizoguchi and Hashiba, 2002). Fewer still have characterised clubhead and ball launch conditions as they relate to overall shot performance (Quintavalla, 2006) and none-to-date have assessed the effect of driver shaft length on launch conditions as they relate to shot performance (drive distance and accuracy).

The present study, by means of recording shot performance and ball launch conditions for subjects using their own drivers as well as the test clubs, also evaluated the interaction of select launch characteristics on shot performance.

The aims of the third study (Study 3) were:

i. To evaluate the effect of driver shaft length on shot performance (carry and dispersion) for elite golfers.

ii. To evaluate the effect of driver shaft length on ball launch conditions of launch velocity, launch angle and backspin and sidespin components.

iii. To characterise the relationship between selected launch condition variables and shot performance

6.1 Methods

Details of the equipment, subjects, testing procedures and data analysis employed in addressing the aims of the current study are presented in the following sections. In order to avoid duplication, where procedures are the same as were used for study 2, it will be noted that reference should be made to that chapter (Chapter 5) for further details where appropriate.

6.1.1 Equipment

Three driving clubs were constructed for the present study (see Section 3.1), matched for all physical properties except shaft length, (46″, 48″ and 50″) and naturally increasing swingweight with shaft length. Club components were more closely matched for physical properties than components used for study 1 and 2 clubs.

Study 2 results showed relatively little variation between data for the 49 and 52″ drivers. Some significant difference was exhibited for carry distance and dispersion, but absolute values were small. Therefore a range of clubs closer to the club length limit of 48″, and with uniform difference in length between the clubs was selected. The use of only 3 test clubs for the present study rather than 4 for studies 1 and 2 meant that subjects' own drivers may be tested without adding to fatigue levels. Table 6.1 shows the test clubs physical characteristics. Note that 'own driver' average shaft length for the test cohort was 44.5″.

It can be seen that associated with an increase in driver shaft length is an increase in swingweight (average increase of 3.5 points per 1″ shaft length) and a diminution of assembled club frequency (7.95Hz per 1″). Swingweight change was previously discussed (Section 2.3). In order to adjust a club for swingweight, mass must be added to parts of the club such as the hosel, clubhead or grip. In doing so not only does this negate the efforts undertaken to assemble clubs with matching components, but significant changes in the feel of the club and shot performance commonly result, due to changes, for example, in clubhead moment of inertia. Therefore, swingweight was accepted for the purposes of this PhD as naturally increasing with shaft length, and all other component properties controlled.

Table 6.1 Test clubs characteristics

Characteristic	Club		
Club length (″/m)	46 / 1.17	48 / 1.22	50 / 1.27
Shaft type	Grafalloy Prolite	Alida Longwood 50/50	Alida Longwood 50/50
Shaft Flex	Stiff	Stiff	Stiff
Shaft torque (˚)	2.8	2.8	2.8
Tip diameter (mm)	3.5	3.5	3.5
Shaft mass (g)	63.0	63.0	63.0
Grip mass (g)	51.0	51.0	51.0
Assembled mass (g)	319.6	314.1	315.0
Head mass (g)	200.9	199.7	199.8
Head volume (cc)	350	350	350
Loft (˚)	9.0	9.0	9.0
Lie (˚)	62.5	63.0	62.0
Face area (mm^2)	3691.3	3689.7	3703.8
Assembled frequency (Hz)	332.2	323.8	300.4
Swingweight (inch/ounces)	229.6	240.0	267.5
Swingweight	D9	E4	F4

A stereoscopic launch monitor was used to measure clubhead and ball launch conditions at impact. Figure 5.2 (Chapter 5) illustrates the positioning of the launch monitor in relation to the tee. The tee was a defined, raised tee area (0.5m elevation). Testing was carried out on the range, 330 yards from tee to hole along a straight, 40 yard wide fairway (‘medium cut’, 5/8″). No subject was able to drive the 330 yards to the hole, therefore all shots were classed as ‘maximal’. Ball carry position was additionally recorded via a triangulation system using two laser range-finders determining orientation and displacement of the ball from the tee and fairway centre when it first lands (see Sections 5.1.2 and 5.1.3). A premium ball type was used.

6.1.2 Subjects and test protocols

Seven category 1 (<5 handicap) golfers (22.1 ± 2.31 yrs, 77.39 ± 9.69 kg, 1.80 ± 0.09 m and 0.21 ± 2.41 handicap) took part in the study which was carried out over three days. Each subject signed an informed consent and completed a medical and golf history questionnaire. Test protocol was then carried out as per study 2. Each subject was allowed a warm-up period for general flexibility (Fradkin *et al.*, 2004) and mobility followed by 10 practice shots hit with their own driver. Subjects were then required to strike a series of 8 shots with each driver, starting with their own driver, followed by the three randomly assigned drivers of 46″, 48″ and 50″ shaft length. After each shot was struck, an investigator wiped clean the clubface and ball with white spirit to ensure a clean contact surface was being used. The launch monitor recorded data for the following launch conditions: clubhead velocity, ball velocity, ball launch angle, ball side angle (deviation) and back and sidespin components. Personnel were in place so that for each shot, data was recorded for launch conditions using the launch monitor, for anecdotal information at the tee (quality of shot and direction), and from each of the laser range finders (distance and bearing of the ball for carry and final position). Two ball spotters worked to accurately locate the first landing point of each shot.

6.1.3 Data collection

Section 5.1.3 details determination of measures of ballspeed, carry and dispersion. For the present study the same methodological procedures were employed, utilising the same digitisation functions to calculate clubhead and ball velocity, and trigonometry to determine carry and dispersion via data collected with the laser range finders. In addition, Figure 6.1 illustrates orientation of launch angle and backspin for digitisation using the stereoscopic stroboscopic high-speed camera.

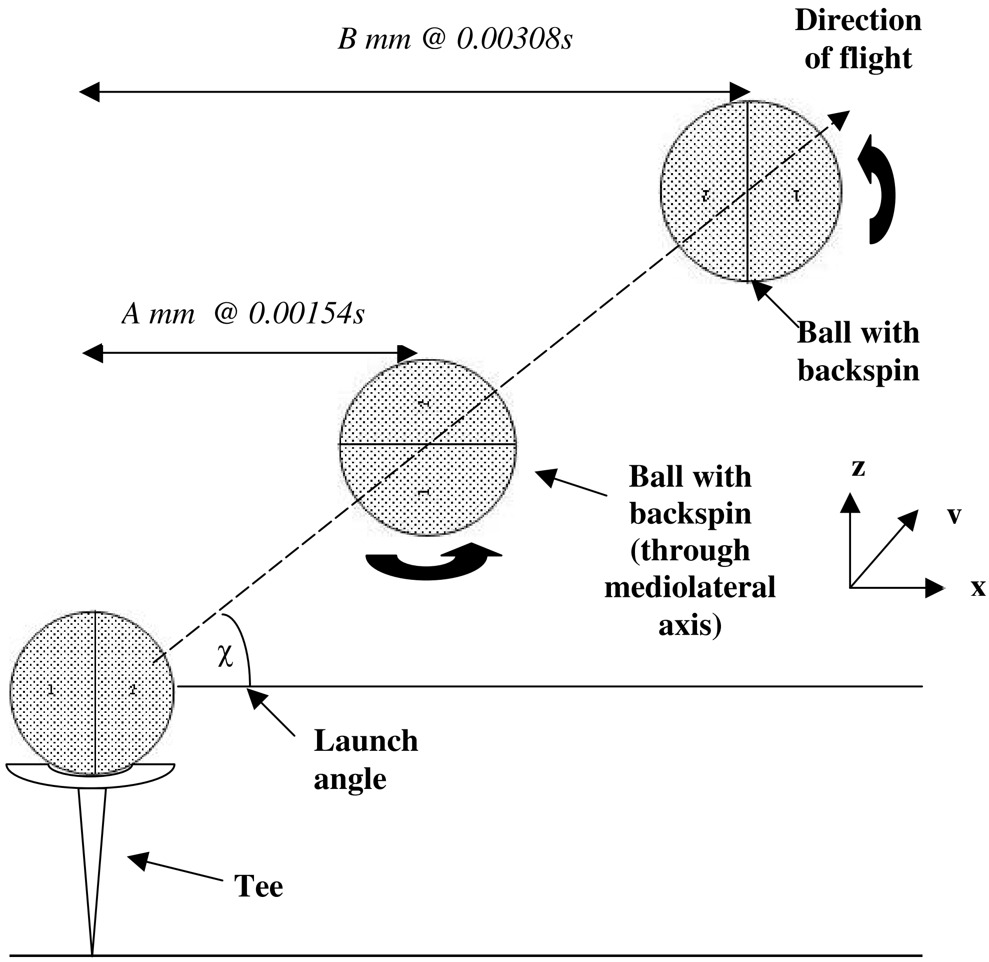


Figure 6.1 Schematic representation of basis for camera-based launch monitor calculation of launch angle, ball speed and spin rate in the x, y, z axes immediately after impact using digital photogrammetry of three images at 650Hz.

Furthermore, Figure 6.2 shows orientation of the side angle and ball sidespin components for launch condition analysis by the stereoscopic stroboscopic high-speed camera.

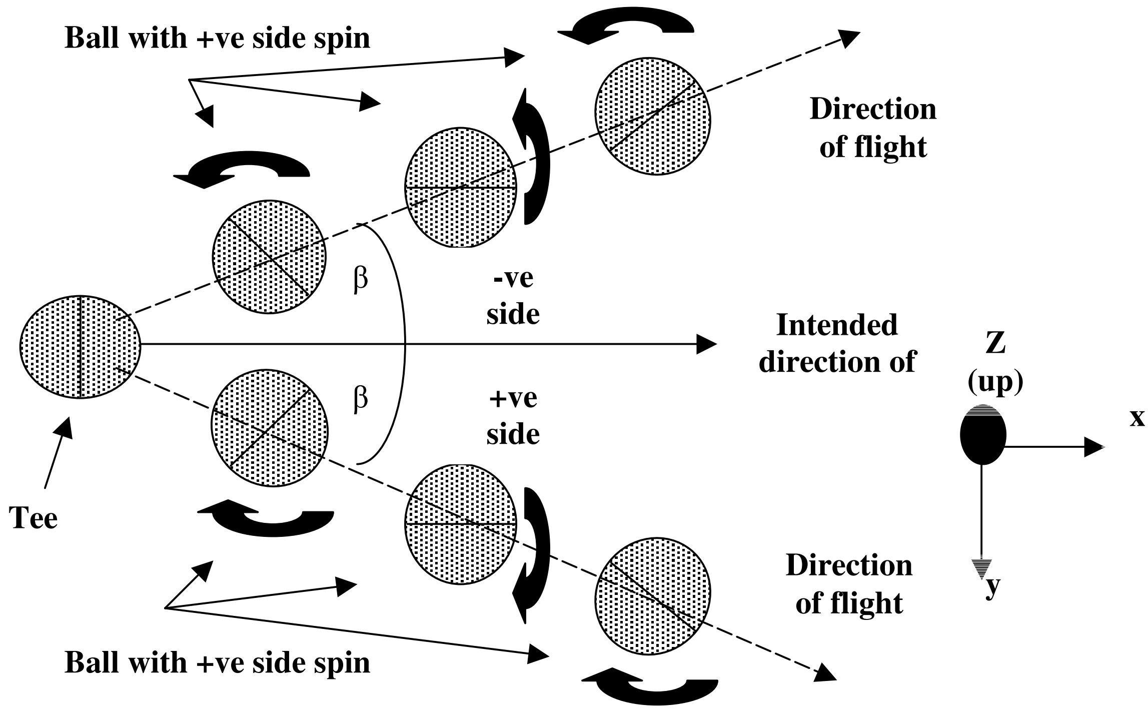


Figure 6.2 Schematic representation of orientation of side angle and side spin component of the ball.

6.1.4 Variable selection

To meet the aims of the present study, outlined in the introduction section of this chapter, variables for analysis were sectionalised into two areas:

1. <u>Performance measures</u>

i. <u>Carry-</u> a measure of drive performance as ball flight distance for shots hit using drivers of different shaft length.

ii. <u>Dispersion-</u> a measure of accuracy as the distance of the initial ball landing from the fairway centre line for shots hits using drivers of different shaft length.

iii. <u>Clubhead Velocity-</u> a measure of the ability to transfer angular torque supplied by the hub and the hands to the club being swung.

2. Launch conditions

i. Ball Velocity- Influenced but not directly necessarily proportional to clubhead velocity as a measure of the initial velocity supplied to the ball and is an indicator of carry distance, but varies with impact characteristics.

ii. Backspin- The backward rotation of the golf ball in flight along its horizontal axis. In general the more lofted a club is, the more backspin it will produce. Aerodynamically, backspin produces lift which creates greater carry, however it also induces drag.

iii. Sidespin- The component of spin of a ball whose axis is not perfectly horizontal for true backspin, resulting in an element of spin to the left (anti-clockwise) or to the right (clockwise) of the intended target line. A common occurrence for shots hit off-centre when the turning clubhead's moment of inertia produces a 'gear-effect' to impart sidespin to the ball creating hook of slice shots. Sidespin is often desirable and aids shaping the ball by skilled players (draw and fade).

iv. Launch angle- Launch angle is the initial elevation angle of the ball (with respect to the ground) immediately after impact with the clubhead.

v. Side angle- The trajectory of the ball, as viewed from above the tee (figure 6.2) in relation to the intended line of shot. In the present study shots hit with a negative side angle are left of the target, and shots with a positive side angle are hit to the right.

6.1.5 Data analysis

Performance measure data and launch condition characteristics data were amalgamated in tabular format using MS™ Excel. Data were reduced for mean, standard deviation and standard deviation of the mean ($^{\sigma}/_{\sqrt{n}}$) where appropriate for all measures. Scatterplot graphs for ball position were plotted for each club, illustrating the variation, if any, of carry and dispersion. Furthermore, scatterplot graphs were plotted for carry against clubhead velocity, ball velocity, launch angle and backspin, and for dispersion against side angle and sidespin and backspin against sidespin, to illustrate the relationship these launch conditions had on shot outcome. Linear regression analyses (R^2) were performed, calculating the least squares fit for a line represented by the following equation:

$$y = mx + b \qquad \text{(Equ. 11)}$$

where m is the slope and b is the intercept.

R^2 is calculated using the following equation:

$$R^2 = 1 - \frac{SSE}{SST} \qquad \text{(Equ. 12)}$$

where

SSE = Sum of Squares error = $\sum(Y_i - \hat{Y}_i)^2$

and

SST = Sum of Squares total = $(\sum Y_i^2) - \frac{(\sum Yi)^2}{n}$

Y_i is the $_i$th data point of the dependent variable Y, $\hat{Y}_i$ is the mean of the $_i$th data point and n is the number of samples.

Regression analyses were performed for 'own driver' series which displayed least inter- and intra-subject variability, thus allowing more valid conclusions to be drawn for relationships between shout outcome and launch conditions. A Pearson's test was also performed to highlight the strength of correlation between the results sets.

Statistical analyses were carried out using SPSS™. A one-way ANOVA was applied to all data to determine whether club length had a significant effect on any measure. Where a statistically significant difference was observed a post-hoc LSD (least significant difference) test was used to determine where the differences rest. In addition, to test for subject and/or trial and club effect on carry and dispersion, a UNIVARIATE test was applied with a follow-up post-hoc LSD identifying where differences rest.

6.2 Results

As per variables sectioned and detailed in Section 6.1.4, results will be presented in this section in the same manner, firstly dealing with performance measures of carry, dispersion, clubhead and ball velocity, followed by results pertaining to launch conditions and the effect that driver shaft length has on each condition studied. In addition, the relationship between launch conditions and performance measures are analysed via regression and correlational analysis. All results are presented both for subjects' own driver and for the three test lengths of 46", 48" and 50".

6.2.1 Shot performance

Table 6.2 details the mean and standard deviation for the performance measures of initial ball velocity, clubhead velocity at impact, carry distance, and dispersion from the fairway centre. In addition, the standard deviation of the mean for shot dispersion is shown ($^{\sigma}/_{\sqrt{n}}$). Absolute and percentage differences for test clubs compared to 'own driver' performance is detailed in Table 6.3.

Table 6.2 Mean (±SD) for shot performance, ball velocity and clubhead velocity for different shaft lengths

Club	Ball Velocity* (ms^{-1})	Clubhead velocity** (ms^{-1})	Carry (yds)	Dispersion (yds)	$^{\sigma}/_{\sqrt{n}}$
Own	70.22 ± 3.04	47.95 ± 2.95	238.56 ± 14.27	1.82 ± 17.00	6.43
46"	71.20 ± 4.38	48.03 ± 1.95	238.87 ± 14.97	-4.07 ± 18.08	6.83
48"	72.29 ± 3.35	48.49 ± 1.95	244.70 ± 14.06	0.77 ± 16.47	6.23
50"	72.99 ± 3.27	49.42 ± 1.60	243.29 ± 16.06	0.57 ± 16.94	6.40

- = left of target line

**Post-Hoc F = 5.34, p<0.01 – own vs48", own vs50", 46"vs50"*

***Post-Hoc F = 3.21, p<0.05 – own vs50", 46"vs50"*

Club length was found to have a significant effect on both ball and clubhead velocity, for own driver against 48" and 50" drivers and for the 46" against the 50" driver for ball velocity, and for own driver against the 50" driver and the 46" against the 50" driver for clubhead velocity. Driver shaft length was found to have no statistically significant effect on carry ($F = 1.786$, $p = 0.152$) nor dispersion ($F = 0.890$, $p = 0.448$).

Table 6.3 shows that both ball velocity ($F = 5.34$, $p < 0.01$) and clubhead velocity ($F = 3.21$, $p < 0.05$) increased linearly as driver shaft length increased. Whilst absolute and percentage margins increased greatest in magnitude for the 50" driver for these two measures, this was not transferred to greater carry distance, illustrated by greater distance and percentage gains for 48" driver shots (+6.14 yards / +2.57% for the 48" driver compared to +4.73 yards / +1.98% for the 50" driver).

Table 6.3 Absolute and percentage differences for shot performance, ball velocity and clubhead velocity for different shaft lengths and change in spread for dispersion

Clubs compared (")	Ball Velocity		Clubhead Velocity		Carry		Dispersion change in spread
	ms^{-1}	%	ms^{-1}	%	yds	%	yds
Own-46"	+0.98	+1.40	+0.08	+0.17	+0.31	+0.13	+1.08
Own-48"	+2.07	+2.95	+0.54	+1.13	+6.14	+2.57	-0.53
Own-50"	+2.77	+3.94	+3.94	+3.07	+4.73	+1.98	-0.06

In contrast to results presented in Section 5.2.2, study 2, where accuracy as represented by spread of shots in relation to the fairway centre line (standard deviation of the mean- 46" 5.24, 47" 5.21, 49" 5.33 and 52" 6.96), on average, shots performed in the present study were found to display a smaller scatter pattern for the 48" driver ($^{\sigma}/_{\sqrt{n}}$ 6.23). Standard deviation for shot dispersion was marginally greater for subjects' own driver and for shots performed with the 46" driver, and shots performed with the longer drivers tended to land, on average, closer to the fairway centre.

However, differences were statistically non-significant ($F = 0.890$, $p = 0.448$) and actual variance was small. For the elite group of subjects studied here, average accuracy was good and consistent. Scatterplots 6.3 to 6.7 for all shots performed with all clubs, and for each individual club, illustrates little obvious difference for dispersion, and only a small increase in carry distance as shaft length increases. It should be noted, though, that whilst subjects studied in the present study were elite golfers, and included one professional golfer, one standard deviation (for all clubs tested) averaged 17.12 yards. For this normally distributed set of data, one standard deviation represented 68.27% of shots. With average dispersion tending to the fairway centre, and the fairway cut 20 yards either side of centre, 79.75% of shots landed 'in regulation'. This figure betters current PGA Tour statistics (Section 2.2.2) that shot accuracy is 70%. As the scatterplots show, a large number of shots still landed 'in the rough' (outside ±20 yards).

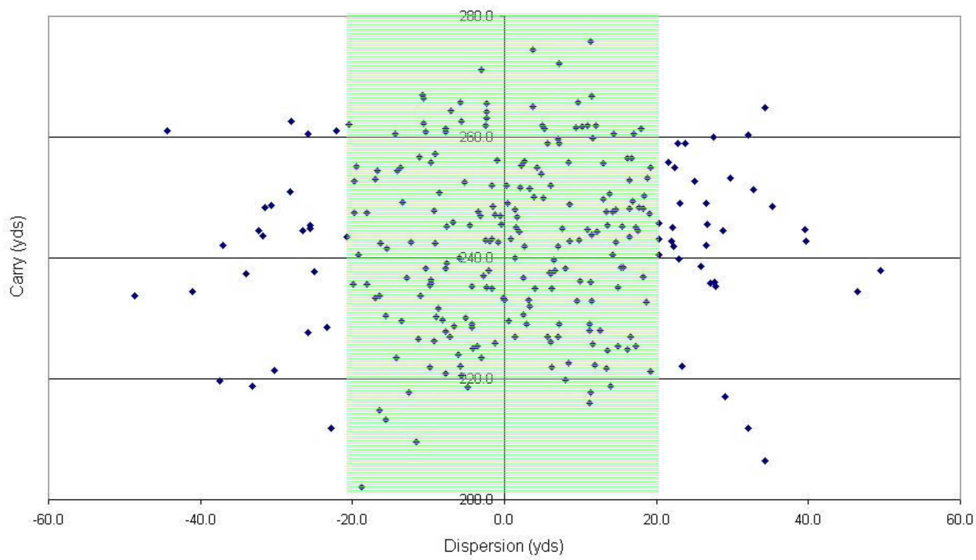


Figure 6.3 Scatterplot for all subjects for all clubs showing spread of performance for drivers ranging in length from 46″ to 50″

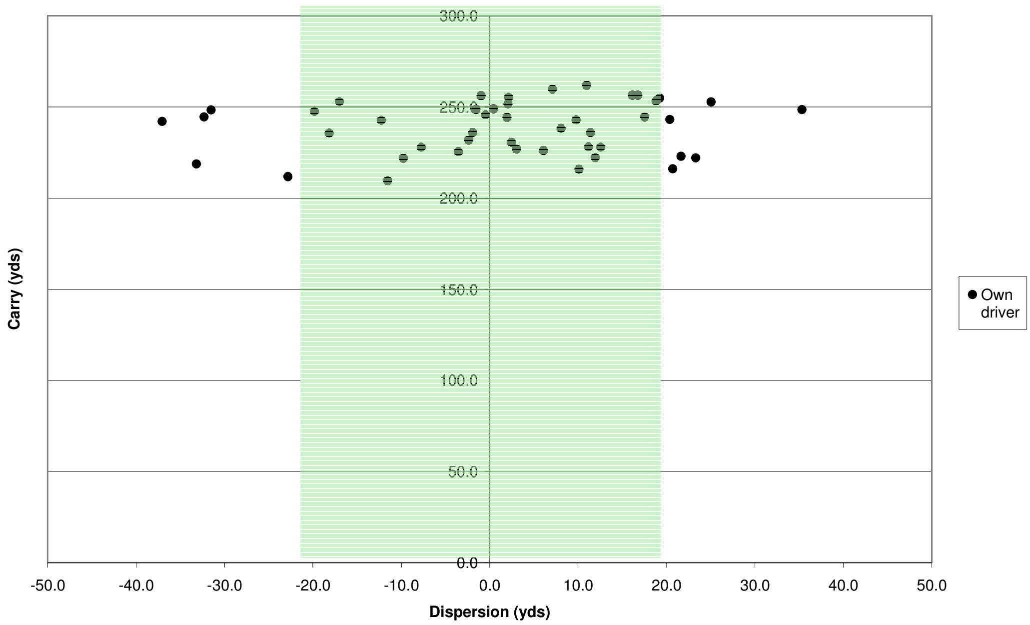


Figure 6.4 Scatterplot for subjects using their own driver

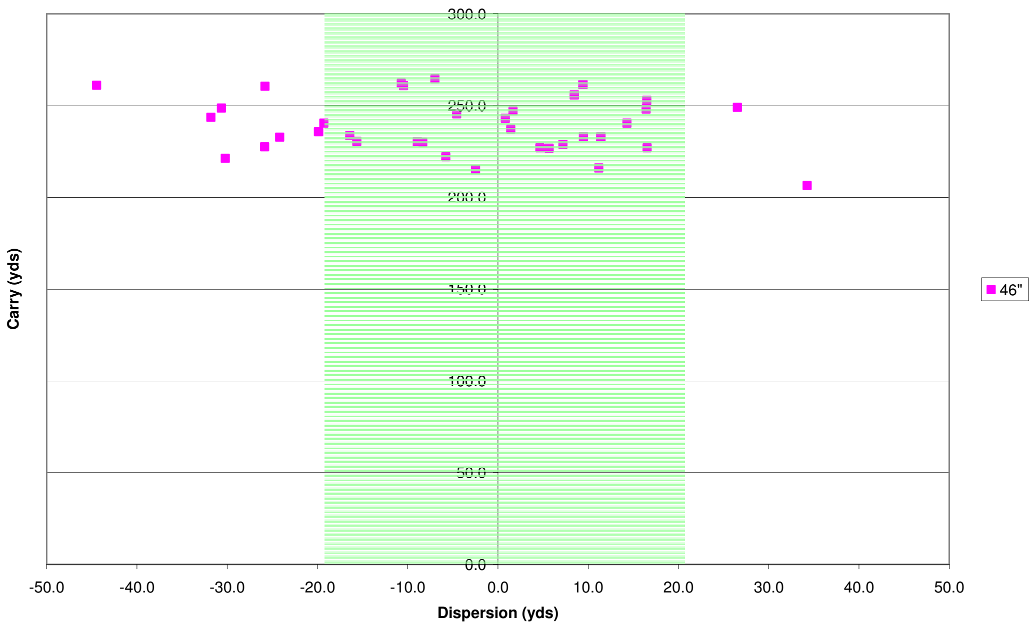


Figure 6.5 Scatterplot for subjects using a 46″ driver

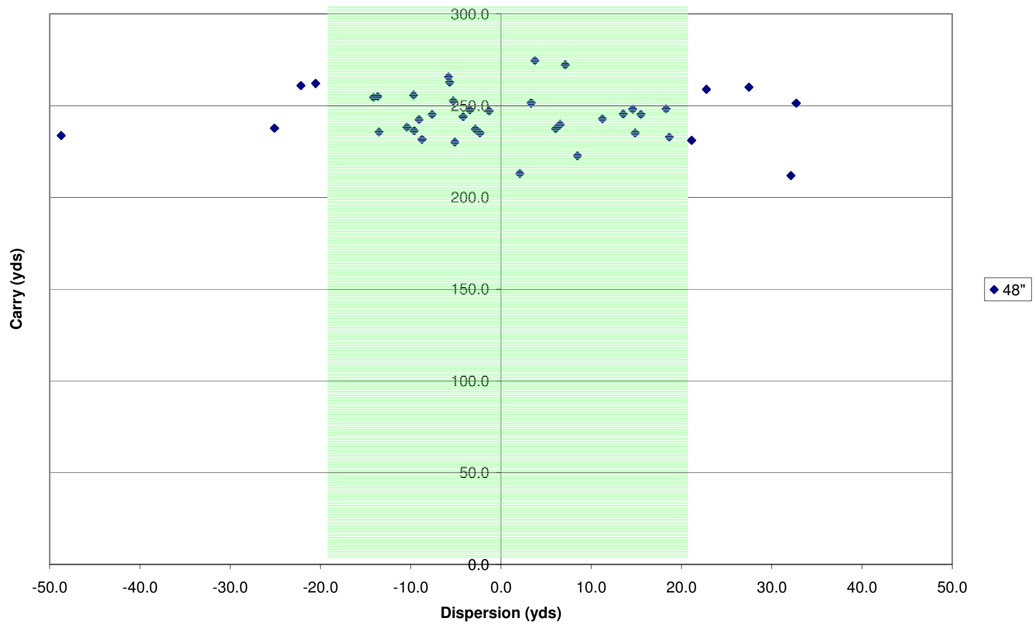


Figure 6.6 Scatterplot for subjects using a 48″ driver

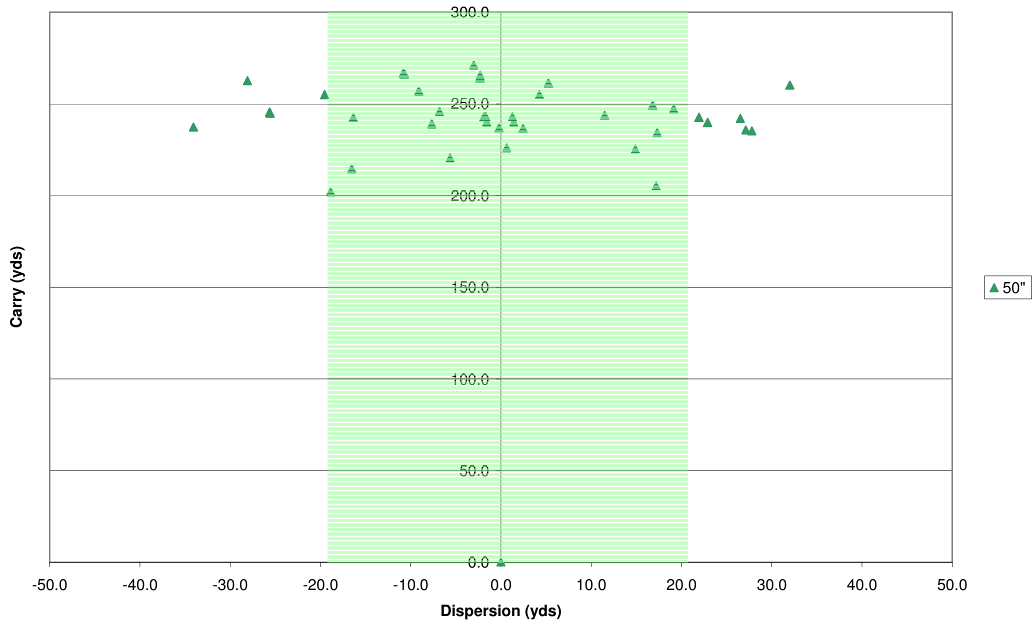


Figure 6.7 Scatterplot for subjects using a 50″ driver

6.2.2 Launch conditions

Table 6.4 shows descriptive statistics for launch characteristics recorded by the stereoscopic launch monitor for all trials for all subjects using each driver. Additionally, Table 6.5 details absolute and percentage differences for the 46″, 48″ and 50″ driver compared to subjects' performance using their own driver.

Table 6.4 Launch conditions mean (±SD) for shots performed using drivers of different shaft length

Club	Side Angle (˚)	Sidespin (RPM)	Launch Angle (˚)	Backspin* (RPM)
Own	1.40 ± 3.69	-48.80 ± 950.15	8.87 ± 2.31	2637.89 ± 541.69
46"	1.82 ± 3.06	280.00 ± 648.41	9.63 ± 2.57	2065.44 ± 736.42
48"	0.74 ± 3.01	170.75 ± 651.29	9.41 ± 2.18	2478.82 ± 631.62
50"	0.58 ± 1.78	239.64 ± 564.79	9.70 ± 2.23	2751.54 ± 1105.70

- = left (of target line)
**Post-Hoc F = 4.149, p<0.01 – own vs46", 46"vs50"*

Table 6.5 Absolute and percentage differences for launch conditions for drivers of different shaft length

Clubs compared	Side Angle		Sidespin		Launch Angle		Backspin	
	(˚)	%	(RPM)	%	(˚)	%	(RPM)	%
Own-46"	+0.42	+30.00	+308.80	+632.79	+0.76	+8.57	-572.45	-27.72
Own-48"	-0.66	-89.19	+219.55	+449.90	+0.54	+6.09	-159.07	-6.42
Own-50"	-0.82	-141.38	+288.44	+591.07	+0.83	+9.36	+113.65	+4.13

Driver shaft length was found to have no statistically significant effect on the majority of launch characteristics. Launch angle ($F = 1.074$, $p = 0.362$) and sidespin ($F = 1.089$, $p = 0.358$) were found to generally increase as driver shaft length increased, although both measures remained relatively low for 48″ driver shots. Launch angle increased by 0.83˚ (9.36%) when using a 50″ driver compared to a subjects own driver (c.44.5″). Sidespin increased by an average 518 revolutions per minute under the same comparison, but varied considerably between-subjects as evidenced by large standard deviation indicating the varied means (launch conditions) by which different golfers achieve similar shot outcome.

Furthermore, side angle ($F = 1.333$, $p = 0.266$) was shown to decrease as shaft length increased and backspin ($F = 4.149$, $p < 0.01$) was shown to vary significantly as clubs of different length were used, but displayed no significant pattern in change across the range of clubs tested. Side angle, or deviation from the intended line of shot, decreased by 0.82° (141.38%) when 50″ driver shots are compared to own driver data. Maintenance of a straight shot indicated by a relatively small side angle, though, may be offset by variance in sidespin, which was mentioned as generally increasing with shaft length increases. Backspin decreased by a relatively large amount (572.45 rpm / 27.72 %) when 46″ driver data is compared to own driver data. Overall, however, average backspin rates remained relatively low for the whole subject cohort, as did dynamic launch angle, but this was solely ball launch angle and did not take into account dynamic loft offered by the clubhead at impact, which proved difficult to measure reliably without asking golfer's to perform considerably greater numbers of shots, thus increasing fatigue. However, the majority of previous literature deals only with ball launch angle data, thus comparisons can only be made using this measure.

Boxplots for all measures (performance and launch characteristics) can be found in Appendix 5.0. Boxplots show the median, quartiles and extreme values for shots performed using each driver length and compliment the graphical representation of performance data in Figures 6.3 to 6.7 and Table 6.2 and launch condition data in table 6.4. The relatively small boxplot ranges displayed for 48″ driver data follows the trend discussed for relatively low side angle, sidespin, launch angle and backspin launch conditions, dispersion, and overall standard deviation for all measures.

Furthermore, one-way ANOVAs highlighted significant subject-effects for all measures except ball spin components (table 6.6). UNIVARIATE analysis also highlighted this significant inter-subject variance ($F=16.21$, $p<0.001$), and served to show that trial effect was not significant, i.e. that intra-subject variance ($F=1.52$, sig.=0.220) did not have a significant effect on any measures (see Appendix 6.0).

Table 6.6 details the significance levels (F-score and significance) for the one-way ANOVA statistical analyses, with LSD (least significant difference) post-hoc results showing where the differences rest.

Table 6.6 Statistical test results for subject-effect

Variable	Test	Test statistics & variant subjects
Carry	1-way ANOVA	F=14.89, p<0.05
	LSD	1vs2,3,5; 2vs3,4,5,6,7; 3vs7 4v7; 5vs6,7
Dispersion	1-way ANOVA	F=9.52, p<0.05
	LSD	1vs3.5.6; 2vs5,6,7; 3vs5,6,7; 4vs5,6; 6vs7
Clubhead	1-way ANOVA	F=52.03, p<0.05
Velocity	LSD	1vs3,4,5,6,7; 2vs3,5,6,7; 3vs4,6,7; 4vs7; 5vs7; 6vs7
Ball	1-way ANOVA	F=32.03, p<0.05
Velocity	LSD	1vs2,3,4,5,6,7; 2vs3,4,5,6,7; 3vs7; 4vs7; 5vs6,7; 6vs7;
Launch	1-way ANOVA	F=6.41, p<0.05
Angle	LSD	1vs4,5,7; 2vs4,5,7; 3vs4,5,7; 4vs6; 6vs7
Side Angle	1-way ANOVA	F=14.00, p<0.05
	LSD	1vs4,5,6,7; 2vs4,6,7; 3vs4,5,7; 4vs5,6; 5vs6,7; 6vs7

6.2.3 Shot performance and launch conditions relationship

Following-on from treating measures in the present study as individual variables, this section presents data showing the relationships between launch conditions and shot performance (carry and dispersion). Whilst regression analysis is shown only for own driver data, tests were performed for each driver for each relationship and it was found that own driver regression trendline and associated equation and R-squared value were representative of all drivers. Only own driver trendline is shown for illustrative simplicity. Table 6.7 also shows the correlations (Pearson's 'r') for the same comparative analyses, and for all driver lengths, highlighting the strength of relationship and statistical significance where it occurred.

Figure 6.8 shows the positive relationship that exists between carry distance and clubhead velocity. With a significant correlation of 0.582 ($p<0.01$) carry distance was shown to increase as clubhead velocity at impact increased. Regression analysis was performed for own driver only.

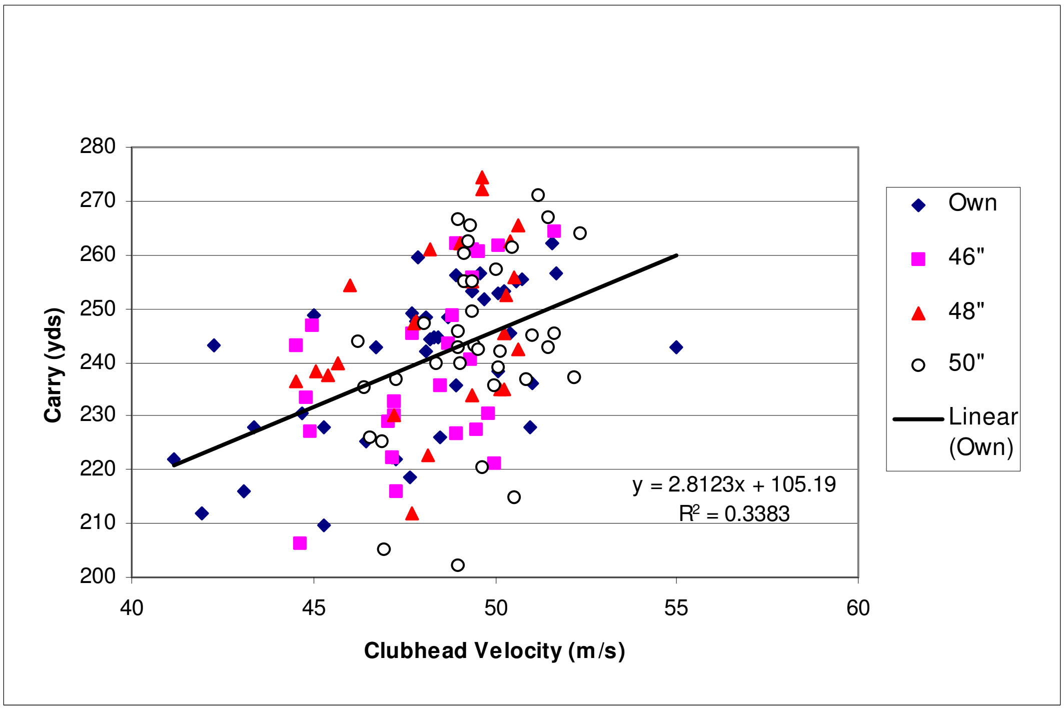


Figure 6.8 Scatterplot for all clubs showing representative relationship between carry and clubhead velocity at impact

Figure 6.9 shows the similar positive relationship that exists between carry distance and ball velocity. A significant correlation score of 0.461 ($p<0.01$) existed between the two variables, carry distance increasing as ball velocity immediately after impact increased. Regression analysis was performed for own driver only.

