Identification of the biomechanical performance determining factors of the 5 iron golf swing when hitting for maximum distance

A thesis submitted for the award of Masters by Research in Biomechanics

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Abstract

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Golf is a very popular sport with approximately 289,120 people playing golf in Ireland (European Golf Association, 2008). The amount of scientific research that has been conducted into the biomechanics of the golfer and club is limited, with the majority of the research focusing on the golf drive. The purpose of this study was to identify the biomechanical performance determining factors of the 5-iron golf swing when hitting for maximum distance. Golfer joint kinematics, club swing characteristics and weight transfer data were obtained from thirty male golfers. This data was collected using a twelve camera (250 Hz) motion analysis system (Vicon, Oxford Metrics, UK), Pro V Swing Analyser (Golftek, USA) and a pressure plate (100 Hz) (RSscan Lab Ltd., UK). Participants were divided into two groups, based on their ball launch speed (high vs. low). Those in the high ball speed group were deemed to be the more skillful group. Statistical analysis was used to identify the variables which differed significantly between the two groups, and could therefore be classified as the performance determining factors. Eight key events were identified during the swing for analysis (take away, mid backswing, late backswing, top of backswing, early downswing, mid downswing, ball contact and mid follow through). Significant differences were found between the two groups for club speed, club impact point, the majority of the measured joint angles and angular velocities (X Factor, shoulder, elbow, wrist, hip and knee) and weight transfer at a number of the key events. Two mechanisms are proposed to explain the greater generation of ball speed in the high ball speed group and these are discussed in relation to the results for the individual joint kinematics.

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Glossary of Terms

Backswing
The backward part of the swing starting from the ground and going back behind the head.

Ball contact
The moment in the swing when the club strikes the ball.

Ball speed
Horizontal speed of the ball (m.s).

Centre of pressure
The point on the body where the resultant of all ground reaction forces act.

Closed Face
When (in relation to the target-line) the clubface is angled toward the player's body.

Club rotation
Measure how quickly the clubface is rotating through the ball contact area (deg.in)

Clubface
The surface of the club head which is designed to strike the golf ball.

Clubface angle
The angle of the clubface at the moment of ball contact.

Club head
The largest part of the club at the bottom end (opposite the grip or handle) of the shaft.

Club head speed
The speed that the clubhead is travelling through ball contact ($m.s^{-1}$)

Downswing
The motion of swinging a club from the top of the backswing to the point of ball contact.

Driver
The longest and lowest-lofted wood is the driver, or 1 wood, and has the longest range of any club in a golfer's bag. It is designed to be hit off the tee for the first shot of long-yardage holes.

Fairway
The area of the course between the tee and the green that is well-maintained allowing a good lie for the ball

Follow through
The continuation of a golf stoke after ball contact.

Handicap
A number assigned to each player based on his ability and used to adjust each player's score to provide equality among the players.

Heel of the clubface
The part of the clubhead that is nearest the shaft.

Impact point
Indicates how far off the centre of the clubface the ball was contacted (cm).

Iron
A club with a flat-faced solid metal head generally numbered from 1 to 9 indicating increasing loft.

Open Face
When (in relation to the target line) the clubface is angled away from the player's body.

Shaft
The part of the club that extends from the grip to the clubhead.

Swing path
The direction the clubhead is traveling.

Swing path angle
The horizontal approach of the club as it moves towards ball contact.

Take away
The act of taking a stance and placing the clubhead behind the ball.

Target-line
The straight line from the ball to its intended target

Tempo
Total time to complete the swing, from takeaway to ball contact (s).

Toe of the clubface
The far end of the clubhead (furthest from the shaft)

Wrist cock
Maintaining the wrists in an abducted (radial deviated) position.

Wrist uncocking
Wrist adduction (ulnar deviation) from an abducted (radial deviated) position.

X factor
The relative rotation of the shoulders with respect to the hips during the golf swing.

1 Introduction

Golf is played by 10-20% of the adult population in most countries (Thériault and Lachance 1998) with estimates of between 35 (Hume, Keogh and Reid 2005) and 55 million (Farrally et al. 2003) participants worldwide. Recent statistics have indicated that there are 414 golf courses and 289,120 people playing golf in Ireland alone (European Golf Association 2009).

The full golf swing using the iron clubs to displace the golf ball as large a distance as possible is a key element of success in golf. Therefore in order to help enhance golfing performance it is important to identify the **"performance determining factors"** of the full golf swing. Comparison of skilled and lesser skilled golfers for their joint and club kinematics and their weight transfer patterns allows for the identification of these performance determining factors. Unfortunately, previous research has focused on the driver club despite the fact that either an equal or even a higher proportion of shots for maximum distance in the game of golf are taken with iron clubs. There is a need therefore for research that focuses on golfing performance using the iron clubs. Only two studies were located that examined the joint kinematics of the golf swing with iron clubs in comparing skilled to lesser skilled golfers using iron clubs (Budney and Bellow 1982, Cheetham et al. 2001). One of these studies (Cheetham et al. 2001) examined the 5 iron club and focused solely on one feature of the full golf swing (the X Factor) around the top of the backswing. As there are a large number of joints involved in the full body golf swing it is important for research to examine the movement of as many of these joints at the same time as possible so to gain a complete understanding of the biomechanics of the full golf swing. In addition, the majority of previous research (including those on the driver) has tended to examine the golf swing at only three distinct events (take away, top of the backswing and ball contact). However, there are clearly additional important functional events during the swing (mid backswing, late backswing, early downswing, late downswing and mid follow through). Analysing these additional events will provide a more detailed and perhaps useful examination of the swing. Therefore the major aim of the present study is:

- **To identify the biomechanical performance determining factors of the 5 iron golf swing when hitting for maximum distance through analysis of joint and club kinematics and weight transfer of skilled and lesser skilled golfers.**

In addition, there appears to be a lack of information on the general swing mechanics utilised when striking the ball for maximum distance with the 5 iron club. A secondary aim of the present study will therefore be:

- **To provide a general description of the joint actions during the 5 iron golf swing when hitting for maximum distance.**

2 Literature Review

2.1 Introduction

The amount of scientific research that has been conducted into golf is limited. A number of books discussing the biomechanics of golf have been written by professionals and coaches, although these usually lack scientific foundation and are mainly based on personal experience and opinion. The growth in the popularity of golf, with both increasing participation and spectator figures, has lead to a greater interest among the golfing community in understanding the science behind golf. Farrally et al. (2003) believed that it was the growth of the prize money in golf in the late 1980s that encouraged a greater professionalism among players, which included the employment of sports scientists to improve performance. This lead to an increase in scientific research in the area in the late 1980s (Neal and Wilson 1985, Richards et al. 1985, Chao et al. 1987, Maddalozzo 1987, Jobe, Perry and Pink 1989). A major step towards increasing golf research was the creation of the World Scientific Congress of Golf in 1990. It is the forum recognized by the Golf Science Steering Group of the World Commission of Science and Sport for the presentation of golf research.

Initially Sport Discus, Pubmed and Google Scholar searches were conducted using the keywords ‘golf’, ‘golf biomechanics’, ‘golf swing’, ‘golf club’, ‘golf kinematics’ and ‘golf kinetics’. Further invaluable sources of reference were the 4 volumes of the ‘Proceedings of Science & Golf World Congress’ (1990, 1994, 1998 and 2002). This search was supplemented by tracking all key references in these papers.

This chapter critically examines the main findings in the literature regarding golf.

2.2 Golf clubs used in research

In completing putts and short chips golfers use very little body movement, whereas, the full golf swing used in tee and fairway shots is a more complex and powerful full body movement pattern. For those shots involving the full golf swing, golfers use the wood and iron clubs; with the predominance of shots being with the iron clubs.

Unfortunately the majority of the limited number of studies (Barrentine, Fleisig and Johnson 1994, McLaughlin and Best 1994, Robinson 1994) have examined the biomechanics of the swing with the driver club. As driver and iron clubs have different roles in the game of golf it is important that they are both researched to provide an understanding of the swing technique utilised for both types of clubs. The lack of research using clubs other than the driver can be illustrated by Lindsay et al. (2002) who stated that they were the first study to measure trunk range of motion using a golf club other than a driver. Their study looked at a driver and a 7 iron club. McCloy et al. (2006) examined the club striking characteristics of three different iron clubs (3, 5 and 7 iron) and they postulated that the dearth in research on launch conditions using iron clubs was because there is a wide range of lofts offered by the range of iron clubs available and therefore there is no perceived need to study this aspect. Also it was their opinion that there was generally no desire by golfers to maximise their club head or ball velocity when using irons, as there is with drivers, as the golfers can select an iron club from a range of clubs in an attempt to achieve the desired shot outcome, as different iron clubs are used to achieve different required distances. However, in order to allow the golfer to select the appropriate club they must know the different distance capabilities of each individual iron club. Other researchers have used maximum distance with iron clubs as their performance measure (Lindsay, Horton and Paley 2002, Fradkin, Sherman and Finch 2004a, Fradkin, Sherman and Finch 2004b) and hitting for maximum distance is achieved through golfers maximising their golf club head and ball velocity.

2.3 Biomechanics of the golf swing

Research into the biomechanics of the golf swing has included analysis of movement (Burden, Grimshaw and Wallace 1998, Lindsay, Horton and Paley 2002, Egret et al. 2003, Egret et al. 2006, Myers et al. 2008, Zheng et al. 2008), muscle activation patterns (Jobe, Perry and Pink 1989, Pink, Perry and Jobe 1993, Bechler et al. 1995, Watkins et al. 1996) and forces (Richards et al. 1985, Barrentine, Fleisig and Johnson 1994, Wallace, Grimshaw and Ashford. 1994, Gatt, Pavol, Parker and Grabiner. 1998, Gatt et al. 1998, Kawashima, Meshizuka and Takeshita. 1998, Ball and Best 2007a, Ball and Best 2007b). McLaughlin and Best (1994) believed that although there is a high volume of general literature relating to the golf swing, the application of scientific quantitative method to golf is limited. Many researchers have pointed out the importance of the early work completed by Cochran and Stobbs (1968) (McLaughlin and Best 1994, Egret et al. 2003, Farrally et al. 2003, Penner 2003). Their book contained the results of a 6 year study of the golf swing, in which they analysed the swings of professional golfers and isolated what they believed to be the performance determining factors of an effective golf swing. Farrally et al. (2003) however, believed that we are a long way from understanding the complex movement pattern of the golf swing. They judged that recent research has yet to provide a convincing explanation of the physics involved in the golf swing that makes a significant advance on the work of Cochran and Stobbs (1968).

The first World Scientific Congress of Golf took place in 1990 and it has met every fours years since then. The proceedings of each of the World Scientific Congress of Golf congresses to date have been published containing a total of 311 scientific papers (Farrally et al. 2003). However, even though the biomechanics of the golf swing is a major determinant of golf performance it was only examined in 29 of these papers (Farrally et al. 2003).

In order to determine the most effective swing technique it is necessary to establish the biomechanical parameters of the swing that translate into a high-quality golf swing. These biomechanical parameters are known as performance determining factors. Figure 2.1 shows a deterministic model of the golf swing (Hume, Keogh and Reid 2005), it details the performance determining factors important in achieving large distance in a drive shot. No specific models are available for the different golf clubs; this model is presented to identity factors that may be important to an effective golf swing using an iron club. The red boxes highlight the factors of the golf swing that are dependent on the biomechanics of the golfer's movements during the golf swing. Starting from the base of the figure the forces produced by the body are dependent on the summation of segmental forces (see section on order of joint actions pg. 23), the ground reaction forces (see section on kinetics of the golf swing pg. 25) and the stretch shorten cycle (see section on the stretch shortening cycle pg. 21). The momentum of the club head is dependent on the velocity of the club which is in turn dependent on such factors as the velocity of the downswing, the duration of the downswing and the range of motion of the joints of the body involved in the golf downswing. These factors will be discussed further in the section on the kinematics of the golf swing. The velocity of the golfer's movements determines the velocity of the club which in turn determines the velocity of the ball at impact and consequently the ball displacement and accuracy.

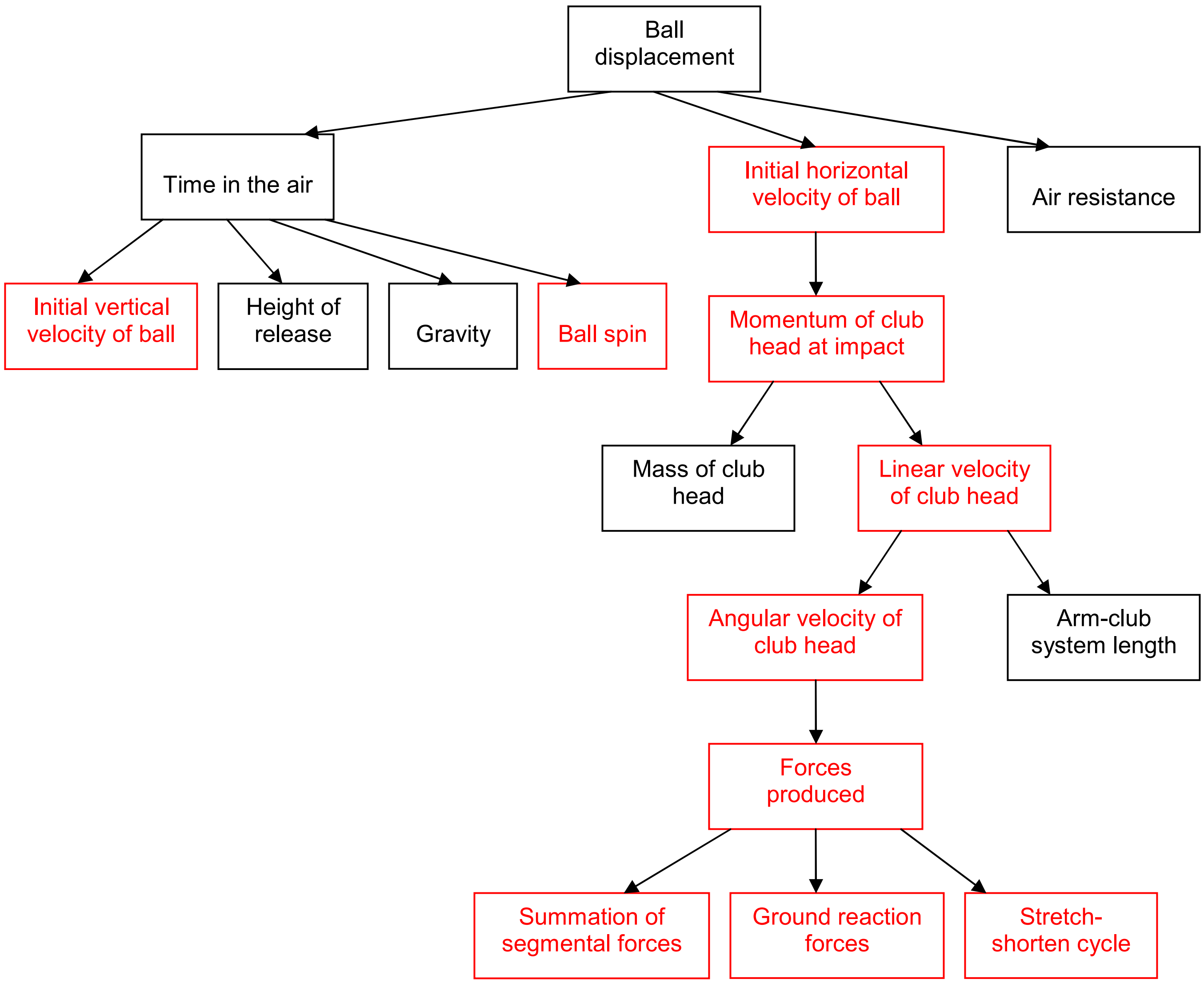


Figure 2.1 A deterministic model of the golf swing showing biomechanical factors related to achieving large distance in a drive shot. Adapted from Hume et al. (2005).

It is important to note that as biomechanical research of golf is generally conducted in a laboratory it isn't always feasible to measure ball displacement. Club head speed is generally used as the predictor of golfing performance (Barrentine, Fleisig and Johnson 1994, McLaughlin and Best 1994, Lephart et al. 2007, Myers et al. 2008). Club head speed was shown to be a valid performance measure by Fradkin et al. (2004a), who found that golfers with a lower handicap had faster club head speeds than higher handicap golfers (r = 0.95). Their study participants were 45 male golfers with varying handicaps (2-27) and they used the 5 iron club.

In order for the performance determining factors of the golf swing using iron clubs to be identified it is necessary for studies to examine the relationship between performance outcomes and the biomechanics of the golf swing when using iron clubs. By examining studies that compare the biomechanics of golf swings of skilled and unskilled golfers it is possible to identify factors that differentiate the golfers of varying skill levels and therefore identify the factors that may determine performance success. However, only two studies (Budney and Bellow 1982, Cheetham et al. 2001) appear to have compared the biomechanics of the golf swing of skilled and unskilled golfers using an iron club. The only other studies found that examined iron clubs were studies they conducted comparisons between different clubs. Three of these studies were identified providing limited information on the biomechanics of the golf swing using the 5, 7 and 9 iron clubs (Nagao and Sawada 1973, Lindsay, Horton and Paley 2002, Egret et al. 2003).

2.3.1 Kinematics of the golf swing

The following section will detail the findings of studies that examined the kinematics of golfers and the golf club. These studies provide numerical data on the angles and movements of the body and club during the golf swing, mostly gained through video or motion analysis. Due to the scarcity of research on the effect of skill level on performance with the iron clubs a separate section is included detailing the effects of skill level using the driver club.

2.3.1.1 Kinematics of the golfer using the iron clubs

The earliest biomechanical research found into iron clubs was conducted by Nagao and Sawada (1973). They examined the driver and the 9 iron with the aim of identify if different movement patterns were utilised for the two different clubs. They provided pertinent information on the 9 iron in relation to lateral stance distance (average 44.3 cm) and the time of downswing (average 0.218 s). They also examined the wrist cock angle during the downswing and showed that the participants did not maintain the wrist in a cocked (radially deviated) position during the downswing, allowing the wrist to release from its cocked position around the middle of the downswing. The next study found by date that examined iron clubs was by Budney and Bellows (1982). They examined five different clubs including the 3, 6 and 9 irons and the pitching wedge. This study was the first found to detail results for the kinematics of the golfer using an iron club and to make a comparison between golfers of varying skill level. They detailed for the 3, 6 and 9 iron and pitching wedge clubs the left arm angular velocity (395.3 deg.s^{-1}, 349.5 deg.s^{-1}, 252.1 deg.s^{-1} and 80.2 deg.s^{-1}, respectively) and left wrist angular velocity (2056.9 deg.s^{-1}, 2034.0 deg.s^{-1},1999.6°.s^{-1} and 1145.9 deg.s^{-1}, respectively) at ball contact for a professional golfer. In addition they compared the wrist angular velocities for two professional and two amateur golfers at impact for the 3, 6 and 9 irons (Table 2.1).

Table 2.1 Comparison of wrist angular velocities (deg.s^{-1}) of two professional (P) and two amateur (A) golfers. Adapted from Budney and Bellows (1982).

Club	Professionals		Amateurs	
	P1	P2	A1 (handicap = 13)	A2 (handicap = 9)
3 iron	2056.9	1655.8	1306.3	1558.4
6 iron	2034.0	1730.3	1312.1	1678.8
9 iron	1999.6	1690.2	1352.2	1558.4

The results for each club are similar within each golfer but there are differences between the golfers. In particular the professional golfers were found to achieve greater velocities than the amateur golfers. There was a significant gap of more than 20 years to the next research found that examined the kinematics of the golfer using iron clubs (Cheetham et al. 2001, Lindsay, Horton and Paley 2002, Egret et al. 2003). Cheetham et al. (2001) examined the X Factor between golfers of different skill levels .The X-Factor describes the relative rotation of the shoulders with respect to the hips during the golf swing, specifically at the top of the backswing (Figure 3.19). Jim McLean first proposed it in Golf Magazine in 1992 and he believed it to be more important than the absolute shoulder turn. McLean’s findings demonstrated that the greater the X-factor the higher a professional was ranked on driving distance (see Table 2.2).

Table 2.2 SMT numbers for 10 of the Tour players longest and shortest hitters. Adapted from McLean (1992).

Player	Shoulder Turn	Hip Turn	X Factor	X Factor as % of Shoulder Turn	Distance Ranking
FIVE LONG HITTTERS					
John Daly	114	66	48	42	1
Tom Purtzer	88	49	39	44	4
Tommy Armour III	69	37	32	46	22
Jay Don Blake	100	59	41	41	29
Mark Hayes	71	37	34	48	37
Average	**88**	**50**	**38**	**43**	**19**
FIVE SHORT HITTERS					
Lennie Clements	86	63	23	27	141
Lance Ten Broeck	83	59	24	29	148
Tom Byrum	89	70	19	21	158
Peter Persons	100	71	29	29	175
Mike Reid	88	62	26	30	184
Average	**89**	**65**	**24**	**27**	**161**

McLean's research used a SportSense Swing Motion Trainer (SMT) to measure the hip and shoulder rotation of the professional golfers. This equipment consisted of a measurement unit strapped to the golfers back and a computer to which the unit sends the measurement information. His results showed that long hitters didn't necessarily have to have a large shoulder rotation, but that their hips rotation was far less than the shorter hitters. Notice for example, how Tommy Armour III rotated his shoulders 69°, far less than Peter Persons at 100°. However, Armour's X Factor as a percentage of shoulder turn is 17% bigger than Persons, and he hit the ball further.

Cheetham et al. (2001) examined the X-Factor using the 5 iron club in ten highly skilled golfers and nine less skilled golfers using the SkillTec 3D-Golf™. This system incorporated electromagnetic tracking and motion capture and analysis software. Conversely to McLean (1992) they found that the X factor was not significantly greater in professionals than amateurs (48° and 44°, respectively).

Cheetham et al. (2001) also tested the hypothesis that professional golfers had a greater increase in X factor early in the downswing than less skilled golfers. They termed this increase the X factor stretch. They found that the X factor stretch oclcurred during the early stages of the downswing for both professional and less skilled golfers and was significantly greater for the professional players (19% increase in X Factor) than the less skilled players (13% increase in the X Factor). They suggested that X factor stretch is more important to an effective swing than simply X factor at the top of backswing and concluded that the X Factor should increase early in the downswing before it rapidly decreases to impact.

The remaining two studies that examined golfer kinematics were club comparison studies by Lindsay et al. (2002) and Egret et al. (2003). Lindsay et al. (2002) provided information on the trunk motion of professional golfers using the 7 iron club, using a lumbar motion monitor for measurements. This system was a triaxial electrogoniometer capable of assessing the motion of the thoracic lumbar spine. Their study reported flexion, lateral bending and rotation angles and velocities of the spine throughout the golf swing (Table 2.3 and Table 2.4).

Table 2.3 Spinal range of motion (°) means ± standard deviations for the take away position and maximum. Adapted from Lindsay et al. (2002).

	Flexion	Extension	Left side bend	Right side bend	Left rotation	Right rotation
Take away	35.1 ± 12.8			6.7 ± 3.2	5.6 ± 4.5	
Maximum	51.0 ± 9.9	3.0 ± 8.9	9.8 ± 5.9	27.9 ± 4.8	34.8 ± 8.8	40.4 ± 10.1

Table 2.4 Average maximum spinal velocities ($°.s^{-1}$) during the golf swing. Adapted from Lindsay et al. (2002).

Flexion	Extension	Left side bend	Right side bend	Left rotation	Right rotation
57.5 ± 32.6	138.3 ± 43.7	40.7 ± 13.5	121.7 ± 24.8	83.5 ± 20.1	180.3 ± 50.8

Egret et al. (2003) detailed shoulder and knee angles, stance distance and time to complete the swing for the 5 iron and pitching wedge. For the stance distance they reported it as 62.3 cm for the 5 iron and 58.6 cm for the pitching wedge. The stance distance reported by Egret et al. (2003) for the 5 iron (62.3 cm) is much larger than that reported by Nagao and Sawada (1973) (44.3 cm) for the 9 iron (detailed above). This may simply be due to Nagao and Sawada (1973) measuring the distance between toe-tip, while Egret et al. (2003) measured the distance between the two external malleoli. Egret et al. (2003) reported that all the golfers in their study began their golf swing with their shoulders in an open position (in the direction of the swing) of 14.5 ± 5.0° for the 5 iron and 13.6 ± 5.8° for the pitching wedge. They also examined left and right knee flexion at take away, the top of backswing and at impact with the ball (Table 2.5). No significant differnces were found between the 5 iron and pitching wedge for knee flexion.

Table 2.5 Right and left knee joint flexion mean ± standard devitiaions at take away, top of backswing and impact for the 5 iron and pitching wedge. Adapted from Egret et al. (2003).

	Right knee (°)			Left knee (°)		
	Take away	**Top of backswing**	**Impact**	**Take away**	**Top of backswing**	**Impact**
5 iron	17.6 ± 6.0	19.1 ± 3.4	24.5 ± 8.4	18.0 ± 7.5	36.5 ± 7.6	17.6 ± 7.5
Pitching wedge	21.9 ± 6.5	19.2 ± 2.6	27.5 ± 7.1	18.9 ± 6.1	37.2 ± 6.8	18.4 ± 6.1

2.3.1.2 Kinematics of the iron golf clubs

In relation to the kinematics of iron clubs during the golf swing the most widely reported measure is club head speed (Budney and Bellow 1982, Chao et al. 1987, Cahalan et al. 1991, Williams and Sih 2002, Egret et al. 2003, McCloy, Wallace and Otto 2006). These studies reported comparable speeds for the club head of irons ranging from 28.6 – 46 $m.s^{-1}$. Only three studies were found that gave further information on iron clubs than club head speed (Lindsay, Horton and Paley 2002, Williams and Sih 2002, McCloy, Wallace and Otto 2006). Lindsay et al. (2002) detailed the shaft angle at the take away position for the 7 iron to be 55°. Williams and Sih (2002) conducted a study to examine the orientation of the clubface at and following impact. They provided information on a range of club head swing characteristics including clubface loft, open/closed, and tilt angles and ball impact location on the clubface for the 5 iron club. Research by McCloy et al. (2006) was carried out to gain understanding of the swing characteristics of iron clubs. They examined club head angle of attack and clubhead velocity of the 3, 5 and 7 iron and the pitching wedge (Table 2.6).

Table 2.6 Clubhead angle of attack (°) and velocity ($m.s^{-1}$) for different iron clubs. Taken from McCloy et al. (2006).

	3 irons	5 iron	7 iron	Pitching wedge
Club head angle of attack (°)	-5.9 ± 1.7	-6.7 ± 1.5	-8.1 ± 1.3	-9.4 ± 1.4
Club head velocity ($m.s^{-1}$)	41.6 ± 1.7	40.4 ± 1.6	38.7 ± 1.7	36.2 ± 2.2

As with the kinematics of the golfer using an iron club there is a lack of information on the kinematics of the iron clubs themselves, with further research needed to fully understand how these clubs are performing during the golf swing.

2.3.1.3 Kinematics of the golfer using the driver club

There are notably more studies available that have examined kinematic differences in golfers of varying skill level using the driver club than the iron clubs. Information on the number of participants and their skill level for each of these studies is detailed in Table 2.7. This section will present the results for these studies detailing where significant differences between skill levels did and did not occur. Where possible comparisons will be made between studies that have examined the same variables, however, these are few. The section will be divided into the phases of the golf swing: take away, backswing, downswing and follow through.

Table 2.7 Details for participants in studies that examined effect of skill level with the driver club.

Study	Participants
McLaughlin and Best 1994	10 low handicap (<4)
	10 middle handicap (9-18)
	10 high handicap (19-27)
McTeigue et al. 1994	51 PGA
	46 senior PGA
	34 amateurs (mean handicap = 17.5)
Mitchell et al. 2003	19 college golfers (mean handicap = 3)
	24 middle age golfers (mean handicap = 9)
	2 senior golfers (mean handicap = 14)
Myers et al. (2008)	20 low ball velocity golfers (< 58.1 $m.s^{-1}$; handicap = 15.1 ± 5.2)
	65 medium ball velocity golfers (58.1 – 71.8 $m.s^{-1}$; handicap = 7.8 ± 6.9)
	14 high ball velocity golfers (<71.8 $m.s^{-1}$; handicap = 1.8 ± 3.2)
Zheng et al. 2008	18 professionals (0 ± 0)
	18 low handicap (3.22 ± 2.0)
	18 mid handicap (12.5 ± 1.9)
	18 high handicap (21.3 ± 3.8)

2.3.1.3.1 Take away

McLaughlin and Best (1994) examined the forward flexion angle of the trunk at the take away position for their three groups. They found that the low handicap group had a significantly greater trunk forward flexion angle than both the middle and high handicap golfers meaning that the low handicap group were in a more upright position than the other two groups (Difference given as ≈ 7°, no absolute values reported). In contrast McTeigue et al. (1994) found no significant difference in this angle for the three different skill levels they assessed (professional = 28 ± 2°, senior professional = 23 ± 3° and amateurs = 23 ± 3°). Research by McTeigue et al. (1994) and Zheng et al. (2008) similarly found no significant difference between the X Factor angle (McTeigue et al. (1994) all participants 5 ± 1°; Zheng et al. (2008) pro = -7 ± 5°, low and mid = -7 ± 6° and high = -9 ± 7°) and side bending angle of the trunk (McTeigue et al. (1994) professional = 6 ± 1°, senior professional = 8 ± 1° and amateur = 7 ±1°; Zheng et al. (2008) pro = 13 ± 4°, low = 15 ± 4°, mid = 12 ± 5° and high = 14 ± 7°) at take away for their participants. Zheng et al. (2008) also examined left and right elbow flexion, wrist cock angle and arm to trunk angle and found no differences between their groups for these angles. They defined the wrist cock angle for both wrists (Figure 2.2 (a) and (b)) as the angle between the proximal direction of the forearm and the distal direction of the club shaft and the arm to trunk angle (Figure 2.2 (c)) as the angle between the inferior direction of the trunk vector and the distal direction of the humerus for both shoulders.

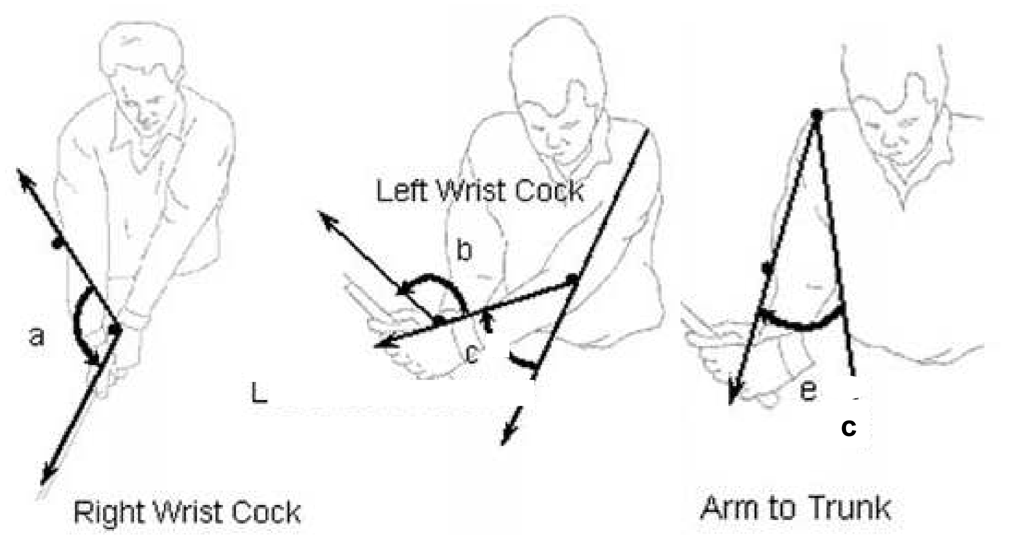


Figure 2.2 Definition for right (a) and left (b) wrist cock angle and arm to trunk angle (c). Adapted from Zheng et al. (Zheng et al. 2008).

2.3.1.3.2 Backswing

Studies that examined differences in participant kinematics by skill level during the backswing assessed a wide range of both upper and lower body kinematic variables. No significant differences were found for upper torso or pelvic rotation angles at the top of the backswing between the two studies that examined them (McTeigue et al. 1994, Myers et al. 2008). Definitions are given for these angles in the studies can be found in Table 2.1and Figure 2.3.

Table 2.8 Definitions for upper torso and pelvic rotation angles by McTeigue et al. (1994) and Myers et al. (2008).

Study	Variable	Definition
McTeigue et al. 1994	Upper body rotation	This is the rotation in degrees of the golfer's torso, measured at the mid-thoracic spine, toward (open) or away (closed) from the target. The number is the sum of the differential rotation. The differential rotation is the relative rotation of the golfer's upper body to hips, also known as the x-factor.
	Hip rotation	This is the rotation in degrees of the golfer's hips toward (open) or away (closed) from the target. Hip rotation in this context is actually rotation of the golfer's pelvis. By definition, hip rotation is zero in the take away position.
Myers et al. 2008	Upper torso rotation	Calculated as the angle between the segment and the global x-axis. The global x-axis was set up so that a neutral take away position of the upper torso and pelvis would be zero degrees.
	Pelvis rotation	Calculated as the angle between the segment and the global x-axis. The global x-axis was set up so that a neutral take away position of the upper torso and pelvis would be zero degrees.

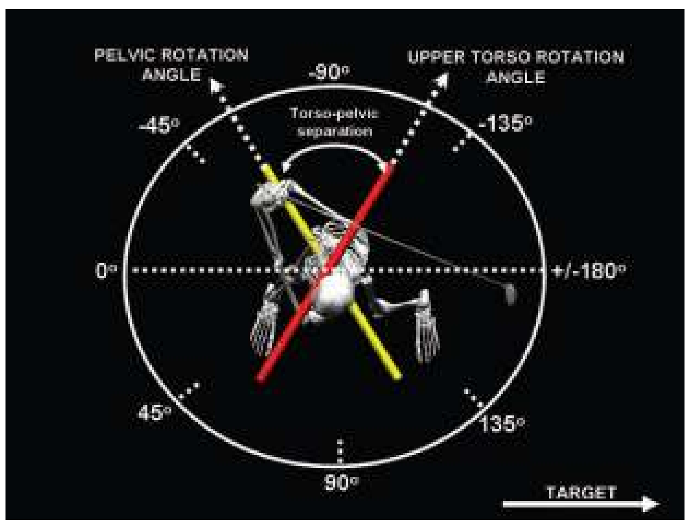
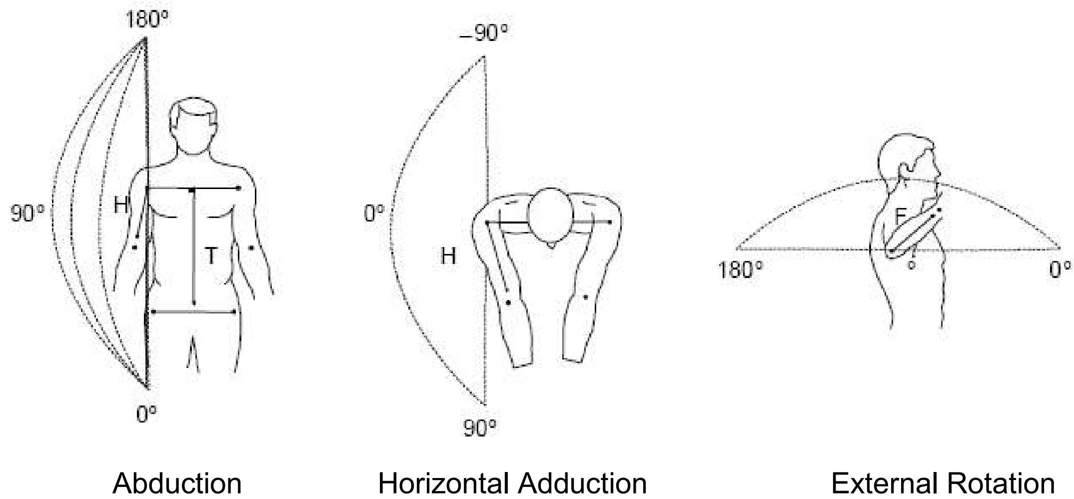


Figure 2.3 Definition for pelvis rotation and upper torso rotation angles. Taken from Myers et al. (2008).

Myers et al. (2008) however, found that the low ball velocity group generated less hip rotation velocity at the top of the backswing than the high ball velocity group (74.8 ± 57.9 $°.s^{-1}$ *vs.* 128.7 ± 52.4 $°.s^{-1}$). No such difference was found for shoulder rotation velocity. Differences between skill level were found by Myers et al. (2008) and Zheng et al. (2008) for the X Factor angle at the top of the backswing. Myers et al. (2008) found that their low and medium ball velocity groups had a smaller X

Factor angle than the high ball velocity group (-44.2 ± 7.7° and -49.5 ± 9.6° *vs.* -59.1 ± 8.2°). Zheng et al. (2008) found that their professional golfers had a significantly greater X Factor angle than their high handicap group (60 ± 7° *vs.* 49 ± 12°). These results showed that the higher skilled golfers used a greater range of motion of the X Factor angle during the backswing than the less skilled golfers. Contrasting results for between skill level differences for the trunk side bending angle at the top of the backswing were found by McTeigue et al. (1994) and Zheng et al. (2008). McTeigue et al. (1994) found that their professional and senior professional golfers had a significantly smaller angle than the amateur golfers (3 ± 1° and 4 ± 2° *vs.* 16 ± 2°) while Zheng et al. (2008) found no significant difference between any of their groups. McTeigue et al. (1994) believed the greater side bending angle found in the amateurs golfers resulted from them sliding the hips away from the target and dropping the left shoulder towards the ground which they believed was in an attempt to keep their head in a still position over the ball. They postulated that the professional players rotated their hips without sliding them away from the target. McTeigue et al. (1994) found no significant difference in the trunk forward bending angle between their three groups.

For a number of different shoulder variables measured by Mitchell et al. (2003) (Figure 2.4) and Zheng et al. (2008) (Figure 2.5) the highly skilled golfers were found to have a significantly greater angle than the less skilled golfers indicating the higher skilled golfers used a greater range of motion.



Note: H = humerus; T = trunk vector; F = angle of forearm.

Figure 2.4 Definitions for shoulder variables measured by Mitchell et al. (2003).

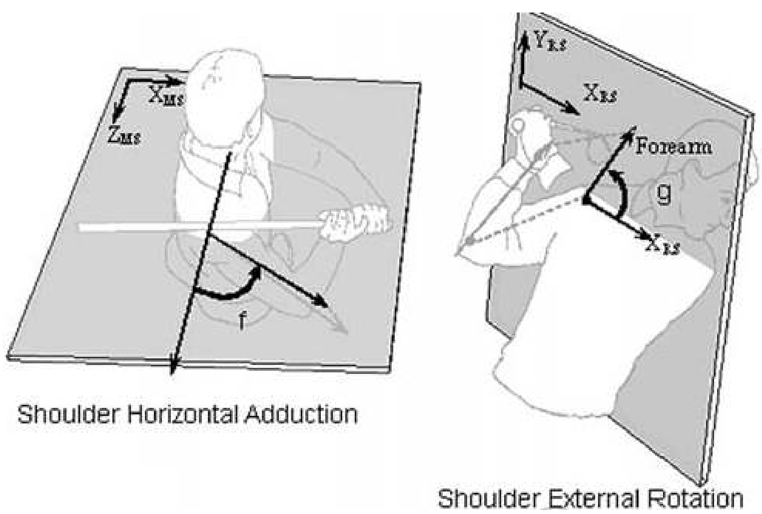


Figure 2.5 Definitions for shoulder variables measured by Zheng et al. (2008).

For left shoulder horizontal adduction Mitchell et al. (2003) found that their college and middle age golfers had a greater maximum angle of adduction than the senior golfers (125 ± 7° and 126 ± 7° *vs.* 119 ± 6°) and they stated that this maximum occurred near the top of the backswing (the exact point where the maximum occurred was not given). Zheng et al. (2008) found their professional and low handicap golfers had a greater angle than their high handicap golfers (125 ± 6° and 123 ± 5° *vs.* 115 ± 8°) at the top of the backswing. Mitchell et al. (2003) also found significant differences between their groups for the minimum right shoulder horizontal adduction angle which again occurred neat the top of the backswing; the college golfers were found to have a significantly greater angle than both the middle age and senior golfers (29 ± 20° vs. 12 ± 23° and 11 ± 20°). For the right shoulder external rotation angle Mitchell et al. (2003) found that the maximum occurred near the top of the backswing and that there was a significant difference between the college, middle age and senior golfers (86 ± 19° *vs.* 71 ± 16° *vs.* 48 ± 17°) Zheng et al. (2008) also found significantly different angles between all their three groups with the rotation angle decreasing with decreasing skill level; their professional golfers produced a greater rotation angle than both the mid and high handicap golfers (66 ± 11° *vs.* 47 ± 24° and 46 ± 17°) at the top of the backswing. For all the other variables examined by Zheng et al. (2008) (elbow flexion angle, arm to trunk angle and wrist cock angle), no significant differences were seen between their groups. McTeigue et al. (1994) was the only study found that examined the duration of the backswing, they found no significant difference between their groups.

2.3.1.3.3 Downswing

Studies that examined the downswing generally reported on the variables at the time of club impact with the ball. No significant differences were found in the studies that examined upper torso and pelvic rotation (Table 2.8 and Figure 2.3) and rotation velocity at impact (McTeigue et al. 1994, Myers et al. 2008). McLaughlin and Best (1994) examined pelvic and knee rotation (rotation of a line joining the hips/knees relative to the take away position) at mid downswing with the middle and high handicap groups recording significantly smaller angles of rotation than the low handicap group (no values were reported).

Zheng et al. (2008) examined the X Factor angle at impact and both the professional and low handicap golfers had a greater angle than the mid and high handicap golfers (24 ± 10° and 22 ± 6° *vs.* 15 ± 5° and 9 ± 9°). Zheng et al. (2008) found no difference between their groups for arm to trunk angle or right elbow flexion. They did however find a difference for left elbow flexion angle with the professional, low and mid handicap golfers elbows found to be in a more extended position than the high handicap golfers (34 ± 6°, 31 ±8° and 35 ± 6° vs. 41 ± 13°). For the trunk side bending angle at impact contrasting results for skill level differences were found by McTeigue et al. (1994) and Zheng et al. (2008). Zheng et al. (2008) found no significant differences between their groups while McTeigue et al. (1994) found that their professional and senior professional golfers had a significantly greater bending angle than the amateurs (31 ± 1° and 28 ± 2° *vs.* 21 ± 2°). McTeigue et al. (1994) stated that the lesser angle of side bending found in the amateurs at impact was possibly due to them sliding their hips more toward the target and rotating their upper body with their shoulders in a more upright position during the downswing than the professional players. For the other two variables examined by McTeigue et al. (1994) trunk forward bending angle and duration no significant differences were found between the groups.

The remaining variable assessed by Zheng et al. (2008) was wrist cock angle (Figure 2.2) at impact. No significant difference between the groups were found for the right wrist, however, both the professional and low handicap golfers had a greater left wrist cock angle than the mid and high handicap golfers (165 ± 4° and 166 ± 5° *vs.* 159 ± 9° and 156 ± 9°). Two other studies were located that examined wrist cock angle during the downswing (McLaughlin and Best 1994, Robinson 1994). McLaughlin and Best (1994) examined the left wrist cock angle at mid downswing (Figure 2.6) and found the wrist cock angle to be significantly less for the low handicap golfers than both the middle and high handicap golfers (no values were reported). Although Robinson (1994) did not measure the wrist cock angle at exactly the same phase of the downswing as McLaughlin and Best , he measured it at the point in the downswing when the left forearm was parallel to the ground, it was similarly found that the higher skilled golfers (professionals) had a significantly less wrist cock angle than the lesser skilled golfers (amateurs) (77° *vs.* 101°, respectively). McLaughlin and Best (1994) believed that their results supported previous findings that delaying the release of the wrist cock angle, indicated by the lesser angle of the higher skilled golfers at mid downswing, produced greater club head velocity at impact. This belief was further supported by Robinson (1994) who found the characteristic that exhibited the most significant correlation with club head velocity was wrist cock angle ($r = 0.78$). McLaughlin and Best (1994) also examined the angular velocity at ball impact of the wrist cock angle and found that low handicap golfers generated greater wrist cock angular velocity than the middle and high handicap golfers. The middle handicap golfers' velocity was also significantly greater than the high handicap golfers (no values were reported).

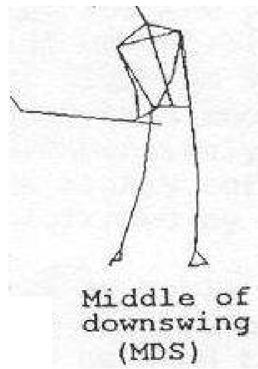


Figure 2.6 Definition of mid downswing. Taken from McLaughlin and Best (1994).

2.3.1.3.4 Follow through

Only one study was found that examined differences between skill levels for the follow through. Mitchell et al. (2003) assessed a number of shoulder joint angles their three groups (college age, middle age and senior golfers). They found significant differences between all groups for right shoulder adduction (122 ± 8° *vs.* 117 ± 7° *vs.* 108 ± 8°) and shoulder rotation angles (160 ± 12° *vs.* 142 ± 18° *vs.* 124 ± 22°) with the angles found to increase with increasing skill level. They also found that the college age golfers and middle age golfers had significantly greater angles than the senior golfers for right shoulder vertical elevation (112 ± 8° and 114 ± 11° *vs.* 103 ± 11°) and left shoulder external rotation (80 ± 11° and 77 ± 14° *vs.* 59 ± 14°). No significant difference was found between the three groups for left shoulder adduction angle.