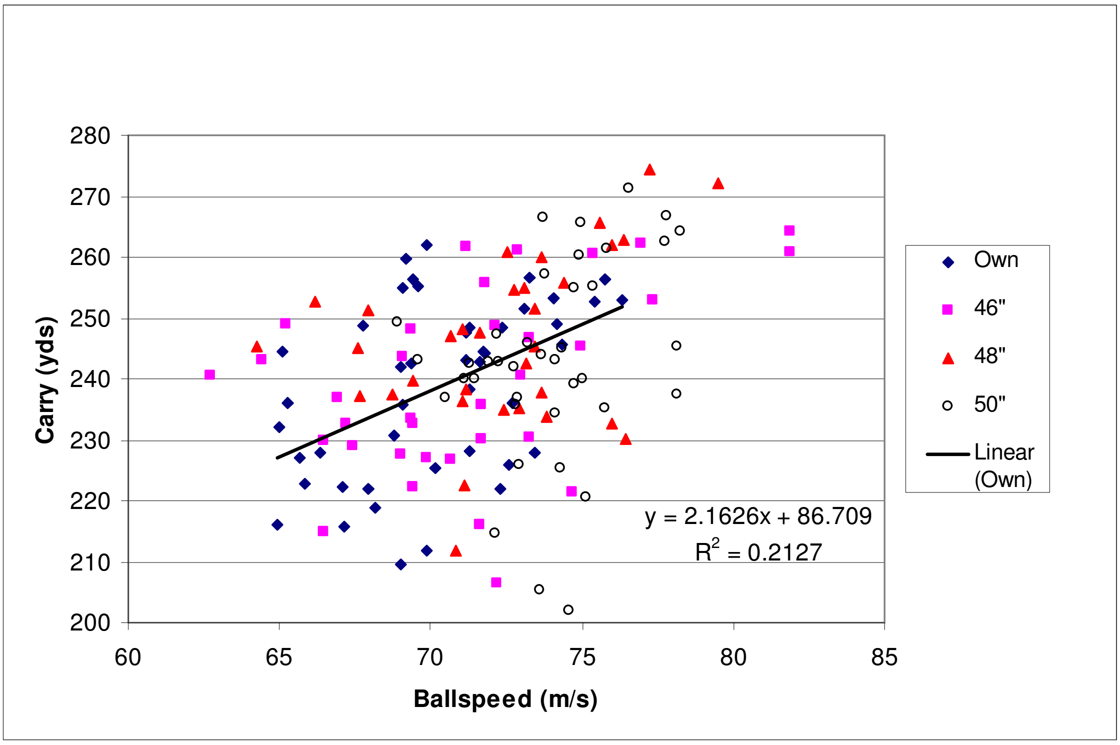


Figure 6.9 Scatterplot for all clubs showing representative relationship between carry and ballspeed at impact

A negative relationship was shown to exist when carry distance and ball launch angle were analysed (Figure 6.10). Applying Pearson's test to all clubs' data a significant correlation of –0.354 ($p<0.05$) was found, carry distance increasing as ball launch angle decreased. However, change in spin, as has been demonstrated in the current study, may outweigh this negative carry/launch angle trend. Regression analysis was performed for own driver only.

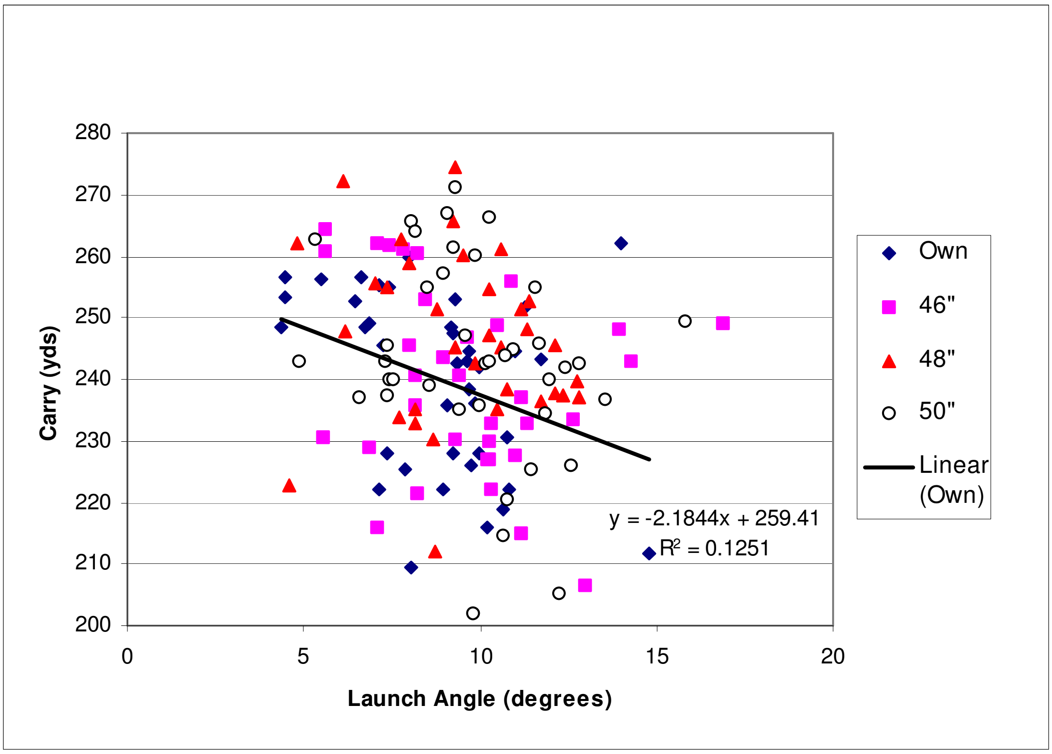


Figure 6.10 Scatterplot for all clubs showing representative relationship between carry and ball launch angle at impact

Figure 6.11 shows a negative relationship between carry distance and ball backspin. A Pearson's correlation of -0.019 (p = 0.914) illustrates the increase in carry distance as backspin decreases. Regression analysis was performed for own driver only. Regression analysis was performed for own driver only.

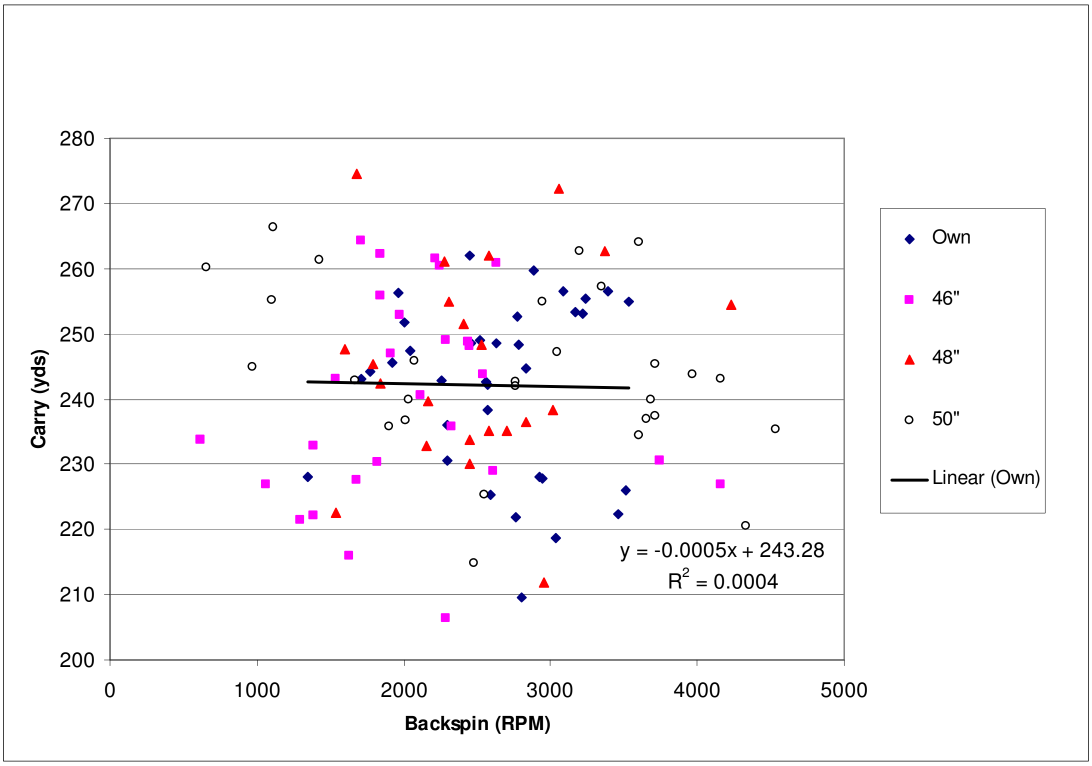


Figure 6.11 Scatterplot for all clubs showing representative relationship between carry and ball backspin at impact

Pearson's correlation of -0.209 shows a positive relationship between dispersion and ball sidespin component. Figure 6.12 ($p < 0.05$) illustrates that as sidespin increases so too does dispersion of the ball from the fairway centre. Regression analysis was performed for own driver only.

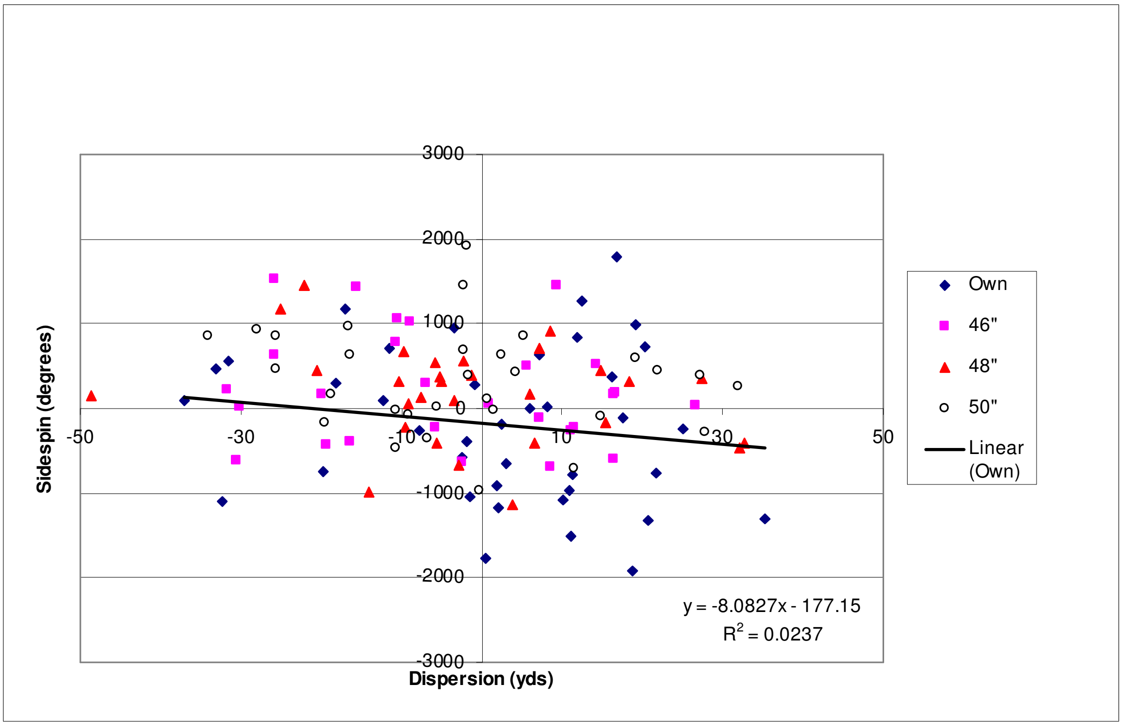


Figure 6.12 Scatterplot for all clubs showing representative relationship between dispersion and ball sidespin at impact

Figure 6.13 shows dispersion and ball side angle data for all driver lengths. A positive relationship was found between the two variables. A weak Pearson's correlation of 0.073 (p = 0.712) illustrated that dispersion increased as side angle increased Regression analysis was performed for own driver only.

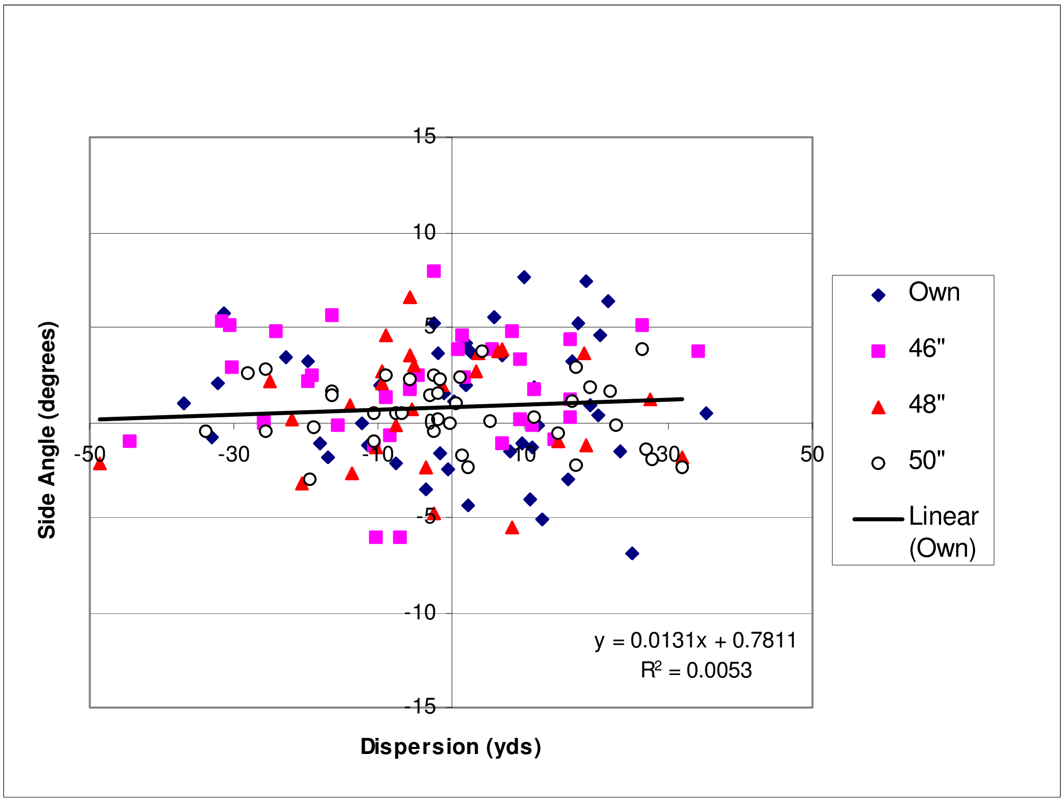


Figure 6.13 Scatterplot for all clubs showing representative relationship between dispersion and ball side angle at impact

Additionally, Figure 6.14 shows the negative relationship between ball backspin and sidespin components. A correlation of 0.053 (p = 0.603) exists between the two components of ball spin (Table 6.7). Regression analysis was performed for own driver only.

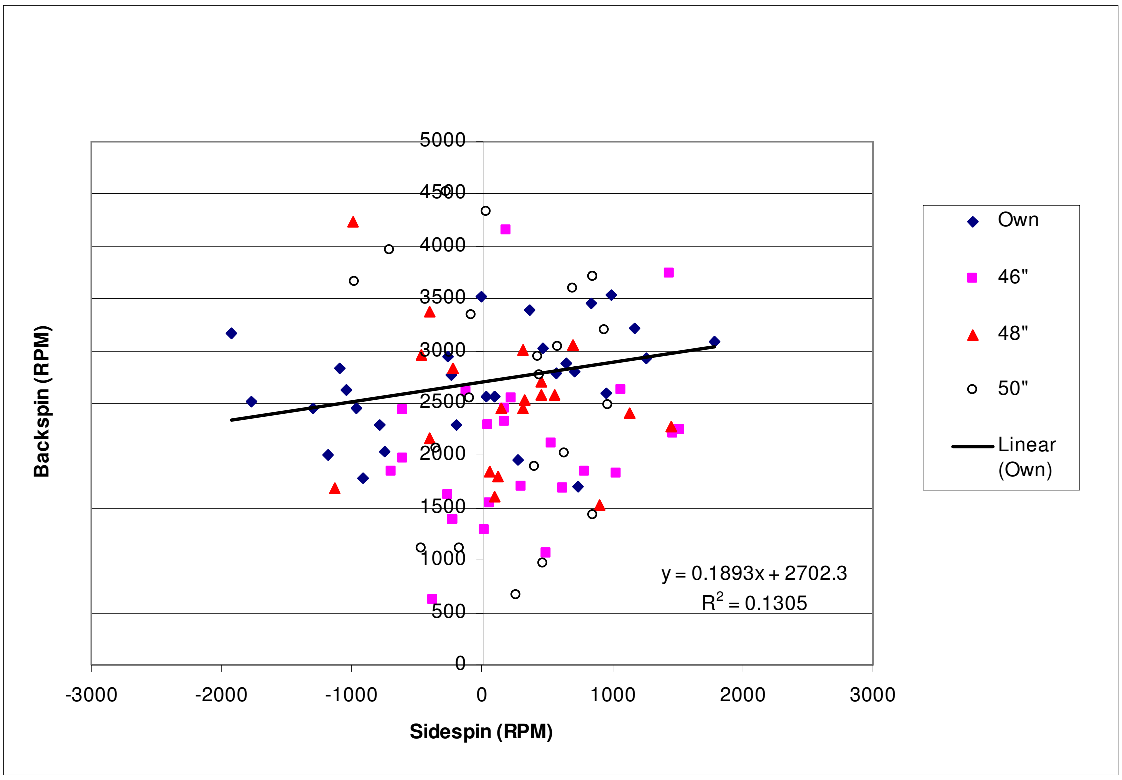


Figure 6.14 Scatterplot for all clubs showing representative relationship between backspin and sidespin at impact

Table 6.7 Correlational analysis for shot performance and launch conditions

Analysis	Correlation (Pearson's 'r')			
	Own	46″	48″	50″
Carry - Clubhead velocity*	0.582	0.482	0.379	0.361
Carry - Ball velocity*	0.461	0.449	0.371	0.301
Carry - Backspin	-0.019	0.071	0.105	-0.334
Carry - Launch angle**	-0.354	-0.242	-0.157	-0.269
Dispersion – Sidespin*	-0.209	-0.168	-0.255	-0.205
Dispersion - Sideangle	0.073	0.076	0.073	-0.115
Backspin - Sidespin	0.053	0.315	-0.216	-0.093

**Significant at the 0.01 level (2-tailed)*

*** Significant at the 0.05 level (2-tailed)*

6.3 Discussion

Drivers of different shaft length were employed to evaluate if variation in shot performance and associated launch conditions were influenced by the length of the club. A premise to this approach was that these experimentally controlled variables would affect absolute magnitudes of a number of identified dependent variables for each shot condition (own driver, 46″, 48″ and 50″). The high number of statistically significant differences in the results confirm the effectiveness of the selected experimental protocol in this regard.

The effectiveness of elite golfers in coping with variations in shaft length was addressed, thus little instruction was given to golfers, and testing environment was as unobtrusive as possible. Subsequently, the specific aims of study 3 are addressed, and in light of the overall aim of this thesis, conclusions drawn from studies 1 and 2 will be commented on and compared to study 3 results. Whilst results presented shot performance measures (carry, dispersion and speed data) and launch conditions characteristics (spin rates and angles) separately, theses results sets need to be discussed as one such is the effect that launch conditions have on shot outcome, as well as the main independent variable of driver shaft length.

6.3.1 Effect of shaft length on shot performance and ball launch characteristics

<u>Carry</u>

Results agree with those presented in study 2, and by Reyes and Mittendorf (1999) and Werner and Greig (2000) that, generally, shots performed with longer drivers will travel further. Whilst shots performed with the 46″ driver, which was an average 1.5″ longer than the golfers' own driver resulted in less then half a yard carry increase, shots performed with the longer drivers averaged an additional 6.1 yards (2.6%) and 4.7 yards (2.0%) for 48″ and 50″ drivers respectively. The point to note here, though, is that this group of elite golfers were not able to extract the theoretical gain in drive distance that the longer 50″ lever should have offered them. This is despite the fact that ball velocity immediately after impact increased consistently as shaft length increased. Thus, impact of the 50″ driver clubhead and the ball, therefore the initial launch conditions imparted to the ball, has a significant effect on the outcome of the shot.

Egret *et al.* (2003), using a 44.9″ driver, recorded an average clubhead velocity at impact of 161.5 ± 9.5 km/h (44.86 ± 2.64 ms^{-1}). Comparisons made with clubhead velocities recorded during our current study, though, show a slower clubhead velocity produced by Egret *et al.*'s subjects due mainly, it would seem, to their higher average handicap (0.4, compared to 0.21 in the present study). In addition, in Reyes and Mittendorf's (1999) combined experimental and mathematical modelling to investigate clubhead speed and ball carry with varying driver length, a long-drive champion tested a 47″ driver with 191g head and a 51″ driver also with a 191g head. Clubhead velocity and carry distance were found to be 55.88ms^{-1} to 56.77ms^{-1} and 292 to 305 yards for the 47″ driver, and 56.77ms^{-1} to 58.56ms^{-1} and 305 to 340 yards for the 51″ driver, demonstrating an average increase of 1.34ms^{-1} and an average 24 yards for an extra shaft length of 4″. The present study showed very similar increases in clubhead velocity of 1.39ms^{-1} for the 4″ increase in shaft length from 46″ to 50″.

Importantly, however, no measures were taken relating to shot accuracy by either Egret *et al.* (2003) or Reyes and Mittendorf (1999), so these results could be likened to testing performed in the laboratory, where ballspeeds for driver testing have been found to increase over identical tests performed from the tee at a target (study 2). The relevance of testing performed without the instruction to aim for a target on the range or fairway should be questioned.

Correlational analysis showed a general positive significant correlation between carry and ball velocity ($r = 0.461$, $p<0.01$), therefore expected increases in carry distance throughout the range of club lengths tested here (44.5″ own driver, 46″, 48″ and 50″). Furthermore, regression analysis and Pearson's test showed similar, even marginally stronger, positive correlation between clubhead velocity at impact and carry distance ($r = 0.582$, $p<0.01$). The elite golfers recruited for the present study, therefore, were better able than the low-handicap golfers recruited for study 1 to maintain and even increase hub angular velocity thus imparting higher rotational velocity to the distal end of the club (Table 4.11).

Regression analysis (Figures 6.10 and 6.11) highlighted a significant relationship between carry distance and launch angle, and a NS relationship between carry and backspin. The overall trends were negative, in that as launch angle and backspin decreased, carry distance increased. Indeed, data for 48″ driver tests showed greater decreases in both these measures compared to all other clubs.

<u>Spin</u>

Quintavalla (2006) investigated the effects of clubhead velocity on driver launch conditions and drive distance and noted the diminishing returns of overall distance with increasing clubhead speeds. That is, impact efficiency decreases and the conditions of spin and launch angle placed on the ball as clubhead velocity increases cause a reduction in the assumed drive distance benefits that increased impact velocity might offer. Increases in backspin rates for golf ball flight serve to decrease flight distance due to an increase in turbulence at the boundary layer of the ball. Coefficients for lift and drag increase with an increased Reynolds number due to the spinning ball boundary layer in the fluid medium of air. Maintaining a relatively low ball backspin during drives therefore serves to decrease drag coefficients and slows retardation of ballspeed in the air. The boundary layer in the forward portion of the ball becomes turbulent with increasing ball speed and the separation point where the ball 'wake' becomes turbulent moves back downstream. Drag is reduced as the Reynolds number required for transition is influenced and the ball will fly further.

It is expected, and shown in the present study (Figure 6.14 and Table 6.7) that increases or decreases in the backspin component of ball spin will result in increases or decreases in sidespin. With true backspin unlikely to exist for a golf ball in flight, the components of ball spin measured by ball launch monitors are backspin and sidespin. Results showed a correlation of 0.053, and that as driver shaft length increased, backspin remained relatively constant and sidespin increased, with associated decreases in side angle having the compound effect of relative maintenance of shot accuracy (dispersion).

Launch angle

Table 6.5 showed that, generally, launch angle increased as driver shaft length increases, coupled with increased ball velocity, clubhead velocity and drive distance. That a decrease in average launch angle is evident for 48″ driver data is most likely to be the result of offset decreased backspin- the effect of significantly decreased backspin would be likely to cancel-out the marginal increase in launch angle, still resulting in increased drive distance via the increased clubhead velocity and decreased backspin. Regression analysis may be misleading such that a correlation may be found that is affected more by inter-subject variance than by club length and carry distance. However, it should by noted that the launch angle range over which results varied in the present study was less than one degree (0.83˚). Results therefore are more likely to be skewed by small subject-effects within the one degree range. Table 6.4 therefore may give a clearer picture of performance trends.

Much of the research into the effects of ball flight due to launch angle have been laboratory-based and conclusions drawn based on rebound velocities from fixed-angle plates often not representative of dynamic loft ranges (e.g. 25˚, 35˚, 45˚, 55˚) (Gobush, 1990; Johnson and Ekstrom, 1999; Johnson and Lieberman, 1994b and Lieberman, 1990). Our data cannot, for obvious reasons be compared to their results, and no study to date has examined the effect of driver shaft length on launch angle and spin rates.

Furthermore, data from the present study cannot be compared to studies that examine total drive distance and associated launch angles. Carry was selected as the measure of drive distance for the present study to remove the day-to-day variation that may exist with respect turf hardness when including roll in drive measurement.

It should be noted that average swing speed for golfers in the present study was 107 mph ($47.9ms^{-1}$). The relatively high swing speeds achieved by the golfers in the present study may account for the low launch angles compared to amateur golfer shots. Methods employed by golfers, objectively noted during testing for the present study and for study 2, to increase drive distance which directly affects ball backspin and launch angle included:

i. Using a less lofted driver to decrease spin rate. Results showed that as launch angle decreased, there was a concomitant decrease in backspin, although for a given impact on a different part of the face lower launch angle usually equates to higher spin.
ii. Teeing the ball farther forward in the stance, towards the left foot for right-handed golfers increases launch angle as impact will take place on the upswing.
iii. Teeing the ball higher also permits impact to be made during the upswing.
iv. Addressing the ball with more weight on the right foot and lower right shoulder will promote a similar stance at impact, thus striking the ball at the beginning of the upswing.
v. Using a more flexible shaft with a lower kickpoint, promoting lag and increasing dynamic loft and clubhead acceleration late into the downswing.

Point five (v) above is most relevant for the present study in that, as Table 6.1 shows via decreased frequency, longer shafts are more flexible. The associated increased acceleration of the lower part of the shaft, and clubhead in late downswing is thought to be one of the main ways in which longer drives are achieved by longer drivers, via increased clubhead velocity at impact (assuming a perfect impact).

<u>Accuracy and combined condition effects</u>

Reasons for increased drive distance and varied shot accuracy with driver shaft length have been discussed during study 2. Trends for drive distance did not differ for this study, in that drive distance also increased as shaft length increased, but not to as high a degree as in study 2. However, in terms of shot accuracy, no significant variance was found. Indeed, there appeared very little absolute variance among all clubs.

Correlational analysis showed positive relationships between dispersion and both sidespin and side angle- as both launch condition measures increased in magnitude so too did dispersion. In contrast, as driver shaft length increased, side angle mean generally decreased, increasing marginally for the 46" driver, subsequently diminishing as driver length increased further. Range for side angle also decreased as shaft length increased. This trend correlates well with dispersion data showing an increase in dispersion (decrease in accuracy) for the 46" driver, followed by a decrease in dispersion (increase in accuracy) as shaft length increased further. This is in contrast with results presented for less skilled golfers in study 2, where here, for an elite group of competitive golfers, shot accuracy is maintained as shaft length increases. Again, this is in contrast with results by Werner and Greig (200) that increases in shaft length resulted in increased drive distance and also decreased accuracy. They stated that the extra carry produced by excessively long drivers is too small to warrant risking a larger hit pattern. However, handicap level for golfers they tested is quite vague, stating *"…numerous golfers hit balls with these clubs…",* and where the pool of golfers seem to have handicaps of 0, 10, 20 and 27.5.

It may be that highly skilled golfers, in much the same fashion as small but apparent variation in shot performance with and without body markers (Section 3.4.2.1) and for shots performed in different testing environments (Section 5.2.1, shots performed on the range with added factors of wind and a target decreased average ball velocity at impact by 3.33ms^{-1} or 5.12% compared to tests carried out in the laboratory), alter their swing for speed and for increases in control when challenged to use clubs with which they are not accustomed. Highly skilled golfers may better be able to change their swing to cope with difficulty, such as awkward iron shot lies, wind factor or 'pressure' shots than less skilled golfers are able to. Use of a longer driver, therefore increased swingweight (1st and 2nd moments) and overall club mass, requires increased muscular force input by the golfer (see study 4 results) to maintain swing kinematics. In developing greater muscle force (discussed further in study 4) force-velocity relationship for concentric contraction indicates that there is an optimum speed at which muscle contracts to develop greatest force. In developing greater force, therefore applying increased amounts of torque to the proximal end of the golf club, highly skilled golfers may inadvertently produce more stable and less varied shots via slower muscular contraction rates. It cannot be ruled out, though that in addition to biomechanical factors, psychologically, subjects in the present study may have adopted a more 'careful' approach to shots performed using drivers longer than normal.

That sidespin generally increased in magnitude, and changed to positive tilting of axis (clockwise) for the 46", 48" and 50" driver tests may also be associated with more control being applied to shots struck with longer drivers. These skilled golfers may have been attempting to shape the ball's flight by maintaining accuracy as shaft length increased and clubs became more difficult to use, or at least having physical characteristics increasingly varied from their own driver, therefore alien.

Results would tend to suggest a valid argument for imposition of a driver shaft length limit of 48″ such that increases in ball velocity and clubhead velocity are shown for shots performed with drivers longer than 48″; further testing/familiarisation with longer drivers may extract more carry distance from the 50″ driver, and that shot accuracy, for elite golfers, does not seem to diminish as shaft length increases.

6.4 Summary

The main aim of the present study was to investigate the launch characteristics and driving performance (carry and accuracy) of elite golfers using drivers of different shaft length. In addition the relationship between driver shaft length and launch condition, and launch conditions and shot outcome during a quasi-experimental study were investigated.

Results showed significant variation between club lengths for both ball velocity and clubhead velocity. Ball velocity increased by 2.77 ms^{-1} (3.94 %) when using a 50″ driver compared to subjects' own driver (average shaft length 44.5″). Similar increases in clubhead velocity were shown. Carry distance generally increased as driver shaft length increased, with longest carry demonstrated using the 48″ driver 6.14 yards (2.57 %) greater than carry produced for subject's own driver. Importantly, accuracy as denoted by shot dispersion, was maintained. Accuracy did not vary significantly with changes in driver shaft length.

Driver shaft length also did not have a significant effect on the majority of launch conditions, however, sideangle generally decreased as shaft length increased and sidespin and launch angle increased- launch angle increase being attributed to gains in carry when using longer drivers. Driver shaft length was found to have a significant effect ($F = 4.149$, $p < 0.01$) on backspin only for a few club lengths (own v 46″, 46″ v 50″), although backspin remained relatively unchanged across the range of clubs tested.

Significant positive relationships were found for regression correlational analysis between carry and clubhead velocity and carry and ball velocity ($p<0.01$), and negative relationships between carry and launch angle and dispersion and sidespin ($p<0.05$). However, considering the directional aspect of dispersion and sidespin, as sidespin increased in magnitude so to did shot dispersion. Additionally non-significant negative relationships were shown for carry and backspin. Positive relationships were shown for dispersion and sideangle and backspin and sidespin.

It is concluded that for highly skilled golfers such as those that were studied here, benefits in drive performance are to be found when using drivers longer than their own, and longer than the current club length limit of 48″ imposed by the governing bodies of golf.

CHAPTER 7

STUDY 4:

Prediction of the effect of shaft length through development and validation of a full-body computer simulation of the golf swing

7.0 Introduction

The present study (Study 4) furthers the work presented in studies 1 to 3 by developing a computer simulation of the golf swing against which previously collected data could be compared. The main aim of the present study was to investigate the effects of shaft length on the golf swing, by means of developing and validating a computer simulation of the golf drive. Simulated results were used to confirm experimentally obtained kinematic data, excluding clubhead/ball impact characteristics, and to predict the effects on muscular activity whilst using drivers of different shaft length.

To date no research has been carried out which has presented a large-scale musculoskeletal human model of the golfer for computer simulation. This work is therefore novel and its application to biomechanical responses to changes of movement patterns and to changes of club physical properties may benefit biomechanics and engineering researchers and golf club manufacturers, as well as providing the PhD sponsors, the R&A Rules Ltd., St. Andrews, with comprehensive theoretical information to inform rule-making decisions.

Nesbit (2005), Nesbit *et al.* (1994, 1996), Nesbit and Ribadeneira (2003), have undertaken development of a human model, in rigid lever form, to investigate joint torque during the golf swing when using irons of different shaft flex. The present study utilised MSC ADAMS™ engineering design software which is used mainly in the automotive and aerospace industries for design and dynamic testing of new components. Added to ADAMS™ was BRG's LifeMOD™ toolkit which provided an interface with ADAMS™ to import from inbuilt databases human component data which included bone, joint and soft tissue tissue geometrical, inertial and physiological properties. Human components were then combined with engineered equipment, in this case a driver club. No known previous golf biomechanical research has been carried out using this software set-up. However, many elements of the study design such as single-subject analysis follow current biomechanical methodological trends.

Biomechanics researchers including Hatze (2005) and Farrally *et al.* (2003) have discussed the need for subject-specific investigation into human motion by means of computer models and movement simulation. They called for development of models that are anthropometrically tailored for individual subjects, therefore providing a better correlation between experimental and theoretical results. Furthermore, statisticians including Bates (1996), Bates *et al.* (2004) and Kinugasa *et al.* (2004) have discussed the appropriate statistical techniques which may be used to perform analyses on data collected during single-subject investigations and have expressed confidence in subsequent conclusions.

The aims of the final study (Study 4) were:

i. To develop and validate a large-scale human model of the golfer and driver.

ii. To evaluate via simulation the effect of driver shaft length hip and shoulder angular velocity.

iii. To evaluate the effect of driver shaft length on the magnitude of maximum hip/shoulder differential (X-factor).

iv. To evaluate the effect of driver shaft length on swing timing.

v. To determine the effect of driver shaft length on kinetic variables during the golf swing, including muscular force output.

7.1 Methods

Details of experimental data collection, model construction, application of experimental data to drive the model and model simulation analysis are discussed in the following sections. Experimental procedures and data collection follow those methods employed for kinematics investigation of the golf swing in study 1. In order to avoid duplication of procedures, reference should be made to Section 4.1. Sections 7.1.1 and 7.1.2 in the present study will detail basic information and information additional to that which was provided in Section 4.1.

7.1.1 Subjects and experimental tests

As previously discussed in section 3.3, this study employed single-subject analysis to investigate the effect of driver shaft length by means of experimentation and theoretical investigation. The present study used a single subject, an elite golfer with a +1 handicap, (25yrs, 1.80m, 91.3kg). The subject was informed of the objectives of the study, completed a set of health history and golf history questionnaires, and signed an informed consent. The subject warmed-up for 10 minutes comprising stretching followed by 10 practice shots hit with their own driver. The subject was then asked to strike a series of 8 shots into an indoor net marked with a target line with each of the 3 randomly assigned drivers of 46", 48" and 50" in length that were constructed for studies 3 and 4.

Spherical skin markers were placed over the selected anatomical landmarks, of which there were 26, plus 1 shaft marker, as detailed in tables 4.2 to 4.8 in study 1 section 4.1.1 Validation markers were also attached to the subject (physically or as a clone), of which there were 12 in the present study (Table 7.1). These markers performed a crucial role in model validation, whereby three-dimensional trajectory data collected experimentally for these markers was not be used to drive the computer model as the original 27 markers did. Rather, their three-dimensional data were compared to three-dimensional trajectory data produced for the same anatomical landmarks by the model. This will be discussed in greater detail in Section 7.2.

Table 7.1 Validation clone and actual markers

L acromion clone	L femoral condyle
R acromion clone	R femoral condyle
L greater trochanter	L medial malleolus
R greater trochanter	R medialis malleolus
L posterior thigh	L5 clone
R posterior thigh	Navel

A new premium golf ball was used for each set of 10 shots. The subject hit a maximum of 10 shots with each driver, allowing for up to 2 trials which did not have full ball launch or kinematic data. Thus 8 complete trials were collected for the subject’s own driver, followed by the 3 randomly assigned drivers of different shaft length. The subject's own driver length was 44.5".

For each shot a MAC™ Falcon Analogue motion analysis system operating at 240 Hz with a residual of 2 mm for each camera tracked 3 seconds of motion including 1 second prior to beginning the swing, until approximately 0.5s after the swing ended. Additionally, the Golftek™ ProV launch monitor recorded clubhead and ball launch conditions for each swing, and an investigator recorded any anecdotal information relating to the quality of the shot offered by the subject. The subject was instructed to aim along a target line into netting hanging 4.5m away. After each shot was struck, an investigator wiped clean the clubface and ball with white spirit to ensure a clean contact surface was being used. The testing was considered complete when at least 8 acceptable swings had been recorded for each driver. Acceptance of a swing was based on data quality (complete three-dimensional frame data) and feedback from the subject.

7.1.2 Experimental data processing

A model was constructed prior to testing in MAC™'s capture software EvaRT™. The computer stick model depicted exact positioning of each marker considered during testing and was tailored for the subject's height, mass and club type. Immediately following each trial raw data files ('p3d' comma delimited) were generated and stored digitally. The p3d files of reconstructed co-ordinates of the markers which infered joint centre of axis and segment COM were transferred from EvaRT™ to KinTrak™ for processing and analysis. Data was smoothed using a low-pass Butterworth filter at 12Hz and an order of 2. P3d files detailed 8 columns: club, trial number, marker number, frame, time, and x, y and z coordinates in relation to the global frame origin (labelled 'Tee1' and positioned anterior to the right foot). Macros were produced in EvaRT™ to automate calculation of:

Right and left knee angles in the frontal plane, right tibia (shank) angle in the sagittal plane, back inclination in the sagittal plane, left arm-trunk angle in the sagittal plane, left arm-club angle in the sagittal plane, shoulder rotation angle in the sagittal plane, hip rotation angle in the sagittal plane, stance width and foot-to-tee distance.

Kinematic variables were sectionalised into 5 areas:

i. Posture at address (ADD)- body segment orientation, lower and upper extremities and posture relative to the tee.
ii. Posture at the top of the backswing (TOB)- upper extremity body segment orientation and relation to club position.
iii. Posture at impact (IMP)- upper and lower extremity body segment orientation.
iv. Angular velocity of the hips and shoulders throughout the swing.
v. Timing for total swing, backswing and downswing.

Further details concerning variables can be found in study 1, Section 4.1.4. Figures 4.8 to 4.16 in study 1, Section 4.1.4 illustrate, albeit schematically, the orientation and basis for calculation of the variables under consideration. Additionally the following assumptions were made for the determination of events during the swing:

- Top of the backswing (TOB) was derived by taking the point in which the shaft marker hits minimum velocity between start and end of the data.

- Impact (IMP) was determined in Kintrak™ when the shaft marker reaches the lowest value in the z (vertical) axis. This corresponded to the time frame where the stereoscopic launch monitor strobe flashed.

- The maximum velocity of the shoulder and hips were determined by the maximum velocity between the top of the backswing and the end of the data.

- All positional data (displacement and angles) were calculated in relation to the x, y and z cardinal axes and also reported relative to body position at address where necessary.

The launch monitor recorded a full range of clubhead and ball launch information, as discussed in study 2, Sections 5.1.2 and 5.1.3. Consideration was given to each measurement in order to deem the shot acceptable, but analyses concerned only clubhead velocity immediately after impact. This was due to the fact that the model later developed did not simulate clubhead/ball impact characteristics. Unacceptable shots were those that the golfer felt were particularly poor therefore not representative of their ability, or those for which the monitor calculated ball velocity ±15 ms^{-1} from what was considered normal for that subject.