2.3.1.4 Kinematics of the driver club

Only three studies were found that detailed differences in driver club kinematics for golfers of different skill levels (Barrentine, Fleisig and Johnson 1994, McLaughlin and Best 1994, Robinson 1994). Two of these studies examined the club head velocity at impact with the higher skilled golfers found to produce greater velocities than the less skilled golfers (McLaughlin and Best 1994, Robinson 1994).

McLaughlin and Best (1994) found that the low handicap golfers (<4) produced a significantly greater velocity than both the middle (9-18) and high (19-27) handicap golfers and Robinson (1994) found their professional golfers produced greater velocity than the amateurs golfers. Robinson (1994) did not statistically analysis this difference. Both Barrentine et al. (1994) and McLaughlin and Best (1994) assessed the maximum club head velocity achieved by their participants. Barrentine et al. (1994) found their professional golfers had a significantly greater maximum club head velocity than the high handicap golfers (16+), and McLaughlin and Best (1994) found that their low handicap (<4) had a significantly greater maximum velocity than both their middle (9-18) and high handicap (19-27) golfers. McLaughlin and Best (1994) additionally found significant differences between their groups for vertical club head velocity at mid downswing and horizontal club head velocity at ball contact. Both the low (<4) and middle (9-18) handicap golfers produced less vertical club head velocity at mid downswing than the high handicap group (19-27) and the low handicap group (<4) produced greater horizontal club head velocity at ball contact than the middle (9-18) and high handicap golfers. The final variable examined by McLaughlin and Best (1994) where a difference were seen to occur between skill levels was the vertical distance between the club head and hands at the top of the backswing. Less distance between the club and the hands was found for the low handicap golfers compared to both the middle (9-18) and high (19-27) handicap golfers, meaning the low handicap group allowed the club head to drop below the level of the hands at the top of the backswing while the other two groups kept the club in a position above then hands. In so doing the low handicap group used a greater range of motion of the club in the horizontal direction during the backswing than the lesser skilled groups.

2.3.2 Stretch shortening cycle

Human movement seldom involves isolated concentric, eccentric or isometric contractions. This is because the body segments are regularly subjected to impact forces, as in running and jumping, or some external force (e.g. gravity) lengthens the muscle. During these periods the muscles are usually contracting eccentrically followed by a concentric contraction. This combination of eccentric and concentric contractions forms a natural muscle function called the stretch shortening cycle

(SSC) (Komi 1984). The SCC is an economical way to cause movement and, as a result, the performance of the muscle can be improved (Knuttgen and Komi 2003). The neuromuscular mechanical output during the concentric contraction is enhanced when compared to an concentric contraction preceded by an isometric contraction or rest (Asmussen and Bonde-Petersen 1974, Komi 2003). This has been demonstrated previously in both animal (Cavagna, Saibene and Margaria 1965, Cavagna, Dusman and Margaria 1968) and human studies (Asmussen and Bonde-Petersen 1974, Bosco, Komi and Ito 1981, Voigt et al. 1995, Bobbert et al. 1996, Moran and Wallace 2007). These human studies used jumping to demonstrate the benefits of the SSC. Results showed benefits of the counter movement jump, which involves the SSC, over a non counter movement jump. For example Bobbert et al. (1996), found that jump height on average was 3.4 cm greater in the countermovement jump than the squat jump (non countermovement jump).

The source of the improved performance has been attributed to a number of mechanisms, such as: storage and reutilisation of elastic energy, increased force at the start of the concentric contraction, neural reflex potentiation and altered properties of the contractile machinery (Bobbert et al. 1996). The ability of the muscle to effectively utilise the SSC depends on the speed of the stretch, the length of the muscle, the force developed at the end of the stretch and the length of time the stretch is held (Cavagna, Saibene and Margaria 1965, Cavagna, Dusman and Margaria 1968). The enhancement in force during the concentric phase due to the eccentric stretching appears to be larger the greater the speed of stretching and the shorter the length of the muscle (Cavagna, Dusman and Margaria 1968, Bosco, Komi and Ito 1981). The improvement in neuromuscular output is also greater the sooner the muscle is allowed to shorten after stretching (Cavagna, Saibene and Margaria 1965, Wilson, Elliott and Wood 1991).

In the golf swing the SSC is utilised as the muscles of the lower and upper body are rapidly stretched prior to shortening. The end of backswing provides the first phase of the SSC, the eccentric contraction, and the downswing is the second phase of the SSC, the concentric contraction. Professional players generally complete the backswing in less time than amateurs, therefore leading to greater velocity of their backswing and consequently a greater speed of stretch (McTeigue et al. 1994), which as mentioned above is important in effectively utilising the SSC. The joint actions involved in the golf swing are believed to utilise the SSC, a description of the X Factor angle will be provided as an example of the contribution of the SSC to the golf swing. As shown by Mc Lean (1992), the greater a golfers X factor angle the higher they ranked on driving distance. McTeigue et al. (1994) proposed that the X factor stretch, as described earlier, maybe of greater importance to achieving driving distance than the X factor. The X factor stretch achieved during the early phase of the downswing provides further eccentric contraction in the upper body as the hips start to rotate back towards the direction of the target before the shoulders. It may be important for golfers to minimise the transition time from the backswing to the downswing as if the benefit of the prior eccentric stretch will diminish.

2.3.3 Order of joint actions

The terms proximal to distal sequencing (Putnam 1993), kinetic link (Kreighbaum and Barthels 1996), summation of speed principle (Bunn 1972) and acceleration-deceleration (Plagenhoef 1971) are all used in an attempt to describe the complex interaction of the body's independent segments interacting to form a functional unit (Ellenbecker and Davies 2001). They are in essence the same principle, which states that "to produce the largest possible speed at the end of a linked chain of segments, the motion should start with the more proximal segments and proceed to the more distal segments, with the more distal segment beginning its motion at the time of the maximum speed of the proximal one, with each successive segment generating a larger end-point speed than the proximal segment" (Marshall and Elliott 2000 p.248). Putnam (1993), added to this principle, that it is often observed, that the speed of at least one of the more proximal segments is greatly diminished by the time the most distal segment reaches its maximum speed. Most assessments of segmental sequencing in throwing, kicking or striking have shown it to occur in a proximal to distal manner (Marshall and Elliott 2000).

When applied to golf, to maximise the speed of the club head at the moment of impact with the ball, the golf swing should start with movements of more proximal segments and progress with faster movements of the more distal segments

(Burden, Grimshaw and Wallace 1998). Therefore, the downswing should be initiated by the rotation of the pelvis about the hip joint and the thorax about the vertebral column, followed by the upper extremities. The results from a small number of studies on golf have shown that the golf swing conforms to proximal to distal sequencing (Milburn 1982, McTeigue et al. 1994, Burden, Grimshaw and Wallace 1998, Sprigings and Neal 2000, Okuda et al. 2002). These studies confirm the use and benefit of proximal to distal sequencing in the golf swing, through findings in EMG activity (Okuda et al. 2002), hip and shoulder rotations (McTeigue et al. 1994, Burden, Grimshaw and Wallace 1998) and wrist action during the golf swing (Milburn 1982, Sprigings and Neal 2000).

Okuda et al. (2002) examined the swing of a professional golfer, recording the EMG activity of a selection of muscles on the upper and lower body during the golf swing using a driver club. The results of this study were in agreement with the use of proximal to distal sequencing in the golf swing. During the final phase of the backswing they found that while the right shoulder musculature continued to assist in elevating the club, selected right lower body muscles (Gluteus medius and biceps femoris) were already beginning to initiate abduction and extension of the right hip. They associated this movement with the coiling of the trunk at the start of the downswing. The sequence continued with activation of right trunk and lower body muscles, and in the final phase of the downswing, activation of the left upper extremity muscles.

Burden et al. (1998), examined the hip and shoulder rotations of eight sub-10 handicap male golfers. They found that 75% of the golfers in their study completed their shoulder rotation for the backswing after the hips had started rotating back towards the target. They concluded that this sequential pattern of hip and shoulder rotation conformed to proximal to distal sequencing. Results from McTeigue et al. (1994), contradict these findings with only 3% of the golfers tested (51 PGA Tour professionals, 46 Senior PGA Tour professionals and 34 amateurs) completing their shoulder rotation for the backswing after the hips had started rotating back towards the target. However, their results did find that 70% of Tour players rotate their hips first in the downswing, which itself conforms to proximal to distal sequencing during this phase.

An investigation into the generation of high club head velocity was conducted by Milburn (1982). Participants consisted of four collegiate level golfers and one low handicap golfer. He used a two-segment model consisting of the arm rotating at the shoulder and the club rotating at the wrist to represent the downswing. A series of equation were derived and used to describe the component features of the downswing. They concluded that the greatest acceleration of the club head occurred when a delay in wrist action occurred. This meant maintaining the wrist in a "cocked" position until late in the downswing, utilising proximal to distal sequencing from the arm to the wrist. They believed this allowed acceleration of the arm to reach a greater value and the acceleration of the club to be summed with the existing maximum angular acceleration of the proximal segment (the arm). Sprigings and Neal (2002), conducted a simulation study on the importance of wrist torque in driving the golf ball. They used a 2D, three segment model (torso, left arm and golf club) to model the downswing of the golf swing. Significant gains in club head speed (≈ 9%) were found if an active wrist torque was applied to the club during the latter stages of the downswing just prior to impact. This wrist torque is commonly referred to as 'uncocking of the wrists' (Hume, Keogh and Reid 2005). They found that optimising the timing of the torque generators used in the model required the use of a proximal to distal sequence.

2.3.4 Kinetics of the golf swing

Studies that have examined the kinetics of the golf swing provide data on the internal and external forces during the swing. This section will review the limited studies that have examined differences in golfer kinetics between varying skill levels using the iron clubs. However, due to the dearth of research that examined the effect of skill level on performance with the iron clubs studies that have used the driver will also be included. The small number of studies found examined weight transfer (Williams and Cavanagh 1983, Richards et al. 1985, Barrentine, Fleisig and Johnson 1994, Koenig, Tamres and Mann. 1994, Robinson 1994, Kawashima, Meshizuka and Takeshita. 1998, Ball and Best 2007a, Ball and Best 2007b) , torque generated at the feet (Barrentine, Fleisig and Johnson 1994, Worsfold, Smith and

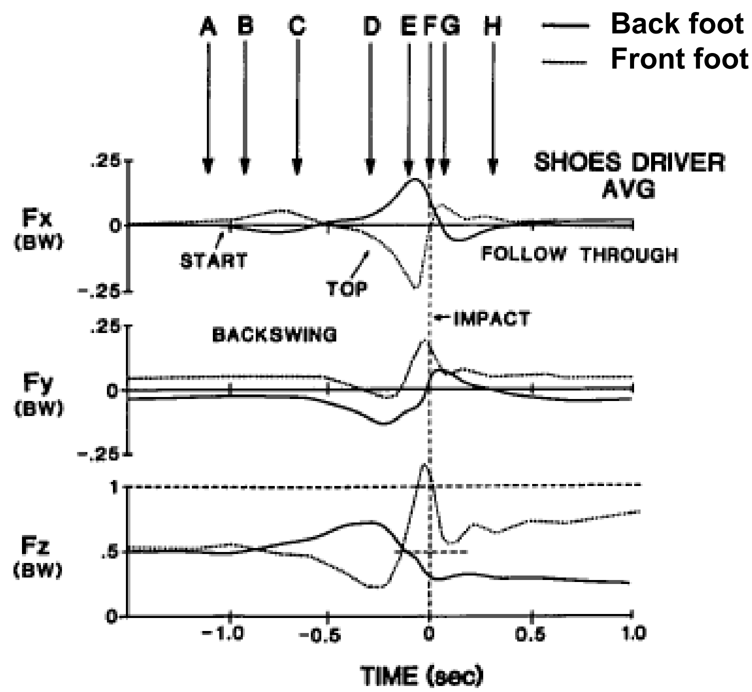
Dyson 2008) and the forces about the knees (Gatt, Pavol, Parker and Grabiner. 1998, Gatt et al. 1998) and back (Hosea, Gatt and Gertnet 1994) during the swing.

2.3.4.1 Weight transfer

In relation to the golf swing, weight transfer describes the movement of bodyweight between the feet during the swing. Six studies were found that examined the effect of skill level on weight transfer (Williams and Cavanagh 1983, Richards et al. 1985, Barrentine, Fleisig and Johnson 1994, Koenig, Tamres and Mann. 1994, Robinson 1994, Kawashima, Meshizuka and Takeshita. 1998). These studies used the measurement of ground reaction forces and centre of pressure displacements to describe the weight transfer utilised by golfers. In addition, to these studies two selected studies by Ball and Best (2007a, 2007b) are reviewed as they importantly identified two subgroups of weight transfer style: ‘front foot’ and ‘reverse’ style.

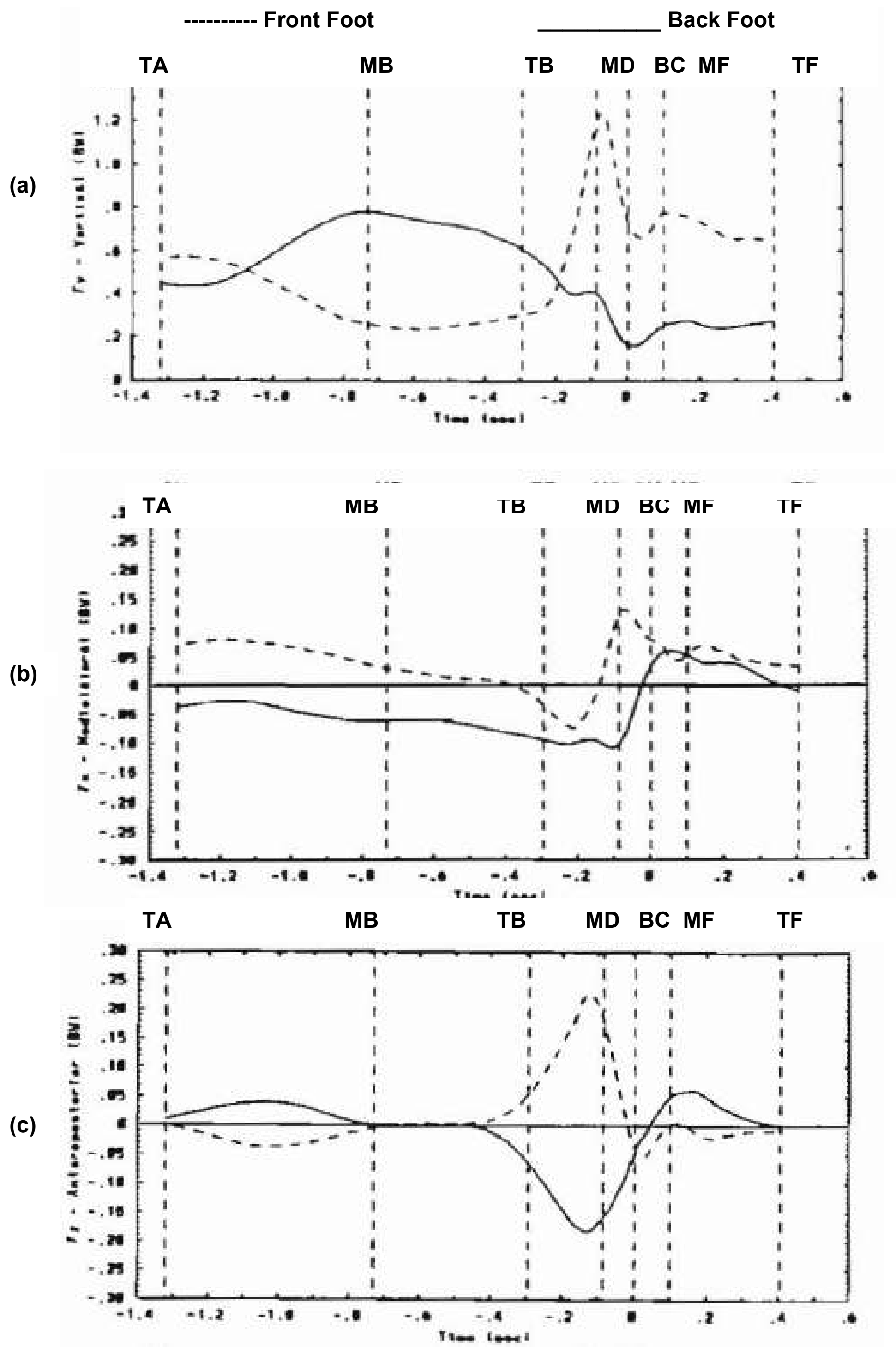
Williams and Cavanagh (1983), Koenig et al. (1994) and Robinson (1994) all examined the ground reaction forces of golfers of varying skill levels. In addition, Williams and Cavanagh (1983) and Koenig et al. (1994) also examined centre of pressure displacements. Williams and Cavanagh (1983) used 10 golfers divided into 3 groups based on handicap [3 low handicap (0-7), 4 mid handicap (8-14) and 3 high handicap (15+)]. The participants used three clubs: driver, 3 iron and 7 iron and the measurements were recorded at 8 swing events: take away, early backswing, middle backswing, top of the backswing, mid downswing, ball contact, early follow through and end of follow through. Koenig et al. (1994) also used the driver, 3 iron and 7 iron, with14 golfers divided into 3 groups [low handicap (0-7), mid handicap (8-14) and high handicap (15+)] at seven swing events. These events were: take away, mid backswing, top of backswing, mid downswing, ball contact, mid follow through and top of follow through. Exact definitions for the swing events used in these two studies were not provided by the authors. Robinson (1994) used the driver club and examined 30 golfers of varying skill levels (professional to high handicap) at four events: take away, top of the backswing, point in the downswing when the left arm is parallel to the ground and ball contact.

Figure 2.7 and Figure 2.8 show the mean force-time curves for the three force components: vertical, anterior/posterior and medial/lateral for all subjects using the driver club reported by Williams and Cavanagh (1983) and Koenig et al. (1994), respectively.



Note: Fx = anterior/posterior force; Fy = medial/lateral force; Fz = vertical force; A = Takeaway; B = Early backswing; C = Mid backswing; D =Top of backswing; E = Mid downswing; F = Ball contact; G = Early follow through; H = End of follow through.

Figure 2.7 Mean force-time curves for both feet for all subjects swings using the driver. Adapted from Williams and Cavanagh (1983).



Note: TA = take away; MB = mid backswing; TB = top of backswing; MD = mid downswing; BC = ball contact; MF = mid follow through; TF = top of follow through.

Figure 2.8 Normalised force-time graphs of the front and back foot averaged for all participants: (a) vertical (b) medial/lateral (c) anterior/posterior. Adapted from Koenig et al. (1994).

Williams and Cavanagh (1983) expressed all force measures in units of body weight (BW) and reported similar force patterns for all three clubs (driver, 3 iron and 7 iron). Vertical force was found to move to the back foot during the backswing with a rapid transfer to the front foot prior to ball contact. The authors reported that just prior to ball contact the vertical force on the back foot to be 1 BW and a total vertical force of approximately 1.6 BW. The medial/lateral forces were directed laterally on both feet during the backswing. Then from just before the top of the backswing until just prior to ball contact the forces were exerted in a negative direction by both feet which the authors believed was responsible for the body moving in the direction of the target. By ball contact the forces had reversed to stop the body's movement from the back to the front foot. The anterior/posterior forces for the feet generally acted in opposition throughout the swing. During the backswing the front foot was pushing backwards while the back foot was pushing forwards in order to rotate the upper body and club. During the downswing these forces were reversed as rotation of the upper body occurred in the opposite direction. Williams and Cavanagh (1983) stated that meaningful quantitative analysis between the groups was not possible due to the small number of participants. They reported from their qualitative analysis that there was as much variation within the individuals in the groups as there was between the groups. Between club comparisons showed significant differences between the driver and the 7 iron's peak vertical force for the front foot just prior to ball contact and also a significant difference was evident between all the clubs for peak anterior/posterior force prior to ball contact for the front foot (no values were reported).

Koenig et al. (1994) used front to back foot ratios to report their findings. Results showed that their participants were found to transfer their weight from an approximately 55:45 front to back foot ratio at take away to a maximum 20:80 ratio at the mid backswing, and ending with a 35:65 ratio at the top of backswing. During their downswing a rapid weight shift was evident back toward the front foot. The high handicap group were found to produce much less weight transfer toward their back foot in the backswing, preferring to maintain a more even balance between their feet (no values however were reported). With regard to the different clubs (driver, 3 iron and 7 iron) differences in the magnitude of the weight transfers were found which the authors stated was due to club inertial effects and swing techniques. The medial/lateral forces from the take away position to the top of backswing were directed away from the direction of the target (to the right). Shortly after the top of the backswing through to mid downswing the forces were directed back towards the direction of the target. Around the time of ball contact the participants then reversed the direction of the medial/lateral forces which the authors stated was in order to stabilise their motion. The less skilled golfers were found to maintain greater force on both feet during the backswing while the higher skilled golfers produced a greater rate of decrease of force on their front foot during the later stages of the downswing. The anterior/posterior forces during the early stages of the backswing were postulated to act to prevent the golfer from rotating as the club is raised backwards. The golfer then used anterior forces on the front foot and posterior forces on the back foot in order to rotate their torso. Towards mid downswing there was a rapid decrease in the forces and after ball contact the forces react to stabilise the motion of the body. In general, the higher skilled golfers produced greater forces for both feet throughout the swing and they initiated their forces towards the top of the backswing earlier than the less skilled golfers.

Robinson (1994) only examined the vertical force component and produced force-time curves for a selected professional (Figure 2.9) and amateur (Figure 2.10) golfer. A significant correlation between the vertical force on the back foot at take away and club velocity at ball contact was evident ($r = 0.45$), with larger vertical force on the back foot associated with larger club head velocity. The professional golfers were found to have 51% of their body weigh on the back foot at take away, while the amateurs had 42%. Results also showed that a more rapid weight transfer from the back foot to the front foot from the top of the backswing to the point in the downswing when the left arm was parallel to the ground correlated to greater club head velocity at impact ($r = 0.61$).

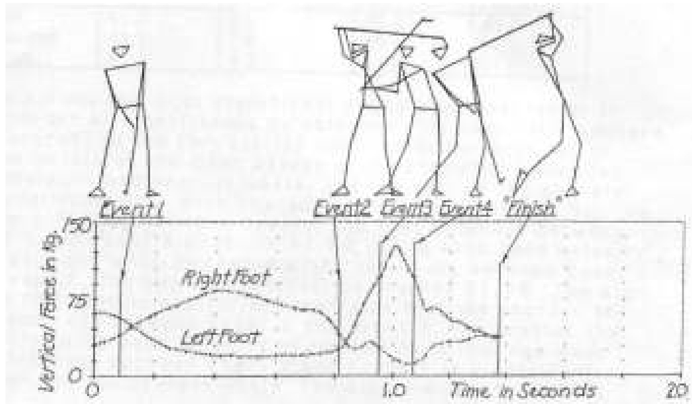


Figure 2.9 Force-time curve for a selected professional golfer. Taken from Robinson (1994).

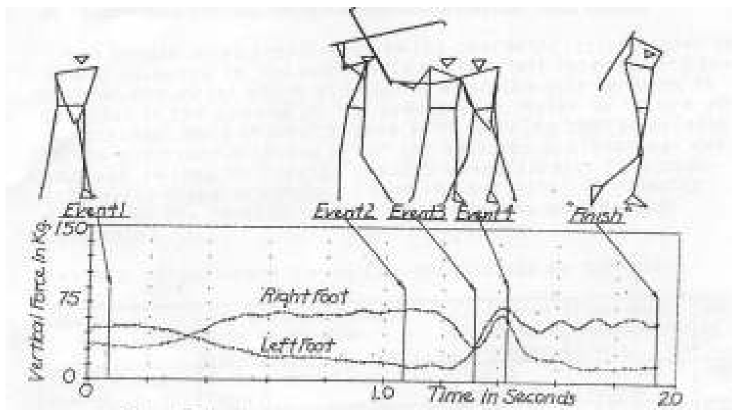


Figure 2.10 Force-time curve for a selected amateur golfer. Taken from Robinson (1994).

Figure 2.11 shows the mean centre of pressure displacement for all subjects using the driver club taken from Williams and Cavanagh (1983). The foot position was estimated to represent its approximate position at take away and therefore it doesn't account for movements of the feet during the swing. At take away the centre of pressure was approximately in the centre of each foot indicating even distribution of pressure. During early backswing it moved forwards in the front foot and backwards in the back foot. Through to mid backswing it continued to move forward for the front foot and reached its most backward position on the back foot. At the top of the backswing it progressed to its most forward position while the back foot changed very little. During the early downswing it remained on the forefoot and moved laterally on the front foot while on the back foot it progressed further forward. At ball contact it had started to move back towards the centre of the front foot while it progressed further forward and medially on the back foot. At early follow through it continued to move laterally on the front foot and forward and medially on the back foot. By the end of the follow through it had returned to approximately its position at take away on the front foot while it was still in a very forward position on the back foot.

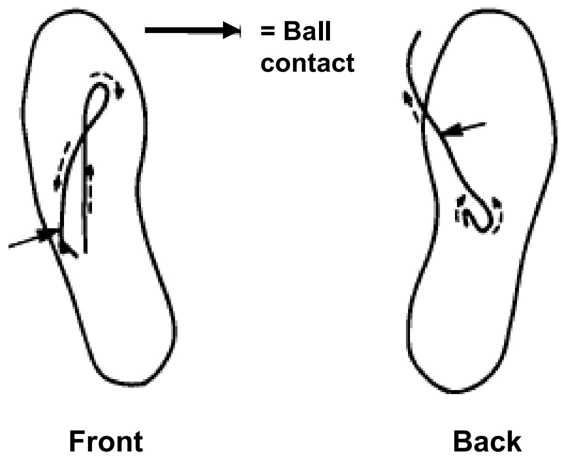


Figure 2.11 Mean centre of pressure displacement for all subjects with the driver. Adapted from Williams and Cavanagh (1983).

Koenig et al. (1994) examined the centre of pressure displacement and ground reaction forces of 14 golfers divided into 3 groups based on skill level [low handicap (0-7), mid handicap (8-14) and high handicap (15+)] at seven swing events. These events were: take away, mid backswing, top of backswing, mid downswing, ball contact, mid follow through and top of follow through. Exact definitions for how these seven swing events were identified were not provided. The participants completed golf swings with three different clubs: driver, 3 iron and 7 iron. An example of a typical golfer's centre of pressure displacement during the golf swing can be found in Figure 2.12.

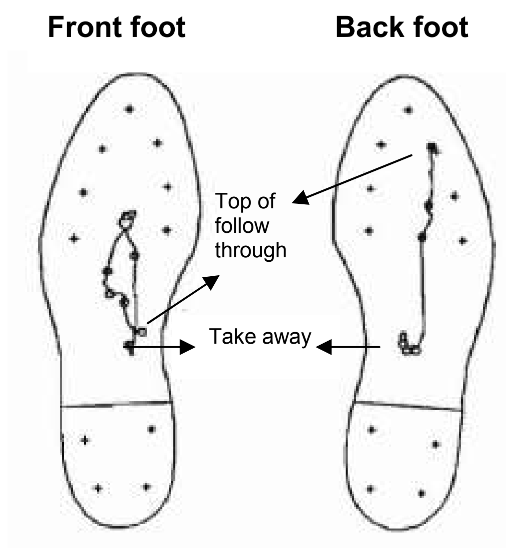


Figure 2.12 Centre of pressure displacement pattern for a typical golfer with circles representing the seven swing events. Adapted from Koenig et al. (1994).

At take away the front foot's centre of pressure is close to the heel. During the backswing the centre of pressure travelled in the anterior direction towards the forefoot which the authors stated was a result of the transfer of weight towards the back foot and the rotation of the club around the body. This movement of the centre of pressure continued until the top of the backswing. Through the downswing the centre of pressure moved in the opposite direction, back towards the heel. The centre of pressure also traveled laterally towards the outside of the front foot (in the direction of the target) which the authors believed was due to the weight transfer back onto the front foot and the swinging of the club back in the direction of the target. Before ball contact the centre of pressure continued back towards the heel and also moved back towards the medial edge of the foot which the authors believed was due to the golfer compensating for the centripetal force produced by the club's inertia. The centre of pressure was found to return close to where it was at the take away position by the end of the swing. The authors noted that a "slight looping" feature was evident at the top of the backswing for the mid and high handicap golfers but not for the low handicap golfers. Additionally, the low handicap golfers were found to keep their centre of pressure closer to the heels and more medial than the mid and high handicap golfers. For the back foot the centre of pressure began at a similar position as the front foot. It moved slightly posteriorly during the backswing followed by rapid movement towards the toes during the downswing. Similar to the front foot the higher skilled golfers kept their centre of pressure towards the heel and the medial side of the foot. Also during the backswing their centre of pressure progressed more towards their heels than the lesser skilled golfers. During the downswing the lesser skilled golfer's centre of pressure moved more laterally and quicker in the anterior direction than the higher skilled golfers. The authors stated that the ability of the higher skilled golfers to kept their centre of pressure more towards their heels and the medial side of their feet related to better stability and performance than the lesser skilled golfers.

The early research by Richards et al. (1985) examined weight transfer for 20 participants divided into 2 groups (10 with a handicap <10 and 10 with a handicap >20) with a 5 iron club. They measured force distribution ratios from heel to toe and from back foot to front foot (right foot to left foot) during the swing. Figure 2.13 provides a sample output from their study.

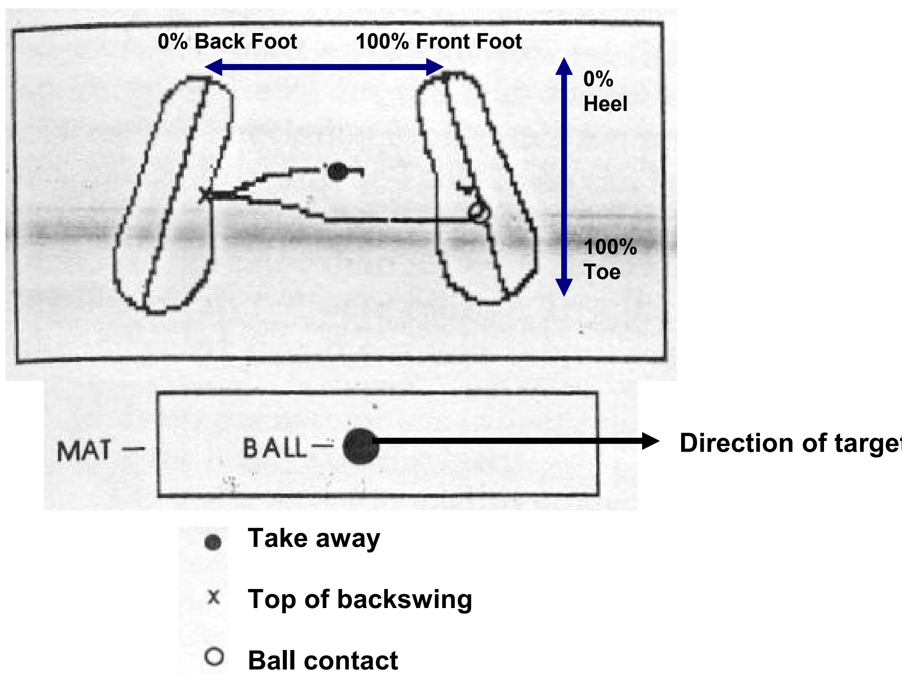


Figure 2.13 Sample output from the force plate surface. Adapted from Richards et al. (1985).

The location of the centre of pressures relative distance from back foot to front foot and relative distance from heel to toe was measured at two events: the top of the backswing and at ball contact. In addition, the minimum relative distance between the centre of pressure and the back foot (min) and the maximum distance the centre of pressure travelled forward of the midline of the front foot were measured (max) (Table 2.9).

Table 2.9 Centre of pressure values (mean % ± standard deviation) taken from Richards et al. (1985).

Variable	Low handicap	High handicap
Back foot to front foot		
Top of backswing	27.5 ± 8.79	21.84 ± 13.56
Ball contact	95.58 ± 12.08	80.91 ± 25.18
Min	16.60 ± 6.50	14.52 ± 10.85
Max	105.35 ± 5.56	98.05 ± 9.14
Heel to toe		
Top of backswing	53.65 ± 8.09	56.11 ± 7.28
Ball contact	33.96 ± 9.01	51.24 ± 8.40

Note: back foot to front foot: 0% = back foot, 100% = front foot; heel to toe: 0% = toe, 100% = heel; Min = minimum distance between centre of pressure and the back foot; Max = farthest point forward the centre of vertical force travelled relative to the midline of the front foot.

Similar results for the two groups for front to back foot centre of pressure distribution were found at the top of backswing and at ball contact (approximately 21-28% at top of backswing and 80-96% at ball contact) with the centre of pressure values for each group within one standard deviation of each other. For the centre of pressure distribution between the heels and toes similarly no difference was found between the two groups at the top of the backswing (approximately 53-57%), however, at ball contact the centre of pressure distribution was approximately 34% for the low handicap group and 51% for the high handicap group. This difference reached statistical significance and the authors stated it indicated the tendency for the low handicap golfers to place their weight closer to their heels at the moment of contact with the ball. Richards et al. (1985) believed that this was due the amount of lower body horizontal rotation utilised by the low handicap golfers prior to ball contact. For the maximum amount the centre of pressure transferred toward the front foot during the swing (Max) the low handicap group were found to allow the pressure to transfer significantly further forward (in the direction of the target) onto the front foot than the high handicap group (105% *vs.* 98%). For the In addition, the overall group variability was less for the highly skilled group than for the less skilled group, indicating that the highly skilled golfers were approaching a somewhat general weight transfer pattern, whereas the less skilled golfers were highly variable as a group.

Research by Kawashima et al. (1998) used the 5 iron club with seven skilled (handicap = 5.5 ± 1.8) and seven unskilled (28.0 + 4.0) males and provided information on the vertical force exerted by the feet, with the foot segmented into six different areas. The six areas were right and left digitus minimum areas (RDM, LDM), right and left hallux areas (RHA, LHA) and right and left foot calcaneous areas (RCA, LCA) (Figure 2.14). The maximal force exerted by the feet was measured during the backswing, downswing, at ball contact and during the follow through (Table 2.10).

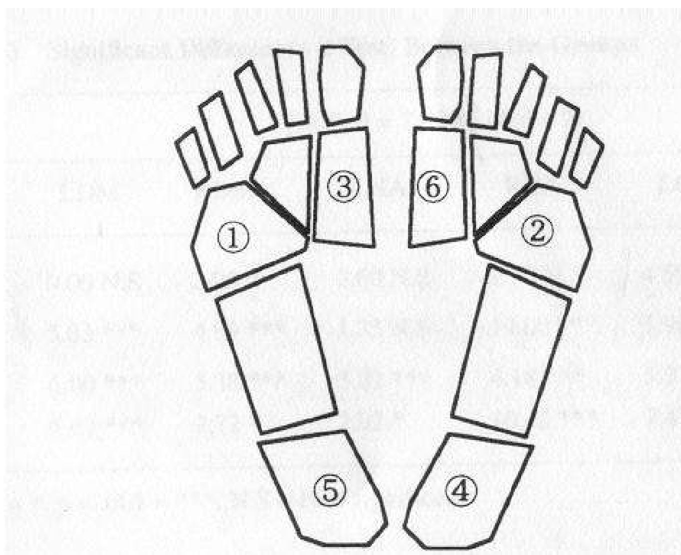


Figure 2.14 Measures foot force areas: (1) LDM, (2) RDM, (3) LHA, (4) RCA, (5) LCA, (6) RHA. Taken from Kawashima et al. (1998).

Table 2.10 Maximal force values (N) of the feet during the golf swing (mean ± standard deviation). Taken from Kawashima et al. (1998).

		LDM	RDM	LHA	RHA	LCA	RCA
Backswing	Skilled	4.9 ± 2.8	17.7 ± 4.5	14.7 ± 2.7	16.2± 3.6	24.3 ± 7.4	17.7 ± 2.3
	Unskilled	4.9 ± 2.3 (NS)	11.1 ± 3.8*	13.6 ± 3.0 (NS)	13.1 ± 3.9 (NS)	10.4 ± 1.3***	16.9 ± 2.0 (NS)
Downswing	Skilled	12.3 ± 3.9	51.7 ± 19.5	16.4 ± 2.4	38.6 ± 3.3	18.6 ± 1.7	21.3 ± 2.9
	Unskilled	24.7 ± 3.5***	14.9 ± 4.1***	14.3 ± 3.1 (NS)	12.3 ± 3.2***	21.7 ± 3.5 (NS)	21.7 ± 2.7 (NS)
Impact	Skilled	8.7 ± 1.6	16 ± 3.2	37.3 ± 4.7	19 ± 3.5	45 ± 4.9	16.3 ± 3.4
	Unskilled	20.1 ± 4.4***	39.4 ± 11.2***	23.1 ± 4.6***	12.1 ± 2.0***	31.9 ± 4.3***	34.4 ± 4.7***
Follow through	Skilled	33.4 ± 3.9	25.7 ± 7.3	21.9± 3.2	22.7 ± 3.2	62.4 ± 5.8	15.3 ± 1.4
	Unskilled	16.7 ± 6.1***	39.4 ± 11.2*	17.7 ± 1.4	7.7 ± 1.3***	40.4 ± 4.3***	33.9 ± 3.3***

Note: LDM = left digitus minimus area; RDM = right digitus minimus; LHA = left hallux area; RHA = right hallux area; LCA = left calcaneous area; RCA = right calcaneous area; NS = not significantly different between groups; * = $p < 0.05$; *** = $p < 0.001$.

During the backswing significant differences occurred between the two groups in two of the six areas; LCA (skilled 24.3 ± 7.4 N *vs.* unskilled 10.4 ± 1.3 N) and RDM (skilled 17.7 ± 4.5 N *vs.* unskilled 11.1 ± 3.8 N). In the downswing the skilled golfers were found to put more force onto their RDM and RHA than the unskilled golfers (51.7 ± 19.5 N *vs.* 14.9 ± 4.1 N and 38.6 ± 3.3 N *vs.* 12.3 ± 3.2 N, respectively). The skilled golfers were additionally found to put less force onto their LDM than the unskilled golfers during the downswing (12.3 ± 3.9 N vs. 24.7 ± 3.5 N, respectively). At ball contact significant differences were found in all six areas of the feet, with the skilled golfers found to put more force on their left feet while the unskilled golfers force remained on their right feet. During the follow through phase the skilled golfers had more force on their LDM (33.4 ± 3.9 N *vs.* 16.7 ± 6.1 N) and LCA (62.4 ± 5.8 N *vs.* 40.4 ± 4.3 N) while the unskilled golfers were found to have more force on their RDM (39.4 ± 11.2 N *vs.* 25.7 ± 7.3 N) and RCA (33.9 ± 3.3 N *vs.* 15.3 ± 1.4 N). The authors concluded that their results suggested that unskilled golfers used incomplete weight transfer between the feet; keeping their force within a central area of the right (RDM to RHA) and left (LHA to LCA) foot.

Barrentine et al. (1994) examined the ground reaction forces (Figure 2.15) and centre of pressure displacements applied by the feet to the ground for 60 golfers divided into 3 groups based on skill level [20 PGA Tour Professionals and PGA Teaching Professionals, 20 low handicap (0-15) and 20 high handicap (16+)] for the driver club (Table 2.11). Results showed that the professional and the low handicap golfers achieved maximum posterior sheer force with their back foot (0.164 ± 0.05 s and 0.176 ± 0.05 s *vs.* 0.235 ± 0.05 s) and anterior sheer force with their front foot (0.176 ± 0.05 s and 0.176 ± 0.04 s *vs.* 0.231 ± 0.05 s) earlier in the downswing compared to the high handicap golfers. It was also found that the professional golfers front foot anterior/posterior centre of pressure displacement was significantly smaller than the high handicap golfers (4.8 ± 1.8 cm *vs.* 5.7 ± 1.8 cm) and the low handicap golfers back foot medial/lateral centre of pressure displacement was significantly greater than the high handicap golfers (4.6 ± 3.1cm *vs.* 3.1 ± 1.8 cm).

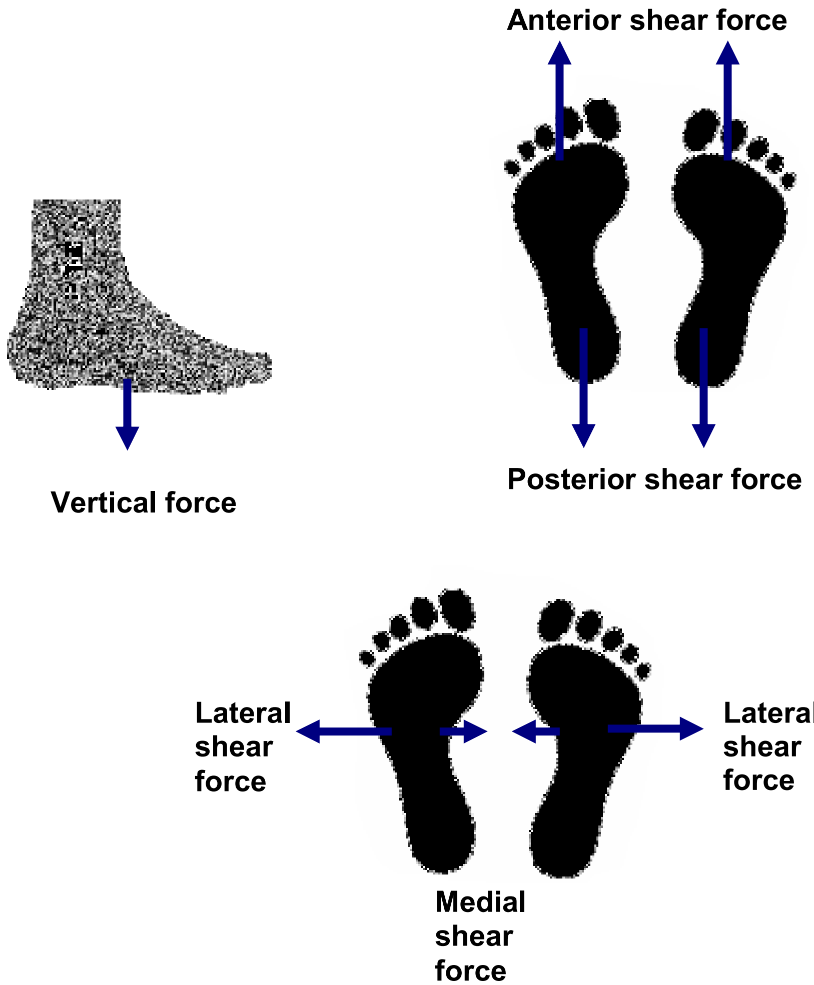


Figure 2.15 Definitions for vertical force, anterior/posterior force, and medial/lateral force utilised by Barrentine et al. (1994).

Table 2.11 Differences between skill levels for centre of pressure displacement, torques and timing for the driver club (mean ± standard deviation). Taken from Barrentine et al. (1994).

Variable	PGA	Low handicap	High handicap	Significant Difference
Centre of pressure displacement				
Front foot anterior-posterior displacement (cm)	4.8 ± 1.8	5.3 ± 1.1	5.7 ± 1.8	a
Rear foot medial-lateral displacement (cm)	4.0 ± 2.3	4.6 ± 3.1	3.1 ± 1.8	b
Timing				
Time of maximum back foot posterior shear force after top of backswing (s)	0.164 ± 0.05	0.176 ± 0.05	0.235 ± 0.05	a,b
Time of maximum front foot anterior shear force after top of backswing (s)	0.176 ± 0.05	0.176 ± 0.04	0.231 ± 0.05	a,b

Note: a = significant difference ($p < 0.05$) between PGA and high handicap groups; b = significant difference ($p < 0.05$) between low and high handicap groups.

In addition, they grouped together all the participants and provided analysis of the between club differences that occurred in the measured variables when using the driver and the 5 iron club (Table 2.12). Significantly greater forces were utilised during the downswing when using the driver club than the 5 iron club. Barrentine et al. (1994) believed these greater forces were utilised by the participants in order to achieve the same acceleration of the driver club as they did with the shorter 5 iron club. After ball contact the participants were found to generate a greater front foot lateral shear force with the driver than the 5 iron club (133.3 ± 35.0 N.m *vs.* 123.2 ± 29.3 N.m).

Table 2.12 Ground reaction forces, centre of pressure displacement and torques for all subjects for the driver and 5 iron club (mean ± standard deviation). Taken from Barrentine et al. (1994).

Variable	Driver	5 iron
Anterior – Posterior Forces		
Maximum back foot posterior shear (N)	145.3 ± 23.6	128.5 ± 22.9*
Time after top of backswing (s)	0.192 ± 0.06	0.200 ± 0.06*
Maximum front foot anterior shear (N)	185.8 ± 37.3	161.5 ± 35.5*
Time after top of backswing (s)	0.194 ± 0.05	0.198 ± 0.05
Anterior – Posterior centre of pressure displacement		
Back foot (cm)	24.4 ± 5.4	23.5 ± 6.2
Front foot (cm)	13.4 ± 4.0	12.5 ± 3.9
Lateral forces		
Maximum back foot lateral shear (N)	126.3 ± 31.9	127.5 ± 29.9
Time after top of backswing (s)	0.049 ± 0.13	0.079 ± 0.10*
Maximum front foot lateral shear (N)	133.3 ± 35.0	123.2 ± 29.3*
Time after ball contact (s)	0.012 ± 0.07	0.034 ± 0.07*
Medial – Lateral centre of pressure displacement		
Back foot (cm)	9.9 ± 6.4	9.7 ± 5.9
Front foot (cm)	6.8 ± 2.2	5.9 ± 2.0*
Vertical forces		
Maximum back foot vertical (N)	703.2 ± 80.5	695.1 ± 81.7*
Time relative to top of the backswing (s)	-0.267 ± 0.16	-0.259 ± 0.16
Maximum front foot vertical (N)	950.6 ± 156.4	963.6 ± 135.9
Time after ball contact (s)	0.010 ± 0.10	0.028 ± 0.08*

Note: * = significant difference ($p < 0.05$) between driver and 5 iron club.