Data were reduced for mean and standard deviation using MS™ Excel. Results are presented in tabular and graphical format and used to compare corresponding model predicted data.

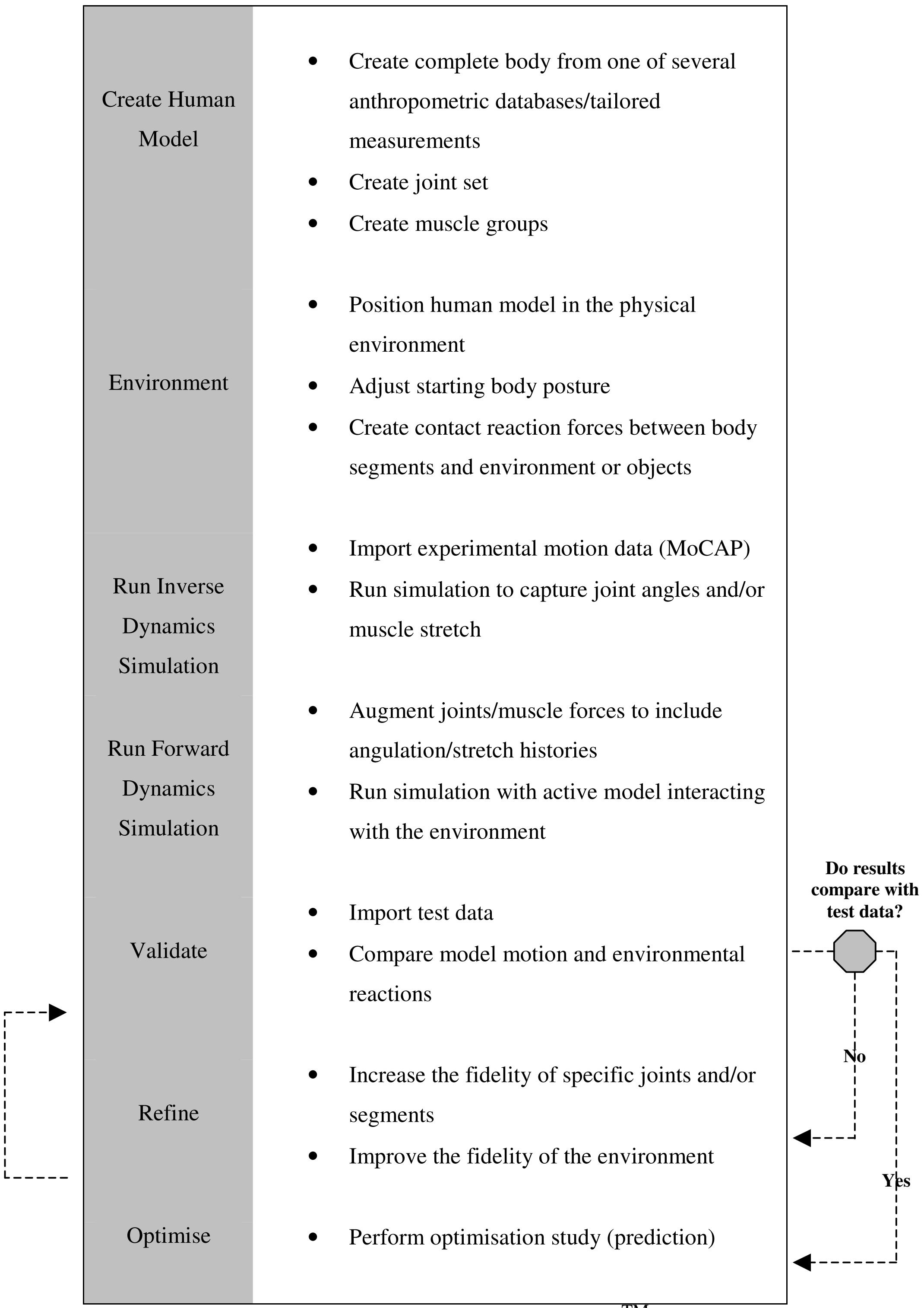
7.1.3 Model construction

<u>Summary</u>

Human model construction, for the current model, using ADAMS™/LifeMOD™ was a 4 stage process:

i. Creation of segments to include inertial properties tailored to the subject being studied.
ii. Definition of the degrees of freedom of the model by means of creation of joints between the segments.
iii. Definition of bone graphical and physical properties.
iv. Application of muscle and connective tissue spanning origin and insertion attachment points.

Figure 7.1 details the modelling process commonly followed using ADAMS™/LifeMOD™ software.



Adapted from LifeMOD™ technical manual (2005)

Figure 7.1 ADAMS™/LifeMOD™ modelling process

Furthermore, as Figure 7.1 depicts, the human model was then placed into a working environment, in this case to include a parametric driver model and ground surface.

There then followed application of experimental data to the model to create movement through a combined inverse and forward dynamics process which resulted in simulation the golf swing. Finally the model was validated by comparing simulated results with previously obtained experimental results and the model refined and optimised as necessary. In total 3 models were constructed, each identical except for driver length of 46", 48" and 50". The sections which follow describe these processes in more detail.

Segments (+ bones)

The usual method of building a human model is to create a complete set of body segments then to reduce the number or redefine the fidelity of the individual segments. Reduction of the number of segments for the current study was not necessary as the aim was to create large-scale model (large scale being greater than 15 segments). In total 19 body segments were created (Figures 7.2 and 7.3), defined in Table 7.2:

Table 7.2 Model segment names

Head	L & R upper arms
Neck	L & R Lower arms
Upper torso	L & R hands
Central torso	L & R upper leg
Lower torso	L & R lower leg
L & R shoulders	L & R feet

The segments were constructed based initially on the LifeMOD^{TM} in-built anthropometric database ‘GeBOD’. GeBOD was developed by the Modelling and Analysis Branch of the Air Force Aerospace Medical Research Laboratory and the University of Daytona Research Institute. The database generates the masses and principal moments of inertia of the segments, the basic geometric shapes of the segments and the locations of the joints which connect the segments. The regression equations that make up the database are based on three surveys of human body dimensions. The adult male data was taken from a survey of 2420 subjects.

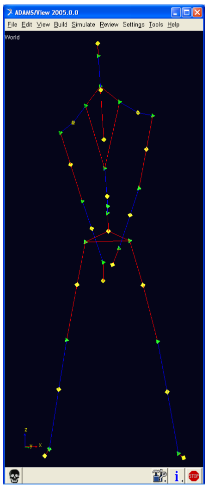


Figure 7.2 19 segment

stick segmental model

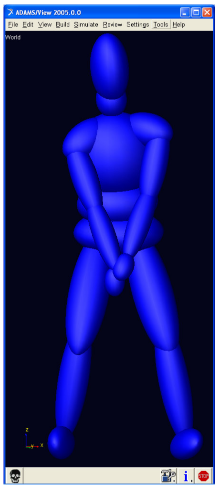


Figure 7.3 19 segment

ellipsoid segmental model

In the first instance, the model in the present study was scaled using the database and the three basic pieces of information of subject age, height and mass, using a decision tree algorithm or allometric scaling (McMahon, 1984). However, in order to create a more accurate representation the model was further tailored to more closely match the subject make-up by applying 50 anthropometric measurements (Figure 7.4). See Appendix 7.0.

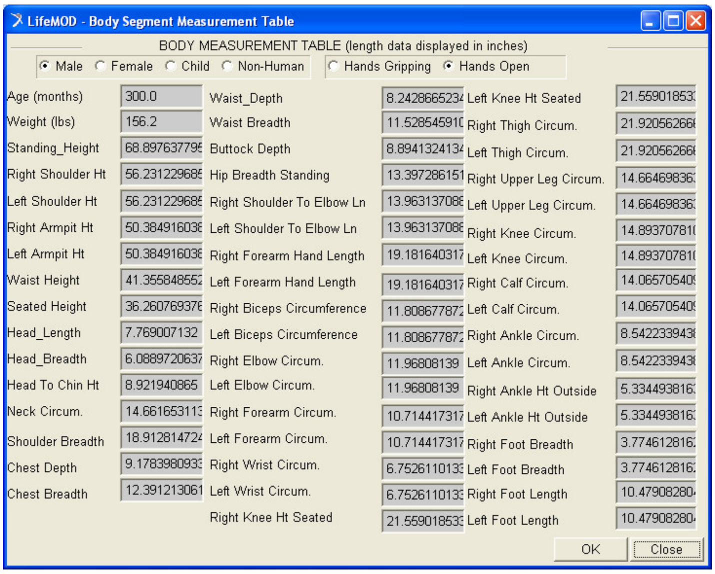


Figure 7.4 Segment parameters edit panel detailing subject's anthropometric measurements

In tailoring the model, inertial parameters more closely matched the subject in question rather than scaled average of the database provided, thus the muscle forces required to move body segments during the swing later in the inverse dynamics procedure may mode closely match that actually produced by the subject.

Following segment construction, bone properties, both for graphical representation, and physical for model rigidity, were added. Greater model fidelity was achieved by stipulating realistic bone mass and scaled geometry (based on the tailored anthropometric measurements), density, Young's modulus and Poissons's ratio. Every bone in the human body is included. Figure 7.5 shows the base human bone set created and Figures 7.6 to 7.8 show more detail of select complex regions of bone.

Figure 7.5 Base bone set

<u>Joints</u>

Joints are kinematic constraints which are used to connect two adjoining body segments. The kinematic joints were a tri-axial hinge joint arrangement, allowing specification of the function of each degree-of-freedom of each joint axes. When a segment floats around in space, it can move in six different directions called 'degrees of freedom' and are thought of as movement along the coordinate axes and rotation about the same axis. An unconstrained segment has 6 degrees-of-freedom. In a model with n segments, the model will have a total of $6n$ degrees-of-freedom unless some of them are constrained. A usual way to constrain degree-of-freedom is to add joints to the model.

Generally, a movement or model containing a very large number of DOF will require a high level of skill to perform experimentally, and will incorporate a large number of constraint equations in the solution of the optimisation problem, therefore increasing computation time for the model. A human, and thus the model in the present study, is constrained such that there are sufficient DOF to perform a large array of movements, but with sufficient constraints via joints to stabilize those movements. Such an arrangement is said to be 'kinematically determinate'. Table 7.3 details the degrees of freedom for joints in the average population as applied to the model in the current study.

Table 7.3 Major segment movements and associated degrees of freedom

Segment	Joint	DOF	Movements
Head	Atlantoaxial	3	• R/L rotation
Trunk	Intervertebral (3)	3	• Flexion, extension, hyperextension, R/L rotation, R/L lateral flexion, circumduction
Arm	Shoulder (2)	3	• Flexion, extension, hyperextension, abduction, adduction, hyperabduction, hyper adduction, horizontal abduction, horizontal adduction, med/lat rotation, circumduction
Arm/Shoulder	Sternoclavicular (2)	3	• Elevation, depression
Forearm	Elbow (2)	1	• Flexion, extension, hyperextension
Hand	Wrist (2)	2	• Flexion, extension, hyperextension, radial flexion, ulnar flexion, circumduction
Thigh	Hip (2)	3	• Flexion, extension, hyperextension, abduction, adduction, hyperabduction, hyper adduction, horizontal abduction, horizontal adduction, med/lat rotation, circumduction
Leg	Knee (2)	2	• Flexion, extension, hyperextension, med/lat rotation
Foot	Ankle (2)	1	• Plantarflexion, dorsiflexion

The model was constructed with 19 segments, thus, applying the DOF as illustrated in table 7.3, had a total of 42 degrees-of-freedom. In that the model has more than 15 segments and state space dimension greater than 76 (38 configurational coordinates plus 38 first derivatives) it can be described as a 'large-scale model' (Hatze, 2005). In the first instance, trainable passive joints for inverse dynamics analysis were created

(Figures 7.6 and 7.7). These joints consisted of a torsional spring force with specified stiffness, damping angular limits and limit stiffness values. Approximate values were extracted from a general gait model deposited on the LifeMOD™ website for public use. A trial-and-error approach further refined joint limits and stiffness for the current model. During inverse dynamics analyses to be performed later these joints recorded the joint angulations while the model is being manipulated with motion agents driven by experimentally collected data. These passive joints (inverse dynamics setting) had two functions:

1. To stabilise the model during the inverse dynamics simulation, and
2. Provide joint friction stiffness for a forward dynamics simulation.

Following use of trainable passive joint elements for inverse dynamics, forward dynamics analysis required the application of calculated joint torque via the recorded joint angulation history to simulate movement. Thus 'trained driver' joints which held the previous inverse dynamics information were installed in the model.

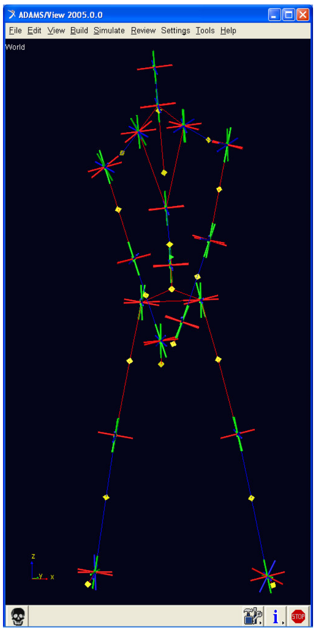


Figure 7.6 19 segment stick model joint structure

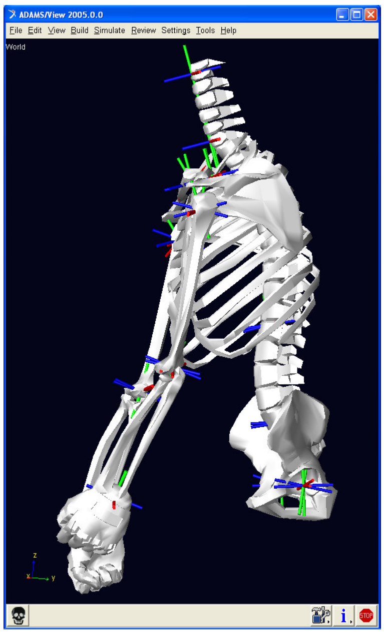


Figure 7.7 Upper extremity skeletal model showing joint axis structure

<u>Soft tissues (muscle and connective tissue)</u>

Soft tissue was modelled as ligaments and muscle-tendons. Both tissue elements transmit tension forces only. Ligaments were represented as passive spring/dampers and muscle-tendon forces consisted of ‘training’ elements for inverse dynamics simulations and ‘active’ contractile elements for forward dynamics simulations, as was the case for joint function. Firstly, muscles were created in the form of training elements or passive non-contributing elements. The model was constructed using a full-body set of 111 muscles available via LifeMOD^{TM}. These are detailed in Appendix 8.0. Attachment points (origin and insertion) was aided by referring to Gray’s Anatomy (2004), Warfel (1993 & 1993) and Eycleshymer and Shoemaker (1970). Motion agents were then attached to the model at the exact anatomical landmarks, and on the club (construction discussed later) as the skin markers were during experimentation. The motion agents were massless model markers (Section 7.1.4) which held the appropriate motion spline data for x, y and z axes movement of the associated body part and were directed to move using the stored experimental time-displacement curve data for each axis of motion. Via this inverse dynamics process muscle concentric/eccentric ($L_{desired}$) patterns were recorded. Having recorded motion histories after being driven by experimental data by the motion agents, and calculated the appropriate force-time history for each muscle, the model was prepared for forward dynamics whereby joints and muscles were set as active and used as actuators to drive the model (see Section 7.1.4).

The muscle actuators were bound not to exceed the physiological capability of individual muscles. As such, physiological cross-sectional area, resting load and maximum tension/stress was defined for each muscle. A net force, optimised, approach to muscle modelling was used. Using this approach, muscles produced the necessary forces in order to replicate the desired motion of the body, while staying within each muscle's physiological limit. The assumption was that if enough muscles were included, the calculated muscle forces would be very close to the actual force values.

Physiological properties for each muscle included:

- physiological cross sectional area (pCSA)
- maximum tissue stress (M_{stress})

- resting load ($F_{resting}$)
- force output filter % (F_{filter})
- overall muscle tone (M_{tone})

These data established an upper limit on the muscle force (F_{max}) for each muscle in the model. The values are calculated as follows:

i. Original pCSA and M_{stress} were taken from the LifeMOD^{TM} database and scaled based on the model subject's height, weight, age, and gender.

ii. The pCSA was also scaled using these anthropometric parameters, but could be customized by tailored muscle tone (M_{tone}%) if needed.

iii. F_{max} = pCSA * M_{stress} (derived from Hatze, 1981b)

Equation 13 details the algorithm for calculating the force in each muscle using the following process. Instantaneous muscle length and velocity relationship is recorded.

i. This is compared to the desired instantaneous muscle length/velocity calculated from the inverse-dynamics simulation.

ii. The difference (error) is corrected by the P_{gain}. The derivative of the error is multiplied by the D_{gain}. This results in a muscle force, F_1, necessary to minimise any error.

iii. If the resulting muscle force F_1 is greater or equal to the physiological maximum F_{max}, $F_1 = F_{max}$.

iv. F_1 is subsequently filtered with a specified filter function F_{filter} to become F_i for the i^{th} muscle

It should be noted that the algorithm use was automated within the software's inverse dynamics process, not calculated manually.

$$F_l = \begin{cases} F_{max} & \text{:if } F_l \geq F_{max} \\ P_{gain}\,(L_{desired} - L_{actual}) + D_{gain}(L_{desired} - L_{actual}) & \text{:if } F_l < F_{max} \\ 0 & \text{:if } L_{desired} \geq L_{actual} \end{cases} \quad \text{(Equ. 13)}$$

$F_i = F_{filter}\,(F_l)$, where $0 \leq F_{filter} \leq 200\%$

(adapted from LifeMOD^{TM} Technical Manual, 2005)

Figures 7.8 to 7.11 illustrate the muscles created, in stick and musculoskeletal guise, and for detailed areas of musculature.

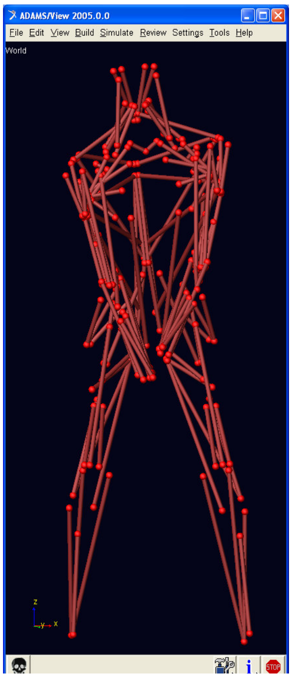


Figure 7.8 Stand-alone full body set of 111 muscles

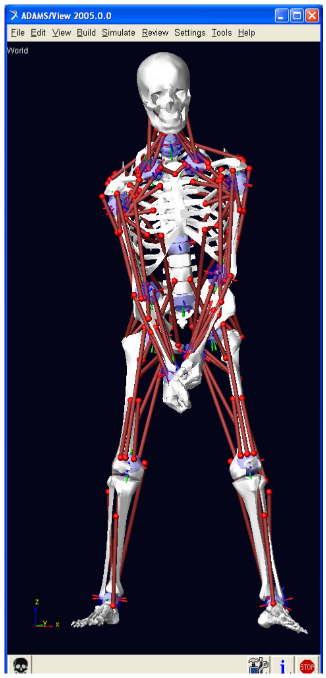


Figure 7.9 Musculoskeletal model showing full muscle set

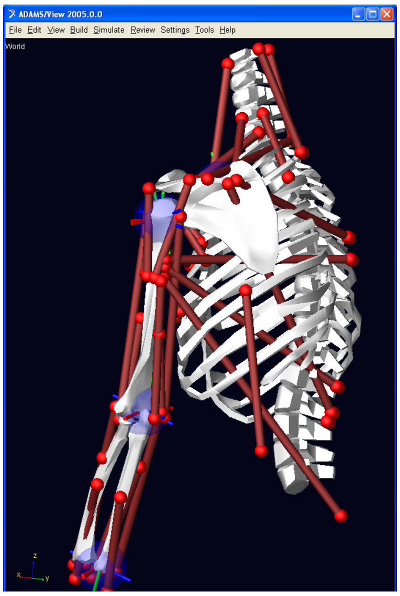


Figure 7.10 Musculoskeletal upper extremity posterior view

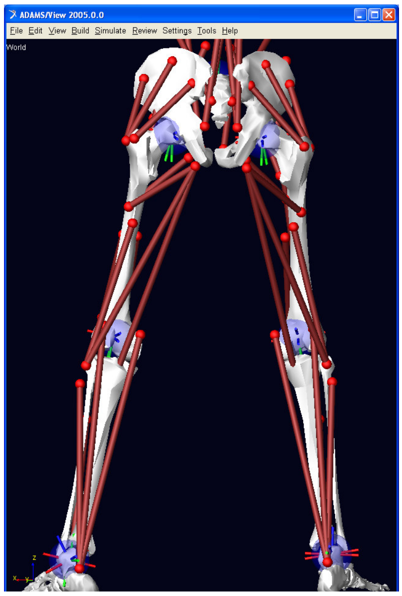


Figure 7.11 Musculoskeletal lower extremity posterior view

Environment & contacts

The human model was placed in an environment which included a parametric driver model and ground surface. The model was positioned on a block plate to represent the ground surface. The feet were attached to the ground surface using point contacts:

- Left foot – fixed element bushing
- Right foot – spherical bushing element allowing movement in the x/y plane for replication of foot eversion/inversion normally demonstrated by golfers.

Figure 7.12 illustrates the feet contact constraints. Additionally, Figure 7.13 shows the 6 non-active contact points created for each foot, which also serve as graphical representation of the foot's surrounding soft tissue. Similarly, the parametric driver model that was constructed was linked to the hands of the human model using a fixed element bushing preventing unwanted movement of the club grip during the simulated swing. The right had was fixed at the metacarpal joint of the fourth finger to the same point on the left hand, and the club fixed to the hands via a one point contact at the left third finger metacarpal joint. The bushing was designed such that it would record maximum stress experienced during the simulated swing, equivalent to peak grip force.

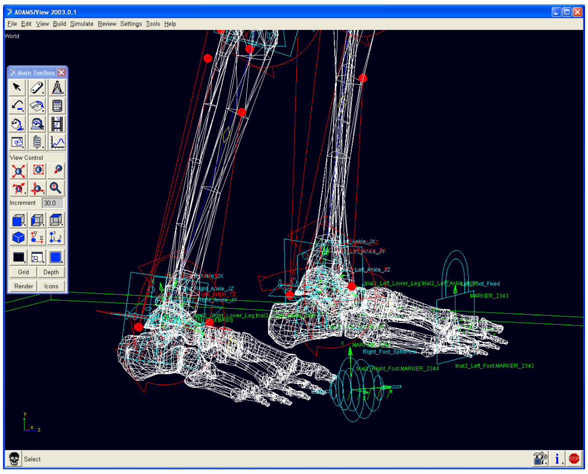


Figure 7.12 Left and right feet constraints

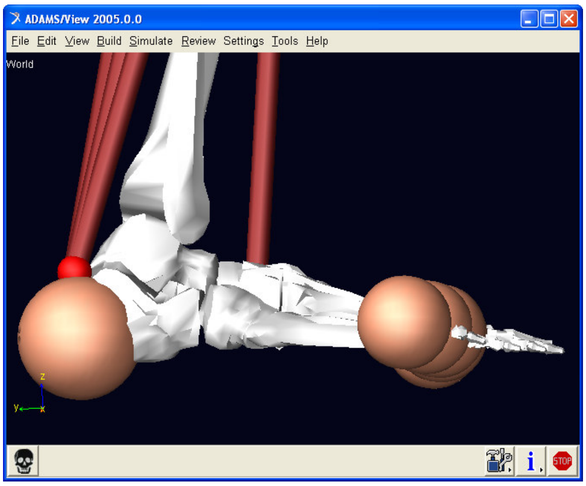


Figure 7.13 Right foot showing non-active ground surface contact points

The parametric driver model was constructed for each of the three human models, one each of driver length 46", 48" and 50". The model consisted of three main elements, the clubhead, the shaft and the grip. Figure 7.14 shows the clubhead and select properties. Model clubheads matched experimental clubheads as closely as was possible. Parameters stipulated were:

- Material – titanium (and associated density, Young's modulus and Poisson's ratio)
- Mass – 0.2kg
- Volume – 350cc
- Inertia – 2.585^{10-5n} kg.m^2(determined experimentally during component testing)

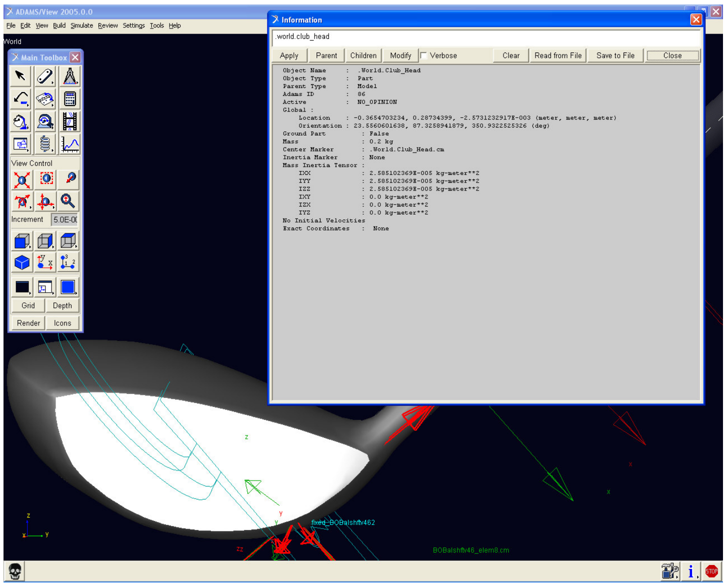


Figure 7.14 Driver clubhead and material properties

A virtual, weightless marker was placed on the toe of the clubhead so that clubhead velocity predictions could be made for this point, rather than the centre of mass of objects in the ADAMS™ environment which is normally the case. Titanium physical properties were available from the ADAMS™ database, thus was easily accessible. On the other hand, construction of the shaft was more complex in that density, Young's modulus and Poisson's ratio for its material needed to be researched and the material constructed in its entirety. Carbon fibre, as the material was, varies widely depending on the ratio of fibre to resin used in the construction process. Therefore, an estimate based on averages of shafts tested during the driver construction phase was used to define material properties. The shaft was constructed as 8 interconnected segments (Figure 7.15) allowing the shaft to flex based on estimated damping properties and trial-and-error to create a stiff shaft. The butt end of the shaft and the hosel end were attached to the grip and clubhead respectively using fixed joint elements. Different shaft lengths were created and the club aligned based on three dimensional positioning of the marker 'Tee' in relation to data for the marker 'shaft' and both 'medial malleolus'. This allowed for correct positioning of the clubhead at address at the tee and the appropriate length of shaft created to meet the hands at the grip point. Therefore, the human model was copied three times and a different length driver constructed for each.

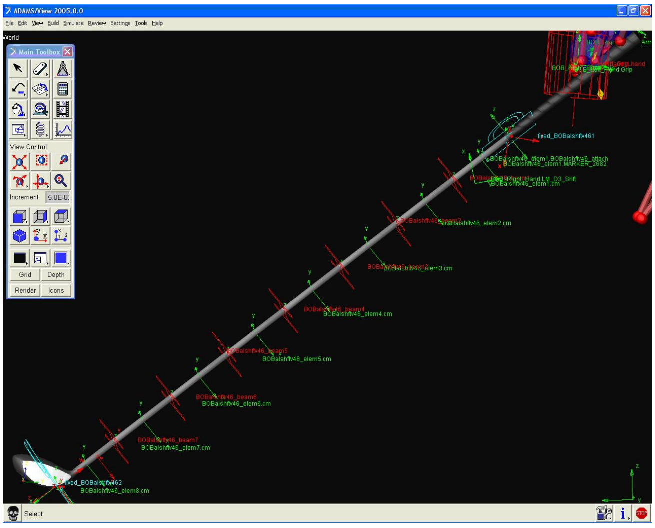


Figure 7.15 Carbon-fibre shaft elements

Thus, a full-body musculoskeletal human model of the golfer and club was constructed (Figure 7.16) but at this stage was motionless. The skull has been removed for illustrative purposes. No orofacial muscles were created.

Figure 7.16 Complete static musculoskeletal golfer model

7.1.4 Application of experimental data for inverse and forward dynamics

Data retained in p3d format mentioned earlier were converted to .slf (stand list file) ASCII format which the LifeMOD^{TM} software could read. An .slf file for the model constructed in the present study is included in Appendix 9.0. The file includes information on units, subject anthropometrics, joints, posture and the motion capture data (Table 7.4). Once one model had been created with appropriate joint stiffness and limits and the model tailored for the subject, creation of an .slf file was a quick method to store this information, attach new trial motion data and import to a different model.

Table 7.4 Extract from a 46" driver trial .slf file for motion data

Time	Part	x	y	z	yaw	pitch	roll
0.00000	1.00000	0.23926724	0.4349624	1.47570142	0.00000	0.00000	0.00000
0.00417	1.00000	0.23926730	0.4349626	1.47570262	0.00000	0.00000	0.00000

Where time = 1/240Hz time
Part = marker number
x/y/z = coordinates of the marker in 3D global frame
Yaw/pitch/roll = additional rotational measurement element (not included in this study)

Importing the .slf file motion data automatically created motion splines- smooth mathematical curves for the motion path of a given marker. Spline data was then transferred to MOCAP markers positioned at the same anatomical landmarks on the model as the respective markers were on the human subject during testing. The MOCAP markers drove rigid motion agents positioned also at the same anatomical landmarks. Both elements were massless and served only to drive the appropriate appropriate body part or club part. Figure 7.17 illustrates the two elements and their attachment to the model.

In addition, during subsequent simulations, the two elements gave an indication of the ability of the model to accurately replicate the experimental motion being applied to it. Attached by a massless spring, the MOCAP marker exactly followed the trajectory of the experimental data which it held, whereas the rigid bone attachment followed the model's interpretation of this motion. When the model reacted incorrectly there could be seen a separation of the two elements indicating the need to refine of joint stiffness, damping, limits or muscle tension.

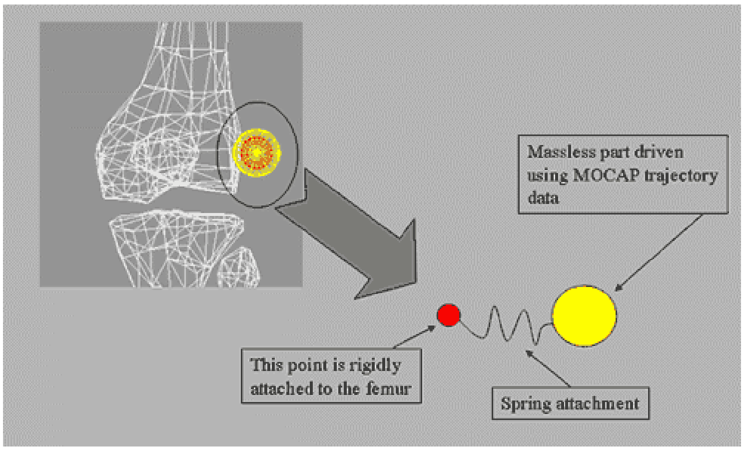


Figure 7.17 Model motion agents

A combined inverse-forward dynamics approach was adopted for the present study, whereby experimental data was input to the model and trainable passive joints and muscles recorded angulation/time histories and based on segmental inertia calculated the internal forces necessary to replicate such a movement. Subsequently a forward dynamic simulation utilised the calculated kinetics and attempted to replicate, with motion agents turned off, the original kinematics. The inverse-forward dynamics simulations were automated within the software. Figure 7.18 schematically illustrates the dynamics process adopted.

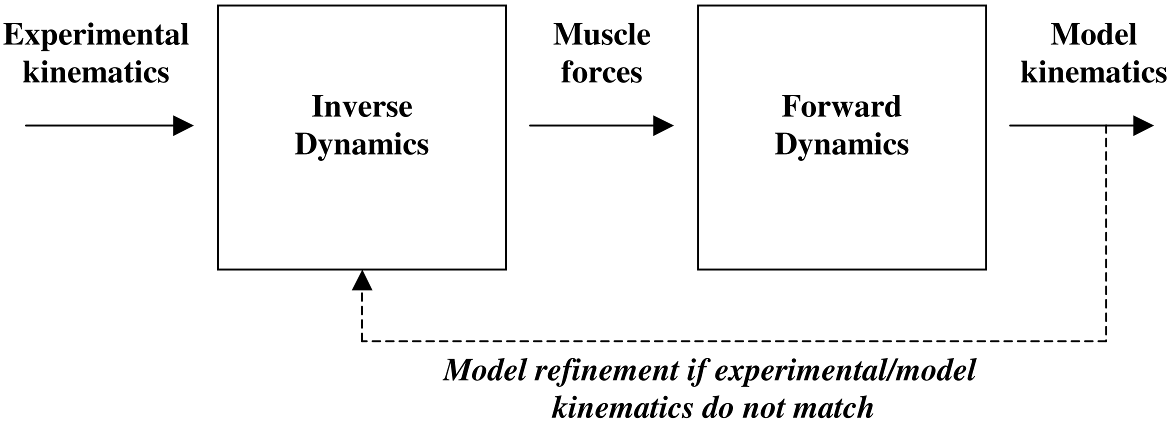


Figure 7.18 Inverse-forward dynamics approach

Inverse-forward dynamics simulations were repeated 8 times for each model. Thus 24 sets of data pertaining to model response when using three different lengths of driver were obtained. The results Section (7.3) will illustrate that standard deviation for model data was very low, and non-existent in some cases. This is to be expected for mathematical calculations of the same condition. Figure 7.19 shows a screen shot for the follow-through and associated clubhead velocity/time graph during a forward dynamics simulation.

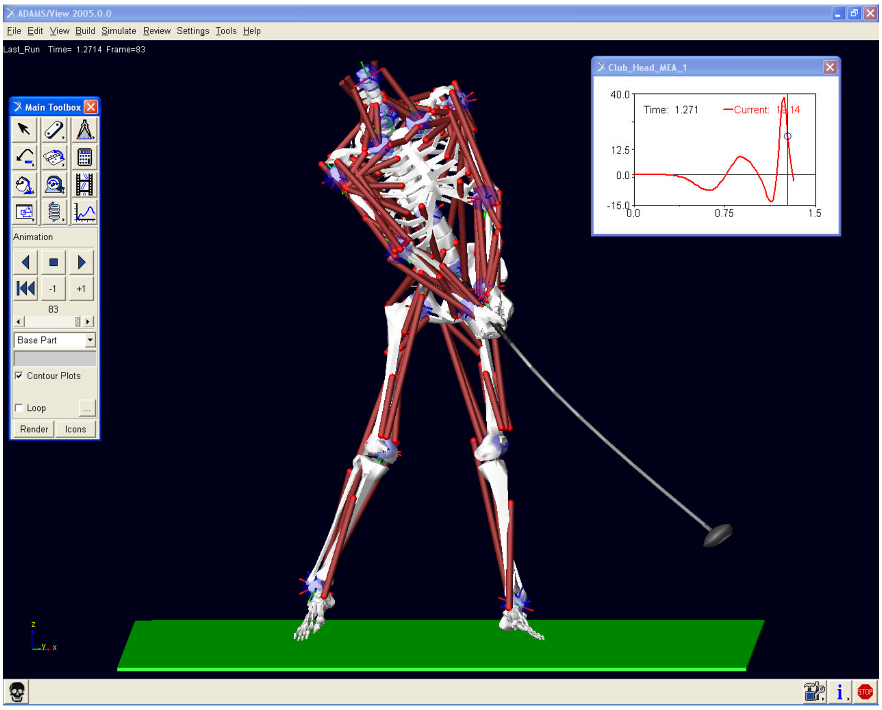


Figure 7.19 Screenshot showing clubhead velocity/time graph for a 46" driver forward dynamics simulation

7.1.5 Variable selection

Results are divided into two sections, 1) those pertaining to validation of the model, and 2) results relating to model predictions of kinematics and kinetics.

1) <u>Model validation</u>

Model validation is normally achieved by comparison of model predicted results with those obtained experimentally for the same condition. For the present study model validation was carried out for velocity, kinematics and kinetics.

i. Velocity – Experimentally determined peak clubhead toe velocity was compared to the same measure predicted by the model for the range of club lengths. Furthermore, a macro was created within MS^{TM} Excel (see Appendix 10.0) which allowed manual calculation of clubhead velocity from p3d files. Club-ball impact was not modelled therefore clubhead velocity and not ball velocity was predicted. Predicted clubhead velocity comparison with experimentally collected clubhead velocity was considered a straightforward and reliable analysis method.

ii. Kinematics – As detailed in Section 7.1.1, 12 additional markers (actual and clone) were tracked during experimentation. Such 'validation' markers were not used to drive the model. These markers were replicated virtually on the model and their trajectories recorded during simulations. In theory, if the model replicated actual movement recorded experimentally, three dimensional time histories of experiment/model markers should match. In performing a correlational analysis, the closer to 1.0 the correlation, and smaller the RMS difference (in degrees) the better the model could be considered as performing the correct swing. This approach is extremely novel and as far as is known, has not been carried out before.

iii. Kinetics – Determination of correct muscle force simulation was achieved by comparison of grip force by the model to grip force reported experimentally in previous research. Grip force was deemed a valid measure of the predicted force produced during the golf swing. Ensuring that the force exerted by the arm muscles and applied to the club compared favourably with previously reported experimental force transducer research meant that reliable simulations had been performed (Rasmussen, 2005). Whilst not a novel method, it did provide a different approach to the commonly reported ground reaction forces used for some biomechanical models.

2) <u>Predicted results</u>

Variables have been selected that relate to data presented in the previous three studies, as well data for predicted muscle force. Results covered four areas:

i. Peak angular velocity of the shoulders, hips and clubhead when using drivers of different shaft lengths
ii. Swing timing for different shaft lengths.
iii. Hip/shoulder differential (X-factor) for different shaft lengths.
iv. Muscle force input when using drivers of different shaft lengths.

Angular velocity of the hub was chosen for analysis to compliment presentation of both hip/shoulder turn differentiation (X-factor stretch) data and predicted muscle force data. Study 1 showed that the X-factor did not vary significantly as low-medium handicapped golfers used drivers of different length. Using an elite golfer, the X-factor was again studied, along with the X-factor stretch to ascertain whether skill level had an effect on the ability to effectively utilise hub turn, leading to eccentrically stretched abdominal muscles (SSC). Consideration was also given to angular velocity of the clubhead to ascertain whether muscles alone, or the physical principle of using a longer lever (or a combination of both) would be attributed to any variation in peak clubhead linear tangential velocity. As in previous studies for low-medium handicapped golfers, swing time was examined for the elite level golfer to determine whether their level of skill affected timing when using drivers of different length.

Where possible, model data was presented alongside its experimental equivalent.

7.1.6 Data analysis

Validation

Correlational analysis was employed for comparison of clubhead and anatomical marker kinematics data. Pearson's tests were performed using SPSS™ supplemented with RMS difference. Additionally, for clubhead velocity, graphs pertaining to manual calculation of clubhead velocity from p3d trajectory files are presented and correlation analyses between model, launch monitor and mathematical results performed. A Kruskal Wallis analysis was applied to test for variation in clubhead velocity due to driver shaft length. As discussed in Section 2.4.1, non-parametric tests were applied to all studies involving single-subject design, thus providing the most powerful analysis (Bates, 1996). A Kruskal Wallis test in the non-parametric equivalent of the one-way ANOVA, for comparing three or more unmatched groups. The test P-value answers the question: what is the chance that random sampling would result in sums of ranks (the test sampling method) as far apart as observed in this experiment. Data relating to grip force is presented as a force-time graph and peak force compared manually to previous research.

Predicted results

A one-way ANOVA was applied to temporal, angular velocity and X-factor data to test for variation due to driver shaft lengths. Where a statistical difference was observed, a post-hoc LSD test was used to determine where the differences rest. Pearson's correlation was also applied to temporal data to highlight the level correlation between data pertaining to different driver lengths. Root mean square (RMS) analysis was carried out for the difference between model and experimental data sets, supplementing Pearson's correlations, ensuring large differences did not exist. Muscle force data is presented in tabular format for basic descriptive analysis. A Friedman's two-way ANOVA was applied to force data to test for any variance due to driver shaft length. Friedman's is considered a non-parametric test (suggested by Bates, 1996) used to compare three or more matched groups. In the present study, muscle force was considered matched and categorised into groups of hub, arm and leg muscles. The P-value obtained identified whether significant differences were observed due to driver length with each group.

Descriptive statistics which included mean, standard deviation and percentages were calculated using MS^{TM} Excel.

7.2 Validation

For model validation, theoretical results should match experimental data. The sections which follow show basic descriptive statistics and correlations between the two data sets.

7.2.1 Clubhead velocity

Descriptive statistics for model and experimental (launch monitor) peak clubhead velocity for each drive length are shown in Table 7.5. Figure 7.20 additionally illustrates the matching trend of increasing peak clubhead velocity with driver length. Correlation between experimental and model data was 0.999 with RMS of 1.93 ms^{-1}. A Kruskal Wallis test for variance showed significant difference in peak clubhead velocity between drivers for both results sets ($p<0.01$).

Table 7.5 Mean (±SD) model and experimental peak clubhead velocity

Club (″)	Model Clubhead Velocity (ms^{-1}) * ^	Experimental Clubhead Velocity (ms^{-1}) * ^^
46	48.302 ± 0.005	50.292 ± 0.632
48	49.703 ± 0.006	51.577 ± 0.333
50	50.102 ± 0.008	52.024 ± 0.826

* Pearson's correlation r = 0.999, $p<0.05$; RMS 1.93 ms^{-1}

^ $\chi^2 = 20.49$, $p \leq 0.01$

^^ $\chi^2 = 14.03$, $p \leq 0.01$

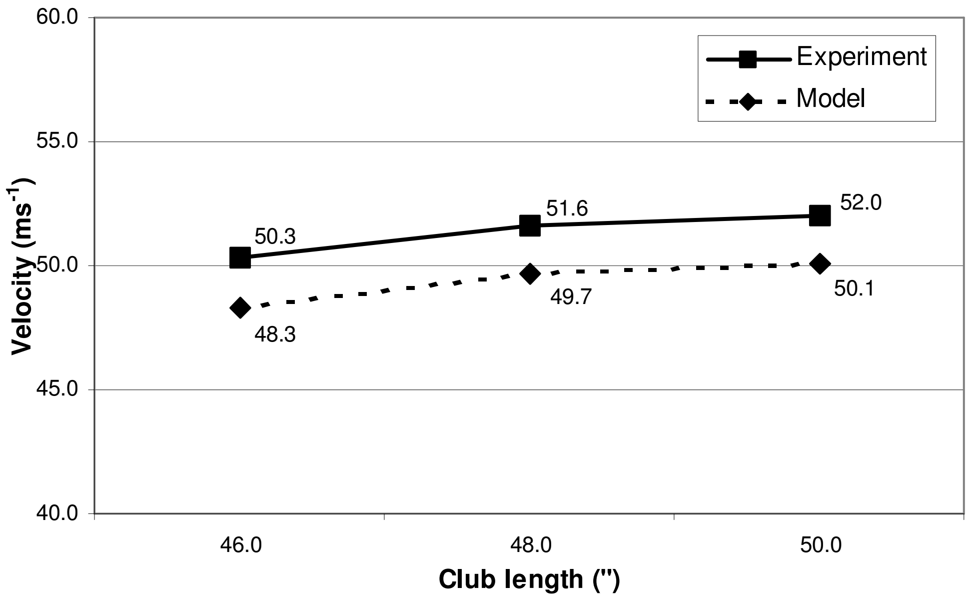


Figure 7.20 Mean peak model and experimental clubhead velocity for each driver length

Figure 7.21 additionally shows the difference in clubhead velocity (1.473ms^{-1}) for a 46" simulation between model predicted peak velocity by the centre-of-mass marker (CM) (46.829 ms^{-1}) and the repositioned toe marker (labelled MARKER_2839) (48.302 ms^{-1}). The toe marker, for the clubs used in the present study, was 46mm distal to the hub than the clubhead CM marker.

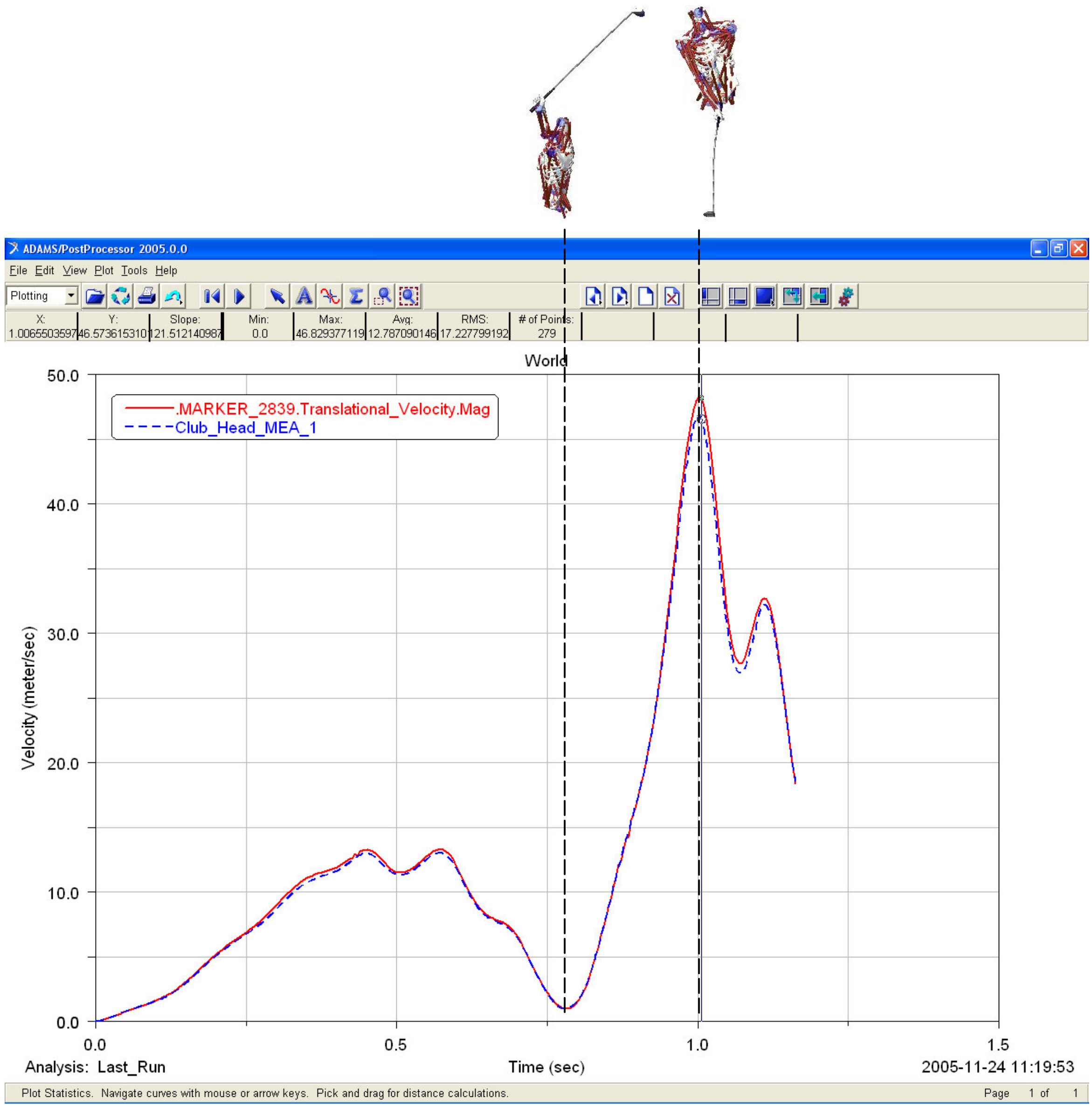


Figure 7.21 46" model clubhead velocity against time for original CM marker and repositioned toe marker

Clubhead velocity was manually calculated using p3d trajectory data obtained experimentally. Figures 7.22 to 7.24 show the velocity/time graphs for the 3 driver lengths. Table 7.6 compares results for peak clubhead velocity for this method against model results and results obtained using the launch monitor. The y-axis is positioned to represent the point of impact and it can be seen that for the subject in question, peak clubhead velocity occurred immediately prior to impact for all driver lengths.

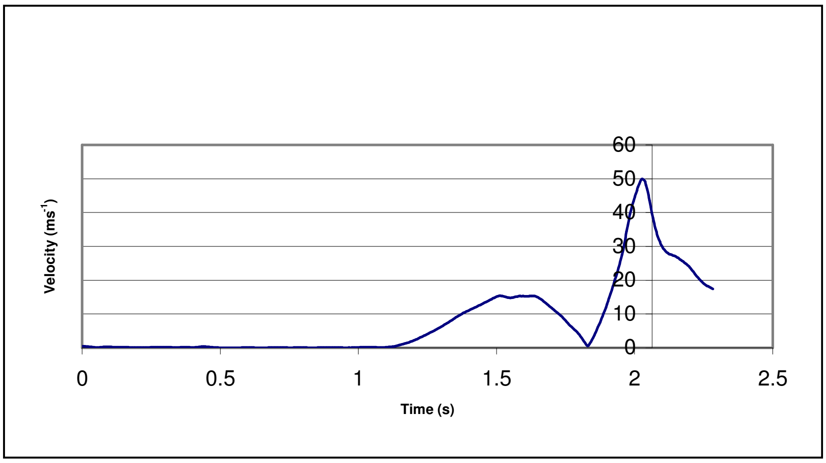


Figure 7.22 Calculated clubhead velocity against time for a tracked 46" driver using 3D trajectory analysis

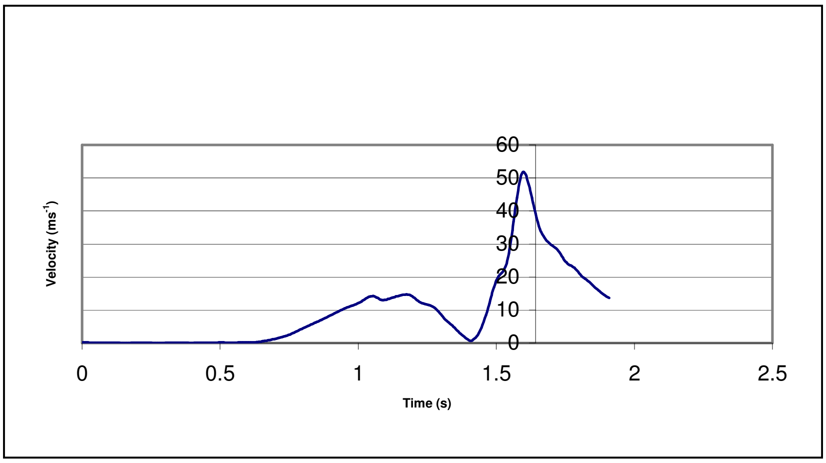


Figure 7.23 Calculated clubhead velocity against time for a tracked 48" driver using 3D trajectory analysis

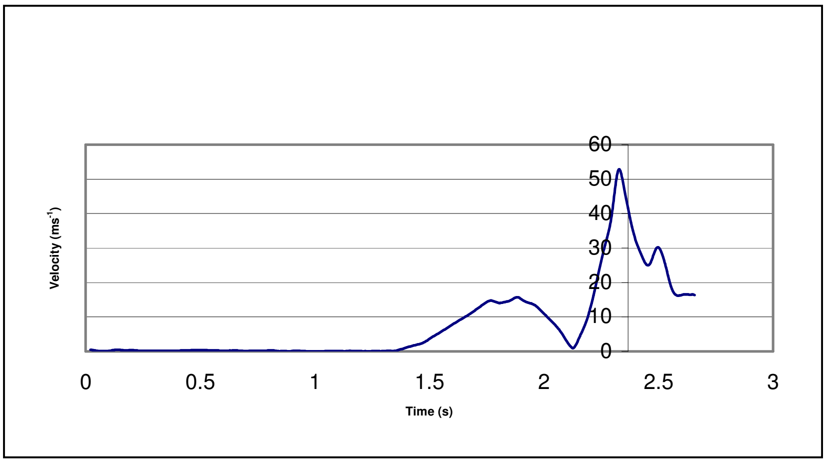


Figure 7.24 Calculated clubhead velocity against time for a tracked 50" driver using 3D trajectory analysis

Pearson's test shows good correlation (0.99, $p<0.05$) between the different methods, where manual calculation compared best with launch monitor data ($r = 0.994$).

Table 7.6 Peak clubhead velocity comparison for club length by manual calculation, launch monitor analysis and model simulation

	Peak Clubhead velocity (ms^{-1})		
Method	46"	48"	50"
Manual calculation	49.91	51.80	52.85
Launch monitor	50.29	51.58	52.02
Model	48.30	49.70	50.10

**Pearson's correlation – manual v launch monitor $r = 0.994$, $p>0.05$; RMS = 0.54 ms^{-1}*

manual v model $r = 0.989$, $p>0.05$; RMS = 2.20 ms^{-1}

launch monitor v model $r = 0.999$, $p<0.05$; RMS = 1.93 ms^{-1}

7.2.2 Marker kinematics

Table 7.7 details correlation scores and RMS difference for analysis between experimental validation marker three-dimensional trajectory and its equivalent model predicted values.

Table 7.7 Validation markers/model anatomical landmark correlation

Marker	Pearson's 'r'	RMS difference (°)
R acromion	0.997*	0.06
L acromion	0.997*	0.06
L5	0.966*	0.11
Navel	0.990*	0.05
R greater trochanter	0.995*	0.05
L greater trochanter	0.987*	0.08
R posterior thigh	0.969*	0.06
L posterior thigh	0.929*	0.05
R inferior patella	0.991*	0.05
L inferior patella	0.991*	0.03
R medial malleolus	0.996*	0.02
L medial malleolus	0.990*	0.03

** $p<0.001$ (2-tailed)*

R = right, L = left

Correlation was statistically significant ($p<0.001$) and was strong for each of the 12 markers, averaging 0.983. Root mean square difference averaged 0.05°. Thus, model kinematics can be said to very closely match actual swing kinematics.

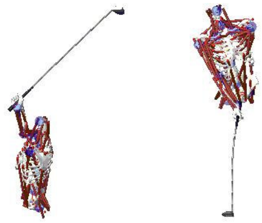
7.2.3 Force output

The final method of validation concerned grip force, as a measure of the ability of the model to correctly predict muscle force output during the swing. Table 7.8 compares model data against two sources and shows that model data lies with the range reported by both. It should be noted that, naturally, grip force will vary between golfers, depending on personal grip preference and swing speed. However, it was deemed important to ensure that muscle force predicted by the model in the present study was representative of actual force determined experimentally.

Table 7.8 Comparison of left hand 3rd finger metacarpal joint peak grip force during the swing between model predicted results and previously reported experimental research

Source	Grip force (N)
Model	13.2
Nikonovas *et al.* (2004)	8-17
Budney (1979)	13-23

Figure 7.25 is a graphical representation of the force/time history for a 46" driver simulation by the model in the present study. Also depicted are the TOB and impact points. It can be seen that peak force occurs during club deceleration in the follow-through.



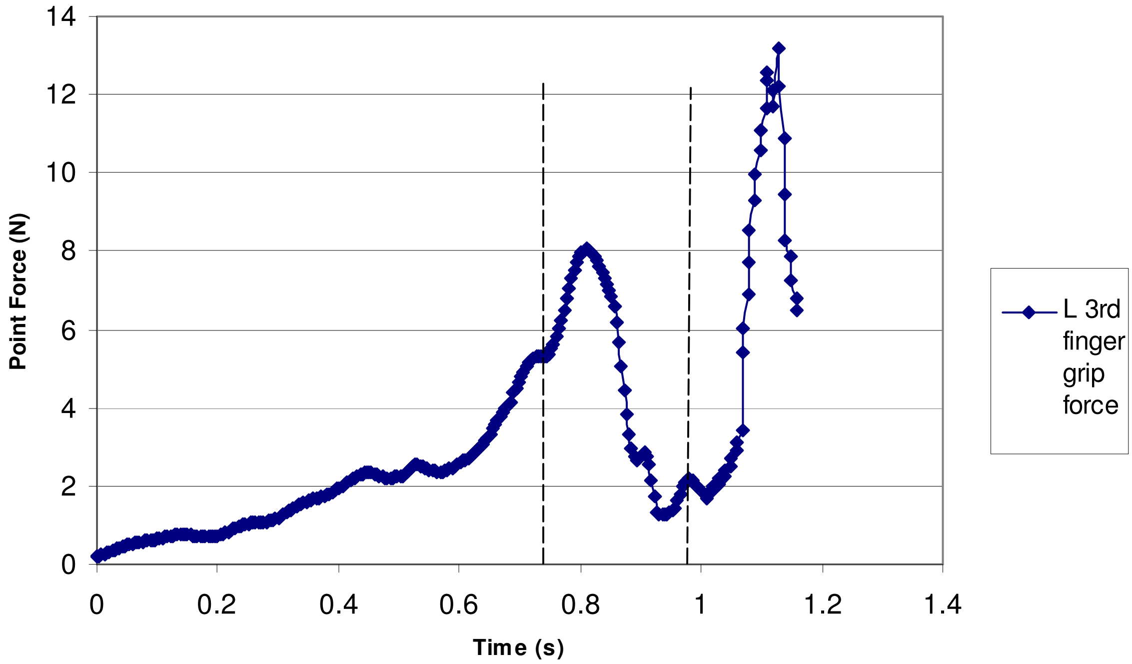


Figure 7.25 Representative model grip force for the left 3rd finger metacarpal joint

7.3 Results

The following section will present results relating to swing kinematics and kinetics predicted by the model for 46", 48" and 50" driver lengths.

7.3.1 Angular velocity

Predicted data for peak shoulder and hip angular velocity are shown in Figures 7.26 and 7.27 respectively. As driver shaft length increased, peak shoulder angular velocity decreased. Peak velocity for the 50" driver simulation was found to be 1.344 rads^{-1} (13.78%) slower than the 46" driver simulation. Peak velocity for the shoulders decreased by 0.436 rads^{-1} (4.47%) with an increase of 2" to a 48" driver. Results showed significant variance between peak shoulder velocity for driver shaft length (F = 33220127.3, p<0.001, 46v48, 46v50, 48v50).

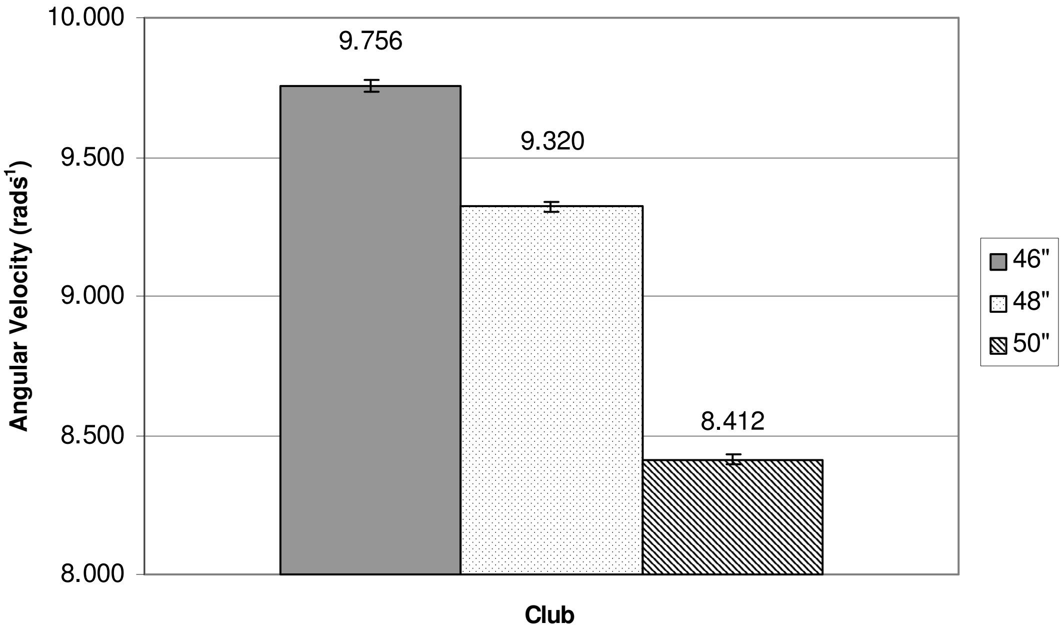


Figure 7.26 Model predicted peak shoulder angular velocity for different driver lengths

Peak hip angular velocity also decreased as driver shaft length increased. 48" driver simulation showed 0.07 rads^{-1} (0.87%) decrease and the 50" simulation predicted 0.803 rads^{-1} (10.00%) decrease compared to the 46" simulation. Peak hip angular velocity was shown to vary significantly as club length increased (F = 1291133.9, p<0.001, 46v48, 46v50, 48v50).

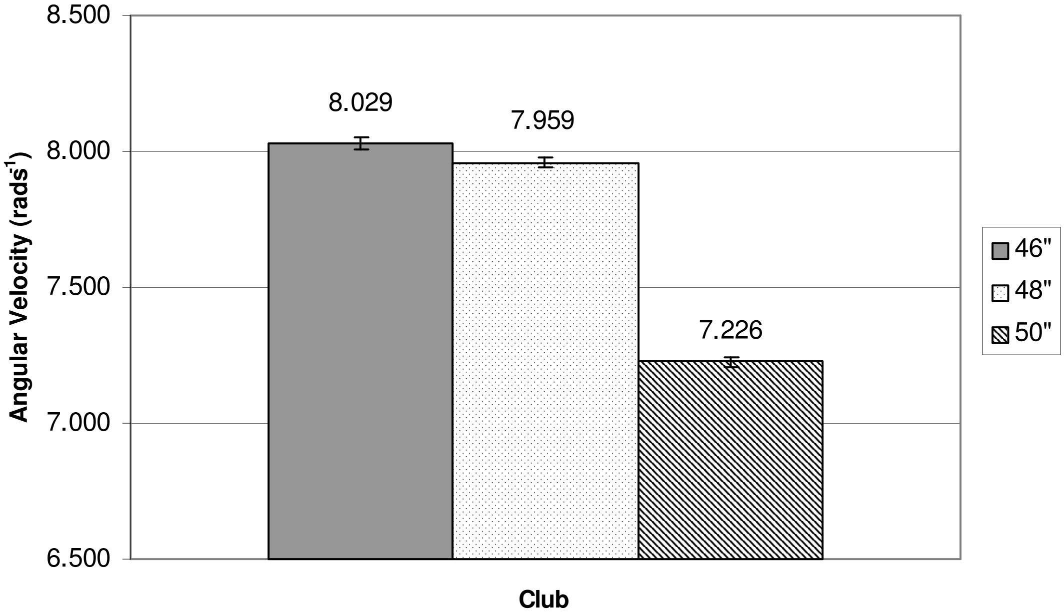


Figure 7.27 Model predicted peak hip angular velocity for different driver lengths

Furthermore, Figures 7.28 and 7.29 graphically illustrate shoulder and hip angular velocity against time for the three simulations combined. Timescale was adjusted and plots presented relative to each other for the purposes of this comparison. Both graphs show, as section 7.3.3 'Timing' Table 7.10 indicates, movements are initiated earlier in the swing during the 48" driver simulation. The 46" driver swing appears somewhat slower, but yet develops greater peak hip and shoulder angular velocity. The 50" driver simulation predicts the slowest swing and decreased peak hub rotational velocities. Note that the graphs are taken directly from LifeMOD^{TM} output which presents rotational velocity in degrees per second. 1 degree/second = 0.017453293 radians/second.

Appendix 12.0 details NS results for peak clubhead angular velocity for each club length. Results showed predicted peak angular velocity of 42.44 rads^{-1}, 41.87 rads^{-1} and 44.56 rads^{-1} for the 46″, 48″ and 50″ simulation respectively. Results showed no consistent relationship between linear and angular velocity, and X-factor stretch or muscle force output, due to length changes.

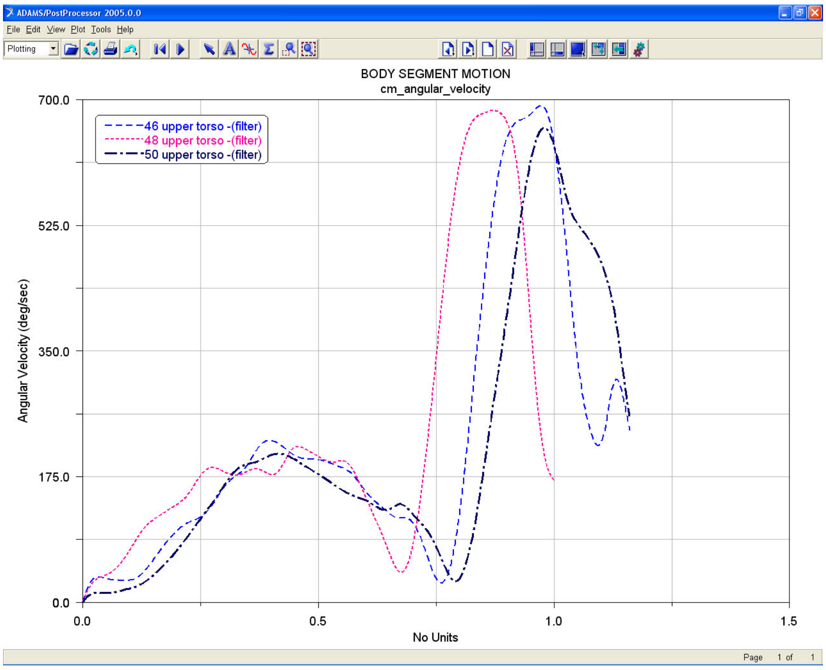


Figure 7.28 Representative simulation of upper torso (shoulders) angular velocity in degrees/second against adjusted relative time scale

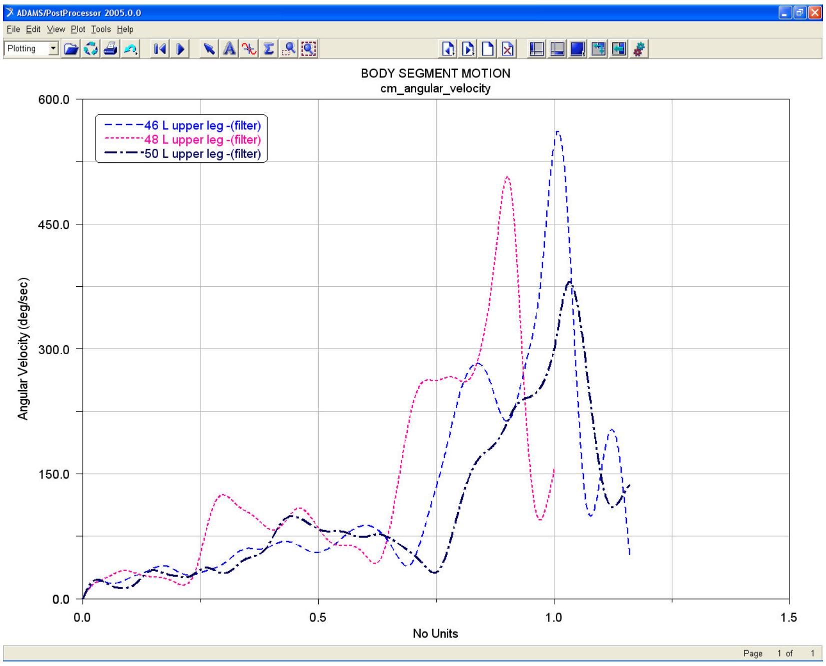


Figure 7.29 Representative simulation of upper leg (hip/pelvic region) angular velocity in degrees/second against adjusted relative time scale

7.3.2 X-factor

Table 7.9 shows descriptive statistics for absolute hip and shoulder rotation angles at their point of greatest separation near the top of the backswing. Also shown is this separation value, the hip/shoulder differential. Presented here are results, showing that the hip/shoulder differential, or X-factor stretch increased by 5.25º (6.54%) and 6.13º (7.55%) for the 48" and 50" driver simulation when compared to the 46" simulation. Absolute shoulder rotation angle, hip rotation angle, and the peak hip/shoulder rotation angle varied significantly.

Table 7.9 Mean (±SD) shoulder and hip rotation angles corresponding to peak hip-shoulder differential

Club (")	Hip Rotation* (º)	Shoulder rotation** (º)	Peak X-factor stretch*** (º)
46	116.00 ± 0.27	41.44 ± 0.32	75.06 ± 0.50
48	117.50 ± 0.18	37.13 ± 0.23	80.31 ± 0.26
50	110.44 ± 0.18	29.25 ± 0.27	81.19 ± 0.26

* *F=2587.43, p<0.001 – 46v48,46v50,48v50*

** *F=4025.82, p<0.001 – 46v48,46v50,48v50*

*** *F=694.07, p<0.001 – 46v48,46v50,48v50*

7.3.3 Timing

Shown in Table 7.10 are mean and standard deviation for total swing time (t_{tot}), backswing time (t_{bs}) and downswing time (t_{ds}), as well as downswing as a % of total swing time. As Figures 7.28 and 7.29 illustrated, total swing time was greatest for the 50" driver simulation at 1.077s, the 46" driver simulation 7.52% quicker at 0.996s, and the 48" driver simulation predicting the shortest total swing time (backswing plus downswing) at 0.981s (8.91% quicker than 50"). Backswing times followed the same trend. However, whilst relatively close indicating maintenance of swing timing, the 48" driver simulation predicted that downswing as a % of total swing time was greatest, thus took longer (23.48%). The 46" driver simulation predicted the shortest downswing phase.

Table 7.10 Total swing time (t_{tot}), backswing time (t_{bs}) and downswing time (t_{ds}) mean (±s.d.) for all club lengths for experimental and model data

Club	Results set	t_{tot} (s)	t_{bs} (s)	t_{ds} (s)	t_{ds} [% of t_{tot}]
46"	Expt.*	0.996 ± 0.001	0.767 ± 0.000	0.230 ± 0.003	23.10
	Model*	0.996 ± 0.000	0.767 ± 0.000	0.229 ± 0.000	22.99
48"	Expt.*	0.983 ± 0.002	0.750 ± 0.001	0.233 ± 0.002	23.73
	Model*	0.981 ± 0.000	0.750 ± 0.000	0.230 ± 0.000	23.48
50"	Expt.*	1.070 ± 0.005	0.826 ± 0.005	0.244 ± 0.005	22.82
	Model*	1.077 ± 0.000	0.827 ± 0.000	0.250 ± 0.000	23.21

* Correlation sig. at the 0.01 level (2-tailed), r = 1.000; RMS = 0.004s

Further validating the model, there existed a high level of correlation between model and experimental swing timing ($r = 1.000$, $p<0.01$). RMS difference for the same comparison was 0.004s. Furthermore, using both model and experimental data, Table 7.11 shows results for one-way ANOVA statistical tests performed to highlight any significant variance between swing times for clubs of different shaft lengths. Only model total swing time did not show significant variance due to club length. Post-hoc LSD tests show where the variances lay.

Table 7.11 Temporal analysis one-way ANOVA post-hoc LSD results

Event	Post-hoc test results
Experimental backswing	F=627.8, p<0.001, 46v48, 46v50, 48v50
Model backswing	F=14361.3, p<0.001, 46v48, 46v50, 48v50
Experimental downswing	F=13.4, p<0.01, 46v48, 48v50
Model downswing	F=3733.0, p<0.001, 46v48, 46v50, 48v50
Experimental total time	F=717.7, p<0.001, 46v48, 46v50, 48v50

Finally, Figure 7.30 graphically illustrates the variation in swing timing for model prediction of clubhead velocity against time. Note that the graph shown was taken from a model using clubhead centre of mass as its measurement point. Timescale has been adjusted so that curves may be shown relative to each other. The legend labels the curves 46, 48 and 50 respectively.

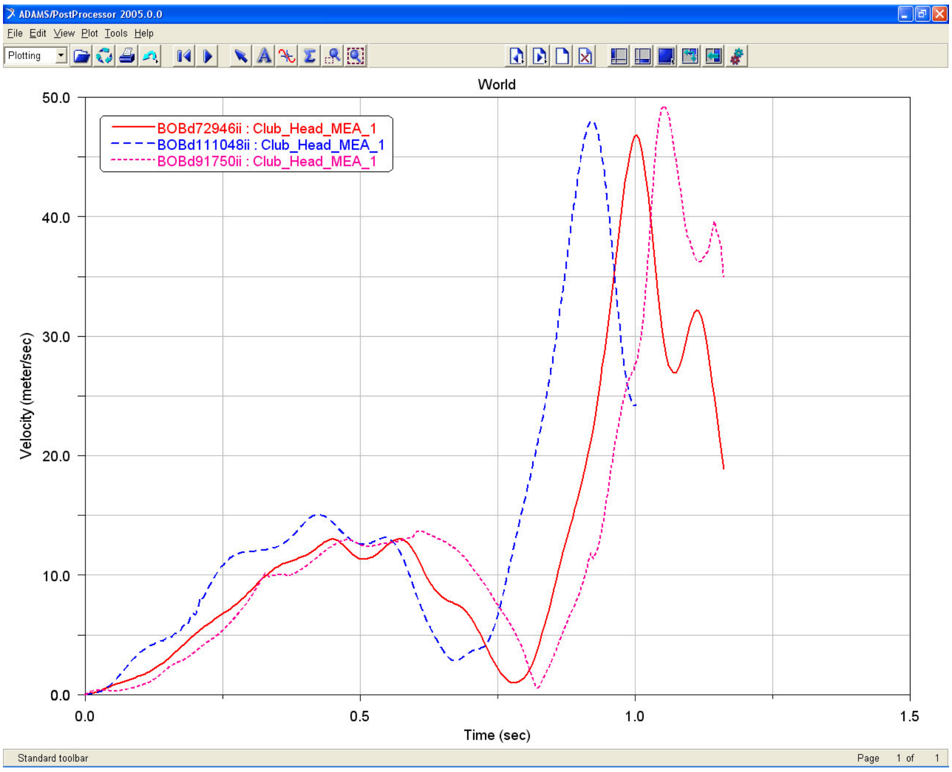


Figure 7.30 Model clubhead velocity against time for CM marker with adjusted time scale showing 46", 48" and 50" driver simulation results

7.3.4 Muscular force output

The model was created with 111 muscles. However, a large number of these muscles are subsets of muscle groups, such as the psoas, gluteals, deltoids and erector spinae. For the purposes of this PhD it was deemed that a more select range of muscles be examined, selection criteria including:

- Muscles examined via EMG analysis in previous golf biomechanics literature.
- Muscles distinctly large and located on the golfer such that those reading this work may be able to relate to an individual muscle's input to the swing.

Previous EMG literature highlighted the increase in activity level for leg muscles over muscles in other parts of the body during the golf swing. Therefore, a greater percentage of the muscles analysed in the present study relate to the legs. 42 muscles were selected for analysis which were sectionalised into three areas: i) Hub, ii) Arm and iii) Legs

Table 7.12 shows descriptive statistics for hub muscle force output for 46", 48" and 50" driver simulations. Additionally, Table 7.15 indicates that for hub muscles, force output increases overall from an average 5.37 N for the 46" driver to 13.12 N for the 50" driver. A non-parametric Friedman's two-way ANOVA indicated that hub muscle force output predictions varied significantly due to driver shaft length ($p<0.01$).

Table 7.12 Mean (±SD) average hub force output for 46", 48" and 50" driver simulations

	Force output (N)		
Muscle	*46"	*48"	*50"
L trapezius	0.05 ± 0.00	0.05 ± 0.02	0.16 ± 0.34
R trapezius	0.09 ± 0.13	0.06 ± 0.02	1.77 ± 4.07
L latissimus dorsi	0.68 ± 1.48	3.12 ± 6.96	34.15 ± 58.07
R latissimus dorsi	3.57 ± 17.07	0.83 ± 2.86	16.16 ± 40.96
L pectoralis major	0.09 ± 0.12	0.08 ± 0.08	3.14 ± 9.64
R pectoralis major	0.09 ± 1.20	0.06 ± 0.06	1.40 ± 5.77
L gluteus maximus	9.16 ± 39.54	10.71 ± 26.67	22.21 ± 60.41
R gluteus maximus	33.62 ± 90.80	18.37 ± 67.10	25.75 ± 62.96
L gluteus medius	0.60 ± 2.00	14.23 ± 36.50	32.40 ± 81.12
R gluteus medius	27.11 ± 67.93	41.85 ± 94.96	46.42 ± 101.30
L oblique	0.00 ± 0.05	0.86 ± 0.32	0.00 ± 0.05
R oblique	0.00 ± 0.05	16.82 ± 8.51	0.00 ± 0.05
L rectus abdominis	0.00 ± 0.05	0.10 ± 0.07	0.00 ± 0.05
R rectus abdominis	0.00 ± 0.05	1.74 ± 0.62	0.00 ± 0.05

L = left, R = right

*$\chi^2 = 12.20$, $p<0.01$

A similar trend was exhibited concerning predicted arm muscle force for three muscles (Tables 7.13 and 7.15). Force output was shown to increase from an average 0.07 N for the 46" driver, to 0.10 N for the 48" driver and 0.42 N for the 50" driver. Absolute value difference was relatively small for these muscles, considered as stabilisers during the golf swing rather than major force producers. Club length did not have a statistically significant effect on muscle force.

Table 7.13 Mean (±SD) average arm force output for 46", 48" and 50" driver simulations

	Force output (N)		
Muscle	46"	48"	50"
L deltoid	0.09 ± 0.15	0.05 ± 0.03	0.28 ± 0.63
R deltoid	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00
L extensor carpi ulnaris	0.07 ± 0.10	0.05 ± 0.00	0.48 ± 1.35
R extensor carpi ulnaris	0.09 ± 0.17	0.39 ± 1.15	1.60 ± 2.37
L pronator teres	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00
R pronator teres	0.10 ± 0.21	0.05 ± 0.00	0.05 ± 0.00

Greater forces were exhibited by the leg muscles during the golf swing for all driver simulations. Tables 7.14 and 7.15 show that muscle force output increased, albeit non-significantly, as driver shaft length increased. On average, for the leg muscles, force output was predicted as increasing by 3.07 N for every 1" increase in shaft length. The calf muscles (gastrocnemius and soleus) and right side vastus lateralis were shown to exhibit greatest increase in force, particularly for the 50" driver.

Overall, as detailed in Table 7.15, force output was shown to increase by approximately 4.5 N (NS, $\chi^2 = 4.294$, $p = 0.117$) for each increase in driver length. A 1" increase in driver length equated to an additional 2.27 N being required on average overall. However, large increases in force were required by some muscle groups in order to maintain kinematics as shaft length increased.