Recent research by Ball and Best (2007b) has examined the assumption of previous research that only one style of weight transfer exists. They aimed to determine if different weight transfer styles existed by applying cluster analysis to centre of pressure measurements (Figure 2.16) for sixty two golfers of varying skill level [from professional to high handicap (11 ± 8)] using the driver club. Centre of pressure measurements from front to back foot were expressed as a percentage of the distance between the feet and were recorded at eight swing events (Table 2.13 and Figure 2.17).

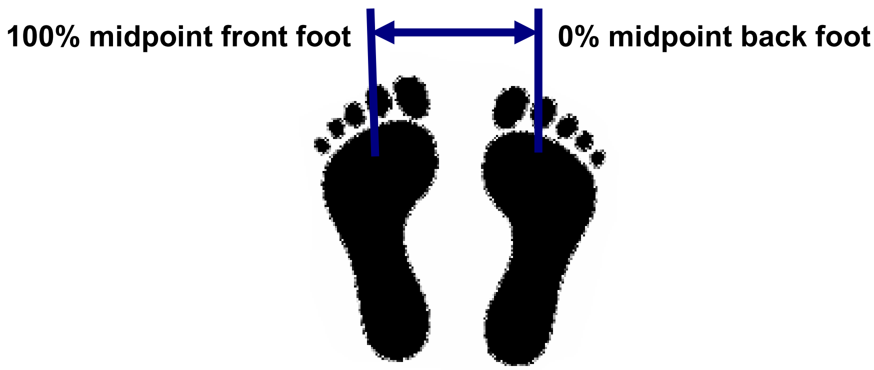


Figure 2.16 Centre of pressure measurement definition utilised by Ball and Best (2007b).

Table 2.13 Definition of eight swing events used by Ball and Best (2007a, 2007b).

Event	Label	Definition
Take away	TA	First backward movement of the club
Mid backswing	MB	Club shaft parallel to the horizontal plane
Late backswing	LB	Club shaft perpendicular to the horizontal plane when the club is projected onto the YZ vertical plane
Top backswing	TB	Instant before shaft begins downswing
Early downswing	ED	Club shaft perpendicular to the horizontal plane when club is projected onto the YZ vertical plane
Mid downswing	MD	Club shaft parallel to the horizontal plane
Ball contact	BC	Instant of club contact with ball
Mid follow through	MF	Club shaft parallel to the horizontal plane

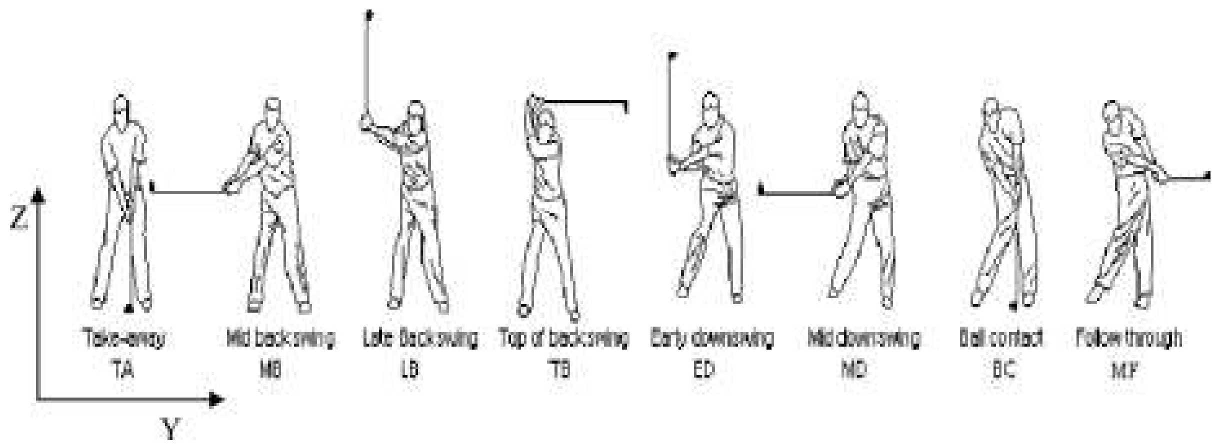
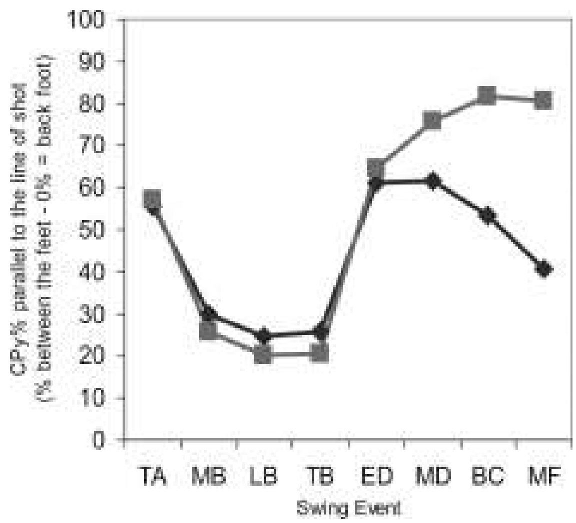


Figure 2.17 Eight swing events used by Ball and Best (2007a, 2007b).

Their analysis revealed two large cluster groups which they termed as the "reverse" group (n = 39) and the "front foot" group (n = 19). Figure 2.18 shows the centre of pressure pattern for these two groups at the eight swing events. Both groups followed a similar pattern from the events of take away to early downswing. After early downswing the reverse groups' centre of pressure moved back towards their back foot while the front foot groups' centre of pressure continued towards their front foot. Statistical analysis revealed significant differences between the groups with the front foot group found to position their centre of pressure nearer the front foot at the events of mid downswing, ball contact and mid follow through. In addition, the front foot group were found to produce a larger maximum, smaller minimum, and greater range of centre of pressure than the reverse group. The maximum centre of pressure velocity was the same for both groups and occurred at the same time (2.5 $m.s^{-1}$; occurred 0.14 s before ball contact). No significant difference was evident between the reverse and front foot groups for skill level indicated by handicap (10.2 ± 10.2 *vs.* 11.1 ± 6.8) or performance indicated by club head velocity at ball contact (44.1 ± 4.9 $m.s^{-1}$ *vs.* 44.1 ± 3.9 $m.s^{-1}$). Given there was no difference between the groups for skill level or performance [and that both groups contained highly skilled golfers with a handicap < 5 (reverse group had 12 and front foot group had 8 highly skilled golfers)] the authors suggested that neither of the two styles were a technical error.



Note: TA = takeaway; MB = mid backswing; LB = late backswing; TB = top of backswing; ED = early downswing; MD = mid downswing; BC = ball contact; MF = mid follow through.

Figure 2.18 Mean centre of pressure position (CPy%) at 8 swing events for the reverse group ♦ and the front foot group ■. Taken from Ball and Best (2007b).

Table 2.14 Significantly different results for the front foot and reverse groups (mean ± standard deviation). Taken from Ball and Best (2007b).

Centre of pressure %	Front foot	Reverse
Mid downswing	76 ± 5	62 ± 10
Ball contact	81 ± 11	53 ± 12
Mid follow through	80 ± 11	41 ± 13
Max	87 ± 9	69 ± 9
Min	12 ± 7	18 ± 8
Range	75 ± 11	51 ± 12

A follow up study by Ball and Best's examined the relationship between centre of pressure measures and club head velocity within each of their two defined groups (Ball and Best 2007a). Their correlation and regression analysis indicated that a larger centre of pressure range ($r = 0.54$, $p < 0.001$) and a maximum centre of pressure velocity ($r = 0.47$, $p = 0.005$) were associated with a larger club head velocity at ball contact for the front foot group. The authors postulated that these positively correlated variables could be related, with a larger range of movement facilitating the production of a larger velocity. They acknowledged further discussion of this possible mechanism was limited due to the absence of kinematic data which they recommended be combined with kinetic data collection in future studies. For the reverse group, positioning of the centre of pressure further from the back foot at the event of late backswing ($r = 0.75$, $p = 0.001$) and a more rapid transfer of the centre of pressure back towards the back foot at ball contact ($r = -0.69$, $p = 0.003$) were associated with a larger club head velocity at ball contact. The authors attempted to explain the relationship between centre of pressure at late backswing and club head velocity through analysis of: (i) the time when the centre of pressure minimum occurred, (ii) the velocity of the centre of pressure and (iii) the start of force production for the downswing. However, future research including kinematic analysis was again recommended to fully understand the relationship.

2.3.4.2 Torque generated at the feet

Barrentine et al. (1994) recorded the torques (Figure 2.19) applied by the feet to the ground for 60 golfers divided into 3 groups based on skill level [20 PGA Tour Professionals and PGA Teaching Professionals, 20 low handicap (0-15) and 20 high handicap (16+)] for the driver club (Table 2.15). The high handicap golfers generated greater back foot torque than the professional and low handicap golfers (30.9 ± 10.8 N.m *vs.* 18.5 ± 4.6 N.m and 17.0 ± 6.3 N.m) and smaller front foot torque than the professional golfers (20.1 ± 7.7 N.m *vs.* 26.3 ± 6.2 N.m). The low handicap golfers achieved maximum torque with the back foot earlier in the downswing which the authors related to the greater club velocity achieved by them. Analysis of differences between the clubs (Table 2.16) showed that the participants were found to generate a greater maximum back foot torque (22.0 ± 9.7 N.m *vs.* 20.8 ± 9.6 N.m) and smaller maximum front foot torque (23.5 ± 7.1 m *vs.* 24.2 ± 6.9 N.m) with the driver than the 5 iron club.

Figure 2.19 Definitions for outward torque utilised by Barrentine et al. (1994).

Table 2.15 Differences between skill levels for torques for the driver club (mean ± standard deviation). Taken from Barrentine et al. (1994).

Variable	PGA	Low handicap	High handicap	Significant Difference
Outward torques				
Back foot torque (N.m)	18.5 ± 4.6	17.0 ± 6.2	30.9 ± 10.8	a,b
Front foot torque (N.m)	26.3 ± 6.2	23.2 ± 6.2	20.1 ± 7.7	a

Note: a = significant difference ($p < 0.05$) between PGA and high handicap groups; b = significant difference ($p < 0.05$) between low and high handicap groups.

Table 2.16 Torques for all subjects for the driver and 5 iron club (mean ± standard deviation). Taken from Barrentine et al. (1994).

Variable	Driver	5 iron
Outward Torques		
Maximum back foot (N.m)	22.0 ± 9.7	20.8 ± 9.6*
Time relative to top of the backswing (sec)	-0.088 ± 0.13	-0.110 ± 0.14*
Maximum front foot (N.m)	23.5 ± 7.1	24.2 ± 6.9*
Time after ball contact (sec)	0.304 ± 0.17	0.269 ± 0.15*

Note: * = significant difference ($p < 0.05$) between driver and 5 iron club.

Worsfold et al. (2008) measured the torque generated at the feet for 24 golfers divided into 3 groups based on skill level [8 low handicap (0-7), 8 mid handicap (8-14) and 8 high handicap (15+)] using different clubs (driver and the 3 and 7 iron) and different shoes. Torque was measured at the front and the back foot by force platforms (Figure 2.20). There was no significant difference found between the handicap groups for the maximum torque of the front (16.6-19.7 N.m) or back foot (5.7-7.8 N.m). The low handicap golfers were found to generate significantly greater mean torque than the mid and high handicap golfers when using the driver club (16.1 N.m vs. 13.4 N.m and 12.4 N.m, respectively). No significant differences between the groups were found for the 3 or 7 iron clubs. Reasonably comparable results between Barrentine et al. (1994) and Worsfold et al. (2008) were found for front foot maximal torque (approximately 20 N.m) and they both found significantly greater torques were generated with the driver club than the iron clubs they examined. The significant differences between the handicap groups found by Barrentine et al. (1994) were not evident in the research by Worsfold et al. (2008).

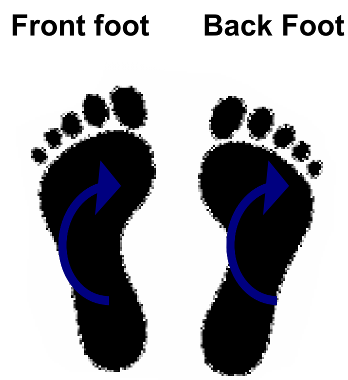


Figure 2.20 Definition of torque measurement by Worsfold et al. (2008). Positive rotation is movement to the lateral side of the back front and medial side of the front foot.

2.3.4.3 Joint kinetics

Gatt et al. (Gatt, Pavol, Parker and Grabiner. 1998, Gatt et al. 1998) provided analysis of knee joint kinetics. They used motion capture and force plates to compute the knee joint kinetics for thirteen golfers (handicap range 4-18 with a mean of 11.2). Peak forces were normalised to body weight (BW) and moments were normalised to the product of body weight and body height (BW.BH). In general, the maximum value for posteriorly directed forces and flexion moments for the front knee and compression forces at the back knee occurred during the backswing. During the downswing the peak forces in the front knee were experienced in the order of compressive, anterior and then medial; and the peak knee moments in the order of extension, internal and then adduction. In relation to the back knee it experienced its peak forces during the downswing in the order of lateral, posterior and then medial; and its peak knee moments in the order of external and abduction, flexion and then adduction. Results showed significant differences in the mean peak force and moments between the lead and trail knees (Table 2.17 and Table 2.18).

Table 2.17 Mean ± standard deviation peak forces along each axis acting on each knee. Adapted from Gatt et al. (1998)

Direction	Front Knee		Back Knee	
	(N)	(%BW)	(N)	(%BW)
Compressive	756.3 ± 187.4	99.9 ± 18.9	540.4 ± 101.2*	71.5 ± 8.7*
Anterior	295.6 ± 91.9	39.0 ± 10.7	149.0 ± 39.1*	19.9 ± 5.0*
Posterior	-2.8 ± 19.0	-0.3 ± 2.6	75.3 ± 26.6*	10.1 ± 3.5*
Medial	73.3 ± 23.6	9.9 ± 3.3	70.9 ± 19.3	9.5 ± 2.8*
Lateral	133.0 ± 80.9	17.0 ± 8.6	87.7 ± 38.3*	11.4 ± 4.2*

* = significantly different from the front knee ($p < 0.001$)

%BW = percentage body weight

Table 2.18 Mean ± standard deviation peak moments along each axis acting on each knee. Adapted from Gatt et al. (1998)

Direction	Front Knee		Back Knee	
	(N.m)	(%BW.BH)	(N.m)	(%BW.BH)
Flexion	20.8 ± 23.3	1.62 ± 1.89	68.4 ± 14.0**	5.15 ± 1.18**
Extension	96.9 ± 29.0	7.17 ± 1.95	58.6 ± 14.4**	4.40 ± 1.16**
Internal	16.1 ± 4.8	1.20 ± 0.33	19.6 ± 8.1*	1.46 ± 0.54*
External	27.7 ± 9.3	2.05 ± 0.65	19.1 ± 5.5**	1.41 ± 0.36**
Abduction	63.7 ± 24.5	4.73 ± 1.73	38.8 ± 17.4**	2.85 ± 1.18**
Adduction	24.4 ± 11.0	1.78 ± 0.66	52.6 ± 16.2**	3.89 ± 0.95**

* = significantly different from the front knee ($p < 0.05$)

** = significantly different from the front knee ($p < 0.001$)

%BW.BH = percentage product of body weight and body height

Only the lead knee flexion and internal rotation moments were found to be significantly correlated to skill level. The regression analysis indicated that mean peak flexion moment at the lead knee increased by 3.08 N.m per handicap point from a baseline (handicap = 0) of -13.6 N.m and by 0.228% BW.BH per handicap point from -0.92% BW.BH. Mean peak internal moment at the lead knee decreased by 0.040% BW.BH per handicap point from a baseline of 1.64% BW.BH. They reported that a total variance of 53% in the mean peak absolute flexion moment, 43% in the mean peak normalized flexion moment and 42% in the mean peak normalized internal rotation moment at the front knee was accounted for by handicap. As none of the other measured variables were found to correlate with handicap the authors hypothesized that handicap may not be an accurate indicator of the efficiency of a golfer's swing. Since handicap is determined from all aspects of a golfer's game (including driving, chipping and putting) and they found some participants used very little lower extremity movement, while others used large amounts of lower extremity they believed their results supported the idea that it is the swing pattern used by a golfer and not their skill level (determined by handicap) that determines the magnitude of the forces and moments at the knees during the golf swing.

Hosea et al. (1994) examined the lateral-bending, shear, compression and torsional forces affecting the lumbar spines third and fourth vertebrae when swinging a 5 iron club. Their participants were four male professionals and four male amateurs with an average USGA handicap of 16. Each participant had reflective markers placed along their spine and extremities and their movements during the golf swing were recorded using four synchronised video cameras. They reported large forces during the golf swing for all the forces measured (lateral-bending, shear, compression and torsional forces) with the amateurs found to generate greater forces than the professionals. The amateurs produced approximately 80% greater peak lateral-bending and shear loads than the professionals did. The amateurs averaged a peak lateral bending and shear force of approximately 950 N and 560 N, respectively, while the professionals peaked at approximately 520 N and 329 N, respectively. A peak compression load of more than 8 times body weight was reported for both the amateur and professional participants. The torsional force during the golf swing produced an average torque of 85.2 N.m in the amateurs and 56.8 N.m in the professionals. This peak torsional force was found to occur during the transition from backswing to downswing and downswing phases as the trunk uncoiled. The amateurs were also found to have a larger standard deviation than the professionals which was reported to owe to greater variations in the amateurs swing pattern.

2.3.5 Muscle activity during the golf swing

This section aims to detail the actions of the muscles during the different phases of the golf swing. Similar to the other areas of golf research discussed above, studies that have investigated muscle activity are limited. The majority of research into muscle activity in the golf swing has used highly skilled golfers as their participants (Moynes et al. 1986, Jobe, Perry and Pink 1989, Pink, Perry and Jobe 1993, Bechler et al. 1995, Kao et al. 1995, Watkins et al. 1996). Bulbulian et al. (2001) was the only study found that used golfers with a high handicap (mean handicap of 16.3 ± 3.4). Two studies were found that compared golfers across skill levels: Abernethy et al. (1990) participant's were five expert and five novice golfers and Hosea et al. (1994) used four professionals and four amateurs (handicap = 16). A number of different clubs have been used in previous research including: the driver (Jobe, Perry and Pink 1989, Bechler et al. 1995, Kao et al. 1995), the 5 iron (Hosea, Gatt and Gertnet 1994), the 7 iron (Abernethy, Neal, Parker and Moran. 1990, Bulbulian, Ball and Seaman 2001), and the pitching wedge (Abernethy, Neal, Parker and Moran. 1990). Three studies were found that did not define the club used in their research (Moynes et al. 1986, Pink, Perry and Jobe 1993, Watkins et al. 1996). The muscle activity in different areas of the body has been examined with most of the research focusing on the trunk (Pink, Perry and Jobe 1993, Hosea, Gatt and Gertnet 1994, Watkins et al. 1996, Bulbulian, Ball and Seaman 2001). The other areas examined were the left arm (Abernethy, Neal, Parker and Moran. 1990), the hip (Bechler et al. 1995), the knee (Bechler et al. 1995) and the shoulder (Moynes et al. 1986, Jobe, Perry and Pink 1989, Kao et al. 1995, Bulbulian, Ball and Seaman 2001). The method utilised to record muscle activity in all studies researched was either surface electrodes (Abernethy, Neal, Parker and Moran. 1990, Pink, Perry and Jobe 1993, Hosea, Gatt and Gertnet 1994, Watkins et al. 1996, Bulbulian, Ball and Seaman 2001) or the Basmajian single needle technique (Moynes et al. 1986, Jobe, Perry and Pink 1989, Bechler et al. 1995, Kao et al. 1995). These studies will be discussed in full below; the majority are detailed individually as no comparative studies were available. In the few studies that examined the same muscles comparisons will be made between them.

Of the nine studies mentioned above six of them were conducted in either the Kerlan Jobe Orthopardic Clinic or the Biomechanics Laboratory of the Centinela

Hospital Medical Centre in Los Angeles, California or as a collaboration between both facilities (Moynes et al. 1986, Jobe, Perry and Pink 1989, Pink, Perry and Jobe 1993, Bechler et al. 1995, Kao et al. 1995, Watkins et al. 1996). The earliest of these studies was conducted by Moynes et al. (1986). They examined the shoulder muscle activity of professional golfers during four phases of the golf swing (Table 2.19) using electrodes inserted into the muscles.

Table 2.19 Description of swing phases used by Moynes et al. (1986).

Swing phase	**Description**
Takeaway	Ball address to the end of the backswing
Forward swing	End of the backswing until club horizontal
Acceleration	Club horizontal to ball contact
Follow through	Ball contact to the end of the motion

The examined muscles were the subscapularis, supraspinatus, infraspinatus, clavicular head of the pectoralis major, latissimus dorsi and anterior, middle and posterior deltoid. They did not report values for the individual muscle results. For the left side of the body they reported minimal to low level activity for all muscles except the subscapularius during the takeaway phase. For the right side low levels of activity were reported in all muscles except the supraspinatus muscle which reported a moderate level of activity. During the forward swing the activity of the subscapularius and latissimus dorsi was reported as moderate for the left side. For the right side, the supraspinatus muscle activity reduced to a low level and all the deltoid muscle segments were also at a low level of activity. The pectoralis major muscle’s activity increased and the subscapularis and latissimus dorsi muscle were active at a moderate level. During the acceleration phase high levels of activity were reported in both the left and right side pectoralis major, latissimus dorsi and subscapularis muscles. The subscapularis muscle was found to maintain its high level of activity during the follow through phase for both the left and right side. The activity level of the pectoralis major and latissimus dorsi reduced to a moderate level in the left side while their high level of activity was maintained in the right side. The infraspinatus muscle activity increased to a moderate level during the follow through, while all the other muscles exhibited a low level of activity for the left side. For the right side low level activity was reported in the supraspinatus, infraspinatus and anterior deltoid muscles and minimal activity was reported in the posterior and middle deltoid muscles.

The next study by year in this group of studies also examined the shoulder and was conducted by Jobe et al. (1989). They further increased the number of swing phases detailed by Moynes et al. (1986) by dividing the follow through into two separate phases; early and late follow through (Table 2.20 and Figure 2.21). These five phases of the golf swing were used by all subsequent studies within this group of studies.

Table 2.20 Description of swing phases used by Jobe et al. (1989).