Table 7.14 Mean (±SD) average leg force output for 46", 48" and 50" driver simulations

	Force output (N)		
Muscle	46"	48"	50"
L adductor magnus	5.11 ± 15.24	4.32 ± 16.84	1.72 ± 6.33
R adductor magnus	21.73 ± 64.59	10.42 ± 43.59	9.40 ± 26.15
L bicep femoris long head	29.84 ± 46.21	54.61 ± 48.48	26.41 ± 45.01
R bicep femoris long head	0.17 ± 0.68	2.92 ± 9.34	0.14 ± 0.38
L bicep femoris	0.05 ± 0.00	0.26 ± 0.43	18.68 ± 40.53
R bicep femoris	0.17 ± 0.68	2.92 ± 9.34	0.14 ± 0.38
L vastus lateralis	54.92 ± 202.62	18.90 ± 105.50	0.65 ± 3.43
R vastus lateralis	7.90 ± 16.50	10.42 ± 28.28	123.75 ± 288.56
L vastus medialis	48.17 ± 156.67	43.90 ± 150.89	13.44 ± 68.16
R vastus medialis	4.43 ± 8.83	6.08 ± 6.63	78.55 ± 184.73
L rectus femoris	45.32 ± 129.47	30.86 ± 107.94	19.57 ± 84.23
R rectus femoris	63.73 ± 111.09	73.85 ± 149.60	86.88 ± 163.53
L semitendinosus	29.84 ± 46.21	54.61 ± 48.48	26.41 ± 45.01
R semitendinosus	15.87 ± 40.74	10.42 ± 33.26	24.07 ± 43.55
L tibalis anterior	58.85 ± 84.98	74.65 ± 119.69	30.53 ± 80.53
R tibalis anterior	0.05 ± 0.06	10.17 ± 18.79	0.37 ± 0.62
L gastrocnemius	83.70 ± 177.12	126.73 ± 170.09	128.38 ± 219.05
R gastrocnemius	41.32 ± 135.64	64.06 ± 160.73	7.01 ± 30.31
L soleus	2.85 ± 8.66	11.67 ± 20.22	158.59 ± 424.76
R soleus	0.06 ± 0.02	40.95 ± 113.63	0.09 ± 0.10

Table 7.15 Mean (±SD) average hub force output for 46", 48" and 50" driver simulations

	Force output (N)		
	46"	48"	50"
Hub	5.37 ± 10.95	7.06 ± 11.74	13.12 ± 16.15
Arms	0.07 ± 0.02	0.10 ± 0.14	0.42 ± 0.61
Legs	23.65 ± 25.79	30.81 ± 32.53	35.93 ± 47.38
Overall	**14.19 ± 21.96**	**18.51 ± 27.59**	**23.26 ± 37.82**

7.4 Discussion

Specific modelling of the golf swing using ADAMS^{TM} had previously been carried out by Nesbit (2005), Nesbit *et al.* (1994, 1996), and Nesbit and Ribadeneira (2003). In these cases rigid-body stick models were constructed with a parametric iron model. Shaft stiffness was investigated and investigations carried out where modelled shaft stiffness increased by 30% with all other variables remaining the same. They found that the swing was mistimed as a result of using a stiffer shaft, and changes were then made to the model to utilise the increased energy available from the stiffer shaft. The timing characteristics and shaft energy information was deemed applicable to the experimental situation to improve a golfer's game. Thus, the construction of full-body models has been seen to have real value both in terms of understanding the biomechanics of the swing, and the dynamic performance of materials for clubs.

The present study has taken this principle significantly further; developing, validating, and making predictions using a large-scale, full-body musculoskeletal human and parametric driver model. The model was subject-specific, answering the need in the field of sports biomechanics (Hatze, 2005; Farrally *et al.*, 2003) for tailored human models to investigate movement analysis. Single-subject analysis in the area of biomechanical research has emerged, and been deemed statistically sound when considering the large degree of movement variability inherent in human motion (Bates, 1996; Bates *et al.*, 2004 and Kinugasa *et al.*, 2004). Pilot studies (chapter 3) and Study 1 and 2 carried out as part of this PhD highlighted the relatively large degree of inter-subject variability that was present with even elite, highly skilled practitioners of golf. Thus, the present study adopted a single-subject approach, removing the variation in swing naturally found between different golfers, and inferring the effect of driver shaft length on one elite (+1 handicap golfer) deemed representative of category 1 golfers (<5 handicap) and who exhibited relatively low levels of intra-subject variability (pilot Study 3.3).

The model was constructed in such a fashion that whilst it was constructed and produced results specifically for one subject, it may be tailored not only for investigation of different club property effects, but for different anthropometric parameters, in other words different golfers.

The following section discusses model validation and the implications driver shaft length has on swing kinematics and kinetics.

7.4.1 Model validation

It would seem that there exist a large number of models presented in biomechanics literature, predicting human movement under certain conditions that are validated poorly. Previous journal papers have stated '*…experimental and virtual analyses compared well…', or* '*compared favourably*', when ideally they should have clearly stated correlation values or at the least presented graphical analysis of model and experimentally determined data. Model validation, as it seems to suggest, means that a model can produce reliable and valid data for the research question it is supposed to provide answers for. Therefore model data must not only compare well with experimental data which it initially replicates, but correlations should be statistically significant, that is $p<0.05$, or confidence greater than 95% that results sets match.

Chapter 2, Section 2.14 discussed several recent research papers where poor correlational analyses have been performed, or where there was relatively large error between model and experimental results. Interpretation of graphs presented by Nesbit *et al.* (1996) would seem to show a 4.5% difference in peak GRF for their full-body golfer model. In Pan *et al.*'s (2004) evaluation of a computer simulation model for human ambulation on stilts it was concluded that the model was able to evaluate, with a 20% tolerance limit, stilt walking at 24″. And Piazza and Delp (2001) compared simulated and experimentally derived forces for knee joint forces for their three-dimensional knee simulation. Medial-lateral net knee forces were shown to compare favourably with experimentally derived data for knee replacement patients, but net forces in the superior-inferior direction in the simulation were approximately 50% of experimentally measured values. Although only three examples, this was work presented either in peer-reviewed journals or conferences, thus accepted as novel and sound work.

The results presented in the current study would therefore seem to suggest a significantly greater level of model validation than has been achieved before in the field of sports biomechanics. With the exception of $r = 0.929$ for model/experimental comparison of the left posterior thigh validation, although still a statistically significant correlation, all correlation between model and experimental data exceed 0.95. Importantly, RMS difference between model and experimental data for the validation markers (Table 7.7) averaged just 0.05°. Indeed all experimental/model correlational analyses showed strong Pearson's values and low RMS difference for peak clubhead velocity ($r = 0.999$, RMS = 1.93 ms^{-1}; 0.989, RMS = 2.20 ms^{-1} for model Vs p3d manual calculation of velocity), kinematics ($r = 0.983$, RMS = 0.05°) and timing ($r = 1.00$, RMS = 0.004 s).

With the addition of the least reliable parameter, muscle force prediction, verified via good comparison with previous experimental force transducer research into the golf swing grip, it can be concluded that a high level of confidence can be placed on the model developed in the present study to accurately replicate and predict swing kinematics and kinetics. Furthermore, a novel method for model kinematics validation was presented.

It should be noted, though, that there do exist limitations to the model:

- Feet are connected to the ground surface via one contact point per foot.
- Hands are connected to the club grip via one contact point.
- Temple markers were not used during experimentation, therefore the model head segment moves laterally.
- Shaft stiffness is estimated.
- Muscle redundancy remains to be an issue despite the large number of muscles utilised.
- Muscle force validation would better be carried out via comparison with own experimentally collected GRF and grip force data.
- A greater number of validation markers would have allowed for verification of hand, arm and clubhead movement patterns.

Chapter 8 Section 8.2 discusses recommendations for future work based on these limitations.

7.4.2 Effect of driver shaft length on swing kinematics

Clubhead velocity

Results relating to clubhead velocity agree with Reyes and Mittendorf (1999), Mittendorf and Reyes (1997), Mizoguchi and Hashiba (2002), Nagao and Sawada (1973), Egret *et al.* (2003) and Werner and Greig (2000) in that clubhead velocity increased as club length increased. Not all the studies mentioned studied variation in driver shaft length, some comparing wedges, irons and drivers, but all reported significant gains in clubhead velocity nonetheless. Only Yu-Ching *et al.* (2001) and Neal *et al.* (1990) purported no significant change in clubhead velocity with club length. The abovementioned are additionally a mixture of experimental and mathematical modelling studies and have examined driver shaft lengths up to 60" in some cases. The present study examined both experimental and theoretical results.

With marginal difference, theoretical and experimental results for the present study showed that peak clubhead velocity increased 0.85 ms^{-1} for every 2" increase in shaft length within the range of lengths tested (46" to 50"). However, this is an average value and it can be seen in figure 7.23 that the rate of increase from 48" to 50" is not as great as for 46" to 48". Previous study results (Table 6.3) showed also that clubhead velocity increases are greater in magnitude lower down the range of shaft lengths tested. Without extrapolation of data, or model simulations for driver lengths greater than 50" it cannot be known if, using the methods and subjects for the present study, clubhead velocity will continue to increase, as was suggested by the authors mentioned above.

It is thought that three main factors influence the development of clubhead velocity:

i. Shaft ‘kick’ during the latter part of the downswing, accentuated by long–shafted, therefore more flexible, drivers.
ii. Wrist uncocking/delayed release late in the downswing promoting rapid acceleration of the clubhead to the ball.
iii. Muscle force production during the swing, thus torque transfer to the club, altered by changes in club shaft length.

Points (i) and (ii) were not within the scope of the present study and therefore will not be addressed, but certainly merit future research, both experimental and theoretical, perhaps using the model developed here. Point (iii) is of greatest concern for the present study as the effective development of muscle force to transfer torque to the club is influenced by several of the variables investigated via the model

Consideration was also given to clubhead angular velocity. Predicted results (Appendix 12.0) showed no consistent relationship between clubhead linear and angular velocity due to driver length changes. Peak clubhead angular velocity did not vary significantly due to driver shaft length as was the case for clubhead linear velocity. The benefits accrued from using a longer lever resulted in a nonconcommitant / inconsistent effect on angular velocity suggesting inconsistent or inadequate muscle force to overcome the additional inertia associated with longer clubs.

X-factor

Results in section 7.3.2 (Table 7.9) showed an increase in peak hip/shoulder differential, termed the 'X-factor stretch' McLean in 1993. The magnitude of increase was observed as being greatest between the 46" and 48" driver simulation (5.25º), with a smaller increase observed between the 48" and 50" simulations (0.88º). This corresponds with the trend in peak clubhead velocity increase across the 4" range tested. McLean suggested that while the X-factor at the top of the backswing may have contributed to greater driving distance, the magnitude of the X-factor stretch seen in the early phase of the downswing possibly being of even greater importance to achieving optimum driving distance.

The action of eccentric stretch of the muscles of the pelvis and trunk region contribute greatest to the swing benefits of increasing peak hip/shoulder differential. The average and total mechanical work that a muscle can produce during a concentric contraction is enhanced if it is immediately preceded by an active pre-stretch (eccentric contraction) (Chapman, 1985; Komi, 1984). Enhancement in mechanical work output during the concentric phase associated with an active pre-stretch, in comparison to a maximum pre-isometric contraction, may be dependent on a number of eccentric loading strategies. Thus enhancement increases with:

i. Increases in eccentric loading.
ii. Increases in speed of stretching and shortening.
iii. Increases in the length to which the muscle is stretched .
iv. Decreases in amplitude of the stretch (independent of velocity of stretch).
v. Decreases in coupling time (eccentric to concentric contraction period).

Reference should be made to Section 2.4.2 for further discussion of such strategies.

The four points raised (Section 2.4.2) relating to muscle stretch-shortening (SSC) and the literature that backs-up these issues seem to indicate a tangible benefit in increasing the magnitude of countermovement stretch, therefore hip/shoulder peak differential in the region of the top of the backswing. An increase in the X-factor stretch would seem to correspond with an increase in peak clubhead velocity. Results also show, though, that as the X-factor stretch increases, peak hip and shoulder angular velocity decreases.

<u>Hip/shoulder angular velocity & timing</u>
Results disagree with those reported by Nagao and Sawada (1973) who claimed that arm rotational velocity increased as club length increased. Hip and/or shoulder angular velocity does not seem to have been studied, or at least presented in peer-reviewed journal format to date by golf biomechanics researchers. Whilst relatively proximal, there may be marked differences in actual function of the hip/shoulder and arms during the swing, thus accounting for the difference in results with Nagao and Sawada.

The present study showed, via model simulation, that both hip and shoulder peak angular velocity decreased as driver shaft length increased. Peak shoulder angular velocity for the 50" driver simulation was 13.78% slower than the 46" driver simulation, and similarly, peak hip angular velocity for the 50" driver simulation was 10.00% slower than in the 46" simulation. Statistical tests showed a significant variance in both peak hip and shoulder angular velocity when different driver lengths were used. Figures 7.26 and 7.27 showed that angular velocity for both measures decreased by a greater amount between 48" and 50" simulations. This would seem to correspond with the trend found for temporal patterns such that the 50" driver simulation duration was longest, and that whilst total swing time for the 48" simulation was actually the shortest of the three, downswing (the most crucial stage for clubhead velocity generation) duration was longest. Therefore it could be said that overall, swing time, and components thereof, increased as driver shaft length increased. Statistical analysis showed that swing time (total duration, and backswing and downswing duration) all varied significantly due to club length.

Whilst the benefits of increased stretch, and shortened muscle spindle firing duration was discussed in relation to the X-factor, it was also mentioned that there exists an optimum velocity at which muscle produce maximum force and a balance must be struck between activating the stretch reflex and swinging the club at a speed at which greatest muscle force can be produced to apply maximum torque to the club. During a concentric contraction (CC), the force-velocity relationship indicates that as the velocity of the contraction increases, the force generated decreases. However, during an eccentric contraction (ECC), the force-velocity relationship is different. At small velocity changes, there is a relatively large increase in force, but further increases in velocity result in little or no force change (Bartlett, 1997). Therefore the small stretch that occurs during the countermovement hip downswing initiation, which is an eccentric contraction, helps create relatively large increases in force.

The amount of maximum force a muscle is capable of producing is partly dependent on the muscle’s length. Within the human body force generation capability increases when the muscle is slightly stretched, for example during peak hip/shoulder angle differential. Parallel-fibered muscles produce maximum tensions at just over resting length, and pinnate-fibered muscles generate maximum tensions at between 120% and 130% of resting length. This phenomenon is due to the contribution of the elastic components of muscle (primarily series elastic elements, SEE), which add tension present in the muscle when the muscle is stretched (Bartlett, 1997). Furthermore, the tension developed within a muscle is proportional to the contraction time. Tension increases with the contraction time up to the peak tension. Slower contraction, exhibited via decreased hip and shoulder peak angular velocity, enhances tension production as time is allowed for the internal tension by the contractile elements to be transmitted as external tension to the tendon through the series elastic elements, which have to be stretched. The magnitude of the force developed by the muscle-tendon complex depends not only on the stimulus but also on the fraction of cross-bridges attached, muscle length and contraction velocity. It is the combination of the length of stretch and the speed of contraction that contributes most to the generation of force for the golf swing.

7.4.3 Effect of driver shaft length on swing kinetics

The previous discussion concerned the relationship between the amount of muscle stretch exhibited at lateral aspects of the hub at the top of the backswing, and the duration of swing components and also as a whole. As driver shaft length increased from 46" to 50" the magnitude of the stretch between the hips and the shoulders increased, the peak angular velocity predicted by the model decreased for both the shoulders and the hips, and the length of the downswing in particular, also increased. Statistical tests showed that these three measures not only varied, but varied significantly ($p<0.01$).

Even before examining the data predicted by the 46", 48" and 50" drivers models relating to optimised muscle force output, conclusions can be drawn such that:

- An increase in muscle length via the stretch reflex (X-factor stretch) as driver shaft length increased has the potential to allow greater development of muscle force.
- Small decreases in hub angular velocity as driver shaft length increased can serve to slow muscular contraction to a rate at which it can produce greater muscle force, if the rate of contraction previously, that is for a 46" club length, was too fast.
- Similarly, small increases in downswing duration as club length increased can slow concentric contraction velocity to a rate at which muscle can produce greater force.

Table 7.15 showed that for 42 hub, arm and leg muscles selected for analysis from the 111 muscles created within the model, muscle force output increased (NS) as driver shaft length increased. Statistical analysis showed that only hub muscle force increased significantly with club length ($p<0.01$). Overall, a 1" increase in shaft length for the 4" range of shaft lengths studied here, muscle force output increased by an average 2.27 N. This increased muscle force output as driver shaft length increased can be associated with the observed increases in X-factor stretch as shaft length also increased.

The kinematic measures outlined above as changing with the length of the driver would seem to be reactionary to the need to increase force output to cope with swinging a long-shafted driver. The need for increased force could be due to:

i. Effort needed to overcome the additional mass and moment of inertia of long-shafted drivers.
ii. Strength needed to stabilise the swing to maintain a 'regular' kinematic swing pattern and produce normal impact characteristics with the ball.

Stabilisation of the swing is relevant in that the club's centre of mass has been moved distally when the driver is made longer such that the clubhead is the most massive component of the club. Sprigings and Neal (2001) investigated the distal movement of a club shaft's mass in relation to improving golf performance. A two dimensional model of a golf club was constructed to simulate the pendulum swing. When an externally generated torque was applied to the club grip to simulate the hands, it was shown that relocating mass further down the shaft proved to have a detrimental effect on the generation of clubhead speed leading to impact, but that letting the club swing 'pendulum-like' had the effect of increasing clubhead velocity in the downswing. Depending on the type of swing a golfer uses, either one with active wrist uncocking/delayed release, or a more passive wrist action, clubhead velocity using a longer driver can increase, as the present study demonstrated both experimentally and theoretically.

Consideration should be given also to the possibility that the subject examined may physiologically have had a large percentage of fast twitch (FT) muscle fibres whereas another elite golfer examined could have a majority of slow twitch (ST) fibres. The force-time relationship for fast twitch fibres is characterised by rapid rise and a shorter relaxation time compared to ST fibres. Physiologically, this can be explained, in part, through a faster rate of release and uptake of Ca^{++} (Calcium) by the sarcoplasmic reticulum. Komi (1986) found that FT fibre ratios were significantly correlated to average force (Pearson's $r = 0.52$), net impulse ($r = 0.45$), and mechanical power ($r = 0.52$). An electromechanical delay (EMD) occurs after electrical (EMG) muscles activity and prior to the generation of force. EMD occurs faster when athletes have an increased FT muscles fibre ratio. In applying this to the golf swing, should the subject studied have had a greater ratio of fast twitch fibres, they may have managed increased shaft length better due more efficient muscle contraction or less wasted time due to ST repolarisation.

Nonetheless, it may be concluded that, with consideration of all contributing factors, the main reason for the increased force during swings with the longer clubs is the requirement to overcome the additional inertia associated with these clubs.

Although muscle force validation was not as rigorous in methodology as was swing kinematics, due in part to the assumptions required to overcome the problem of redundancy in muscle modelling, it is thought that the simulated muscle force data presented here is realistic and valid and give a good indication of the internal mechanics during the golf swing.

7.5 Summary

In conclusion, a large-scale musculoskeletal model has been developed that has the capacity to rapidly produce selected kinematic and kinetic results relating to variations in the golf swing when using drivers of different shaft lengths. It has been shown, both experimentally and theoretically, that there exists a modest but significant increase in peak clubhead velocity when drivers longer than 46″ are used. Also, peak hub (shoulders/hips) angular velocity decreases significantly and hip-shoulder peak differential at the top of the backswing and swing time increase significantly as driver shaft length increased. Concomitantly, the model predicts that more effort is required to swing a long shafted driver with similar kinematics to a driver of normal length. Increases in peak clubhead linear velocity are thought to result from a combination of shaft length increases and muscle force increase.

Results agree with Cochran and Stobbs (1968), who were among the first to study the effect of driver length, noting that the longer the club, the more difficult it would be to bring the clubface squarely to the ball, but a golfer should be able to move a clubhead on a long shaft faster.

The model is subject-specific, tailored for an elite golfer, but has the capacity to be altered in terms of anthropometrics and posture to simulate different golfers and different swing types. Furthermore, it is believed that the model can be used to examine the effect of altering a range of club physical properties for example shaft and clubhead materials, clubhead volume and moment of inertia, shaft flex and clubhead, shaft or grip mass. Having been validated well, confidence can be placed on producing meaningful data for biomechanical analysis of the swing and club dynamics.

CHAPTER 8

Summary, conclusions and recommendations for future research

8.0 Summary

The following section summarises the main findings from Studies 1 to 4. Also highlighted are the results from preliminary study 4 (Section 3.4) as these are considered pertinent to the biomechanical analysis of the golf swing.

Preliminary study 4 - Effect of skin markers on golf driving performance.

- Ball velocity immediately after impact ($z = -2.521$, $p < 0.05$), and backspin and sidespin components ($z = -2.38$, $p < 0.05$) of initial ball flight were significantly different ($p < 0.05$) for shots performed in the laboratory with and without skin markers attached to the subject.
- Shots performed with markers attached to the subject averaged 2.92 ms^{-1} greater ball velocity (+ 4.19%).
- Shots performed with markers showed significantly greater ball sidespin ($z = -2.38$, $p < 0.05$) indicating that the shots would deviate more from the target line.
- However, the majority of variables (clubhead velocity, clubhead orientation, swing tempo and ball launch angle) did not change due to the presence of skin markers indicating the validity of experimental laboratory golf kinematic tests.

Study 1 - Kinematic analysis of the golf swing for low-medium handicapped golfers using drivers of different shaft length.

- Posture at address, top of the backswing and at impact did not vary significantly ($p > 0.05$) for low-medium handicapped golfers using drivers of different shaft length.
- Subjects accommodated longer shafts by increasing stance width ($F = 0.047$, $p = 0.986$), foot-to-tee distance ($F = 0.438$, $p = 0.728$) and by standing more upright ($F = 0.642$, $p = 0.593$).
- Low-medium handicapped golfers did not demonstrate any change in the hip-shoulder differential angle (X-factor) at the top of the backswing when using longer drivers.
- Peak hip angular velocity decreased as driver length increased ($F = 0.151$, $p = 0.929$). Peak shoulder angular velocity generally decreased as driver length increased ($F = 0.523$, $p = 0.668$).

- Total swing time increased significantly as driver length increased ($F = 2.515$, $p < 0.05$).
- Relative swing timing, that is downswing time as a percentage of total time, remained unaffected by driver length.
- There existed significant inter-subject variability for total and relative swing timing among the low-medium handicapped golfers tested ($F = 95.041$, $p < 0.0001$).

<u>Study 2</u> - Analysis of driving performance and accuracy for shots performed on the range and in the laboratory using clubs of different shaft length.

- Low-medium handicapped golfers produced a 3.33 ± 0.81 ms^{-1}, or 5.12 % increase ($p > 0.05$) in ball velocity at impact for shots performed in the laboratory compared with shots performed on the golf course.
- Shots performed with a 52" driver were significantly longer than those performed with a 46" driver, resulting in an average 14 yards greater ball carry ($F = 6.92$, $p < 0.001$). On average, greatest increases in ball carry were observed for shots performed using drivers longer than 47".
- Dispersion differed significantly only between results for the 46" and 49" drivers and 49" and 52" drivers ($F = 6.92$, $p < 0.05$). Shots performed with the 49" driver were significantly farther left of the fairway centre than for shots performed using the other drivers. Indicated by standard deviation of the mean, shot accuracy decreased generally ($F = 2.50$, $p = 0.063$) as shaft length increased.

<u>Study 3</u> - Analysis of driving performance for elite golfers using drivers of different shaft length.

- Results for elite golfers showed that clubhead velocity prior to impact ($F = 3.21$, $p < 0.05$) and ball velocity immediately after impact ($F = 5.34$, $p < 0.01$) increased significantly as driver shaft length increased. Ball velocity increased by 2.77 ms^{-1} (3.94%) when using a 50″ driver compared to subjects’ own drivers of average shaft length 44.5″. Similar increases in clubhead velocity were shown.
- Ball carry increased ($F = 1.786$, $p = 0.152$) as shaft length increased from golfers’ own driver of 44.5″, to 46" and to 48". Ball carry increased for the longest driver,

50", compared to subjects' own drivers, but not as great in magnitude as when using the 48" driver.

- Shot accuracy remained unaffected by driver length.
- Ball launch conditions of spin components and launch angle remained unaffected by driver length. Launch angle increased ($F = 1.074$, $p = 0.362$) as driver shaft length increased.

Study 4 - Prediction of the effect of shaft length through development and validation of a full-body computer simulation of the golf swing.

- The correlation between model and experimental kinematic data were 0.983 ($p < 0.001$) with RMS difference of 0.05°.
- The correlation between model and experimental peak clubhead velocity was 0.999 ($p<0.05$). RMS for the same comparison was 1.93 ms^{-1}. Both sets of results indicated that clubhead velocity increased as driver shaft length increased, by an average 0.85 ms^{-1} for every 2" increase.
- Simulated grip force output agreed well with previously reported experimental force transducer literature.
- Peak hip ($F = 1291133.9$, $p < 0.001$) and shoulder ($F = 33220127.3$, $p < 0.001$) angular velocity decreased significantly as driver shaft length increased. Peak shoulder velocity was 13.8 % slower for the 50" simulation compared to the 46" simulation. Similarly, peak hip angular velocity showed a 10.0% decrease for the same club length comparison.
- Peak hip/shoulder differential angle at the region of the top of the backswing (X-factor stretch) increased significantly ($F = 694.07$, $p < 0.001$) as driver shaft length increased. The 50" simulation demonstrated a 6.13° (7.55%) increase compared to the 46" simulation.
- Swing timing differed significantly due to driver length. Total swing time ($F = 717.7$, $p < 0.001$) and downswing time ($F = 13.4$, $p < 0.01$) increased significantly as driver length increased. However, relative timing, that is the downswing as a percentage of total swing time, remained unaffected. Correlation between model and experimental data were 1.00 ($p < 0.01$) with RMS difference of 0.004 s.

- Simulations showed that for select groups of muscle representing trunk, arm and leg movements, for the range of clubs studied (46" to 50") each 2" increase in driver length required an additional 4.5 N force to maintain normal swing kinematics (χ^2 = 4.294, $p = 0.117$).

8.1 Conclusions

The conclusions which follow address the aims of the present study stated in the introduction chapter, and the aims for each study, stated at the beginning of their respective chapters.

1. Posture at address, top-of-the-backswing and at impact were generally unaffected by changes in shaft length within the range of driver lengths studied (45" – 52"). Low-medium handicapped golfers accommodated longer drivers by increasing stance width, increasing foot-to-tee distance and by standing more upright at address. Associated with maintenance of the kinematics of the golf drive, swing tempo was not affected by driver shaft length changes.

2. Increases in the radius of gyration as a result of stance width and foot-to-tee distance alteration, and increased effort needed to overcome greater club inertial effects as driver shaft length increased may have been the cause of decreased peak hip and shoulder angular velocity.

3. Peak differential angle (X-factor stretch) between the hips and the shoulders in the region of the top of the backswing increased as driver shaft length increased for elite golfers. As part of the kinetic chain and summation of forces, this is thought to have been a contributing factor to increased peak clubhead and ball velocity, resulting in greater ball carry.

4. As shaft length increased from 46" to 52", ball carry increased significantly for low-medium handicapped golfers. Ball carry also increased for elite golfers (NS). Low-medium handicapped golfers produced greatest increases in carry distance with drivers of 49" and 52". Elite golfers produced greater increases in carry distance

with 46" and 48" drivers compared to their own drivers of average length 44.5". However, increases were still evident for drivers of 50".

5. Ball launch conditions of backspin and sidespin components and launch angle remained unaffected as shaft length increased, resulting in no significant decrease in drive accuracy for either low-medium handicapped or elite golfers.

6. A large-scale musculoskeletal human model and parametric driver model, driven using experimental marker trajectory data, simulated the golf swing and demonstrated a strong correlation between model results and experimental results relating to swing kinematics. Model results confirmed that peak clubhead velocity increased as driver shaft length increased. The model simulation also predicted that muscle force increases were required to swing longer drivers. Increased muscle force is thought to result from increased peak hip/shoulder differential at the top of the backswing, changes in swing rhythm relating to slower backswings, and decreased hub angular velocity as driver shaft length increased. Increases in peak clubhead linear velocity are thought to result from a combination of shaft length increases and muscle force increase.

In summary, it is evident that using a driver with a shaft length greater than 48" can result in modest increases in drive distance. Small decreases in drive accuracy are associated with using longer drivers. However, individual skill and the level of intra-subject variability seems to play a greater role in the accuracy of drives exhibited by any golfer. Ball impact characteristics (spin/launch angle) nor postural kinematics seem to account for changes in shot outcome, rather increases in hip/shoulder differential angle at the top of the backswing and increased predicted muscle force output seem to result in increased drive distance.

8.2 Recommendations for future work

The work presented in the current study has sought to fill gaps in the literature identified in Chapter 2 and discussed in Section 2.13. It is believed the research conducted in completing this thesis adequately addressed the main aims and adds to the body of knowledge which currently exists in this field of research. However, given additional time and improved resources, enhancements to the methods employed thus results obtained could have been achieved.

Several issues have been discussed throughout this thesis. These relate to subject recruitment and limitations to the model that has been developed. Investigation of shaft ‘kick’ and the action of wrist cocking/uncocking has also been noted. Section 7.4.1 discussed limitations concerning the musculoskeletal model that has been developed. Future development of this model could involve: multi-point equipment/environment contacts with the hands and the feet. This would allow better representation of the interaction of the golfer with its environment and the understanding of the application of forces and torques. With the addition of multi-point contacts created for the feet, simulated GRF patterns could be compared to experimentally obtained force plate data to both help validate the kinetics of the model and provide further insight into weight transfer patterns during the golf swing. The model could also benefit from performing further laboratory trials with the addition of temple skin markers. Thus, movement of the head segment in the model would be driven using subject-specific data, creating a more realistic simulation than the passive head movement currently simulated.

Regarding the investigation of the complex wrist action during the downswing, future research could involve experimentally tracking a greater number of wrist, hand and club markers. This would permit simulation of the golf swing with less interpolation of data to predict hand and wrist movement, providing insight into the effect of delayed wrist uncocking for example. Combined with investigation of the stiffness of the driver shaft, for example change of shaft stiffness associated with driver length, experimental and simulated results on this matter may provide further insight into the mechanisms by which increased ball carry is achieved as driver shaft length increases.

Indeed, it has been noted in Section 7.4.1 that shaft stiffness properties are estimated for the current model. Whilst based on experimentally obtained club frequencies, model shaft stiffness was also achieved by observing shaft flex for a range of material damping properties. Experimentally tracking multiple sphere markers positioned along the driver shaft length would allow for more accurate representation of shaft flex during simulated golf swings. More specifically, the acceleration of the lower part of the shaft and clubhead immediately prior to impact, for drivers of different length, could also provide more insight into the reasons for increased ball carry or shot accuracy variation.

Model results in the current study relate to a specific elite golfer, deemed representative of category one golfers. However the model may relatively easily be anthropometrically tailored for any subject, male or female, left or right handed, and experimental data imported for their swing to drive a new forward dynamics simulation. Therefore, a database relating to the kinematics and kinetics of the golf swing for a range of golfers of different physical stature and skill level could be compiled. Manipulation of the parametric driver model to simulate drivers of different shaft length, clubhead or shaft mass, clubhead moment of inertia, or club material properties, to name just a few examples, is possible for this range of golfers. Future work is planned which involves simulation of the golf swing for an elite golfer using a range of irons. As in the current study, the kinematics and kinetics of the swing will be investigated, and compared to experimentally obtained data to highlight any changes in the swing.

APPENDICES

APPENDIX 1.0 Subject informed consent form

A

CONSENT FORM FOR PARTICIPATION IN RESEARCH PROJECTS AND CLINICAL TRIALS

TITLE OF PROJECT: Effect of different shaft lengths on golf driving performance

OUTLINE EXPLANATION: The aim of the research is to determine the effects of different drivers on golf performance. Specific objectives include an examination of the relationship between shaft length and swing mechanics as they relate to performance.

This project is multi-faceted and will continue over a sustained period of time during which an extensive database will be generated. Physical characteristics (age, height, weight, body mass index, body fat percentage) will be recorded along with physical fitness measurements including strength, power and flexibility. These parameters will be determined via field-based tests. Golf swing characteristics will be determined from video analysis, ball launch monitors and radar tracking systems. Up to 40 quality golf shots will be required per subject. Tests will be conducted in a laboratory and on a purpose-built practice hole. All data will be stored in accordance with the Data Protection Act 1998, and will be analysed and may be submitted for the scientific and popular publication.

Experimental procedures contain no inherent risks over and above those that may reasonably be associated with performing the same actions under the physical training and golf practice conditions. Volunteers should expect no direct benefits, although basic feedback relating to results will be given when requested. Subjects are free to withdraw consent and discontinue participation at any time without procedure.

I (Name) …………………………………………………………………………….

of (address) ………………………………………………………………………….

………………………………………………………………………………………..

hereby consent to take part in the above investigation, the nature and purpose of which have been explained to me. Any questions I wished to ask have been answered to my satisfaction. I understand that I may withdraw from the investigation at any stage without giving a reason for doing so and that this will in no way affect the care I receive as a patient.

Signed
(Volunteer) . . . . Date …………………….

(Investigator). . . . . Date …………………….

(Witness, where appropriate) . . . . Date……………………..

APPENDIX 2.0 Health history questionnaire

B

CONFIDENTIAL

HEALTH HISTORY QUESTIONNAIRE

NAME

DATE OF BIRTH

ADDRESS

E-MAIL ADDRESS

TELEPHONE: HOME MOBILE

PAST HISTORY (Have you ever had?)

	YES	NO	NOTES
Rheumatic fever / heart murmur	[ ]	[ ]	
High blood pressure	[ ]	[ ]	
Any heart trouble	[ ]	[ ]	
Asthma	[ ]	[ ]	
Diabetes	[ ]	[ ]	
Epilepsy	[ ]	[ ]	
Joint or muscular disorder / injury	[ ]	[ ]	
Sciatica	[ ]	[ ]	

PRESENT SYMPTOMS (Have you recently had?)

	YES	NO	NOTES
Chest pain or discomfort	[ ]	[ ]	
Back pain	[ ]	[ ]	
Sciatica	[ ]	[ ]	
Aching joints	[ ]	[ ]	

Recurrent injury	[ ]	[ ]
Are you presently taking any medications?	[ ]	[ ]
Any other medical / physical fitness problems not already indicated?	[ ]	[ ]
Do you currently smoke?	[ ]	[ ]

If so, what and how much? ________________________ ____________ per day

APPENDIX 3.0 Golf history questionnaire

C

Golf history/ physical fitness Questionnaire
Physical Fitness of golfers and dynamics of the golf swing

1) a. Name

b. Club/s membership and dates

2) a. Handicap (Current)

b. Previous h'caps and best (dates)

c. Goals for year/ future

3) Gender

4) DOB

5) Golf Experience:
   a) Number of years playing

   b) Age at which first played/ trends since

   c) Frequency of play

   d) Types of practice/ duration and frequency

   e) Lessons taken (from whom)

Golf history/ physical fitness Questionnaire (contd.)

6) Training/ **other** sports

   a) Type of physical training/ sport(s)

   b) Frequency of physical training/ participation

   c) Duration

   d) Number of years of physical training/ sports participation

7) Injuries: full details for playing years of **all injuries** (specify golf specific injuries)

8) Equipment and length of usage (include full ranges/ **spec/** when bought and details of use)

a) Driver(s)

<u>Other information</u>

Form completed by: ___________________________________

Date: _______________________

APPENDIX 4.0 Ethical approval report submitted following approval by the University of Ulster Research Ethics Committee.

UNIVERSITY OF ULSTER

RESEARCH ETHICAL COMMITTEE- <u>1 YEAR REPORT</u>

(All applications must be typewritten)

1. **TITLE OF PROJECT: ***
   Effect of different shafts and clubhead volumes on golf driving performance

2. **PROPOSED STARTING DATE:** December 2003

3. **APPROXIMATE DURATION OF PROJECT:** 3 years

4. **PRINCIPAL INVESTIGATOR:**

   Name: Ian Kenny

   Qualifications: B.Sc (Hons)

   Position: PhD student

   Employing Authority: University of Ulster

   Department: Life & Health Sciences   Telephone Number: 028 90366987

   Address for Correspondence: Room 15J20
   University of Ulster, Jordanstown
   Shore Road,
   Newtownabbey,
   Co. Antrim
   BT37 0QB

5. **OTHER STAFF**

   Please give name, position and function of other staff involved in the proposed research:

Dr Eric Wallace	Dr Desmond Brown
Reader in Biomechanics	Senior lecturer Electrical & Mechanical Engineering
-Project supervisor	-Project supervisor

6. **FUNDING**

   Please give details of the cost of the Project and the sources of funding. Please distinguish between funding being sought and funds already obtained.

   Studentship granted- CAST award funded by the Department of Education & Learning (DEL) and the R&A Rules Ltd., St. Andrews.

7. **PLACES WHERE THE RESEARCH WILL BE DONE**

Please specify where the research is to be carried out, eg Hospital, Laboratory:

On-Campus laboratory at the University of Ulster, Jordanstown, and on-site at various golf courses.

UPDATE

2 studies will be conducted on the range, at Greenmount College golf facility, Antrim, and one study will be carried out in the laboratory at the United States Golf Association (USGA) testing facility, New Jersey. The USGA provides ethical approval and insurance for all testing carried out at its facility and the study to be carried out there has been planned by the USGA, my sponsors the R&A, and myself.

8. **PLEASE PROVIDE A FULL DESCRIPTION OF THE STUDY UNDER THE FOLLOWING HEADINGS** (INCLUDING RELATIONSHIP TO PREVIOUS WORK):

a. **Background to the study**

Research to date in the biomechanics of golf has been largely experimental in nature, with both kinematic and kinetic data derived to ascertain the effects of club specifications on golf performance. The proposed work in this application will extend this work to provide appropriate experimental data which can be used to drive simulation models of the golfer. Modelling work of this kind has been carried out for other sporting activities (such as gymnastics) but little has been done specifically in golf biomechanics and golf technology. This work is extremely novel and will certainly provide scope and challenge. Scientific protocols routinely used in biomechanics research will be applied, along with engineering and design methods in the modelling work to be undertaken.

b. **Aims of the study**
(Please include anticipated use of outcomes, the potential benefit to the patient and the potential benefit to science, both in the short term and in the future)

The aim of this project is to characterise and model the responses of golfers using drivers of different shaft and clubhead properties. The work will complement the ongoing metallurgy research in the area being undertaken at the University of Birmingham. The ongoing "Effects of Golf Technology on Performance" project at the University of Ulster within which the current study will be undertaken, will determine the effects of different golf parameters on the biomechanics of the golf swing and hence performance.

After completion of golf driver and swing testing carried out as part of a related research project at the university of Birmingham, characterisation results from these driver shafts will be used in biomechanical models to analyse the swing results. The experimental results obtained from biomechanical investigations to date, as part of the wider golf technology research at UU, plus additional tests will be input to computer modelling software (Adams/ Figure) to permit multiple combinations of variables to be considered.