Swing phase	Description
Takeaway	Ball address to the end of the backswing
Forward swing	End of the backswing until club horizontal
Acceleration	Club horizontal to ball contact
Early follow through	Early follow through to club horizontal
Late follow through	Club horizontal to the end of the swing

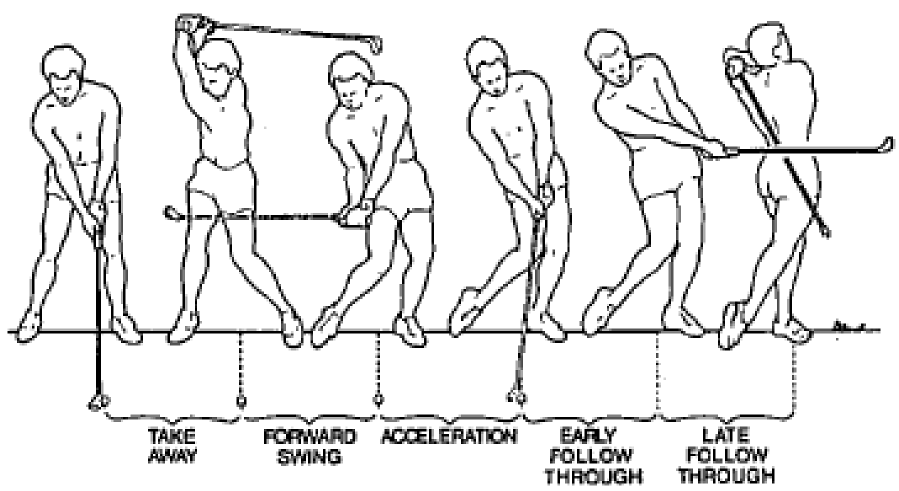


Figure 2.21 Phases of the golf swing. Taken from Jobe et al. (1989).

Jobe et al. (1989) examined shoulder muscle activity in men (6 participants) and women (7 participants) professional golfers using the driver club. The muscles examined were supraspinatus, infraspinatus, subscapularis, pectoralis major, latissimus dorsi and anterior, middle and posterior deltoids for both the left and right shoulders. A manual muscle test (MMT) was used to confirm correct electrode placement and the peak 1 second EMG signal during the MMT was selected as the normalising value (100%). During the swing the muscle activity patterns were assessed every 20 ms and expressed as a percentage of the normalisation value. The percent MMT for each phase of the swing was averaged for each muscle. Some differences were found between the muscle activities of the men and women; however, these differences did not reach statistical significance. Results for the combined muscle activity of the men and women can be found in Table 2.21. The muscle activity values reported by Jobe et al. (1989) were consistent with the levels reported by Moynes et al. (1986).

Table 2.21 Combined muscle activity for men and women professional golfers (mean % MMT ± standard deviation). Adapted from Jobe et al. (1989).

Muscle	Takeaway	Forward swing	Acceleration	Early follow through	Late follow through
Left arm					
Supraspinatus	21 ± 12	21 ± 15	18 ± 11	28 ± 20	28 ± 14
Infraspinatus	14 ± 12	16 ± 13	27 ± 25	61 ± 32	40 + 24
Subscapularis	33 ± 23	29 ± 24	41 ± 34	23 ± 27	35 ± 27
Latissimus dorsi	17 ± 13	46 ± 25	31 ± 28	32 ± 33	18 ± 15
Pectoralis major	21 ± 32	18 ± 14	93 ± 75	74 ± 74	39 ± 23
Anterior deltoid	13 ± 13	9 ± 9	10 ± 10	21 ± 25	26 ± 30
Middle deltoid	3 ± 3	4 ± 6	2 ± 2	7 ± 9	5 ± 3
Posterior deltoid	5 ± 8	24 ± 20	11 ± 9	9 ± 9	8 ± 14
Right arm					
Supraspinatus	25 ± 20	14 ± 14	12 ± 14	7 ± 5	7 ± 5
Infraspinatus	27 ± 24	13 ± 16	7 ±8	12 ± 13	9 ± 10
Subscapularis	16 ± 12	49 ± 31	68 ± 67	64 ± 67	56 ± 44
Latissimus dorsi	9 ± 7	50 ± 38	47 ± 44	39 ± 39	28 ± 19
Pectoralis major	12 ± 9	64 ± 30	93 ± 55	74 ± 55	37 ± 35
Anterior deltoid	5 ± 6	21 ± 23	10 ± 10	11 ± 15	8 ± 8
Middle deltoid	3 ± 3	2 ± 3	2 ± 5	6 ± 10	8 ± 8
Posterior deltoid	17 ± 25	10 ± 15	9 ± 13	17 ± 16	11 ± 12

The research by Kao et al. (1995) examined the muscle activity of the scapular muscles of fifteen highly skilled golfers (handicap <5). Fourteen of the participants were right handed and one was left handed. The muscles studied were the levator scapulae, the rhomboid muscle, the upper, middle and lower trapezius and the upper (4th rib) and lower (6th rib) serratus anterior of both the left and right shoulder. Results for the activity of these muscles during the different phases in the golf swing can be found in Table 2.22. During the takeaway the activity of the levator scapulae, rhomboid muscles and the upper, middle and lower trapezius in the leading arm (non dominant arm) were low allowing for scapular protraction (5 ± 3%, 7 ± 13%, 5 ± 4%, 3 ± 3%, and 7 ± 10% MMT, respectively). In contrast the activity of these same muscles was high in the trial arm (dominant arm) during takeaway to allow for the retraction and upper rotation of the scapula (29 ± 19%, 30 ± 18%, 24 ± 14%, 37 ± 12% and 52 ± 28% MMT, respectively). The upper and lower serratus anterior muscle in the trail arm had low activity during takeaway (6 ± 4% and 9 ± 5% MMT, respectively). In the leading arm activity for the upper and lower serratus anterior muscle was consistent across all phases for the swing (20-31% MMT) which they believed suggested this muscle had a stabilising function during the golf swing. The levator scapulae and rhomboid muscles reached their peak in the trailing arm during forward swing (38 ± 39% and 46 ± 27% MMT, respectively). In the lead arm activity peaks for these muscles occurred during forward swing for the rhomboid muscles (68 ± 27% MMT) and during acceleration for the levator scapulae (62 ± 46% MMT). For the upper, middle and lower portions of the trapezius muscle activity increased during forward swing (29 ± 26%, 51 ± 26% and 49 ± 27% MMT, respectively) and acceleration (57 ± 46%, 42 ± 50% and 36 ± 21% MMT, respectively) to retract and upwardly rotate the scapula of the leading arm as the club moved forward. In the trial arm the activity reduced following takeaway and remained low during the remainder of the swing to allow scapular protraction. Lower activity in all the examined muscles was evident during early and late follow through. Comparisons of these results with other studies were not possible as no other studies were found that examined these muscles.

Table 2.22 Muscle activity of the scapular muscles during the golf swing (mean percent MMT ± standard deviation). Adapted from Kao et al. (1995).

Muscle	Takeaway	Forward swing	Acceleration	Early follow through	Late follow through
Trailing arm					
Levator scapulae	29 ± 19	38 ± 39	34 ± 41	12 ± 12	4 ± 4
Rhomboid muscles	30 ± 18	46 ± 27	32 ± 24	21 ± 12	5 ± 4
Upper trapezius	24 ± 14	4 ± 4	13 ± 20	23 ± 19	5 ± 6
Middle trapezius	37 ± 12	18 ± 24	19 ± 26	26 ± 21	12 ± 15
Lower trapezius	52 ± 28	17 ± 12	16 ± 28	22 ± 22	10 ± 15
Upper serratus	6 ± 4	58 ± 39	69 ± 29	52 ± 18	40 ± 14
Lower serratus	9 ± 5	29 ± 17	51 ± 33	47 ± 25	40 ± 18
Leading arm					
Levator scapulae	5 ± 3	42 ± 20	62 ± 46	39 ± 26	29 ± 24
Rhomboid muscles	7 ± 13	68 ± 27	57 ± 46	26 ± 26	30 ± 33
Upper trapezius	5 ± 4	29 ± 26	42 ± 50	34 ± 29	27 ± 18
Middle trapezius	3 ± 3	51 ± 26	36 ± 21	21 ± 18	28 ± 20
Lower trapezius	7 ± 10	49 ± 27	37 ± 28	20 ± 16	35 ± 18
Upper serratus	30 ± 15	20 ± 29	31 ± 31	31 ± 18	21 ± 13
Lower serratus	27 ± 11	20 ± 21	21 ± 24	29 ± 20	29 ± 21

Both Pink et al. (1993) and Watkins et al. (1996) reported the muscle activity in the trunk muscles during the golf swing (Table 2.23 and Table 2.24, respectively). They both used highly skilled golfers for their analysis; Pink et al. (1993) used twenty three golfers with a handicap of 5 or below and Watkins et al. (1996) used 13 professional golfers. Neither study provided information on the club they used in.

Table 2.23 Muscle activity during the golf swing (mean percent MMT ± standard deviation). Adapted from Pink et al. (1993).

Muscle	Takeaway	Forward swing	Acceleration	Early follow through	Late follow through
Erector spinae					
Left side	29 ± 12	34 ± 15	50 ± 30	39 ± 29	28 ± 19
Right side	20 ± 9	75 ± 29	58 ± 22	29 ± 13	28 ± 22
Abdominal obliques					
Left side	22 ± 19	54 ± 43	42 ± 28	38 ± 26	41 ± 27
Right side	20 ± 22	62 ± 28	64 ± 37	57 ± 35	43 ± 33

Table 2.24 Muscle activity of the trunk during the golf swing (mean % MMT). Adapted from Watkins et al. (Watkins et al. 1996)

Muscle	Takeaway	Forward swing	Acceleration	Early follow through	Late follow through
Abdominal oblique					
Left side	24	63	38	38	39
Right side	23	52	59	51	34
Gluteus maximus					
Left side	11	35	53	33	14
Right side	15	84	21	14	8
Erector spinae					
Left side	26	35	44	31	19
Right side	16	55	38	19	15
Rectus abdominis					
Upper	4	30	35	21	9
Lower	13	31	34	28	16

They both examined the erector spinae and abdominal obliques and found reasonably comparable results for the majority of their results. Pink et al. (1993) however, reported 20% higher levels of activity in the right side erector spinae during the forward swing and acceleration phases than Watkins et al. (Watkins et al. 1996). It is unclear why this difference between the studies occurred.

Relatively low muscle activity was recorded for the erector spinae and abdominal obliques during the backswing, ranging from an average of 20 – 29% MMT. Pink et al. (1993) stated that during the forward swing, when the body is rotating from the right side to the left side, gravity and rotational forces were restricted by the participants in order to maintain their body position. This was evident by the greater muscle activity in the right side than the left side (erector spinae: 75% *vs.* 34% MMT; abdominal obliques: 62% *vs.* 54% MMT). During the acceleration phase as the body moved back to a more central position both sides of the erector spinae muscles were used to control for gravitational forces (Left 58% MMT and right 50% MMT) and the abdominal oblique muscle were working bilaterally to facilitate trunk rotation (Left 64% MMT and right 42% MMT). Following ball impact, as the trunk continued to rotate in follow through, muscle activity was still evident however at a much lesser intensity than was found in the forward swing and acceleration phases.

At late follow through muscle activity ranged from 28 – 43% MMT. They postulated that their results allowed for the conclusion that the erector spinae muscles main role in the golf swing may be in stabilisation of the trunk while the abdominal muscles may be responsible for trunk flexion and rotation. Watkins et al. (1996) also examined the muscle activity of the gluteus maximus and rectus abdominis. The activity of these muscles is relatively low during the take away. During the forward swing they reported the high level of activity of the gluteus maximus, in particular the right side (84% MMT), indicated the importance of these muscles in generating power into the acceleration phase. The higher level of activity in the left gluteus maximus than the right (53% *vs.* 21% MMT) during the acceleration phase was postulated to suggest the stabilising effect of the left side and the "pushing off" effect of the right side of the muscle during this phase. During the early and late follow through the activity of the gluteus maximus and restus abdominis reduced to a low level.

The final study within this subgroup was conducted by Bechler et al. (Bechler et al. 1995). They examined muscle activity of the hip and knee for thirteen male and three female golfers with handicaps of less than 5 using the driver club. The muscles monitored were the upper gluteus maximus, lower gluteus maximus, gluteus medias, adductor magnus, biceps femoris (long head), semimembranosus, and vastus lateralis an both the front (left) and back (right) leg. Data was collected for four golf swings by each participant, with no significant difference found between the genders the data was grouped together (Table 2.25). The least amount of muscle activity in the hips and knees was evident during the takeaway. The hamstrings remained mildly active (<30 % MMT) during this phase, which was thought to maintain the knees in their slightly flexed position. The biceps femoris muscle had greater activity at this phase (23% MMT) than the semimenbranosus muscle (5% MMT) as the biceps femoris is believed to assist the inward rotation of the front leg. The forward swing phase is the most active phase for the back leg. During this phase the gluteus maximus, gluteus medias, biceps femoris, and semimenbranosus push the back hip forward and initiate pelvic rotation. The gluteus maximus of the back leg is the most active muscle during the forward swing phase (upper gluteus maximus: 100 ± 55% MMT; lower gluteus maximus 98 ± 43% MMT) as it is thought to push the previously flexed hip forward. The vastus lateralis of the front leg also reached its maximum activity during the forward swing phase (88 ± 44% MMT). It was proposed that it stabilised the front knee as the leg pushed against the ground to allow pelvis rotation. During acceleration the majority of the muscle activity was found to occur in the front leg. Peak muscle activity was reached in the front leg by the gluteus maximus (upper gluteus maximus: 58 ± 61% MMT; lower gluteus maximus 58 ± 63% MMT), biceps femoris (83 ± 58% MMT) and semimenbranosus (51 ± 31% MMT) during this phase. They proposed that the actions of these muscles during the acceleration phase to maintain the knee in a flexed position allowed the transfer of power from the pelvis rotation to the trunk and arms. During early follow through muscle activity was higher in the front leg and then back leg with the exception of the gluteus medias. Its muscle activity remained high (59% MMT) as they stated it assisted pelvis rotation by abducting and extending the back hip. In the front leg the biceps femoris muscle activity remained high (79% MMT) as it is thought to resist front knee extension during the transfer of weight to the front leg. As the participants progressed to late follow through muscle activity was decreased in all muscles.

Table 2.25 Muscle activity of the lower body during the golf swing (mean percent MMT ± standard deviation). Adapted from Beckler et al. (1995).

Muscle	Takeaway	Forward swing	Acceleration	Early follow through	Late follow through
Back leg (right)					
Adductor magnus	17 ± 17	36 ± 29	30 ± 23	22 ± 19	17 ± 14
Upper gluteus maximus	20 ± 14	100 ± 55	28 ± 49	13 ± 18	11 ± 10
Lower gluteus maximus	16 ± 13	98 ± 43	27 ± 28	12 ± 13	7 ± 6
Gluteus medius	21 ± 10	74 ± 36	51 ± 36	59 ± 37	22 ± 20
Biceps femoris (long head)	27 ± 27	78 ± 35	16 ± 21	7 ± 11	10 ± 11
Semimenbranosus	28 ± 14	67 ± 37	17 ± 21	17 ± 25	7 ± 11
Vastus lateralis	25 ± 25	39 ± 49	40 ± 36	41 ± 32	40 ± 25
Front leg (left)					
Adductor magnus	8 ± 8	63 ± 22	43 ± 25	36 ± 12	35 ± 19
Upper gluteus maximus	9 ± 9	50 ± 47	58 ± 61	47 ± 59	21 ± 15
Lower gluteus maximus	7 ± 4	50 ± 42	58 ± 63	39 ± 28	16 ± 31
Gluteus medius	7 ± 8	36 ± 20	32 ± 24	20 ± 12	31 ± 26
Biceps femoris (long head)	23 ± 12	60 ± 43	83 ± 58	79 ± 67	41 ± 38
Semimenbranosus	5 ± 4	39 ± 17	51 ± 31	45 ± 24	42 ± 24
Vastus lateralis	14 ± 13	88 ± 40	58 ± 50	59 ± 41	42 ± 25

The remaining three studies found that examined muscle activity provided information on the trunk, shoulder and the left arm. Bulbulian et al. (2001) used surface electrodes to examine the muscle activity of the trunk and shoulder of 6 male and 1 female (handicap 16.3 ± 3.4) participants during a normal golf swing and a modified short backswing with a 7 iron club. They examined a modified short backswing to identify if it leads to reduced back injury and pain than the normal backswing and concluded that it did. The muscles examined were the left and right lumbars, external obliques, latissimus dorsi and the right pectoralis major. The root mean square (rms) values for the EMG data was calculated during the intervals of 750 – 250 ms before impact (initial forward swing phase), 250 to 0 ms before impact (acceleration phase) and 0 to 500 ms after impact (follow through phase).They didn't report individual results for the normal golf swing, only comparing the differences between the two types of golf swings. Approximate values for the examined muscles are provided in Table 2.26. The peak values for all muscles were found to occur during the acceleration phase.

Table 2.26 Approximate muscle activity (RMS in m.V) values for the shoulder and trunk during the golf swing. Adapted from Bulbulian et al. (2001).

Muscle	Initial forward swing phase (750 – 250 ms before impact)	Acceleration phase (250 – 0 ms before impact)	Follow through phase (0 – 500 ms after impact)
Lumbar			
Left	50	275	58
Right	100	240	90
External oblique			
Left	55	200	110
Right	48	75	70
Latissimus dorsi			
Left	93	275	115
Right	82	175	70
Pectoralis major			
Right	55	260	105

The final two studies that will be discussed are the only two studies found that provided comparisons between golfers of different skill levels. Hosea et al. (1994) examined the muscle activity around the lumbar spines third and fourth vertebrae when swinging a 5 iron club. Their participants were four male professionals and four male amateurs with an average USGA handicap of 16. The muscle activity was obtained using surface electrodes and was compared with the maximal isometric activity of each particular muscle group. Results showed that the overall muscle activity of the amateurs reached nearly 90% of their peak muscle activity compared to 80% for the professionals. They did not provide values for the muscles they examined. They found that in general the initial twisting of the trunk during the backswing is initiated by the left external oblique, and to a lesser degree, the left rectus abdominis and left third lumbar paraspinal muscles. From the top of the backswing through to ball impact the muscles on the right side of the trunk were found to lead the swing. The right external oblique muscle fires maximally and the right rectus abdominis and external oblique developed a higher activity peak the same muscles on the left side.

Abernethy et al. (1990) examined the differences in muscle activity with skill level, their participants included five expert and five novice golfers. The participants were required to complete golf swings for accuracy under different conditions. These conditions consisted of hitting with three different golf club (pitching wedge, 9 iron and 7 iron) to three distances (20, 40 and 60 m) in addition to a full shot. Muscle activity was recorded for the following muscles of the left arm: wrist flexors, wrist extensors, biceps brachii, triceps brachii and anterior deltoid. Results showed considerable inter-subject variation among the expert golfers; however, their individual muscle activation patterns were consistent from trial to trial. In contrast the novices showed much less consistent patterns of muscle activity in particular when they were required to hit shots to the three distances (20, 40 and 60 m). No individual values for muscle activity were provided in this study.

3 Methodology

3.1 Introduction

The methods employed in the study are detailed below. Ethical approval was granted for this study by Dublin City University's ethics committee (Appendix A Ethics Application pg.178).

3.2 Participants

Forty male right-handed golfers were recruited for the study. Twenty were recruited who had a handicap of less than five and twenty who had a handicap of between ten and eighteen. Table 3.1 lists the anthropometric data for the participants in each group. It has been shown that differences occur in the kinematics of the golf swing of men and women (Egret et al. 2006). Therefore, to increase homogeniality only one gender were recruited for this study. Participants were recruited from the DCU staff golf society, DCU student population and local golf clubs by email and poster advertisements (Appendix B Email and poster recruitment advertisements pg.192). The participants were predominately recreational golfers, with one ex professional golfer taking part. All participants were provided with a plain language statement (Appendix C Plain Language Statement pg.194) detailing the study procedures. Participants were required to complete a PAR-Q (Physical Activity Readiness Questionnaire) (Appendix D Physical Activity Readiness Questionnaire pg.196) and informed consent prior to participating (Appendix E Informed consent form pg.197).

Table 3.1 Anthropometric data for participants (mean ± standard deviation).

Group	Age	Weight (kg)	Height (cm)	Handicap
< 5 handicap	28.0 ± 10.4	80.03 ± 8.6	178.95 ± 6.32	3.1 ± 2.25
10 - 18 handicap	38.1 ± 18.0	84.24 ± 9.67	177.88 ± 5.62	12.75 ± 2.69

3.2.1 Inclusion criteria

Participants eighteen years or older, with a Golfing Union of Ireland registered handicap of less than five or between ten and eighteen and who were injury free.

3.2.2 Exclusion criteria

Participants with any medical condition that may contraindicate exercise participation.

3.3 Experiment design

This study was undertaken to examine the kinematics of the golfer and the 5-iron golf club, and the weight transfer utilised by the golfer during the golf swing. All testing was completed in the Biomechanics Laboratory in Dublin City University. The participants underwent a practice session in the laboratory to familiarise themselves with the testing procedure. Each of the forty participants was required to visit the laboratory once for their testing session. The testing session consisted of a prescribed warm up, recording of fifteen golf swings and a participant selected cool down period. Fifteen swings were recorded in the present study for two reasons: firstly the present study was part of a larger study which aimed to examine intra golfer variability and secondly it was thought that the collection of fifteen trials would allow a more accurate means of isolating their three best trials by ball speed to represent their best swing. The prescribed warm up consisted of five minutes walking on a treadmill (2.5 $km.h^{-1}$) followed by 3 mins of practice swing. In addition the participants were given time to perform stretching if they wished. Ten of the participants were asked to return for a second visit to assess the reliability of the testing procedure.

The testing setup (Figure 3.1) consisted of a twelve camera Vicon motion analysis system (Oxford Metrics, UK) used to record the motion of the participant and their golf club throughout the golf swing. The motion analysis system operated at 250 Hz. A pressure plate (RScan, Belguim), sampling at 100 Hz, was used to record the participant's weight transfer. The sampling rate of 100Hz for the pressure plate was selected through pilot work. For the pilot work data was collected from five golfers at a sampling rate of 500Hz and then resampled at 400, 300, 200, 100, and 50Hz. It was found that the lowest sampling rate that resulted in no meaningful decrease in measurement accuracy for either centre of pressure data or centre of pressure velocity data was 100Hz and this sampling rate was then chosen for the study.

A ProV swing analyzer (Golftek Inc., USA) was used to record the golf club swing characteristics. The Pro V swing analyser utilises an overhead light to perform its measurements. The Vicon motion analysis system and the pressure plate were synchronised to collect data simultaneously.

The participants were required to hit the ball from a tee on the Pro V swing analyser into a net located three metres from the swing analyser. There was a pole placed behind the net which was used as a reference point for the target line which the participants were instructed to aim for when hitting the ball.