Golf technology has advanced to date to a stage where certain rules concerning the design of drivers are being bent or broken. Factors such as moving parts, be that the club face or the shaft, will be investigated in this study. The outcomes envisaged are optimum values for clubhead size and shaft length within the constraints of performance and golf technology rules, benefiting both club manufacturers and rule-makers.

c. **Methods to be used in the study**
(Please describe what methods will be used, including diagnostic, therapeutic, intervention or other procedures which subjects may be asked to undergo)

Subjects will be analysed by means of image analysis, that is without interference, the investigator simply observing and analysing the data collected from golf swings that subjects perform. Subjects will perform a series of swings using drivers of various lengths and clubhead sizes, both in an indoor golf-driving set-up and on the golf course itself.
10-12 subjects will be tested on two separate occasions to account for inter-test variability and objectivity, the same swing pattern and equipment being used for each experiment. Intra-subject variability will be investigated through repeated trials of each experiment, 10 trials being required from each subject.
Experiment 1 and 2 will be identical. Each subject will perform 10 swings using one set of custom-made drivers, and 10 swings using a different set of custom-made drivers, i.e. 20 in total.
Motion tracking systems will be used where reflective markers are placed on the subjects' clothes or skin at anatomical reference points, ie. joints that are to be analysed. Tracking systems are comprised of a series of video cameras that capture high-speed motion.

Data collected will be reduced through use of statistical computer packages, eventually to be input as data to drive 3D computer software to build a golf simulation model.

UPDATE
Study (experiment) 3 was carried out on the range at Greenmount College, Antrim, from the 30^{th} June-2^{nd} July 2004. 12 subjects were tested. 4 drivers were used to investigate driving performance using each of the different clubs, varying by shaft length. Each subject performed 6 trials with each driver, resulting in 24 trials in total- an additional 4 trials over that which was proposed initially (see above). Statistical analyses have been carried out and conclusions drawn benefiting planning for study 4.

An additional study, 3, is proposed for January of 2005. This study will be carried out in the laboratory at the USGA testing facility, New Jersey. Its purpose is to collect motion data that will be used to drive the computer golf simulation model. 1 skilled (+2 handicap) golfer will again perform 6 trials with 4 different drivers, 24 in total. Motion tracking systems will provide motion/time data for movement of reflective markers attached to anatomical landmarks on the body.

Warm-up and safety protocols that were applied during study 1 will be adhered to also for studies 2 and 3. There have been no health or safety incidents to report. UU laboratory technicians are present for all tests ensuring procedures adhere to safety regulations outlined by the University.

d. **Subjects**

Please state:

i. The number of patients to be studied: None

ii. The number of healthy volunteers to be studied: Approximately 12

iii. Sex and age range: Male, 18-60

iv. Method of recruitment: Mainly UU golf bursary players

v. Exclusions: Non-golfers and golfers with recent injury history

vi. Provide details of any payments or other inducements to be made to the subjects:

None

vii. Indicate whether or not, if patients are involved, their general practitioner will be informed or permission sought from their consultant.

N/A

e. **Statistical design and analysis** *(see notes)*

i. Indicate the steps you have taken to ensure that the results will be statistically meaningful:

Empirical, or experimental data that will form the first part of the research project will be validated by means of repeated measures statistical tests (SPSS) and by successfully driving the simulation model. Furthermore, the model will itself be validated through further experimental data collected as a comparison.
The development of a simulation model will provide means for an infinite number of trials and experiments relating to varying driver effect on performance, all of which will no longer require intervention to human subjects.

UPDATE
Study power that has been aimed for is 80% with a statistical level of 5% ($p \leq 0.05$) being tested. Sample size ($n=12$) has been sufficient to achieve such a power and is in accordance with other recent published biomechanical studies. Single-subject methodology is a very relevant current issue in the field of biomechanics and studies have been previously published in peer-reviewed journals using such subject samples. Our 3rd study addresses this issue and will be validated by the theoretical computer modelling and statistical procedures (repeated measures ANOVA) advised by Bates *et al.* (1996).

ii. If questionnaires are to be used indicate broadly the area of content and explain what aspect of the questionnaire requires ethical approval (please attach copies of any questionnaire which is to be used).

See attached (B and C).
B details the medical history of the subject as well as any present medical conditions. Identification of some medical conditions will alert the investigator as to the suitability of the subject for the current investigation.

C details the golfing and sporting history of the subject indicating the level of play which they are currently at, any sports-related injuries that may have a biomechanical effect on the golf swing, and lastly the golf equipment that the subject uses.

9. **DETAILS OF PROCEDURES**

Does your research involve clinical procedures which affect the direct care provided to the patient?

No

If so complete this section and the following sections. If not proceed to Section 12.

a. What adverse effects are expected with these procedures?

b. Are there any possible serious risks or dangers associated with their use? (Append details if space is insufficient)

c. Isotopes - give details of any Isotopes to be used including dose, frequency and route:

i. Has the advice of the Radiation Protection Officer been sought?

ii. Has the applicant a DHSS Licence for this purpose?

iii. Specify a routine investigation of equivalent radiation exposure.

Please specify other additional investigations, substances or agents required for the research (including cardiac catheterisation , ultrasound, radiography, ECG, EEG, etc)

10. **DRUG STUDY**

a. If the study involves a drug trial, what stage has been reached in the evaluation of the drug?

b. Is there participation or sponsorship by a pharmaceutical company?

c. If so, give details of financial support from pharmaceutical company (if any).

11. **WHAT ASPECT OF THE PROCEDURES DESCRIBED ARE NOT PART OF ROUTINE CLINICAL CARE?**

12. **THE HEALTH AND COMFORT OF THE SUBJECTS**

Will there be any risk of damage to the health of the subjects, or of any pain, discomfort, distress or inconvenience? If so, please give an assessment of the seriousness of any possible damage to health, and of any pain, discomfort etc and of the degree of risk.

Minimal risk of injury- no inherent risks over and above those that may reasonably be associated with performing the same actions under the physical training and golf practice conditions. Instruction for appropriate warm-up, technique and cool-down will be given in order to reduce the risk of injury.

13. **CONSENT**

a. **Explanation**

Will the subjects be given an oral, a written, or no explanation of the research?

Written (see attached A)

(If a written explanation is to be given, 16 copies must be submitted with this application - the written explanation should be expressed in terms accessible and meaningful to the subjects participating in the research. If an oral explanation only is to be given please include a written outline of this explanation on the consent form for the information of the Committee.)

b. **Consent Form**

Please submit 16 copies of the full consent form with your application.

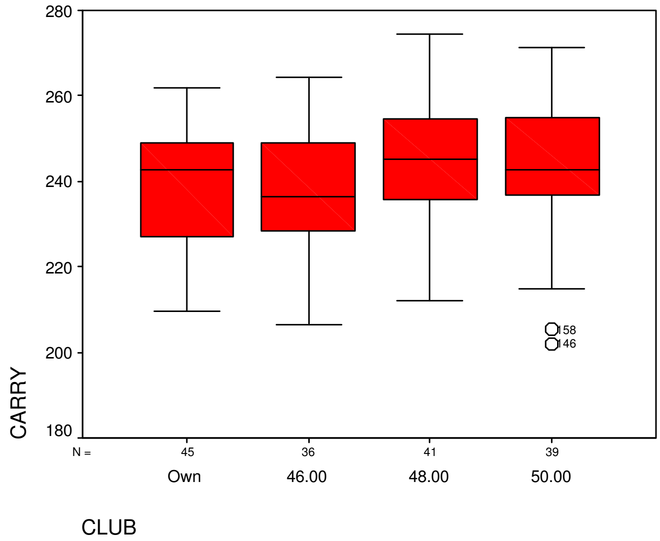
14. **WHAT ARE THE ETHICAL PROBLEMS WHICH APPEAR TO THE APPLICANTS TO ARISE FROM THIS APPLICATION?**

Please set them out and add any comments considered likely to assist the committee.

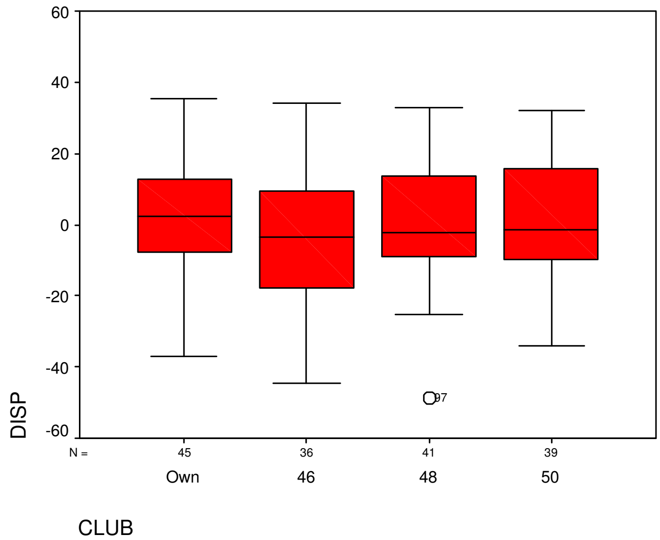
None envisaged

APPENDIX 5.0 Boxplots showing median, quartiles and extreme values for data collected from all subjects during Study 3.

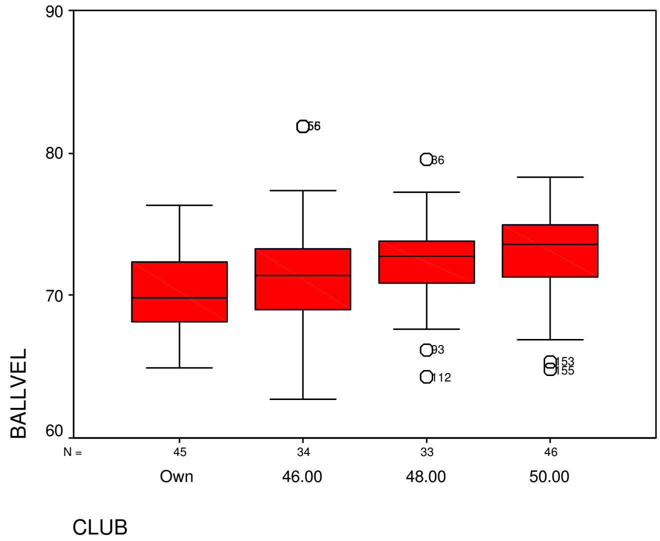
BALL CARRY



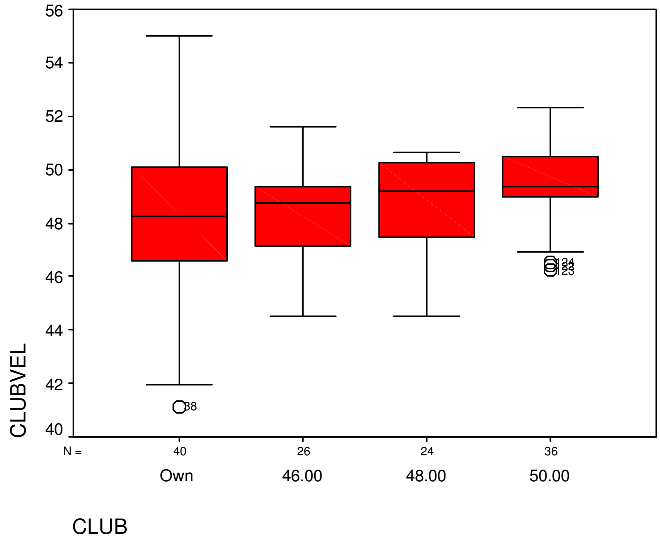
DISPERSION



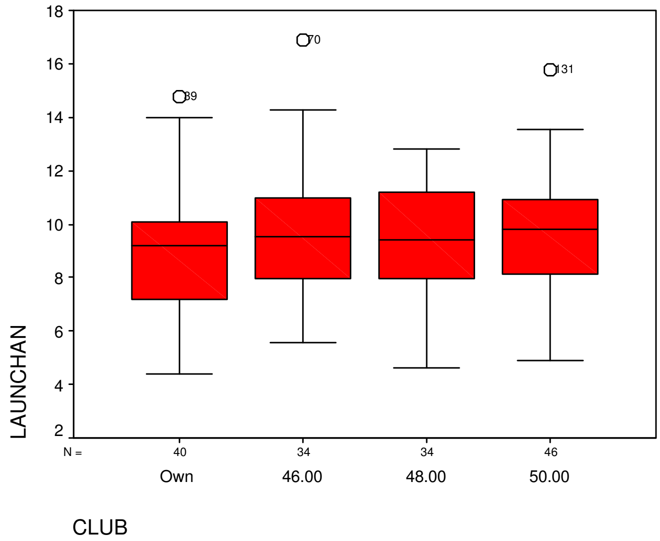
BALLVELOCITY (ms^{-1})



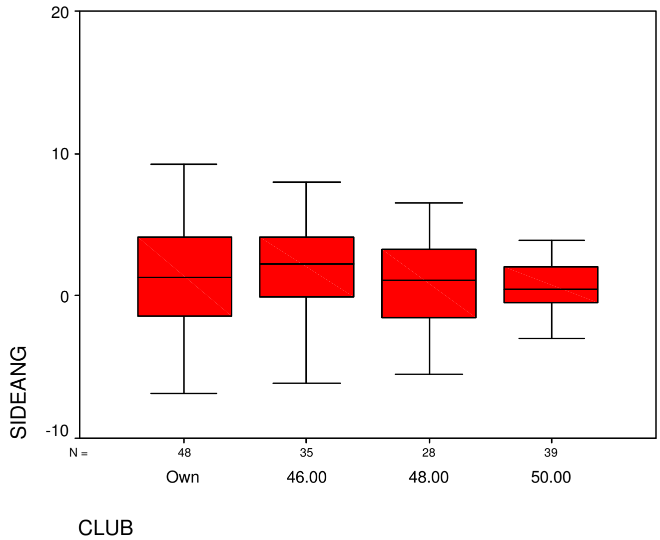
CLUBHEAD VELOCITY (ms^{-1})



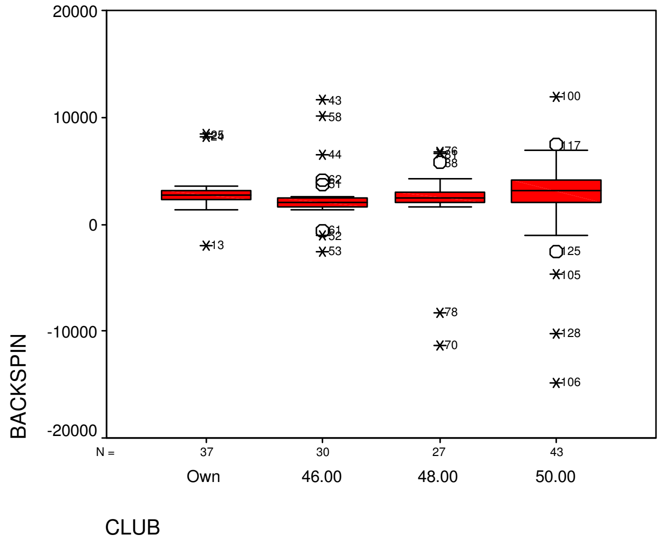
LAUNCH ANGLE (º)



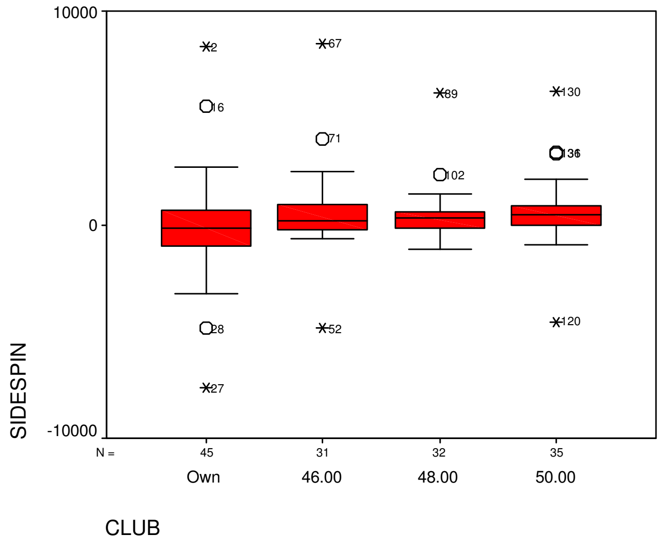
SIDE ANGLE (º)



BALL BACKSPIN (RPM)



BALL SIDESPIN (RPM)



APPENDIX 6.0 UNIVARIATE test for Study 3 highlighting no significant trial effect for individual subjects (p = 0.220), but showing significant subject (inter-subject) effect (p = 0.000) on performance measures.

Tests of Between-Subjects Effects

Dependent Variable: BALLSP

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	45719.717	1	45719.717	2135.259	.000
	Error	592.909	27.691	21.412[a]		
CLUB	Hypothesis	276.984	2	138.492	7.151	.013
	Error	182.731	9.435	19.367[b]		
TRIAL	Hypothesis	62.768	3	20.923	1.522	.220
	Error	673.473	49	13.744[c]		
SUBJ	Hypothesis	1513.257	5	302.651	16.208	.000
	Error	212.998	11.407	18.672[d]		
BKSPIN	Hypothesis	5.069	1	5.069	.369	.546
	Error	673.473	49	13.744[c]		
LNCHANG	Hypothesis	84.140	1	84.140	6.122	.017
	Error	673.473	49	13.744[c]		
CLUB * SUBJ	Hypothesis	191.430	10	19.143	1.393	.212
	Error	673.473	49	13.744[c]		

a. 2.654E-02 MS(SUBJ) + .973 MS(Error)

b. 1.041 MS(CLUB * SUBJ) - 4.143E-02 MS(Error)

c. MS(Error)

d. .913 MS(CLUB * SUBJ) + 8.715E-02 MS(Error)

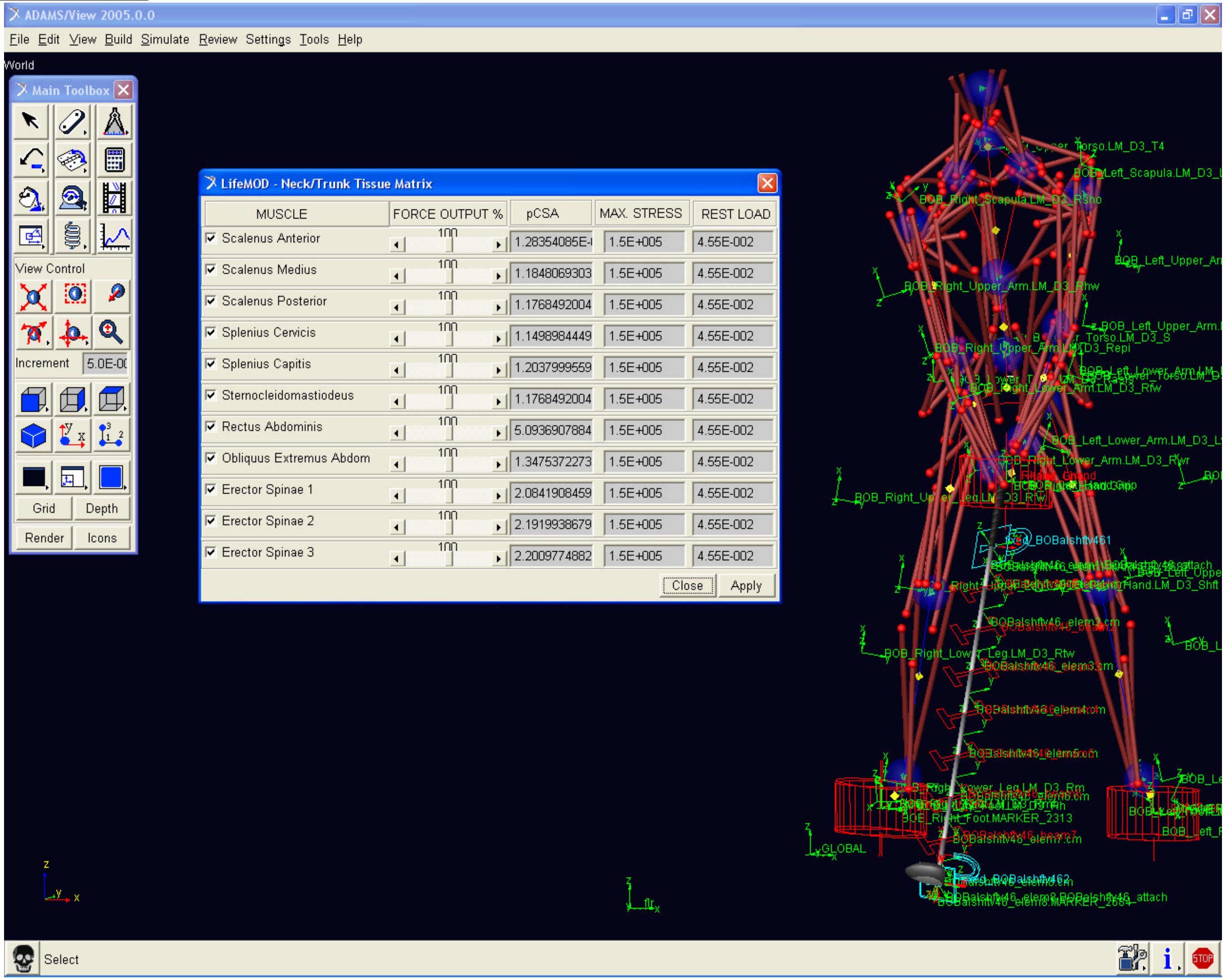
APPENDIX 7.0 Single-subject anthropometric data for model segment construction for Study 4.

Age (mths)	295.0000	Waist depth	10.7500	L knee ht seated	19.5000
Mass (lbs)	201.3000	Waist breadth	13.3750	R thigh circum	20.2500
Standing ht	71.6250	Buttock depth	11.4375	L thigh circum	20.1875
R shoulder ht	57.3125	Hip breadth standing	17.3750	R upper thigh circum	23.2000
L shoulder ht	58.0000	R shoulder-to-elbow lth	12.1875	L upper thigh circum	23.1875
R armpit ht	51.1250	L shoulder-to-elbow lth	11.9375	R knee circum	15.3750
L armpit ht	52.1250	R forearm-to-hand lth	11.0000	L knee circum	15.3750
Waist ht	41.1875	L forearm-to-hand lth	11.0625	R calf circum	14.4375
Seated ht	36.1875	R biceps circum	12.6250	L calf circum	14.3750
Head length	7.5000	L biceps circum	12.5000	R ankle circum	10.3125
Headt breadth	6.4375	R elbow circum	10.7500	L ankle circum	10.0625
Head-to-chin ht	8.1875	L elbow circum	11.3750	R ankle lateral ht	3.0625
Neck circum	16.0625	R forearm circum	10.5620	L ankle lateral ht	3.2500
Shoulder breadth	18.3125	L forearm circum	11.1250	R foot breadth	3.5625
Chest depth	10.1875	R waist circum	6.6875	L foot breadth	3.5000
Chest breadth	13.3125	L waist ht seated	6.6250	R foot length	10.0625
		R knee ht seated	20.1250	L foot length	10.1875

*All measurements given in inches unless otherwise stated, as required for input to software
ht = height
lth = length
circum = circumference

APPENDIX 8.0 List of all 111 modelled muscles for Study 4, sectionalised by trunk, arms and legs.

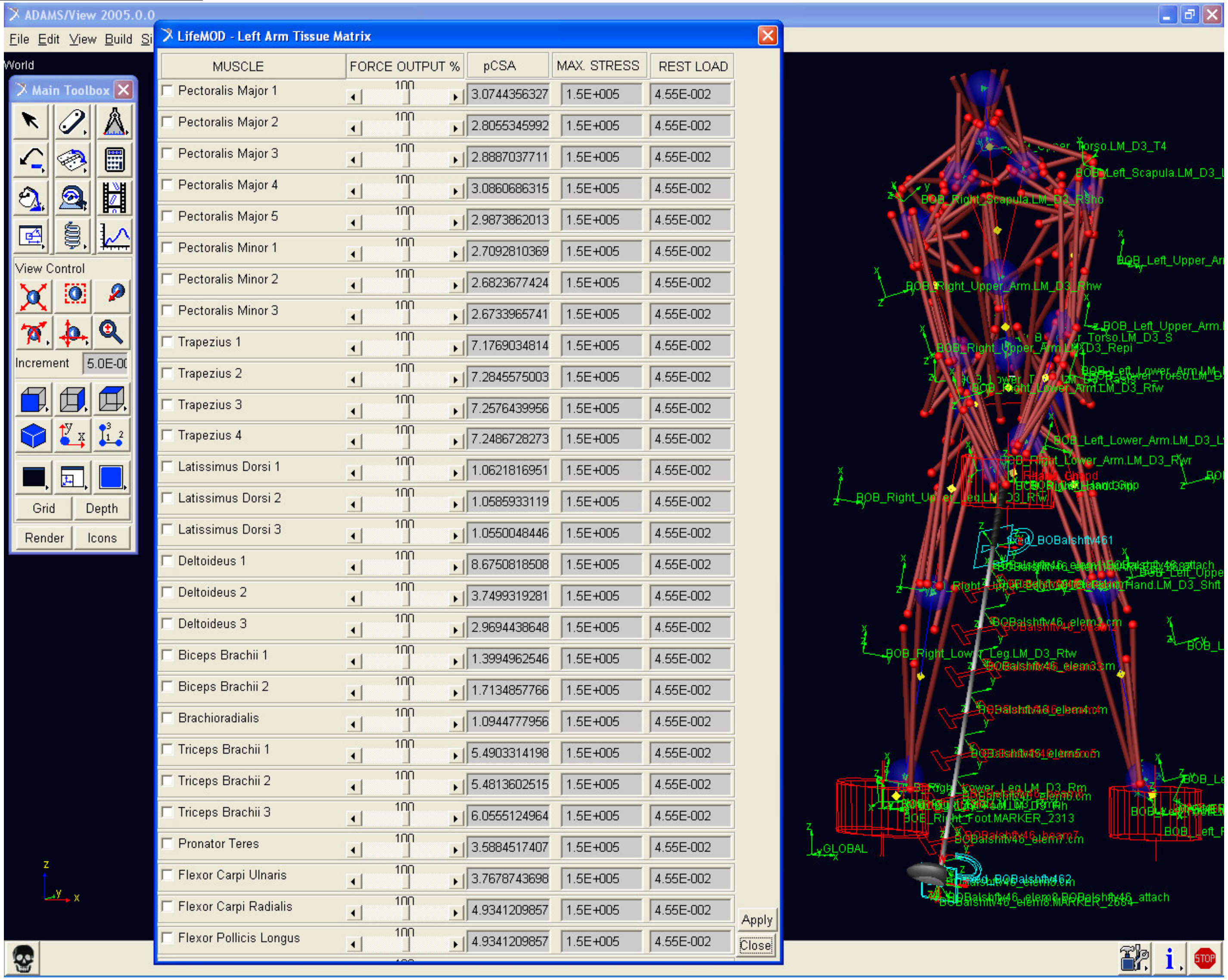
Modelled neck/trunk muscles



LifeMOD - Neck/Trunk Tissue Matrix

MUSCLE	FORCE OUTPUT %	pCSA	MAX. STRESS	REST LOAD
Scalenus Anterior	100	1.28354085E-	1.5E+005	4.55E-002
Scalenus Medius	100	1.1848069303	1.5E+005	4.55E-002
Scalenus Posterior	100	1.1768492004	1.5E+005	4.55E-002
Splenius Cervicis	100	1.1498984449	1.5E+005	4.55E-002
Splenius Capitis	100	1.2037999559	1.5E+005	4.55E-002
Sternocleidomastiodeus	100	1.1768492004	1.5E+005	4.55E-002
Rectus Abdominis	100	5.0936907884	1.5E+005	4.55E-002
Obliquus Extremus Abdom	100	1.3475372273	1.5E+005	4.55E-002
Erector Spinae 1	100	2.0841908459	1.5E+005	4.55E-002
Erector Spinae 2	100	2.1919938679	1.5E+005	4.55E-002
Erector Spinae 3	100	2.2009774882	1.5E+005	4.55E-002

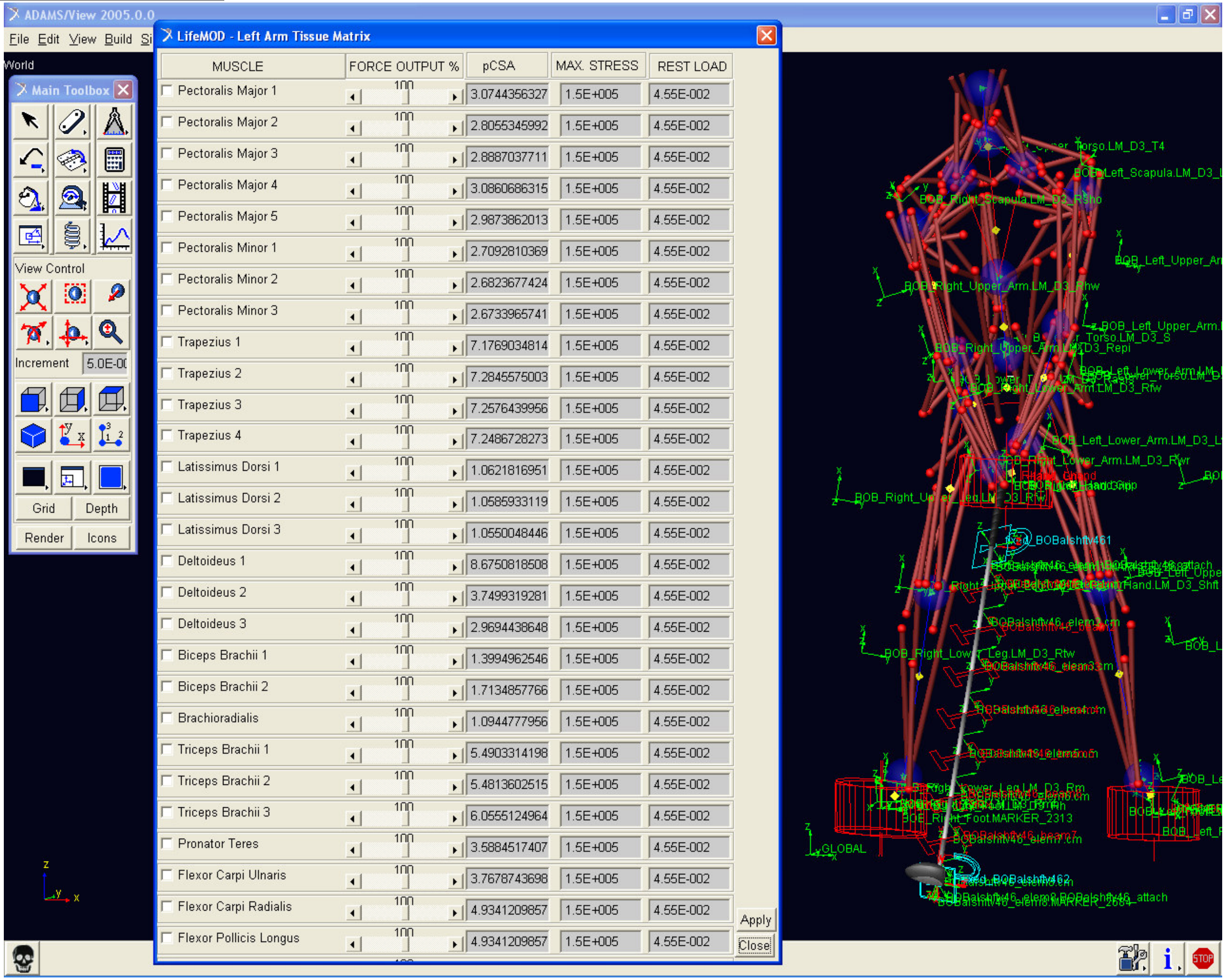
Modelled left arm/trunk muscles



MUSCLE	FORCE OUTPUT %	pCSA	MAX. STRESS	REST LOAD
Pectoralis Major 1	100	3.0744356327	1.5E+005	4.55E-002
Pectoralis Major 2	100	2.8055345992	1.5E+005	4.55E-002
Pectoralis Major 3	100	2.8887037711	1.5E+005	4.55E-002
Pectoralis Major 4	100	3.0860686315	1.5E+005	4.55E-002
Pectoralis Major 5	100	2.9873862013	1.5E+005	4.55E-002
Pectoralis Minor 1	100	2.7092810369	1.5E+005	4.55E-002
Pectoralis Minor 2	100	2.6823677424	1.5E+005	4.55E-002
Pectoralis Minor 3	100	2.6733965741	1.5E+005	4.55E-002
Trapezius 1	100	7.1769034814	1.5E+005	4.55E-002
Trapezius 2	100	7.2845575003	1.5E+005	4.55E-002
Trapezius 3	100	7.2576439956	1.5E+005	4.55E-002
Trapezius 4	100	7.2486728273	1.5E+005	4.55E-002
Latissimus Dorsi 1	100	1.0621816951	1.5E+005	4.55E-002
Latissimus Dorsi 2	100	1.0585933119	1.5E+005	4.55E-002
Latissimus Dorsi 3	100	1.0550048446	1.5E+005	4.55E-002
Deltoideus 1	100	8.6750818508	1.5E+005	4.55E-002
Deltoideus 2	100	3.7499319281	1.5E+005	4.55E-002
Deltoideus 3	100	2.9694438648	1.5E+005	4.55E-002
Biceps Brachii 1	100	1.3994962546	1.5E+005	4.55E-002
Biceps Brachii 2	100	1.7134857766	1.5E+005	4.55E-002
Brachioradialis	100	1.0944777956	1.5E+005	4.55E-002
Triceps Brachii 1	100	5.4903314198	1.5E+005	4.55E-002
Triceps Brachii 2	100	5.4813602515	1.5E+005	4.55E-002
Triceps Brachii 3	100	6.0555124964	1.5E+005	4.55E-002
Pronator Teres	100	3.5884517407	1.5E+005	4.55E-002
Flexor Carpi Ulnaris	100	3.7678743698	1.5E+005	4.55E-002
Flexor Carpi Radialis	100	4.9341209857	1.5E+005	4.55E-002
Flexor Pollicis Longus	100	4.9341209857	1.5E+005	4.55E-002

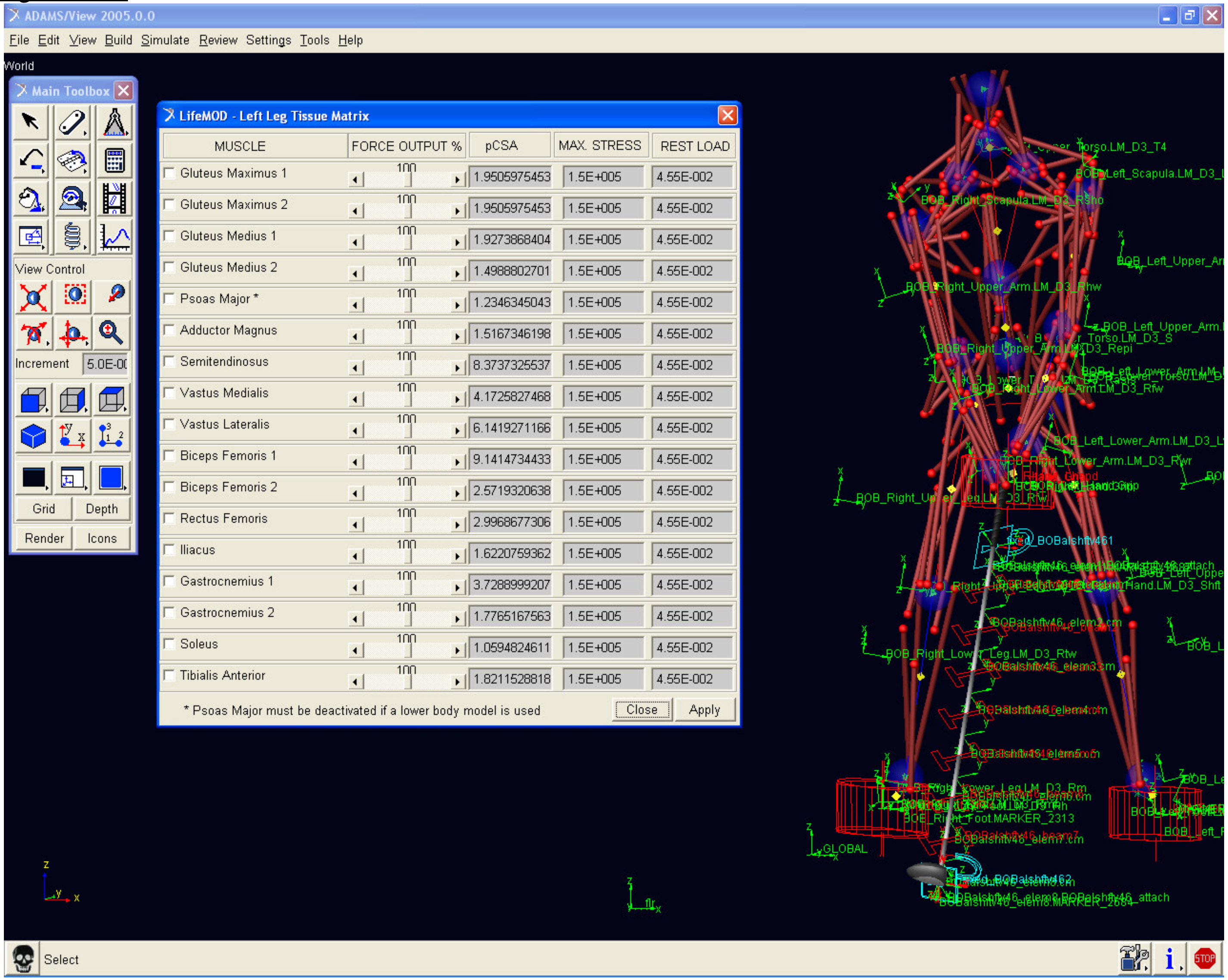
and… Flexor dititorum profundus, Extensor carpi rad longus, Extensor digiti minimi, Abductor pollicis longus, Subclavius

<u>Modelled right arm/trunk muscles</u>

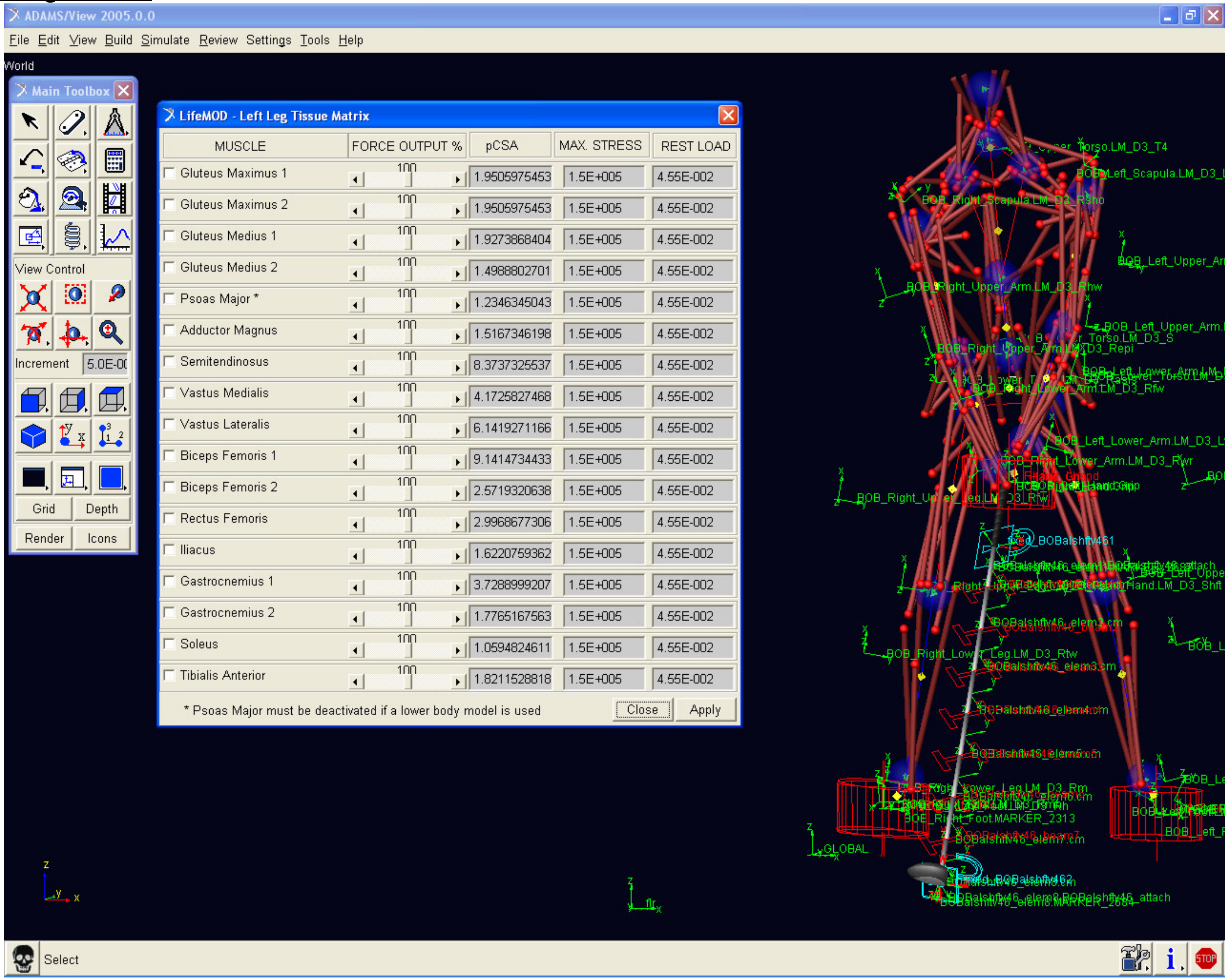


and… Flexor dititorum profundus, Extensor carpi rad longus, Extensor digiti minimi, Abductor pollicis longus, Subclavius

<u>Modelled left leg muscles</u>



Modelled right leg muscles



APPENDIX 9.0 Example .slf file used for model construction during Study 4. File includes instructions for units, anthropometric scaling, joint type and range of motion, initial postural information, and marker trajectory data for one complete frame.

```
$-------------------------------------------------------------------------UNITS
[UNITS]
LENGTH                 ='meter'
FORCE                  ='newton'
ANGLE                  ='degrees'
MASS                   ='kg'
TIME                   ='second'
$-----------------------------------------------------------ANTHROPOMETRIC_DATA
[ANTHROPOMETRIC_DATA]
SUBJECT_NAME             = 'd729'
GENDER                   = 1.0
TOTAL_BODY_HEIGHT        = 1.80
TOTAL_BODY_MASS          = 91.30
AGE                      = 303.0
HANDS                    = 2.0
NOHAT                    = 1.0
$--------------------------------------------------------------------JOINT_DATA
[JOINT_DATA]
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UPPER_NECK_Y              ='FIXED,'
UPPER_NECK_Z              ='FIXED,'
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```

```
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LEFT_KNEE_Y                ='FIXED,'
LEFT_KNEE_Z                ='FIXED,'
LEFT_ANKLE_X               ='PASSIVE,5.0e+002,5.0e+001,70.0,-70.0,1.0e+003,'
LEFT_ANKLE_Y               ='PASSIVE,5.0e+002,5.0e+001,60.0,-60.0,1.0e+003,'
LEFT_ANKLE_Z               ='PASSIVE,5.0e+002,5.0e+001,50.0,-50.0,1.0e+003,'
$-------------------------------------------------------------------POSTURE_DATA
[POSTURE_DATA]
POS_LOC                    ='0.17471143,0.67760114,1.01065784,180.0,70.0,90.0,'
Upper_Neck                 ='0.0,0.0,0.0,'
Lower_Neck                 ='0.0,0.0,0.0,'
Thoracic                   ='0.0,0.0,0.0,'
Lumbar                     ='0.0,0.0,0.0,'
Right_Scapular             ='0.0,0.0,0.0,'
Right_Shoulder             ='0.0,0.0,0.0,'
Right_Elbow                ='0.0,0.0,0.0,'
```

```
Right_Wrist                ='0.0,0.0,0.0,'
Left_Scapular              ='0.0,0.0,0.0,'
Left_Shoulder              ='0.0,0.0,0.0,'
Left_Elbow                 ='0.0,0.0,0.0,'
Left_Wrist                 ='0.0,0.0,0.0,'
Right_Hip                  ='0.0,0.0,0.0,'
Right_Knee                 ='0.0,0.0,0.0,'
Right_Ankle                ='0.0,0.0,0.0,'
Left_Hip                   ='0.0,0.0,0.0,'
Left_Knee                  ='0.0,0.0,0.0,'
Left_Ankle                 ='0.0,0.0,0.0,'
$---------------------------------------------------------------------MARKER_SET
[MARKER_SET]
TYPE = 'golf'
T4= 'ON'
RSHO= 'ON'
RHUW= 'ON'
REPI= 'ON'
RFOW= 'ON'
RWRI= 'ON'
LSHO= 'ON'
LHUW= 'ON'
LEPI= 'ON'
LFOW= 'ON'
LWRI= 'ON'
SACRU= 'ON'
RASIS= 'ON'
RFEMW= 'ON'
RFEMC= 'ON'
RTIBW= 'ON'
RLATM= 'ON'
RHEEL= 'ON'
R2MET= 'ON'
LASIS= 'ON'
LFEMW= 'ON'
LFEMC= 'ON'
LTIBW= 'ON'
LLATM= 'ON'
LHEEL= 'ON'
L2MET= 'ON'
SHFT= 'ON'
$--------------------------------------------------------------------MOTION_DATA
[MOTION_DATA]
{ time part   x      y      z      yaw    pitch  roll   }
```

0.00000	1.00000	0.23926724	0.4349624	1.47570142	0.00000	0.00000	0.00000
0.00000	2.00000	0.15874983	0.24707863	1.37229456	0.00000	0.00000	0.00000
0.00000	3.00000	0.10151485	0.18962959	1.11734827	0.00000	0.00000	0.00000
0.00000	4.00000	0.1804169	0.21813602	1.02640784	0.00000	0.00000	0.00000
0.00000	5.00000	0.29348358	0.12513942	0.91364191	0.00000	0.00000	0.00000
0.00000	6.00000	0.31082227	0.17082167	0.79370081	0.00000	0.00000	0.00000
0.00000	7.00000	0.46516727	0.37238849	1.42722742	0.00000	0.00000	0.00000
0.00000	8.00000	0.55444806	0.3198924	1.17042139	0.00000	0.00000	0.00000
0.00000	9.00000	0.50227856	0.35330994	1.09136462	0.00000	0.00000	0.00000
0.00000	10.00000	0.48737149	0.22354555	0.94899054	0.00000	0.00000	0.00000
0.00000	11.00000	0.42431689	0.25341757	0.85752704	0.00000	0.00000	0.00000
0.00000	12.00000	0.17471143	0.67760114	1.01065784	0.00000	0.00000	0.00000
0.00000	13.00000	0.1550098	0.39448325	0.9787959	0.00000	0.00000	0.00000
0.00000	14.00000	-0.02631342	0.35510837	0.68496423	0.00000	0.00000	0.00000
0.00000	15.00000	0.07097889	0.32283762	0.5305376	0.00000	0.00000	0.00000
0.00000	16.00000	-0.06606158	0.33988602	0.34359894	0.00000	0.00000	0.00000
0.00000	17.00000	-0.01817099	0.44060464	0.11508878	0.00000	0.00000	0.00000
0.00000	18.00000	0.02678518	0.51962518	0.07783906	0.00000	0.00000	0.00000
0.00000	19.00000	0.03907552	0.28784909	0.08030916	0.00000	0.00000	0.00000
0.00000	20.00000	0.39543552	0.51324292	0.97756689	0.00000	0.00000	0.00000
0.00000	21.00000	0.55013251	0.633198	0.68036829	0.00000	0.00000	0.00000
0.00000	22.00000	0.51863239	0.55783868	0.5174176	0.00000	0.00000	0.00000
0.00000	23.00000	0.59871161	0.66016199	0.33632953	0.00000	0.00000	0.00000
0.00000	24.00000	0.51446954	0.66173138	0.10638649	0.00000	0.00000	0.00000
0.00000	25.00000	0.42524857	0.69728607	0.06894794	0.00000	0.00000	0.00000
0.00000	26.00000	0.59250983	0.52152045	0.07862698	0.00000	0.00000	0.00000
0.00000	27.00000	0.47674323	0.05521843	0.56560242	0.00000	0.00000	0.00000
0.00417	1.00000	0.23922954	0.43493381	1.47563989	0.00000	0.00000	0.00000
0.00417	2.00000	0.15876776	0.24706332	1.37235022	0.00000	0.00000	0.00000
0.00417	3.00000	0.1014293	0.18966803	1.11736414	0.00000	0.00000	0.00000
0.00417	4.00000	0.18014316	0.2180231	1.02631812	0.00000	0.00000	0.00000
0.00417	5.00000	0.2933399	0.12511501	0.91366748	0.00000	0.00000	0.00000
0.00417	6.00000	0.31110577	0.1706821	0.79355292	0.00000	0.00000	0.00000
0.00417	7.00000	0.4651055	0.37251196	1.42716064	0.00000	0.00000	0.00000
0.00417	8.00000	0.55421466	0.31991669	1.17071167	0.00000	0.00000	0.00000
0.00417	9.00000	0.50214432	0.35327597	1.09135876	0.00000	0.00000	0.00000
0.00417	10.00000	0.48730542	0.22387888	0.94876556	0.00000	0.00000	0.00000

APPENDIX 10.0 Excel macro used for manual calculation of clubhead velocity from MAC^{TM} p3d files for Study 4.

```
Sub extract()

With Sheets("Sheet1")

j = 1
shaft = (46 + 4) * 0.0254
While .Cells(j, "A").Value <> ""
   distance = Sqr((.Cells(j, "C").Value - .Cells(j, "I").Value) ^ 2 _
      + (.Cells(j, "D").Value - .Cells(j, "J").Value) ^ 2 _
      + (.Cells(j, "E").Value - .Cells(j, "K").Value) ^ 2)
   Sheets("Sheet2").Cells(j, "A").Value = .Cells(j, "A").Value
   Sheets("Sheet2").Cells(j, "B").Value = distance
   lambda = shaft / distance
   p_x = (.Cells(j, "I").Value - .Cells(j, "C").Value) * lambda + .Cells(j, "C").Value
   p_y = (.Cells(j, "J").Value - .Cells(j, "D").Value) * lambda + .Cells(j, "D").Value
   p_z = (.Cells(j, "K").Value - .Cells(j, "E").Value) * lambda + .Cells(j, "E").Value
   Sheets("Sheet2").Cells(j, "C").Value = p_x
   Sheets("Sheet2").Cells(j, "D").Value = p_y
   Sheets("Sheet2").Cells(j, "E").Value = p_z
   j = j + 1
Wend