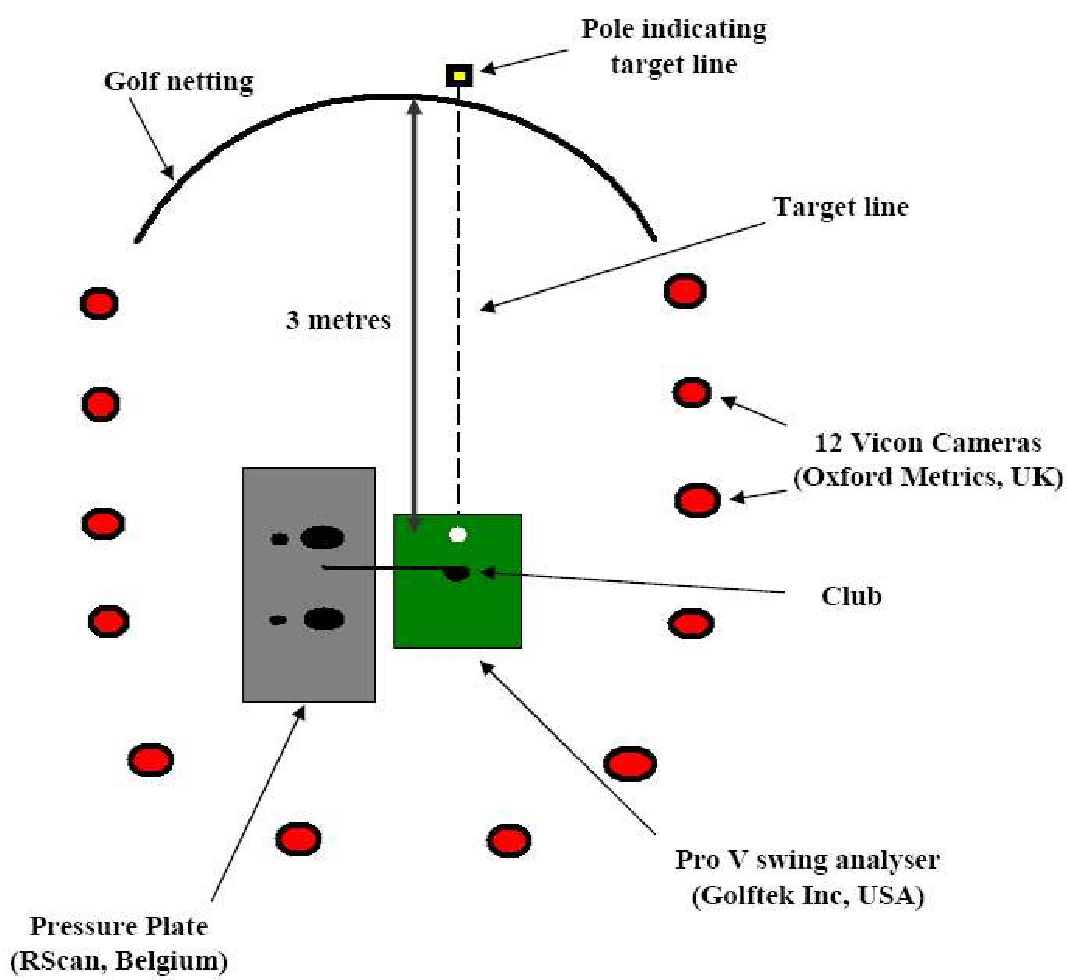


Figure 3.1 Testing setup

3.4 Experimental procedure

Prior to the participant arriving at the laboratory the Vicon system was calibrated. A two step calibration procedure was used to calibrate the capture volume. The calibration was accepted when the camera residuals for all cameras was under 2 mm (Richards 1999).

The Pro V swing analyser was positioned so that the golf ball on the tee of the analyser was in line with the X axis of the laboratory coordinate system (Figure 3.2). This allowed for the identification of the frame at which golf club contact with the ball occurred using the Vicon system, which will be detailed further on in the methodology.

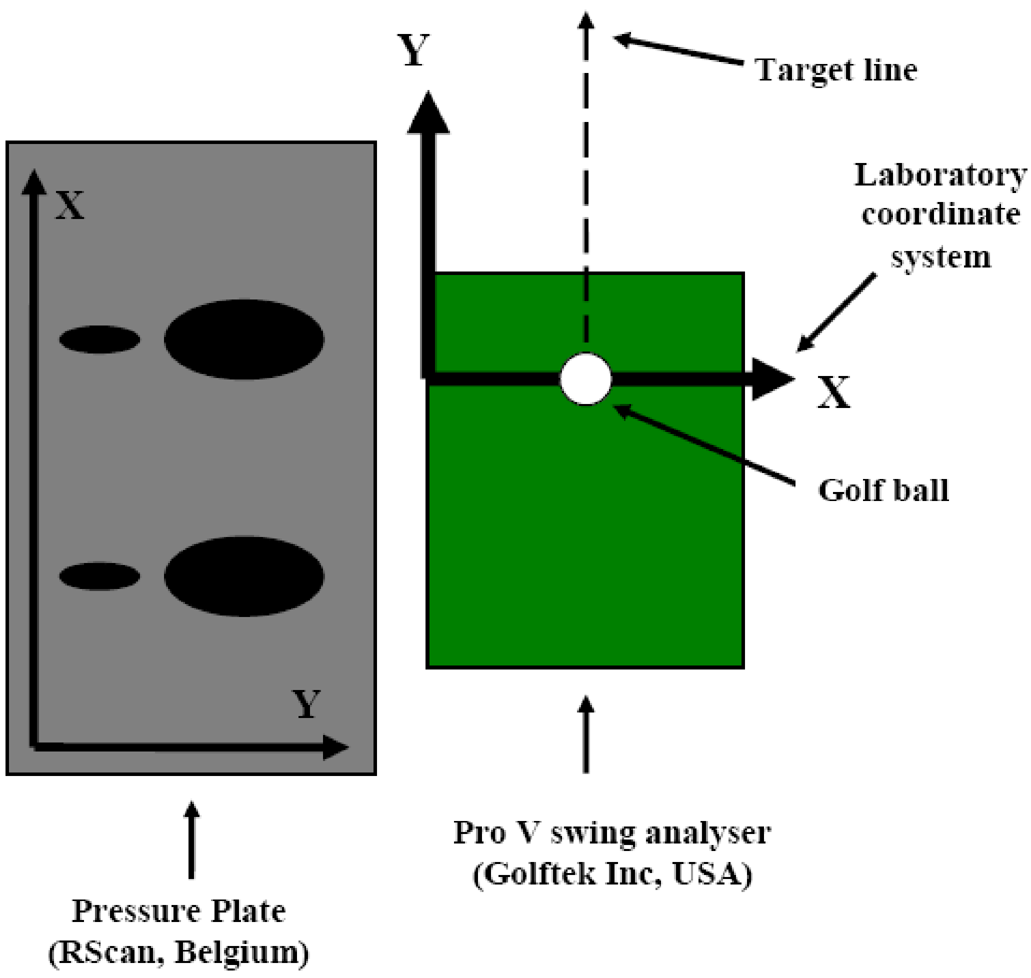


Figure 3.2 Pro V swing analyser aligned with lab coordinate system.

Participants were required to bring their own 5 iron club and to wear only a pair of shorts for the testing session. Firstly, the participant's anthropometric data required for the motion analysis system was collected (Appendix F Anthropometric data required for Vicon motion analysis system pg.199). Forty one reflective spheres (14 mm diameter) were then placed on the participant (Figure 3.3 - Figure 3.7).

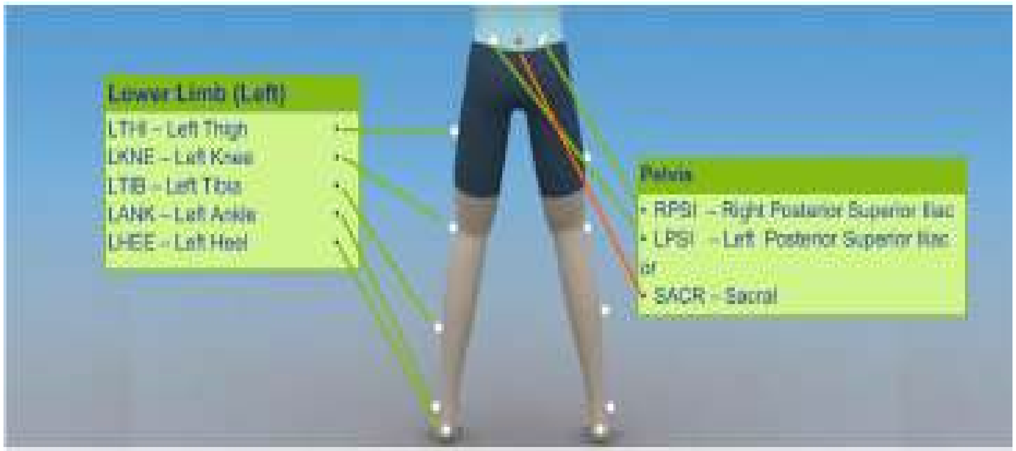


Figure 3.3 Marker placement for golf lower body model – back view

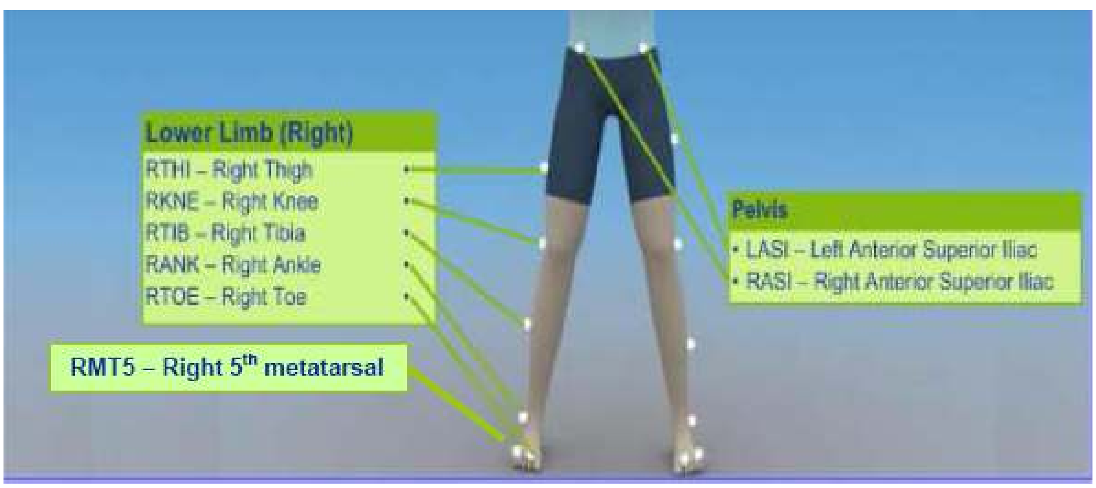


Figure 3.4 Marker placement for golf lower body model – front view

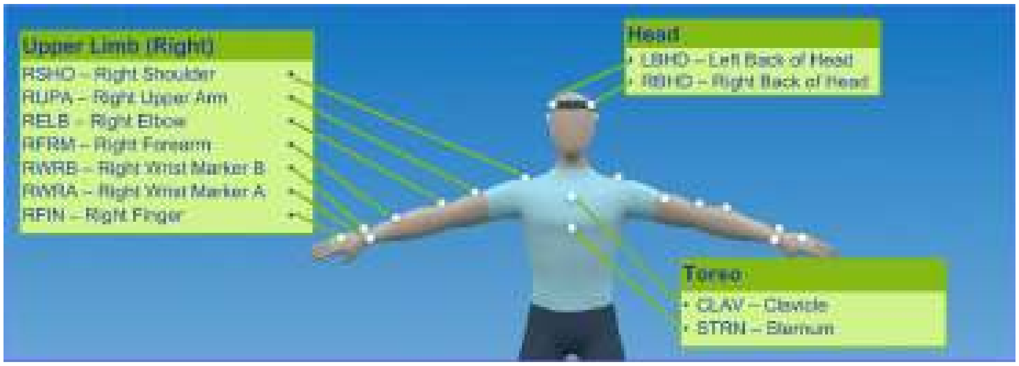


Figure 3.5 Marker placement for golf upper body model – front view

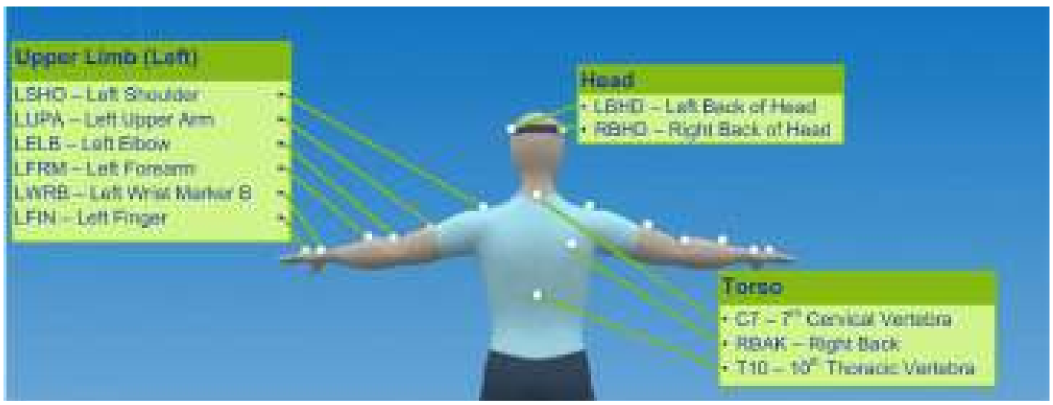


Figure 3.6 Marker placement for golf upper body model – back view

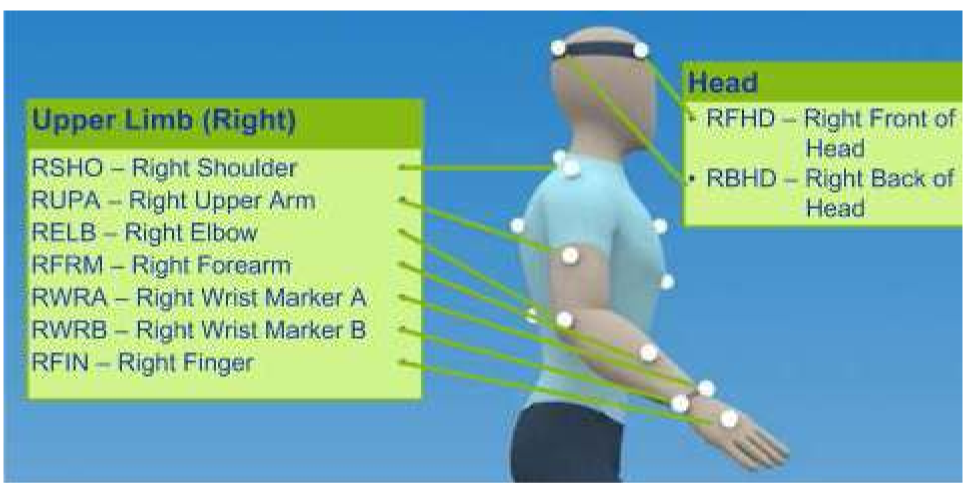
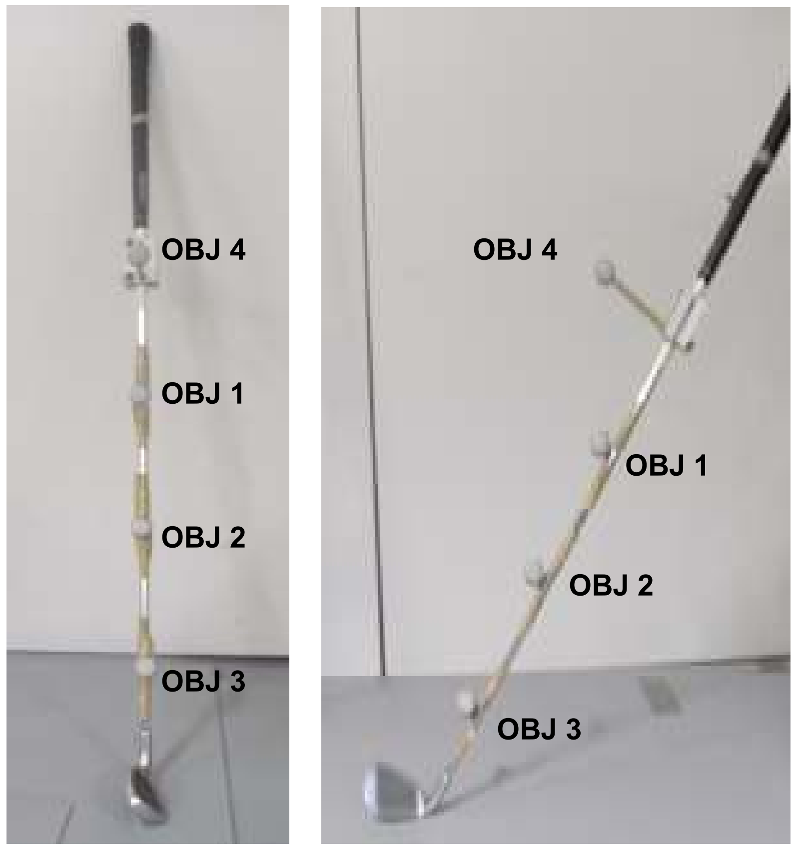


Figure 3.7 Marker placement for golf upper body model – side view

Four reflective spheres were placed on their club (Figure 3.8). The definitions for the marker placements on the participant and club can be found in Appendix G Definitions for marker placement on the participant pg.200. Three markers were attached directly to the club and one was placed at the end of a solid metal bar attached to the club. The solid metal bar was connected to a metal clamp attached to the club. All four markers were aligned along the mid axis of the golf club. The cameras were set up in the laboratory at such distances and angles to optimise data capture.



(a) (b)

Figure 3.8 Marker placements on golf club (a) front view (b) side view.

The participant was then asked to address the ball in their usual manner. The pressure plate position was adjusted so that the participant's feet were in the centre of the pressure plate (Figure 3.9). The height of the pressure plate from the ground was the same as the Pro V swing analyser. The participant was then instructed to warm up and when they were ready testing begin. The participant was instructed to 'hit the ball as hard as possible towards the target-line, with the aim to maximize both distance and accuracy, as if in a competitive situation'. A total of fifteen swings were recorded for each participant.

Figure 3.9 Testing setup with participant at take away position.

3.5 Measurements

The Vicon motion analysis system recorded the motion of the markers on the participant and their golf club throughout the golf swing, which allowed for the calculation of the participant's joint angles throughout the golf swing. The calculated joint angles were the shoulder angles in the three planes (flexion/extension, abduction/adduction and internal/external rotation), elbow flexion/extension, wrist abduction/adduction, hip angles in the three planes (flexion/extension, abduction/adduction and internal/external rotation), knee flexion extension and the X factor angle. The X-Factor describes the relative rotation of the shoulders with respect to the hips during the golf swing. Descriptions and definitions of how these angles are calculated can be found in Figure 3.10 to Figure 3.19 and Table 3.2. All images were adapted from images taken from (BrianMAC 2008), unless otherwise stated.

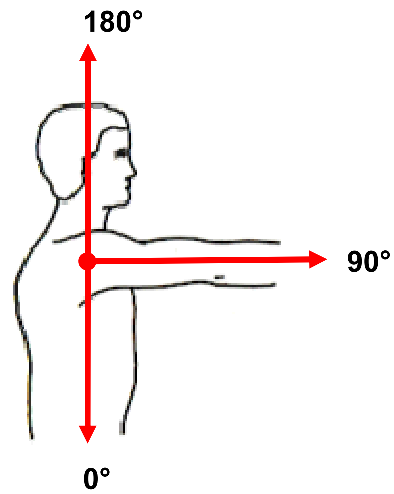


Figure 3.10 Shoulder flexion angle description.

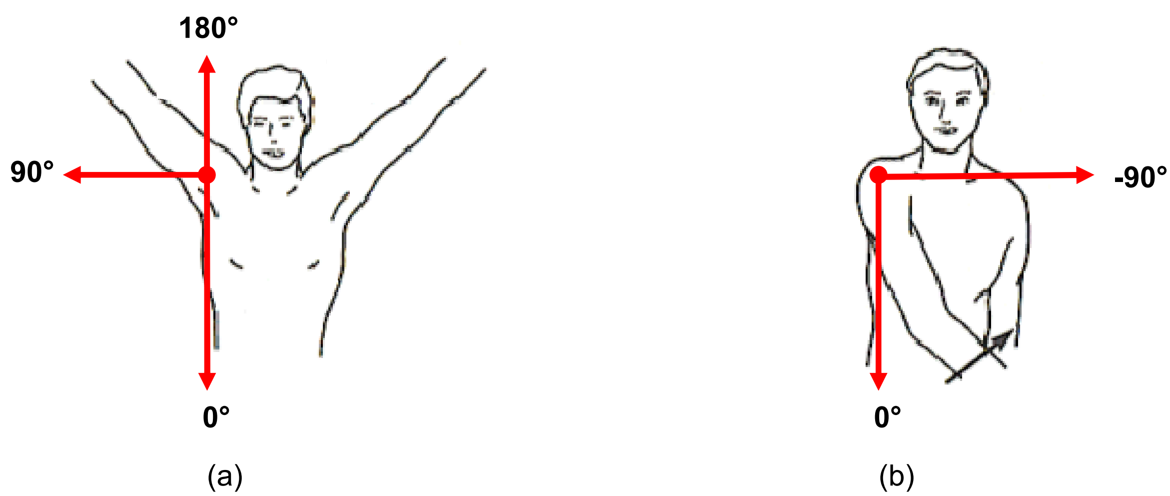


Figure 3.11 Shoulder abduction (a) and adduction (b) angle description

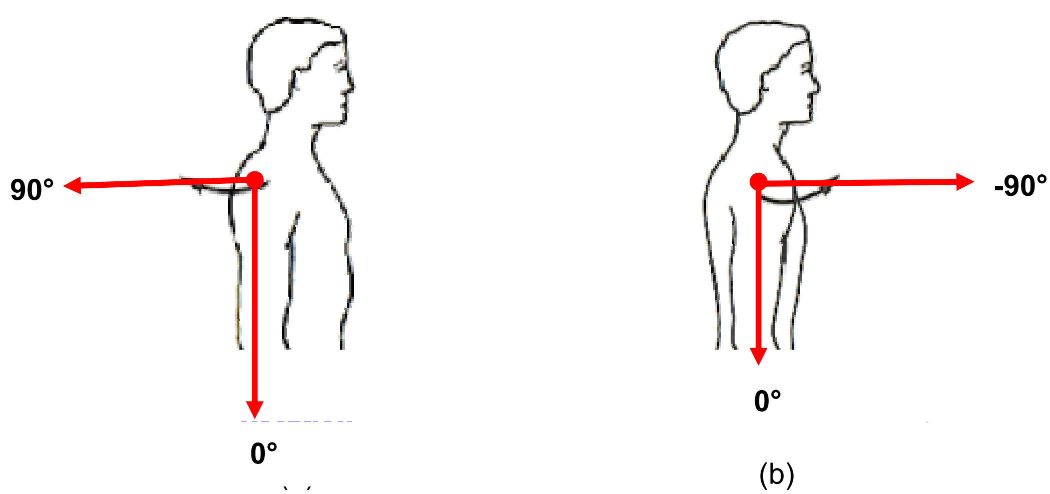


Figure 3.12 Shoulder external (a) and internal (b) rotation angle description

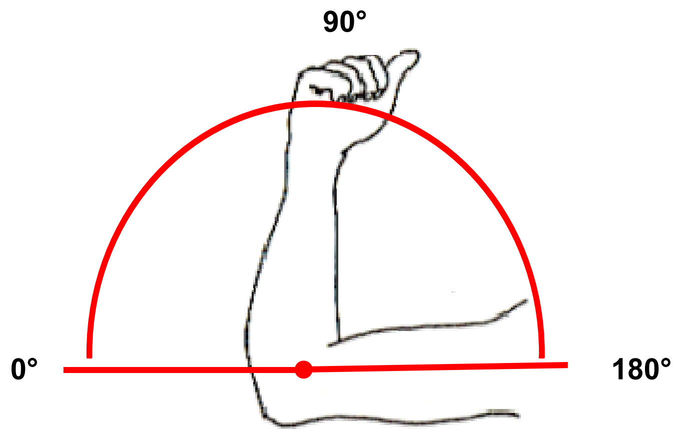


Figure 3.13 Elbow flexion angle description

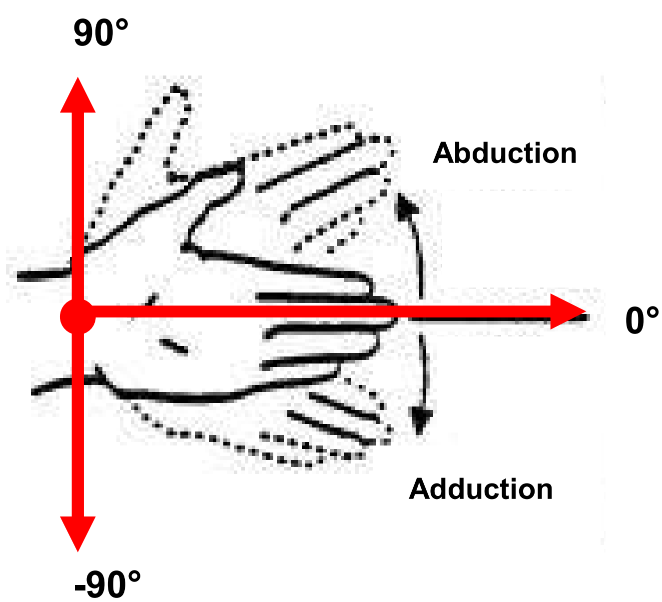


Figure 3.14 Wrist abduction/adduction angle description. Image adapted from Nelson (2008)