End With

With Sheets("Sheet2")
j = 1
While .Cells(j + 1, "A").Value <> ""
   delta_t = (.Cells(j + 1, "A").Value - .Cells(j, "A").Value)
   v_x = (.Cells(j + 1, "C").Value - .Cells(j, "C").Value) / delta_t
   v_y = (.Cells(j + 1, "D").Value - .Cells(j, "D").Value) / delta_t
   v_z = (.Cells(j + 1, "E").Value - .Cells(j, "E").Value) / delta_t
   vtot = Sqr(v_x ^ 2 + v_y ^ 2 + v_z ^ 2)
   Sheets("Sheet2").Cells(j, "F").Value = vtot
   j = j + 1
Wend
End With
                              End Sub
```

APPENDIX 11.0 Select whole body kinematics at address, top-of-backswing and impact for individual low-medium handicap golfers using drivers of different shaft length for Study 1.

Club (″)	arknee	alknee	arshank	abkincl	alarmtnk	ashldrot	ahiprot
46	27.82	23.46	100.82	69.89	35.31	-3.81	-18.68
46	25.4	28.5	101.05	81.54	31.09	-11.13	-9
46	14.06	20.87	96.62	73.92	39.25	-5.12	-5.39
46	27.61	19.28	100.29	73.44	36.55	-10.26	-0.15
46	36.61	30.76	103.95	76.28	40.71	-5.35	-5.1
46	27.65	33.07	96.29	62.13	38.11	-4.67	-4.01
46	34.55	64.16	92.78	70.59	47.93	-16.3	1.89
46	26.56	23.77	98.37	66.2	40.53	-9.25	-9.79
45	22.33	12.12	95.96	72.26	38.71	-10.77	-12.77
47	28.38	23.55	101.45	69.71	35.05	-4.49	-18.57
47	23.34	26.87	100.27	80.59	32.38	-12.63	-9.17
47	12.06	19.7	96.55	75.56	38.4	-2.36	-3.34
47	30.79	20.28	102.55	78.28	35.75	-8.51	-5.2
47	38.76	33.28	104.66	79.03	43.17	-6.99	-6.05
47	26.74	33.62	94.53	62.85	39.21	-3.23	-2.05
47	48.25	69.49	93.42	69	48.86	-19.39	-0.79
47	25.57	24.12	97.93	68.87	39.07	-7.27	-7.05
47	23.32	9.79	95.9	73.13	37.15	-13.04	-13.04
49	26.38	22.37	100.51	71.33	35.33	-5.48	-18.76
49	24.19	26.44	100.9	81.26	32.19	-12.88	-9.63
49	12.3	20.35	93.32	76.1	36.19	-2.26	-4.38
49	33.88	21.69	106.15	86.29	35.34	-9.23	-4.69
49	35.65	31.96	103.91	81.31	42.57	-8.32	-7.82
49	26.97	34.12	95.57	63.55	39.03	-2.43	-2.19
49	33.18	62.94	93.23	68.76	47.91	-18.61	-1.17
49	26.04	23.7	98.58	70.34	37.99	-7.31	-8.38
49	21.35	7.89	96.21	73.19	38.15	-12.94	-14.5
52	23.1	21.71	98.59	73.19	34.56	-4.67	-18.14
52	25.62	27.75	102.19	82.43	33.56	-12.2	-7.48
52	11.37	20.03	95.64	76.01	37.57	-2.25	-1.79
52	30.56	21.12	103.64	84.8	36.34	-8.12	-3.96
52	38.55	33.95	105.23	82.16	42.28	-7.45	-6.55
52	25.2	33.84	95.38	66.21	39.38	-3.74	-3
52	34.78	56.11	94.85	70.48	48.5	-20.61	-2.05
52	25.17	21.99	98.68	69.79	38.78	-7.23	-7.29
52	21.66	6.76	96.39	75.04	38.35	-13.59	-14.51

Key

a = address
t = top-of-backswing
i = impact
rknee = right knee angle
lknee = left knee angle
rshank = right shank angle
bkincl = back inclination
larmtnk = left-ar-trunk angle
shldrot = shoulder rotation angle
hiprot = hip rotation angle
larmclb = left-arm-club angle
stwidth = stance width

Club (″)	alarmclb	astwidth	afoottee	tshldrot	thiprot	tbkincl	tlarmtnk
46	125.88	441.73	971.94	97.54	30.2	71.95	83.36
46	134.37	508.93	174.1	90.12	35.18	80.8	84.71
46	141.9	609.11	979.01	107.15	47.33	72.89	78.31
46	124.21	530.01	986.38	95.46	51.85	82.4	89.98
46	129.57	500.82	978.64	82.26	35.41	81.57	89.25
46	126.55	637.93	1011.44	95.5	42.61	61.79	83.98
46	145.82	584.89	1015.55	95.18	45.39	77.56	84.75
46	142.32	470.27	918.72	96.87	40.34	70.45	89.2
45	125.12	609.41	1118.68	96.77	52.3	76.14	85.07
47	125.14	446.25	1025.39	96.19	27.6	72.5	82.55
47	135.87	518.91	150.28	87.5	33.18	80.96	83.84
47	143.08	612.5	998.64	108.73	47.57	73.58	77.21
47	124.65	518.09	1009.89	94.6	51.83	84.57	87.98
47	133.5	502.75	1003.78	86.85	36.68	83.84	89.12
47	126.96	642.55	1044	96.61	43.62	62.94	86.02
47	146.62	580.38	1046.49	93.04	42.36	77.7	84.26
47	137.97	492.78	944.43	102.1	46.24	72.06	89.13
47	122.03	612.71	1153.32	96.05	51.46	77.76	83.62
49	125.45	444.11	1077.07	95.65	28.07	73.29	82.81
49	134.59	518.12	93.36	90.46	35	81.76	83.88
49	137.44	612.61	1059.66	108.04	47.82	74.27	77.21
49	124.4	523.09	1089.46	92.02	47.53	89.28	84.87
49	134.67	514.96	1077.99	85.51	36.89	84.8	87.47
49	125.79	644.88	1104.42	98.52	45.23	64.1	87
49	145.41	575.24	1098.95	94.36	43.86	77.89	84.2
49	136.28	470.27	918.72	101.87	44.51	73.44	89.29
49	123.07	614.4	1224.65	93.97	51.96	78.38	83.29
52	126.29	452.06	1161.79	100.44	33.14	75.09	83.99
52	132.73	535.04	106.82	91.82	36.24	82.48	84.33
52	136.6	582.32	1158.04	108.81	49.95	75.16	75.73
52	126.01	532.65	1189.43	93.73	50.57	89.04	86.19
52	132.67	518.45	1163.59	87.32	37.47	85.41	87.07
52	125.21	639.75	1210.17	98.16	44.75	66.31	86.36
52	147.58	578.66	1184.83	93.87	41.81	79.41	83.23
52	136.93	526.03	1105.14	104.39	47.75	74.38	89.17
52	123.09	628.25	1327.2	96.11	55.16	82.09	83.22

Club (″)	irknee	ilknee	ibkincl	irshank	ilarmtnk	ishldrot	ihiprot
46	42.24	12.16	82.88	82.88	36.65	-20.58	-55.72
46	43.33	26.95	84.62	93.42	38.92	-25.87	-55.13
46	10.46	15.98	77	72.39	46.6	-7.34	-28.78
46	19.98	13.85	80.22	89.11	38.35	-11.89	-25.07
46	47.19	30.23	91.45	56.87	33.13	-6.6	-38.18
46	40.38	47.48	67.1	79.18	33.25	-12.95	-25.84
46	126.81	143.49	78.44	83.59	43.02	-0.33	-29.6
46	39.06	23.91	76.75	84.73	35.43	-24.45	-50.73
45	23.21	20.73	73.03	82.87	36.76	-11.66	-31.48
47	45.29	13.23	83.06	79.98	37.35	-23.46	-58.93
47	45.03	26.33	84.19	94.03	40.98	-28.39	-54.7
47	8.63	13.99	80.11	68.4	45.92	-3.98	-24.35
47	18.77	10.89	84.42	87.5	37.62	-11.32	-22.62
47	47	31.66	93.63	85.78	33.09	-4.91	-37.04
47	40.32	47.49	66.91	77.27	33.37	-14.05	-24.97
47	131.97	144.78	77.38	81.79	43.19	-3.56	-30.65
47	37.99	27.51	76.43	85.93	33.45	-21.43	-45.55
47	22.54	21.13	74.21	79.89	36.27	-11.89	-32.19
49	44.65	11.65	83.96	79.36	36.99	-25.32	-60.48
49	41.78	27.82	87	93.01	41.78	-29.3	-57.13
49	7.29	12.44	81.04	64.31	44.59	-5.3	-24.46
49	19.49	10.26	90.61	89.06	37.6	-13.54	-23.63
49	45.98	30.81	94.3	85.32	32.68	-6.82	-37.77
49	37.32	46.06	67.92	77.79	33.33	-13.63	-23.73
49	124.18	144.41	78.77	79.51	42.51	-4.29	-29.66
49	32.67	27.69	77.72	86.25	34.43	-18.45	-42.34
49	21.85	20.33	74.04	78.9	36.76	-14.74	-33.11
52	42.06	12.6	86.29	76.51	36.47	-28.04	-59.44
52	44.51	26.99	87.33	91.15	44.43	-32.67	-57.92
52	6.76	14.32	80.98	67.05	47.59	-5.48	-23.31
52	18.27	10.4	88.88	86.55	39.31	-14.18	-21.59
52	45.14	30.9	95.85	86.24	33.42	-7.09	-36.25
52	36.27	45.16	69.27	77.25	34.82	-15.71	-25.97
52	125.82	145.35	80.66	78.15	42.88	-7.42	-31.25
52	35.64	26.79	79.28	81.18	35.56	-25.5	-46.05
52	21.33	19.11	75.86	76.99	38.2	-20.05	-36.5

APPENDIX 12.0 Mean (± S.D.) peak clubhead angular velocity for club length for Study 4.

Club (″)	Peak Clubhead Angular Velocity* ($rads^{-1}$)
46	42.55 ± 0.01
48	41.87 ± 0.01
50	44.56 ± 0.01

*NS

REFERENCES

Abdelnour, T.A., Passerello, C.E. and Huston R.L. (1975) An analytical analysis of walking. *American Society of Mechanical Engineers,* 75-WA/Bio-4.

Abdel-Aziz, Y.A. and Karara H.M. (1971) Direct linear transformation from comparator coordinates into object-space coordinates in close-range photogrammetry, *Papers from the American Society of Photogrammetry, Symposium on Close-Range Photogrammetry*, Urbana, Illinois 433, 1-18.

Abuzzahab, F.S., Lim, T.H., Harris, G.F., Hasehawa, T. and Kidder, S.M. (1995) A method for covering surfaces of reflective gait markers, *Gait and Posture,* **3** (3), 264-265.

Adlington, G.S. (1996) Proper swing technique and biomechanics of golf, *Clinics in Sports Medicine*, **15**, 9-25.

Alexander, E.J. and Andriacchi, T.P. (2001) Correcting for deformation in skin-based marker systems, *Journal of Biomechanics,* **34**, 355-361.

Alexander, R.McN. (2003), Modelling approaches in biomechanics, *Royal Society, London, Philosophical Transactions*, **358**, 1429-1435.

Anderson, F.C., Arnold, A.S., Pandy, M.G., Goldberg, S.R. and Delp, S.L. (2005) Simulation of walking, In Human Walking, 3rd Edition (Ed. Rose, J. and Gamble, J.G.), Lippincott Williams and Williams, Inc., Philadelphia, 195-210.

Anderson, F.C. and Pandy, M.G. (1999) A dynamic optimisation solution for vertical jumping in three dimensions, *Computer Methods in Biomechanics and Biomedical Engineering*, **2** (3), 201-231.

Anderson, F.C. and Pandy, M.G. (2001) Dynamic optimisation of human walking", *Journal of Biomechanical Engineering*, **123** (5), 381-390.

Anderson, F.C., Ziegler, J.M., Pandy, M.G. and Whalen, R.T. (1995) Application of high-performance computing to numerical simulation of human movement, *Journal of Biomechanical Engineering*, **117** (1), 155-157.

Anderson, F.C., Ziegler, J.M., Pandy, M.G. and Whalen, R.T. (1996) Solving large-scale optimal control problems for human movement supercomputers. In Building a man in the machine: computational medicine (Ed. Witten M. and Vincent D.J.), *Public Health and Biotechnology: Part II*. World Scientific, 1088-1118.

Aoyama, S. (1990) A modern method for the measurement of aerodynamic lift and drag on golf balls, In Science and Golf: proceedings of the first world scientific congress of golf, (Ed. Cochran A.J. & Farrally M.R), E&F.N. Spon, London, 199-204.

Aoyama, S. (1994) Changes in golf ball performance over the last 25 years. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 348-354.

Asmussen, E. and Bonde-Petersen, F. (1974) Storage of elastic energy in skeletal muscles in man, *Acta Physiol Scand,* **91**, 385–392.

Asmussen, E. and Bonde-Peterson, F. (1974a), Apparent efficiency and storage of elastic energy in human muscles during exercise, *Acta. Physiol. Scand.*, **92**, 537-545.

Asuda, M. and Kojima S. (1994) Kick back effect of club-head at impact. In Science and Golf: proceedings of the first world scientific congress of golf, (Ed. Cochran A.J. & Farrally M.R), E&F.N. Spon, London, 284-289.

Audu, M.L. (1987) Optimal control modelling of the lower extremity musculoskeletal motion, PhD thesis, Case Western Reserve University, Cleveland, Ohio, pps216.

Banks, S.A., Markovich, G.D. and Hodge, W.A. (1997) In vivo kinematics of cruciate-retraining and substituting knee arthoplastics, *Journal of Arthroplasty*, **12**, 297-304.

Bartlett, R. (1997) Biomechanical analysis of movement in sport and exercise, BASES, Leeds.

Bartlett, R. (1997) Introduction to sports biomechanics, BASES, Leeds.

Bastow, M. D. (1982) Anthropometrics revisited, *Proceedings of the Nutritional Society,* **41**, 381-388.

Bates, B. T. (1996) Single-subject methodology: an alternative approach, *Medicine & Science in Sports & Exercise,* **28** (5), 631-638.

Bates, B. T., Rodger, C.J. and Dufek, J.S. (2004) Single-subject analysis, In Innovative analyses of human movement, (Ed. Stergiou, N.), Illinois, Human Kinetics, 3-28.

Bechler, J.R., Jobe, F.W., Pink, M., Perry, J. and Ruwe P.A. (1995) Electromyographic analysis of the hip and knee during the golf swing, *Clinical Journal of Spors Medicine*, **5**, 162-166.

Bemben, M.G., Sato, Y. and Abe, T. (2005) The use of anthropometry for assessing muscle size. *International Journal for Kaatsu Training Research*, **1**, 33-36.

Bernstein, N. (1967) Coordination and regulation of movements, Pergamon Publications, New York.

Bhargava, L.J., Pandy, M.G. and Anderson F.C. (2004) A phenomenological model for estimating metabolic energy consumption in muscle contraction, *Journal of Biomechanics*, **37** (1), 81-88.

Bobbert, M.F. and Casius, L.J. (2005) Is the effect of a countermovement on jump height due to active state development? *Medicine and Science in Sports and Exercise*, **37** (3), 440-446.

Bobbert, M.F., Gerritsen, K.G., Litjens, M.C. and Van Soest, A.J. (1996) Why is countermovement jump height greater than squat jump height? *Medicine and Science in Sports and Exercise*; **28** (11), 1402-1412.

Bobbert, M.F., Huijing, P.A. and van ingen Schenau, G.J. (1987a). Drop jumping I. The influence of jumping technique on the biomechanics of jumping. *Medicine and Science in Sports and Exercise*, **19**, 332-338.

Bobbert, M.F., Mackay, M., Schinkelshoek, D., Huijing, P.A. and Ingen Schenau, G.J. (1986) Biomechanical analysis of drop and countermovement jumps, *European Journal of Applied Physiology*, **54** (6), 556-573.

Bobbert, M.F. and Van Ingen Schenau, G.J. (1988) Coordination in vertical jumping. *Journal of Biomechanics*, **21** (3), 249-262.

Bosco, C., Komi, P.V. and Ito, A. (1981) Prestretch potentiation of human skeletal muscle during ballistic movement. *Acta. Physiol,* **111**,135-140.

Bosco, C., Tihanyi, J., Komi, PV., Fekete, G., and Apor, P. (1982) Store and recoil of elastic energy in slow and fast types of human skeletal muscles, *J. Acta. Physiology Scandinavica*, **116**, 343-349.

Bradley, J.P. and Tibone, J.E. (1991) Electromyographic analysis of muscle action about the shoulder, *Clinical Journal of Sports Medicine*, **10**, 789-805.

Brampton, B. (1991) In Golf: Technique, tactics, training, (Ed. Tait, A.), Crowood Press, Wiltshire.

Brozek, J. (1956) Physique and nutritional status of adult men, *Human Biology*, **28** (2), 124-140.

Brumer, A. (2003) The new graphite shafts are lighter, stronger, better. Should you make the same switch tour players are making? *Golf Digest*, January 2003.

Brumer, A. (2005) The Only Shaft Story You Need to Read. *Golf Digest*, September 2005.

Brylawski, A.M. (1994) An investigation of three dimensional deformation of a golf club during downswing. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 265-270.

Bryson, A.E. and Ho, Y.C. (1975), Applied optimal Control, Washington, DC:Hemisphere.

Budney, D.R. (1979) Measuring grip pressure during the golf swing. *Research Quarterly,* **50** (2), 272-277.

Budney, D. and Bellow, D.G. (1982) On the swing mechanics of a matched set of golf clubs, *Research Quarterly for Exercise and Sport*, **53** (3), 185-192.

Bulbulian, R., Ball, K., and Seaman, D. (2001) The Short Golf Backswing: Effects on Performance and Spinal Health Implications. *Journal of Manipulative and Physiological Therapeutics*, **24** (9), 569-575.

Bunn, J.W. (1972) Scientific principles of coaching, Englewood Cliffs, Prentice-Hall, Jew Jersey.

Burden, A.M., Grimshaw, P.N. and Wallace E.S., (1998) Hip and shoulder rotations during the golf swing of sub-10 handicap players, *Journal of Sports Sciences*, **16**, 165-176.

Butler, J.H. and Winfield D. C. (1994) The dynamic performance of the golf shaft during the downswing. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 259-264.

Cappozzo A., Cappello A, Croce U.D. and Pensalfini F. (1997) Surface marker cluster design criteria for 3D bone movement reconstruction, *IEEE Transaction on Biomedical Engineering*, **44** (12), 1165-1174.

Cappozzo, A., Gazzani, F. and Macellari, V. (1988). Skin marker artifacts in gait analysis. *Proceedings of the 6th meeting of the European Society of Biomechanics*, Butterworth, London, 23.

Cavagna, G.A., Dusman, B. and Margaria, R. (1968) Positive work done by a previously stretched muscle, *Journal of Applied Physiology*, **24** (1), 21-32.

Chalmers, D. (2004) Research involving humans: a time for change? *Journal of Law, Medicine and Ethics,* **32** (4), 583-595.

Chapman, A.E. (1985), The mechanical properties of human muscle, *Exercise and Sports Science Review*, **13**, 443-501.

Cheetham, P.J., Martin, P.E., Mottram R.E. and St. Laurent B.F. (2001) The importance of stretching the "X-factor" in the downswing of golf: the "X-factor stretch. In Optimising performance in golf, (Ed. Thomas, P.R.), Brisbane, Australian Academic Press Pty. Ltd., 192-199.

Cochran, A.J. (2002) The impact of science and technology on golf equipment- a personal view, *The Engineering of Sport 4.* (Ed. Ujihashi, S. & Haake, S.J.) Oxford, Blackwell Science**,** 3-15.

Cochran, A. and Stobbs, J. (Ed.) (1968) The search for the perfect swing, JB Lippincott Co., Philadelphia.

Cochran, A.J. and Stobbs, J. (1996) Search for the Perfect Swing: The Proven Scientific Approach to Fundamentally Improving Your Game. Triumph Books, Chicago.

Cochran, A.J. (1998) Club face flexibility and coefficient of restitution. In Science and Golf III: Proceedings of the world scientific congress of golf (Ed. Farrally M.R. and Cochran A.J.), Human Kinetics, Leeds, 486-492.

Cole, G. (2003) Application of forward dynamics simulation to the study of human movement, Available at www.pims.math.ca/industrial/2003/lunchbox/cole-12-05.html, accessed 18/2/04.

Cox, R.H. (1994) Sport psychology. Concepts and applications (3rd edition), Brown and Benchmark, Dubuque.

Cross, R. and Bower R. (2006) Effects of swingweight on swing speed and racket power. *Journal of Sports Sciences*, **24** (1), 23-30.

Daly, G.R. (1996) Titanium golf club heads take off long and straight. *Titanium news*, **26** (1 Winter), 1-2.

Damsgaard, M., Rasmussen, J., Torholm, S., Surma, E. and de Zee, M. (2001) AnyBody- a system for biomechanical analysis and ergonomic design, Presented at the 2nd Max Planck workshop on Engineering Design Optimisation, Nyborg, Denmark, 12-14 October.

Davids, K, Glazier, P, Araujo, D and Bartlett, R (2003), Movement systems as dynamical systems: the functional role of variability and its implications for sports medicine, *Sports Medicine*, **33** (4), 245-260.

Davy, D.T. and Audu, M.L. (1987), A dynamic optimisation technique for predicting muscle forces in the swing phase of gait, *Journal of Biomechanics*, **20**, 187-201.

de Haan, A., Van Ingen Schenau, G.J., Ettema, G.J., Huijing, P.A. and Lodder, M.A. (1989) Efficiency of rat medial gastrocnemius muscle in contractions with and without and active prestretch, *Journal of Experimental Biology*, **141**, 327-341.

de Zee, M., Andersen, T.B., Hansen, L., Wong, C., Rasmussen, J. and Simonsen, E.B (2003) Simulation of lifting using the better of two worlds: forward and inverse dynamics, *IX International Symposium on Computer Simulation in Biomechanics*, Sydney, Australia, 2nd-4th July 2003.

de Zee, M., Hansen, L., Andersen, T.B., Wong, C., Rasmussen, J. and Simonsen, E.B. (2003), On the Development of a Rigid-Body Spine Model, *Presented at the International Congress on Computational Bioengineering*, Spain, June 30th-July 3rd.

Delp, S. and Heegard, J. (2004) Modelling and simulation of human movement, Module notes, available at www.stanford.edu/group/nmbl/classes/me382/pdfFiles/Lecture2.pdf, accessed 16-8-05.

Delp, S.L., Ringwelski, D.A., and Carroll, N.C. (1994) Transfer of the rectus femoris: effects of transfer site on moment arms about the knee and hip. *Journal of Biomechanics*, **27** (10), 1201-1211.

Demster, W.T. and Gaughran G.R.L. (1967), Properties of body segments based on size and weigh", *American Journal of Anatomy*, **120**, 33-54.

Easterbrook, J.A. (1959) The effect of emotion on cure utilization and the organization of behaviour, *Psychological Review*, **66**, 183-201.

Edman, K.A., Elzinga, G. and Noble, M.I. (1978) Enhancement of mechanical performance by stretch during tetanic contractions of vertebrate skeletal muscle fibres. *Journal Physiology*, **281**, 139-155.

Edman, K.A., Elzinga, G. and Noble, M.I. (1982) Residual force enhancement after stretch of contracting frog single muscle fibers. *Journal General Physiology*, **80** (5), 769-784.

Egret, C.I., Nicolle, B., Dujardin, F.H., Weber, J. and Chollet, D. (2005) Kinematic Analysis of the golf swing in men and women experienced golfers, *International Journal of Sports Medicine,* **27** (6), 463-467.

Egret, C.I., Vincent, O., Weber, J., Dujardin, F.H. and Chollet, D. (2003) Analysis of 3D kinematics concerning three different clubs in golf swing, *International Journal of Sports Medicine*, **24**, 465-469.

Egret, C., Weber, J., Dujardin, F. and Chollet, D. (2004) The effect of electromyographic equipment on golf swing kinematics, *Isokinetics and Exercise Science,* **12** (3), 199-202.

Rousanoglou, E.N., Oskouei, A.E. & Herzog, W. (2006) Force depression following muscle shortening in sub-maximal voluntary contractions of human adductor pollicis, *Journal of Biomechanics*, **40** (1), 1-8.

Elliot, B., Wallis, R., Sakurai, S., Lloyd, D. & Besier, T. (2002) The measurement of shoulder alignment in cricket fast bowling, *Journal of Sports Sciences*, **20**, 507-510.

Ettema, G.J., Huijing, P.A., van Ingen Schenau, G.J. and de Haan, A. (1990) Effects of prestretch at the onset of stimulation on mechanical work output of rat medial gastrocnemius muscle-tendon complex, *Journal of Experimental Biology*, **152**, 333-351.

Ettema, G.J.C., van Soest, A.J. and Huijing, P.A. (1990), The role of series elastic structures in prestretch-induced work enhancement during isotonic and isokinetic contractions, *Journal of Experimental Biology*, **154**, 121-136.

Eycleshymer, A.C., & Shoemaker, D.M. (1970) A cross-section anatomy: Appleton-Century-Crofts, New York.

Farrally, M. R., Cochran, A.J., Crews, D.J., Hurdzan, M.J., Price, R.J., Snow, J. T. and P. R. Thomas (2003) Golf science research at the beginning of the twenty-first century, *Journal of Sports Sciences*, **21**, 753-765.

Fleisig, G., Zheng, N., Stodden, D.F. and Andrews, J.R. (2000) Relationship between bat mass properties and bat velocity, *Sports Engineering*, **4**, 1-4.

Fradkin, A.J., Sherman, C.A. and Finch, C.F. (2004) How well does club head speed correlate with golf handicaps, *Journal of Science and Medicine in Sport*, **7** (4), 465-472.

Fradkin, A.J., Sherman, C.A. and Finch, C.F. (2004a) Improving golf performance with a warm up conditioning programme, *British Journal of Sports Medicine*, **38**, 762-765.

Fregly, B.J. and Zajac, F.E. (1996) A state-space analysis of mechanical energy generation, absorption, and transfer during pedalling, *Journal of Biomechanics*, **29**, 81-90

Froes, F.H. (1999) Will the titanium golf club be tomorrow's mashy niblock? *Journal of Metals*, **51** (6),18-20.

Fuller, N.J., Hardingham, C.R., Graves, M., Screaton, N., Dixon, A.K., Ward, L.C., and Elia, M. (1999) Predicting composition of leg sections with anthropometry and bioelectrical impedance analysis, using magnetic resonance imaging as reference, *Clinical Science*, **96** (6), 647-657.

Gallenstein, J. and Huston, R.L. (1973) Analysis of swimming motions, *Human Factors*, **15**, 91-98.

Gatt, C.J.J., Pavol, M.J., Parker, R.D. and Grabiner, M.D. (1998) Three-dimensional knee joint kinematics during a golf swing. Influences of skill level and footwear, *American Journal of Sports Medicie,* **26** (2), 285-294.

Gazzani, D. (1993) Comparative assessment of two algorithms for calibrating stereophotogrammetric systems, *Journal of Biomechanics*, **26**, 1449-1454.

Geisler, P.R. (2001) In Golf: Sports injury. Prevention and rehabilitation. (Ed. Shamus, E. and Shamus, J.), McGraw-Hill, New York, 185-225.

Glazebrook, M.A. (1994) An electromyographic analysis and an investigation of intervention strategies, *American Journal of Sports Medicine*, **22**, 674-679.

Glazier, P.S., Davids, K. and Bartlett, R.M. (2003) Dynamical systems theory: a relevant framework for performance-oriented sports biomechanics research, available at http://sportsci.org/jour/03/psg.htm,accessed 12/06/04.

Gobush, W (1990) Impact force measurements on golf balls, In Science and Golf: proceedings of the first world scientific congress of golf, (Ed. Cochran A.J. & Farrally M.R), E&F.N. Spon, London, pp219-224.

Gobush, W., Pelletier, D. and Days C. (1994) Video monitoring system to measure initial launch characteristics of golf ball. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 340-347.

Godoy, R., Goodman, E., Levins, R. and Leonard, W.R. (2005) Anthropometric variability in the USA: 1971-2002, *Annals of Human Biology*, **32** (4), 469-486.

Golfsmith Europe, available at www.golfsmith-europe.co.uk, accessed 11-1-06.

Golfweb (2006), PGA Tour official site, available at www.golfweb.com, accessed 19.2.06.

Gray's Anatomy (2004), 39th Edition, Churchill Livingstone, London.

Grey, M.J., Pierce, C.W., Milner, T.E., Sinkjaer, T. (2001) Soleus stretch reflex during cycling, *Motor Control*, **5** (1), 36-49.

Ghosh, T.K. (1974) Dynamics and optimisation of a human motion problem. Phd Thesis. University of Florida, Microfilm 74-27, 873, Ann Arbor, Michigan.

Ghosh, T.K. and Boykin, W.H. (1974) Dynamics of the human kip-up manoeuvre, *American Society of Mechanical Engineers,* Paper 74-WA/Aut-7.

Golf UK (2003), Feb, Mintel International Group, available from www.mintel.com, accessed 27.7.06.

Gruen, A. (1997) Fundamentals of videogrammetry- A review, *Human Movement Science* **16** (2-3), 155-187.

Guyton, A. (1986) Textbook of medical physiology, W.B. Sanders Co., West Washington Sq., USA.

Hanavan, E.P. Jr (1966) A personalised mathematical model of the human body", *Journal of Spacecraft*, **3,** 446-448.

Hannaford, B., Kim, W.S., Lee, S.H. and Stark, L. (1986) Neurological control of head movements: inverse modelling and electromyographic evidence, *Mathematical Biosicences*, **78**, 159-178.

Harper, T.E., Roberts, J.R. and Jones, R. (2005) Driver swingweighting: a worthwhile process?" *Proceedings of the Institution of Mechanical Engineers- Part B: Journal of Engineering Manufacture,* **219,** (B), 385-393.

Hart, J.H., Curtis, D., Hamilton, N.D.R. and Haake, S.J. (2004). Scanning large geometries for use in computational fluid dynamic analysis, *The Engineering of Sport 5*, **1**, University of California, International Sports Engineering Association,601-608.

Hatze, H. (1976) The complete optimisation of human movement. *Mathematical Biosciences*, **28**, 99-135.

Hatze, H. (1979) Models of sports biomechanics and myocybernetic optimisation of movements. Problems to today and an outlook for the future (German), *Sportwissenschaft*, **9**.

Hatze, H. (1981b) Estimation of myodynamics parameter values from observations on isometrically contracting muscle groups, *European Journal of Applied Physiology and Occupational Physiology*, **46**, 325-338.

Hatze, H. (1983) Computerised optimisation of sports motions. An overview of possibilities, methods and recent developments, *Journal of Sports Science*, **1**, 3-12.

Hatze, H. (2002) The fundamental problem of myoskeletal inverse dynamics and its applications, *Journal of Biomechanics*, **35**, 109-115.

Hatze, H. (2005) Towards a comprehensive large-scale computer model of the human neuromusculoskeletal system. *Theoretical Issues in Ergonomics Science*, **6** (3-4), 239-250.

Hatze, H. (2005a) Parameter identification for human body segment models, *Theoretical Issues in Ergonomics Science,* **6** (3-4), 331-334.

Hay, J.G. (1983), Biomechanics of sport: an overview, In (Ed.Wood G.A.) Collected Papers on Sports Biomechanics, Nedlands: University of Western Australia,1-21.

Hedrick M. and Twigg M. (1994) The feel of a golf shot: Can we measure it? In (Ed. Cochran A.) Golf: The Scientific Way, Aston Publishing Group, Hemel Hempstead,131-133.

Higgins, J.R. (1977) Human movement: an integrated approach, Mosby, St. Louis.

Hill, A.V. (1953) The mechanics of active muscle, *Proceedings of the Royal Society London (Biological Sciences)*, **141**,104-117.

Hill, A.V. (1970) First and last experiments in muscle mechanics, Cambridge University Press, Cambridge.

Hocknell, A., Jones, R. and Rothberg, S.J. (1999) Computational and experimental analysis of the golf impact, In Science and Golf III: Proceedings of the world scientific congress of golf (Ed. Farrally M.R. and Cochran A.J.), Human Kinetics, Leeds, 526-534.

Hocknell, A. (2002) High-performance driver design: benefits for all golfers, *Journal of Sports Sciences,* **20** (8), 643-649.

Holden, J.P., Orsini, J.A., Siegel, K.L., Kepple, T.M., Gerber, L.H. and Stanhope, S.J. (1997) Surface movement errors in shanks kinematics and knee kinematics during gait, *Gait and Posture,* **5**, 217-227.

Horwood, G.P. (1994) Golf shafts - a technical perspective. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 247-258.

Hubbard, M. and Trinkle, J.C. (1985) Clearing Maximum Height with Constrained Kinetic Energy, *ASME Journal of Applied Mechanics*, **52** (1), 179-184.

Hull, M.L. and Hawkins, D.A. (1990) Analysis of muscular work in mult-segmental movement:application to cycling. In (Ed. Winters, J.M., Woo, S.L.-Y), Multiple muscle systems: biomechanics and movement organization. Springer, NY, 621-638.

Hume, P.A., Keogh, J. and Reid, D. (2005) The role of biomechanics in maximising distance and accuracy of golf shots, *Sports Medicine,* **35** (5), 429-449.

Huntley, M., Davis, C.L., Stranwood, M. and Otto, S.R. (2004) Characterisation of 'seams' in carbon-fibre composite golf shafts, *Engineering of Sport 5*, 223-229.

Inoue, Y. and Kai Y. (2002) Study on the dynamics of the golf swing and the mechanism of the wrist turn, *Engineering of Sport 4*, 231-232.

Iwatsubo, T., Adachi, K., Kitagawa, T. and Onuki M. (2002). A study of link models for dynamic analysis of golf swing motion, *Sports Engineering,* **5**, 232.

Iwatsubo, T., Kawamura, S. and Furuichi, K. (2002) Influence of the characteristics of golf club head on release velocity and spin velocity of golf ball after impact, In Science and golf IV: Proceedings of the world scientific congress of golf (Ed. Thain, E.), Routledge, London, 410-425.

Iwatsubo, T., Kawamura, S., Miyamoto, K. and Yamaguchi, T. (2000) Numerical analysis of golf club head and ball at various impact points, *Sports Engineering,* **3 (4)**, 195-204.

Iwatsubo, T. and Nakajima D. (2006) Evaluation of long and short shafts of golf club by real swing, *Engineering of Sport 6*, **3**, 347-352.

Jackson, J. (1993) Total club fitting, Dynacraft Golf Products Inc., Newark, OH.

Jacobson. M.D., Raab, R., Fazeli, B.M., Abrams, R.A., Botte, M.J. and Lieber, R.L. (1992), Architectural design of the intrinsic hand muscles, *The Journal of Hand Surgery*, **17a** (5), 804-809.

Jagacinski, R.J., Greenberg, N. and Liao, M.-J. (1997) Tempo, rhythm and aging in golf, *Journal of Motor Behaviour*, **29** (2), 159-173.

James, T. (1996) Get back in the swing, *Australian Doctor*, April, 61-65.

James, C.R. and Bates, B.T. (1997) Experimental and statistical design issues in human movement research, *Measurement in Physical Education and Exercise Science*, **1** (1). 55-69.

Jobe, F.W., Moynes, D.R. and Antonelli, D.J. (1986) Rotator cuff function during the golf swing, *The American Journal of Sports Medicine*, **14** (5), 388-382.

Jobe, F.W., Perry, J. and Pink, M. (1989) Electromyographic shoulder activity in men and women professional golfers, *The American Journal of Sports Medicine*, **17** (6), 782-787.

Johnson, M.E (2006) Inching for more yards, Golf World, available at www.golfdigest.com, accessed 15.4.06.

Johnson, S.H. and Ekstrom, E. (1998) Experimental Study of Golf Ball Oblique Impact, In Science and Golf III: Proceedings of the world scientific congress of golf (Ed. Farrally M.R. and Cochran A.J.), Human Kinetics, Leeds, 519, 1999.

Johnson, S.H. and Lieberman, B.B. (1994b) An analytical model for ball-barrier impact Part 2: A model for oblique impact, In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 315-320.

Jorgensen, T. (1994) The Physics of Golf, American Institute of Physics Press, New York, USA.

Kahne, S. and Salasin, J. (1969) Computer simulation in athletic performance, *Proceedings of the Annual Meeting of the National College of Physical Education Association for Men*, Chicago, 25-29.

Kamen, G. (1983) The acquisition of maximal isometric plantar flexor strength: a force-time curve analysis, *Journal of Motor Behaviour*, **15** (1), 63-73.

Kamen, G. (2004) Neuromotor issues in human performance: introduction. *Research Quarterly in Exercise and Sport*, **75** (1),1-2.

Kaneko, Y. and Sato, F. (Ed.) (2000). *The adaptation of golf swing to inertia property of the golf swing*, The Engineering of Sport: Research, Development, and Innovation. Oxford, Blackwell Science, 469-476.

Kao, J.T., Pink, M., Jobe, F.W. and Perry, J. (1995) Electromyographic analysis of the scapular muscles during a golf swing, *American Journal of Sports Medicine*, **23**, 19-23.

Karlsson, D. and Tranberg, R. (1999) On skin movement artefact-resonant frequencies of skin markers attached to the leg, *Human Movement Science,* **18** (5), 627-635.

Kasarskis, E.J., Berryman, S., English, T., Nyland, J., Vanderleest, J.G., Schneider, A., Berger, R. and McClain, C. (1997) The use of upper extremity anthropometrics in the clinical assessment of patients with amyotrophic lateral sclerosis, *Muscle & Nerve*, **20** (3), 330-335.

Kautz, S.A. and Hull, M.L. (1995) Dynamic optimisation analysis for equipment setup problems in endurance cycling, *Journal of Biomechanics*, **28**, 1391-1401.

King, M.A. and Yeadon, M.R. (2004) Maximising somersault rotation in tumbling, *Journal of Biomechanics,* **37**, 471-477.

Kinugasa, T., Cerin, E. and Hooper, S. (2004) Single-subject research designs and data analyses for assessing elite athletes' conditioning, *Sports Medicine,* **34**(15), 1035-1050.

Kirtley, C. (2002) Sensitivity of the modified Helen Hayes model to marker placement errors, 7th International Symposium on the 3D Analysis of Human Movement, Newcastle, UK.

Knight, C.A. (2004). Neuromotor issues in the learning and control of golf skill, *Research Quarterly for Exercise and Sport,* **75** (1), 9-15.

Knowles, S., Mather, J.S.B. and Jowett, S. (1998) Testing the virtual golf club, *The Engineering of Sport*, Blackwell Science, Oxford, 333-41.

Komi, P.V. (1984) Physiological and biochemical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed, in Exercise and Sports Science Reviews, **12**, 81-119.

Komi, P.V. (1986) Training of muscle strength and power: interaction of neuromotoric, hypertrophic and mechanical factors, *International Journal of Sports Medicine*, **7**, 10-15.

Komi, P.V. (1992), Stretch-shortening cycle, In Strength and power in sport (Ed. Komi P.V.), Blackwell, Oxfordshire,196-179.

Komi, P.V. and Bosco, C. (1978), Utilisation of stored elastic energy in extensor muscles by men and women, *Medicine and Science in Sports*, **10** (4), 261-265.

Komura, T., Shinagawa, Y. and Kunii, T. (1997) A muscle-based feed-forward controller of the human body, *Computer Graphics Forum*, **16**, C165-C167.

Komura, T., Shinagawa, Y. & Kunii, T.L. (2000) Creating and retargeting motion by the musculoskeletal human body model, *The Visual Computer*, **16**, 254-270.

Kroll, W. (1965) Isometric training effects upon central facilitation, *Research Quarterly*, **36** (4), 427-432.

Lagasse, P.P. (1979) Prediction of maximum speed of human movement by two selected muscular coordination mechanisms and by maximum static strength, *Perceptual and Motor Skills*, **49** (1), 151-161.

Latash, M.L., Scholz, J.P. and Schoner, G. (2002) Motor control strategies revealed in the structure of motor variability, *Exercise and Sports Science Review*, **30** (1), 26-31.

Lee, M. and Kim, C. (2004) Design optimization of graphite golf shafts based on weight and dynamics of swing, *Engineering of Sport,* **5**, 248-255.

Lesh, M.D., Mansour, J.M. and Simon, S.R. (1979) A gait analysis subsystem for smoothing and differentiation of human motion data, *Journal of Biomechanical Engineering,* **101**, 205-212.

Li, G., Pierce, J.E. and Herndon, J.H. (2006) A global optimisation method for prediction of muscle forces of human musculoskeletal muscle, *Journal of Biomechanics*, **39** (3), 522-529.

Libkuman, T.M., Otani, H., Steger, N. (2002) Training in timing improves accuracy in golf, *Journal of General Psychology,* **129** (2), 77-96.

Lieber, R.L., Jacobson, M.D., Fazeli, B.M., Abrams, R.A. and Botte, M.J. (1992) Architecture of selected muscles of the arm and forearm: Anatomy and implications for tendon transfer, *American Society for Surgery of the Hand*, **17a** (5), 787-798.

Lieberman B.B. (1990) Estimating lift and drag coefficients from golf ball trajectories, In Science and Golf: proceedings of the first world scientific congress of golf, (Ed. Cochran A.J. & Farrally M.R), E&F.N. Spon, London, 187-192.

LifeMOD Technical Manual (2005) available at www.lifemodeler.com, accessed 24/5/06.

Lim, Y.-T. (1998) Lower trunk muscle activities during the golf swing- pilot study, *North American Congress on Biomechanics*, August 14-18, Ontario, Canada.

Lindsay, D.M., Horton, J.F. and Paley, R.D. (2002) Trunk motion of male professional golfers using two different golf clubs, *Journal of Applied Biomechanics*, **18**, 366-373.

Linthorne, NP, 2000, Optimum take-off range in vertical jumping, In Book of abstracts, *3rd Australian Biomechanics conference,* Griffith University, 49-50.

Lundberg, A. (1996) On the use of bone and skin markers in kinematics research. *Human Movement Science*, **15**, 753-758.

Lundin, P. (1985) Plyometrics: A review of plyometric training, *NSCA Journal*, **7** (3), 69-74.

Maddalozzo, G.F.J. (1987) An anatomical and biomechanical analysis of the full golf swing, *National Strength & Conditioning Association Journal*, **9** (4), 6-8, 77-79.

Maltby, R. (1982) Golf club design, fitting, alterations and repair. The principles and procedures, 2nd edition, Ralph Maltby Enterprises Inc., Newark.

Maltby, R. (1990) Golf club design, fitting, alterations and repair. The principles and procedures, Ralph Maltby Enterprises Inc., Newark.

Miao T., Watari M., Kawaguchi M. and Ikeda M. (1998) A study of clubhead speed as a function of grip speed for a variety of shaft flexibility, *Science and Golf III. Proceedings of the 1998 World Scientific Congress of Golf.* (Ed. Farrally M.R. & Cochran A.J.). Leeds, Human Kinetics, 554-561.

Masuda, M. and Kojima, S. (1994) Kick back effect of club-head at impact. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 284-289.

Maurel, W. (1998) 3D modelling of the human upper limb including the biomechanics of joints, muscles and soft tissues, PhD Thesis, Departement d'Informatique: Ecole Polytechnique Federale de Lausanne, pps171.

McConville, J.T., Clauser, C.E., Churchill, T.D., Cuzzi, J. and Kaleps, I. (1980) Anthropometric relationships of body and body segment moments of inertia, Report AFAMRL-TR-80-119, Air Force Base Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

McCrank, J.M. and Seger D.R. (1964) Torque free rotational dynamics of a variable-configuration body- application to weightless man, GAW/Mech 64-19, Wright-Patterson Air Force Base, Ohio.

McGuan S.P. (1996) Personalised Musculoskeletal Human Models for Use in Dynamic Gait Simulation for Clinical and Sports Applications, *Portuguese Journal of Human Performance Studies.*

McGuan S.P. (2001) Human Modelling- From Bubblemen to Skeletons, Presented at the SAE Digital Human Modelling Conference, Arlington, VA, January.

McGuan, S.P. (2002) Achieving commercial success with biomechanics simulation, xxth International Symposium on Biomechanics in Sports, Caceres, Spain, July.

McHardy, A. and Pollard, H. (2005) Muscle activity during the golf swing, British *Journal of Sports Medicine*, **39**, 799-804.

McLean, J. (1992) Widen the gap, *Golf Magazine*, 42-53.

McLean, J. (1993) X Factor 2: closing the gap, *Golf Magazine*, 28-32.

McLean, J. and Andrisani, J. (1997) The X-factor swing: and other secrets to power and distance, Harper Collins Publishers, New York.

McMahon, T.A. (1984) Muscle, reflexes, and locomotion, Princeton University Press, Princeton, New Jersey.

McTeigue, M., Lamb, S.R., Mottram, R. and Pirozzolo, F. (1994) Spine and hip motion analysis during the golf swing. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 50-58.

Merrins, E. (1979) Is you timing in tune? *Golf Magazine*, September, 36-39.

Metzler, V., Arampatzis, A. and Brüggemann G.-P. (2002) Influence of 2D and 3D body segment models on energy calculations during kinematic analysis of running, *European Journal of Applied Physiology*, **86**, 337-341.

Milburn, P.D. (1982) Summation of segmental velocities in the golf swing, *Medicine and Science in Sports and Exercise*, **14** (1), 60-64.

Miller, D.I. (1973) Computer simulation of springboard diving. In (Ed. Cerquiglini, S., Venerando, A. and Wartenweiler, J.), Biomechanics III, University Park Press. Baltimore, 116-119.

Miller, D.I. (1974) Simulation of sports techniques by digital computer and programmable computer, *Journal of Health, Physical Education, Recreation*, **45,** 65-67.

Miller, D.I. (1979) Modelling in biomechanics: an overview, *Medicine and Science in Sports*, **11** (2), 115-122.

Milne, R. D. and J. P. Davis (1992) The role of the shaft in the golf swing, *Journal of Biomechanics,* **25** (9), 975-83.

Mitchell, S.R., Jones, R. and King, M. (2000) Head speed vs. racket inertia in the tennis serve, *Sports Engineering*, **3**, 99-110.

Mitchell, K., Banks, S., Morgan, D. and Sugaya, H. (2003) Shoulder motions during the golf swing in male amateur golfers, *Journal of Orthopaedic and Sports Physical Therapy,* **33** (4), 196-203.

Mittendorf, A. and Reyes, M.G. (1997), available at www.golfphysics.com, accessed 2.9.05.

Mizoguchi, M. and Hashiba, T. (2002) Matching the shaft length of a golf club to an individual's golf swing motion, *The Engineering of Sport 4*, 695-700.

Moritani, L.E. (1978) Electromyographic analysis of muscle strength gain: neural and hypertrophic effects, *NSCA Journal*, **5**, 32-37.

Moriyama, K, Yamaguchi, T, Yabu, M. and Tsunoda M (2004) The influence of mechanical impedance of the golf club and the golf ball on. ball spin, *The Engineering of sport 5*, 337-343.

Moynes, D.R., Perry, J., Antonelli, D.J. and Jobe, F.W. (1986) Electromyography and motion analysis of the upper extremity in sports, *Physical Therapy*, **66** (12), 1905-1911.

Nagano, A. and Gerritsen, K.G.M. (1999) A forward dynamics simulation of human hopping: modelling afferent feedback, VII International Symposium on Computer Simulation in Biomechanics, Calgary, Canada, 5-7th August.

Neal, R.J., Abernethy, B. and Moran, M.J. (1990) The influence of club length and shot distance on the temporal characteristics of the swings of expert and novice golfers, In Science and Golf: proceedings of the first world scientific congress of golf, (Ed. Cochran A.J. & Farrally M.R), E&F.N. Spon, London, 36-42.

Neal R.J. and Dalgleish M.J. (2000) Does club fitting change swing mechanics? A case study. Technical report to Henry Griffitts, Australia.

Nagao, N. and Y. Sawada (1973). A kinematic analysis in golf swing concerning driver shot and No. 9 iron shot, *Journal of Sports Medicine and Physical Fitness,* **13** (1), 4-16.

Neilson, PD. (1993) The problem of redundancy in movement control: the adaptive model theory approach, *Psychological Research*, **55** (2), 99-106.

Neptune, R.R., Kautz, S.A. and Hull, M.L. (1997) The effect of pedalling rate on coordination in cycling, *Journal of Biomechanics*, **10**, 1051-1058.

Neptune, R.R., Kautz S.A. and Hull M.L. (1998) Evaluation of performance criteria for simulation of submaximal steady-state cycling using a forward dynamic model, *Journal of Biomechanical Engineering*, **120**, 334-341.

Neptune, R.R., Kautz, S.A. and Zajac, F.E. (2000), Muscle contributions to specific biomechanical functions do not change in forward versus backward pedalling, *Journal of Biomechanics*, **33** (2), 155-64.

Nesbit, S.M. (2005) A three dimensional kinematic and kinetic study of the golf swing, Journal of Sports Science and Medicine, **4** (4), 499-519.

Nesbit, S.M., Cole, J.S., Hartzell, K.A., Oglesby, K.A. and Radich, A.F. (1994) Dynamic model and computer simulation of a golf swing. In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 71-76

Nesbit, S.M., Hartzell, T.A., Nalevanko, J.C., Starr, R.M., White, M.G., Anderson, J.E. and Gerlacki, J.N. (1996) A discussion of iron golf club head inertia tensors and their effects on the golfer, *Journal of Applied Biomechanics,* **12**, 449-469.

Nesbit, S.M. and Ribadeneira, M.X. (2003) Sport biomechanical analysis using full-body computer models, IASTED: Proceedings of the 14th IASTED International Conference on Modelling and Simulation, Palm Springs, USA, 24th-26th February.

Newell, K.M. and Corcos D.M. (Ed.) (1993) Variability and motor control, Human Kinetics, Champaign., Illinois.

Newman, S., Clay, S. and Strickland, P. (1997) The dynamic flexing of a golf club shaft during a typical swing, In Proceedings of the 4th Annual Conference on Mechatronics and Machine Vision in Practice (Cat no. 97TB100192), Toowoomba, Queensland, Australia, 265-270.

Nicklaus, J. (1974) Golf my way, Simon & Schuster, New York.

Nikonovas, A., Harrison A.J.L., Hoult, S. and Sammut, D. (2004) The application of force-sensing resistor sensors for measuring forces developed by the human hand, *Journal of Engineering in Medicine*, **218** (H), 121-126.

Olds, T. (2004) The rise and fall of anthropometry, *Journal of Sports Sciences*, **22**, 319-320.

Olsavsky, T. (1994) The effects of driver head size on performance, In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 321-326.

O'Sullivan, F., O'Sullivan, J., Bull, A.M. and McGregor, A.H. (2003), Modelling multivariate biomechanical measurements of the spine during a rowing exercise, *Clinical Biomechanics*, **18** (6), 488-493.

Otten, E. (2003) Inverse and forward dynamics: models of multi-body systems, *Philosophical Transactions of the Royal Society - Series B - Biological Sciences*, **358**, 1493-1500.

Owens, D. and Bunker L.K. (1992), Advanced Golf, Step to Success, Leisure Press, Champaign, Illinois.

Pandy. M.G. and Anderson F.C. (2000) Dynamic simulation of human movement using large-scale models of the body, *Phonetica*, **57**, 219-28.

Pandy, M.G. (2003) Simple and complex models for studying muscle function in walking, *Royal Society, London, Philosophical Transactions*, **358**, 1501-1509.

Pan, C.S., Miller, K.M., Chiou, S. and Wu, J.Z. (2004) Evaluation of a computer simulation model for human ambulation on stilts, *Journal of Mechanics in Medicine and Biology*, **4** (3), 283-303.

Pandy, M.G., Zajac, F.E., Sim, E. and Levine, W.S. (1990) An optimal control model for maximum-height human jumping, *Journal of biomechanics*, **23**, 1185-1198.

Panjabi, M. (1979) Validation of mathematical models, *Journal of Biomechanics*, **12** (3), 238.

Panne van de, M. (1996) Parametrised gait analysis, *IEEE Computer Graphics and Applications*, **16**, 40-49.

Penner R.A. (2001a) The physics of golf: the optimum loft of a driver, *American Journal of Physics*, **69** (5), 563-568

Penner, R.A (2001b) The physics of golf: The convex face of a driver, *American Journal of Physics*, **69** (10), 1073-1081.

Penner, A. (2002), The Physics of Golf, *Reports on progress in physics,* **66**, 131-171.

Piazza, S.J. and Delp S.L. (2001) Three-dimensional dynamic simulation of total knee replacement motion during a step-up task, *Journal of Biomechanical Engineering*, **123**, 599-606.

Pickering, W.M. (1998) A computational study of the double pendulum model of the golf swing, *The Engineering of Sport*, 353-60.

Pickering, W.M. and Vickers, G.T. (1999) On the double pendulum model of the golf swing, *Sports Engineering,* **2**, 161-172.

Pinemeadow Golf, (2006) available at www.pinemewadowgolf.com accessed 13/2/06.

Pink, M., Jobe, F. and Perry, J. (1990) Electromyographic analysis of the shoulder during the golf swing, *The American Journal of Sports Medicine*, **18**, 137-140.

Pink, M., Perry, J. and Jobe, F. (1993) Electromyographic analysis of the trunk in golfers, *The American Journal of Sports Medicine*, **21** (3), 385-388.

Quintavalla, S.J. (2006) Experimental determination of the effects of clubhead speed on driver launch conditions and the effect on drive distance for balls used by the PGA tour, *USGA Technical Report RB/cor2006-01*.

R&A (2004) Rules of Golf, R&A Rules Limited, The Royal and Ancient Golf Club of St. Andrews.

Raasch, C.C., Zajac, F.E., Baoming, M. and Levine, W.S. (1997) Muscle coordination of maximum-speed pedaling, *Journal of Biomechanics*, **30** (6), 595-602.

Ramey, M.R. (1973) The significance of angular momentum in long jumping, *Research Quarterly*, **44**, 488-497.

Ramey, M.R. and Yang, A.T. (1981) A simulation procedure for human motion studies, *Journal of Biomechanics*, **14** (4), 203-213.

Rasmussen, J. (2005) Model Validation, *AnyBODY Interest Group Newsletter*, June 29.

Rasmussen, J., Dahlquist, J., Damsgaard, M., de Zee, M. & Christensen, S.T. (2003) Musculoskeletal modelling as an ergonomic design method, International Ergonomics Association XVth Triennial Conference, Seoul, Korea, 24th-29th August.

Reboussin, D.M. and Morgan, T.M. (1996) Statistical considerations in the use and analysis of single-subject designs, *Medicine & Science in Sports & Exercise,* **28** (5), 639-644.

Reinschmidt, C., van den Bogert, A.J., Lundberg, A., Nigg, B.M., Murphy, N., Stacoff, A. and Stano, A. (1997) Tibiofemoral and tibiocalcaneal motion during walking: external vs skeletal markers, *Gait and Posture,* **6** (2), 98-109.

Reinschmidt, C., van den Bogert, A.J., Murphy, N., Lundberg, A.N. and Nigg, B.M. (1997) Tibiocalcaneal motion during running- measured with external and bone markers, *Clinical Biomechanics,* **12**, 12-16.

Reinschmidt, C., van den Bogert, A.J., Nigg, B.M., Lundberg, A. and Murphy, N. (1997a) Effect of skin movement on the analysis of skeletal knee joint motion during running, *Journal of Biomechanics,* **30**, 729-732.

Reyes, M.G. and Mittendorf, A. (1999) A mathematical swing model for a long-driving champion, In Science and Golf III: Proceedings of the world scientific congress of golf (Ed. Farrally M.R. and Cochran A.J.), Human Kinetics, Leeds, 13-19.

Richards, J., Farrell, M., Kent, J. and Kraft, R. (1985) Weight transfer patterns during the golf swing, *Research Quarterly for Exercise and Sport*, **56**, 361-365.

Riddle, C. and Kane, T.R. (1968) Reorientation of the human body by means of arm motions, *Technical Report No. 182*, Division of Engineering Mechanics, Stanford University.

Roberts, J., Jones, R., Harwood, C., Mitchell, S. and Rothberg, S. (2001) Human perceptions of sports equipment under playing conditions, *Journal of Sports Sciences*, **19**, 485-497.

Roberts, J.R., Jones, R., Mansfield, N.J. and Rothberg, S.J. (2005) Evaluation of vibrotactile sensations in the 'feel' of a golf shot, *Journal of Sound and Vibration*, **285** (1/2), 303-319.

Roberts, J.R., Jones R. and Rothberg S.J. (2001) Measurement of contact time in short duration sports ball impacts: an experimental method and correlation with the perceptions of elite golfers, *Sports Engineering*, **4** (4), 191.

Rullkoetter, P.J., McGuan, S. and Maletsky, L.P. (1999) Development and verification of a virtual knee simulator for TKR evaluation, 45th Annual Meeting, Orthopaedic Research Society, 1st-4th February.

Russell, A.P., Le Rossignol, P.F. and Sparrow, W.A. (1998) Prediction of elite schoolboy 2000m rowing ergometer performance from metabolic, anthropometric and strength variables, *Journal of Sports Sciences*, **16**, 749-754.

Sanders, R.H. and Owens, P.C. (1992) Hub movement during the swing of elite and novice golfers", *International Journal of Sport Biomechanics*, **8**, 320-330.

Schenck, JM. and Forward E.M.. (1965) Quantitative strength changes with test repetitions, *Physical Therapy*, **45**, 562-569.

Schmidt, R.A. (1991) Motor Learning and Performance: From principles to practice, Human Kinetics, Champaign, Illinois.

Schmidt, R.A., Zelaznik, H., Hawkins, B., Frank, J.S. and Quinn, J.T. (1979) Motor-output variability: a theory for the accuracy of rapid motor acts, *Psychological review*, **86**, 415-451.

Schwartz, B. and Barsky, S.F. (1977) The home advantage, *Social Forces*, **55**, 641-661.

Serpas, F., Yanagawa, T. and Pandy, M. (2002) Forward dynamics simulation of anterior cruciate ligament forces developed during isokinetic dynamometry, *Computer Methods in Biomechanics & Biomedical Engineering*, **5** (1), 33-43.

Shira, C. and Froes F.H. (1997) Advanced materials in golf clubs: the titanium phenomenon, *Journal of Metals*, **49** (5), 35-37.

Shrive, N.G., O.Connor, J.J. and Goodfellow, J.W. (1978) Load-bearing in the knee joint, *Clinical Orthopaedics and Related Research*, **131**, 279-87.

Shmanske, S. (2000) Gender, skill, and earnings in professional golf, *Journal of Sports Economics,* **1** (4), 385-400.

Simons, J.C. and Gardner, M.S. (1960) Self-manoeuvring for the orbital worker, WADD-TR-60-748, Wright-Patterson Air Force Base, Ohio.

Siston, R.A., and Delp, S.L (2006) Evaluation of a New Algorithm to Determine the Hip Joint Center, *Journal of Biomechanics*, **39**, 125-130.

Smith, LE. (1970) Speed of muscular contraction, *Perceptual and Mot Skills*, **31** (1), 171-176.

Smith, L., Broker, J. and Nathan, A. (2003) A study of softball player swing speed, In (Ed. Subic, A., Travailo, P. and Alam, F.) Sports dynamics: Discovery and application, Melbourne, VIC: RMIT University, 12-17.

Smits, A.J. and Ogg S. (2004) Golf Ball aerodynamics, *Engineering of Sport 5*, 3-10.

Smits, A.J. and Smith, D.R. (1994) A new aerodynamic model of a golf ball in flight, In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 340-347

Soong, T.C. (1982) Biomechanical (analyses and applications) of shot putt and discus and javelin throws, In (Ed. Ghista D.N.) Human Body Dynamics: Impact, Occupational and Athletic Aspects, Oxford: Clarendon, 462-497.

Sprigings, E.J. and Mackenzie, S.J. (2002) Examining the delayed release in the golf swing using computer simulation, *Sports Engineering*, **5**, 23-32.

Sprigings, E.J. and Neal, R.J. (2000) An insight into the importance of wrist torque in driving the golf ball: a simulation study, *Journal of Applied Biomechanics*, **16**, 356-366.

Sprigings, E.J. and Neal, R.J. (2001) Shifting a portion of the clubshaft's mass distally: does it improve performance? *Sports Engineering*, **4**, 15-21.

Srinivasan, M. and Ruina, A. (2006) Computer optimisation of a minimal biped model discovers walking and running, *Nature*, **439** (5), 72-75.

Stapp, J.P. (1971) Closing remarks: The future, *Symposium of biodynamic models and their applications*, AMRL_TR_71_29. Wright-Patterson Air Force Base, Ohio.

Steben, R.E. and Steben, A.H. (1981), The validity of the stretch-shortening cycle in selected jumping events, *Journal of Sports Medicine*, **21**, 28-37.

Stockill, N. & Bartlett, R. (1992) Possible errors in measurement of shoulder alignment using 3-D cinematography. In (Ed. Abrantes, J.) Proceedings of the XIV International Symposium on Biomechanics in Sports, Edicoes, Lisbon, 209-212.

Suzuki, S. and Inooka, H. (1999) A new golf-swing robot emulating golfer's skill, *Sports Engineering*, **2** (1), 13-22.

Temprado, J.J., Della-Grast, M., Farrell, M. and Laurent, M. (1997) A novice-expert comparison of (intra-limb) coordination sub-serving the volleyball serve, *Human Movement Science,* **16**, 653-676.

Thelen, D.G., Anderson, F.C. and Delp, S.L. (2003) Generating dynamic simulations of movement using computed muscle control, *Journal of Biomechanics*, **36**, 321-328.

Thelen, D.G. and Anderson, F.C. (2006) Using computer muscle control to generate forward dynamic simulations of human walking from experimental data, *Journal of Biomechanics*, **39**, 1107-1115.

Ting, L.L. (2004) Effect of teardrop shaped dimple design on the golf ball aerodynamic performce, *Engineering of Sport 5*, 42-48.

Tolhurst D. (1989) What you need to know before you buy. Golf Monthly, Equipment Supplement, April 1989

Turvey, M.T. (1990) Coordination, *American Psychologist,* **45**, 938-953.

van Ingen Schanau, G.J., Bobbert, M.F. and de Hann, A. (1997a) Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics*, **13**, 389-415.

van Ingen Schenau, G.J., Bobbert, M.F. and Rozendal, R.H. (1987) The unique action of bi-articular muscles in complex movements, *Journal of Anatomy*, **155**, 1-5.

Vaughan, C.L. (1984) Computer simulation of human motion in sports biomechanics, *Exercise & Sports Science Reviews*, **12**, 373-416.

Wallace, E.S., Graham, D. and Bleakley, E.W. (1990) Foot-to-ground pressure patterns during the golf drive: a case study involving a low handicap player and a high handicap player, In Science and Golf: proceedings of the first world scientific congress of golf, (Ed. Cochran A.J. & Farrally M.R), E&F.N. Spon, London, 25-29.

Wallace, E.S. and Hubbell, J.E. (2001) The effect of golf club shaft stiffness on golf performance variables- implications for club-fitting. In (Ed. Froes, F.H. and Haake, S.J.) Materials and Science in Sports, TMW Society, 23-35.

Wallace, E.S., Hubbell, J.E. and Rodgers, M.J. (2004) Driver shaft length influences on posture and swing tempo in skilled golfers, *Engineering of Sport 5*, 216-223.

Warfel, J.H. (1993) The head, neck and trunk, sixth edition, Lea and Fabiger, Philadelphia.

Warfel, J.H. (1993) The extremities. Muscles and motor points, sixth edition, Lea and Fabiger, Philadelphia.

Watkins, R.G., Uppal, G.S., Perry, J., Pink, M. and Dinsay, J.M. (1996) Dynamic electromyographic analysis of trunk musculature in professional golfers, *The American Journal of Sports Medicine*, **24** (4), 535-538.

Werner, F.D. and Greig, R.C., (2000) How golf clubs really work and how to optimise their design, Origin Inc., Jackson.

Whitsett, C.E. Jr. (1963) Some dynamic response characteristics of weightless man, AMRL-TDR-63-18, Wright-Patterson Air Force Base, Ohio.

Whitsett, C.E. Jr (1964) A mathematical model to represent weightless man, *Aerospace Medicine*, **35**, 11-16.

Wilhelms, J. and van Gelder, A. (1997) Anatomically based modelling, In Proceedings of the 24th annual conference on computer graphics and interactive techniques: International conference on Computer Graphics and Interactive Techniques, ACM Press/Addison Wesley Publishing Co., New York, U.S.A., 173-180.

Williams, K.R. and Sih B.L. (2002) Changes in golf clubface orientation following impact with the ball, *Sports Engineering,* **5** (2), 65.

Wilmore, J.H. and Costill, D.L. (1994) Physiology of sport and exercise, Human Kinetics, Champaign, Illinois.

Wishon, T. (2004) The skinny on longer clubs, available at www.PGA.com, accessed 15.4.06

Yamaguchi, G.T., Morgan, D.W. and Si, J. (1995) A computationally efficient method for solving the redundant problem in biomechanics, *Journal of Biomechanics*, **28** (8), 999-1005.

Yamaguchi, G.T. and Zajac, F.E. (1990) Restoring unassisted natural gait to paraplegics via functional neuromuscular stimulation: a computer simulation study, *IEEE Transactions on Biomedical Engineering*, **37**, 886-902.

Yeadon, M.R. (1994) Computer Simulation and Sport Biomechanics, Canadian Society for Biomechanics: Proceedings of Eighth Biennial Conference and Symposium, Calgary, 156-157.

Yeadon, M.R., Atha, J. and Hales, F.D. (1990) The simulation of aerial movement- IV. A computer simulation model, *Journal of Biomechanics*, **23** (1), 85-89.

Young, A., Stokes, M. and Crowe, M. (1985) The size and strength of the quadriceps muscles of old and young men, *Clinical Physiology*, **5** (2), 145-154.

Yu-Ching, L., Der-Chia, L. and Tzyy-Yuang, S. (2001) The effects of golf shaft and clubhead on the velocity of clubhead and club. In (Ed. Blackwell, J.R.) Proceedings of the XIX International Symposium on Biomechanics in Sports, San Francisco: Exercise of Sport Science Dept, 20th-27th June, 367-370.

Zagarola, M.V., Lieberman, B. and Smits, A.J. (1994) An indoor testing range to measure the aerodynamic performance of golf balls, In Science and Golf II: Proceedings of the world scientific congress of golf, (Ed. Cochran, A.J. and Farrally, M.R.), E&FN Spon, London, 348-354.

Zajac, F.E. (1992) How musculotendon architecture and joint geometry affect the capacity of muscles to move and exert force on objects: A review with application to arm and forearm tendon transfer design, *The Journal of Hand Surgery* [Am], **17A** (5), 799-804.

Zajac, F.E. (1993) Muscle coordination of movement: a perspective, *Journal of Biomechanics*, **26** Suppl.1, 109-124.

Zajac, F.E., Neptune, R.R. and Kautz, S.A. (2002) Biomechanics and muscle coordination of human walking Part I: Introduction to concepts, power transfer, dynamics and simulations, *Gait & Posture*, **16**, 215-232.

Zajac, F.E., Neptune, R.R. and Kautz, S.A. (2003) Biomechanics and muscle coordination of human walking Part II: Lessons from dynamical simulations and clinical implications, *Gait & Posture*, **17**, 1-17.

Zajonic R.B. (1965) Social facilitation, *Science*, **149**, 269-274.

Zhang X., Shu, X.O., Gao, Y.-T., Yang, G., Matthews, C.E., Li, Q., Jin, F. and Zheng, W. (2004) Anthropometric predictors of coronary heart disease in Chinese women, *International Journal of Obesity*, **28**, 734-740.