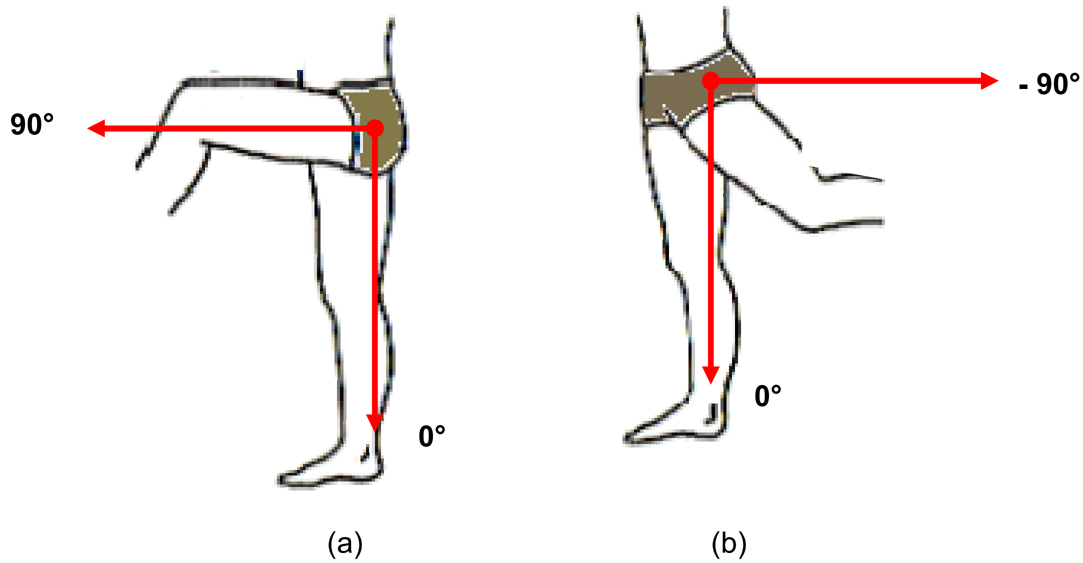


Figure 3.15 Hip flexion (a) and extension (b) angle description.

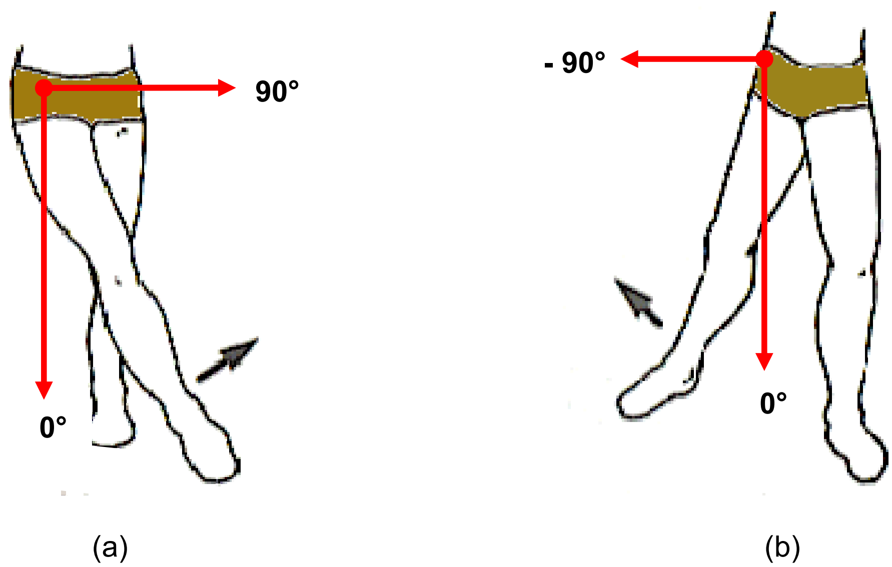


Figure 3.16 Hip adduction (a) and abduction (b) angle description.

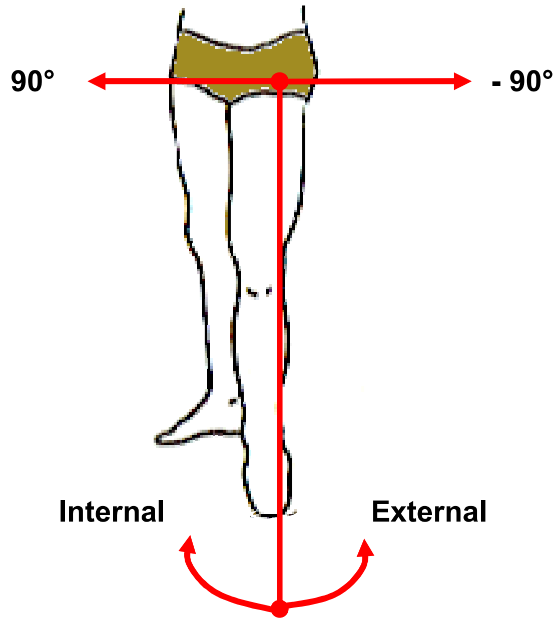


Figure 3.17 Hip internal and external rotation description

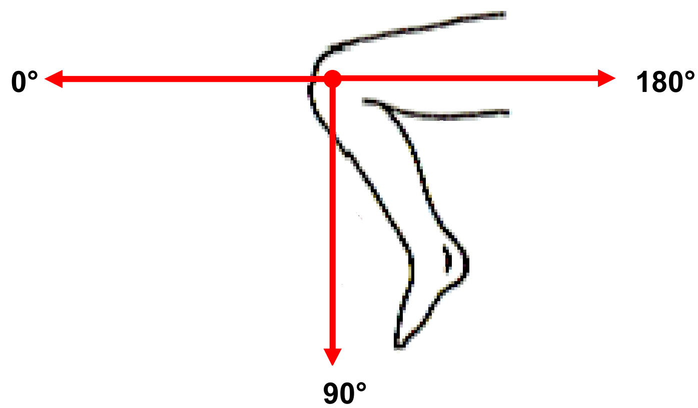


Figure 3.18 Knee flexion angle description

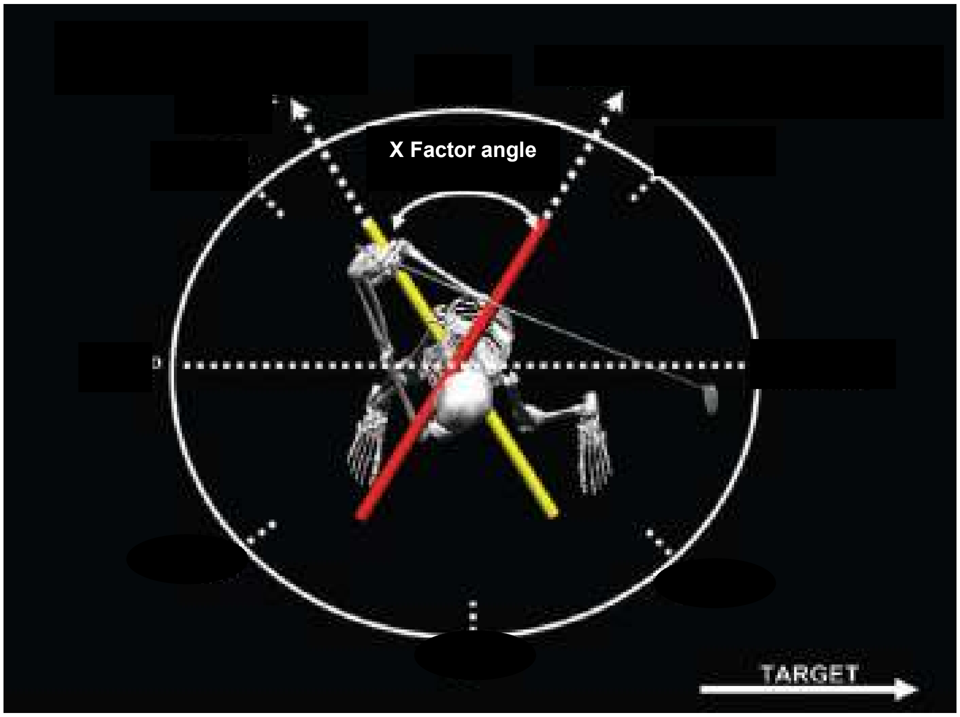


Figure 3.19 X Factor angle description. Image adapted from Myers et al. (2008).

Table 3.2 Definitions of joint angle calculations.

Angle	Definition
Hip	Relative angle between the pelvis and the thigh
Knee	Relative angle between the thigh and the shank
Shoulder	Relative angle between the upper arm and the thorax
Elbow	Relative angle between the upper arm and the forearm
Wrist	Relative angle between the forearm and the hand
X Factor	Relative angle calculated as the difference between the hip and shoulder angles

With relation to the golf club, the angle of the club shaft was measured in the three planes X, Y and Z, descriptions of which can be seen in Figure 3.20 - Figure 3.22.

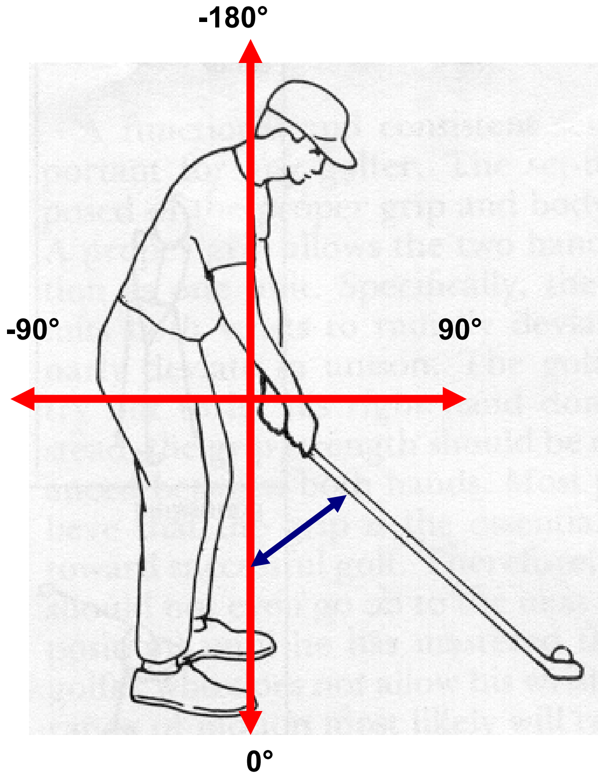


Figure 3.20 Club shaft angle X description. Image adapted from Stover et al. ((1994).

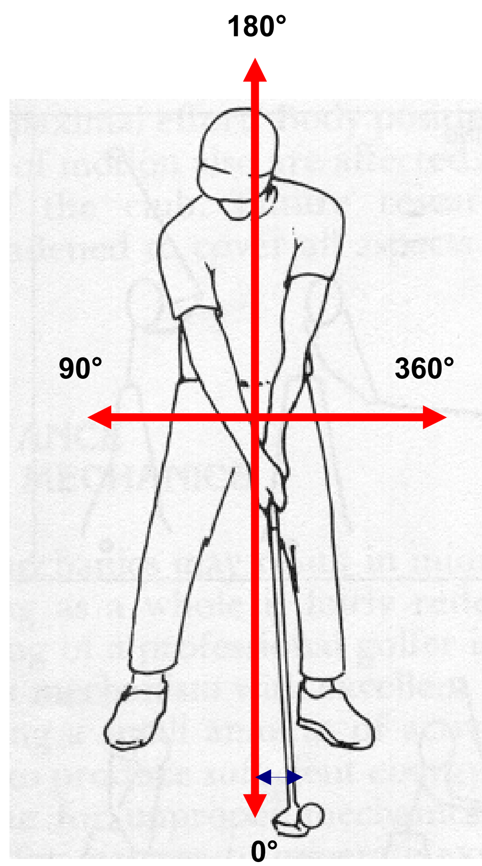


Figure 3.21 Club shaft angle Y description. Image adapted from Stover et al. (1994).

270°

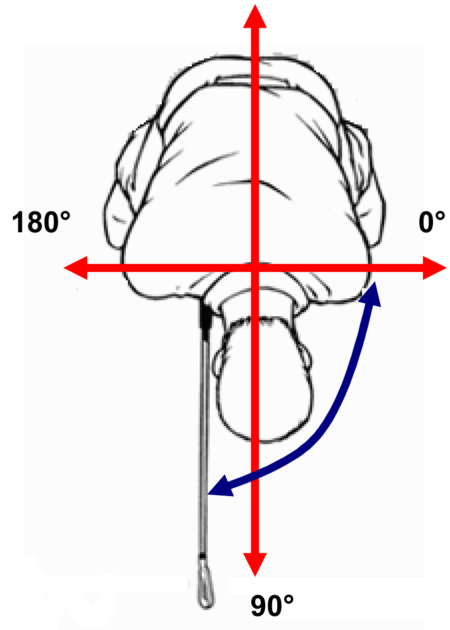


Figure 3.22 Club shaft angle Z description. Image adapted from Cotter (2008).

The pressure plate (RScan, Belguim) measured the position of the centre of pressure of the participant throughout their golf swing. The changing velocity of the centre of pressure was also calculated throughout the golf swing.

The Pro V swing analyser measured ball speed, club head speed, clubface angle, swing path angle, impact, tempo, rotation and SHF (Solid Hit Factor). Definitions for these measures can be found in Appendix H Golftek Pro V Swing analyser measurement definitions pg.202 and how these measures are calculated can be found in Appendix I Golftek Pro V Swing analyser measurement calculations pg.203.

A summary of the measured variables in the present study can be found in Figure 3.23.

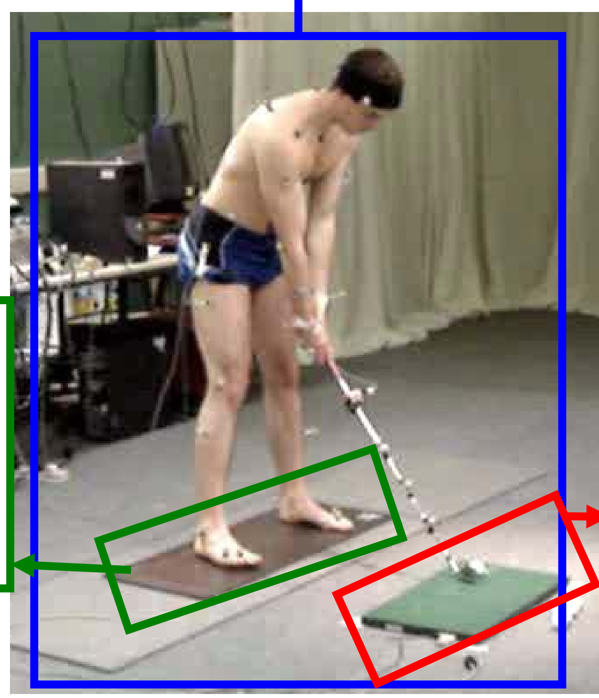
Vicon measurements:

Angle and angular velocity at each of the eight swing events for:

- Club shaft in the X, Y and Z plane
- X Factor
- Left and right :
  - Shoulder flexion/extension, abduction/adduction and internal/external rotation
  - Elbow flexion/extension
  - Wrist abduction/adduction
  - Hip flexion/extension, abduction/adduction and internal/external rotation
  - Knee flexion/extension

Additionally:

- X Factor stretch
- X Factor stretch time
- Time duration between each of the eight swing events



Rscan pressure plate measurements:

- Centre of pressure position and velocity in the X and Y direction at each of the eight swing events

Pro V Swing Analyser measurements:

- Club Speed
- Ball Speed
- Clubface angle
- Swing path angle
- Tempo
- Club rotation
- Impact point

Note: The eight swing events are takeaway, mid backswing, late backswing, top of backswing, early downswing, mid downswing, ball contact and mid follow through (Figure 2.17)

Figure 3.23 Summary of measured variables in the present study.

3.6 Data analysis

Firstly, the golf club swing characteristics (from the Pro V swing analyser) results were analysed. The fifteen trials for each participant were sorted by ball speed. Ball speed was chosen as it is one of the strongest determinants of the distance the ball travels. The participants were asked to hit the ball as far as they could so therefore the trials with the fastest ball speed would indicate the trials in which the golf ball would have travelled furthest. The three best trials (as determined by ball speed) were assessed individually and then these individual results were averaged to give a representative value. The averaging of a number of trials to create a representative trial is common practice in golf research (Myers et al. 2008, Zheng et al. 2008).

Initially, the participants in the present study were grouped by handicap. This was based on the reported finding of Fradkin et al. (Fradkin, Sherman and Finch 2004a) that club speed and handicap were highly correlated (r = 0.95). However, after initial analysis of these variables in the present study a weaker correlation was found (r = 0.69) with some of the 10-18 handicap group generating higher ball speeds that the <5 handicap group (Figure 3.24).

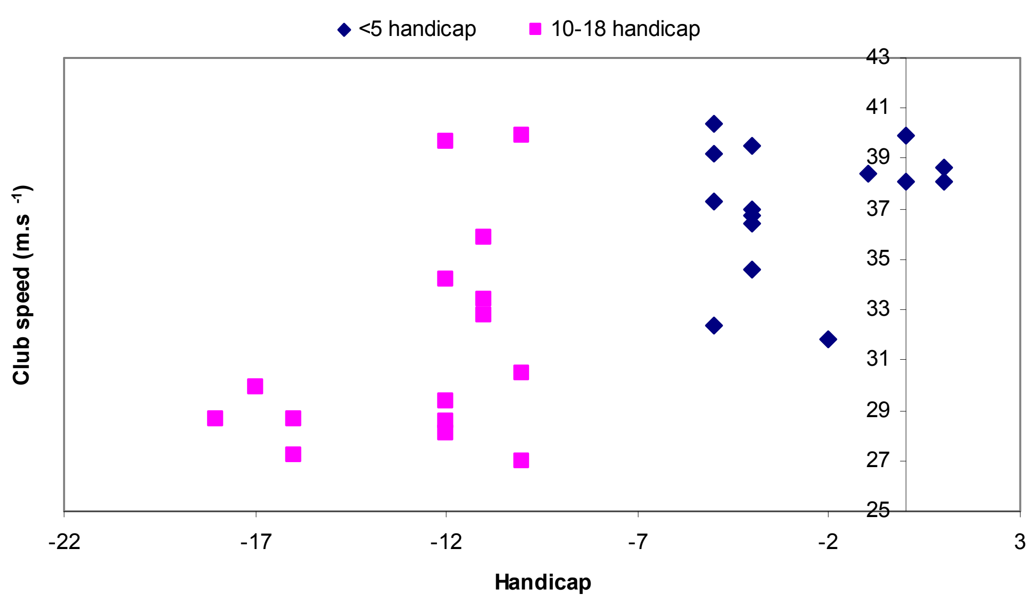


Figure 3.24 Handicap versus club speed ($m.s^{-1}$) for the two groups (<5 handicap and 10-18 handicap).

A possible reason for the differences in club speed could be the fact that a golfer's handicap is calculated from their overall playing ability, taking into account all aspects of their game (including driving, chipping and putting). For example a golfer with a low handicap may not have the ability to hit the ball far but they might be excellent at putting and that is why their handicap is low. Therefore, grouping by handicap may not be the most appropriate way to group golfers when examining a specific aspect of their game, in this case the capacity to maximise hitting distance with the 5 iron club. The limitation to grouping participants by handicap has previously been discussed by Wallace et al. (Wallace, Grimshaw and Ashford. 1994) who stated that there is not a direct link between handicap and driving skill.

It was therefore decided that grouping the participants by ball speed would better suit this study, which was to, specifically examine striking for maximum distance with the 5 iron. This was based on the premise that ball speed and club speed are highly related (Figure 2.1) with analysis in the present study showing a high correlation between them ($r = 0.95$). A recent study by Myers et al. (Myers et al. 2008) which examined joint kinematics also utilised ball speed to group their participants. This method of grouping participants is not without limitations. This method uses ball velocity solely to predict golfing performance. While the ball velocity is a major factor in determining the distance the ball travels it is recognised by the author that it does not take into account the accuracy of the shot.

The participants were sorted according to their ball speed (Figure 3.25). From this, it was seen that 50% of the participants in the 10-18 handicap group averaged greater ball speed than the participant with the slowest ball speed in the <5 handicap group. In order to create two distinct groups with regard to ball speed (high ball speed and low ball speed), it was necessary to remove some of the participants from the analysis. The median value for all the participants ball speed was calculated and the five participants whose average ball speed was above and the five participants whose average ball speed was below the median were removed from the analysis. This left two groups of 15 participants each; the 15 participants with the highest ball speed and the 15 participants with the lowest ball speed. The anthropometric data for the two groups can be found in Table 3.3.

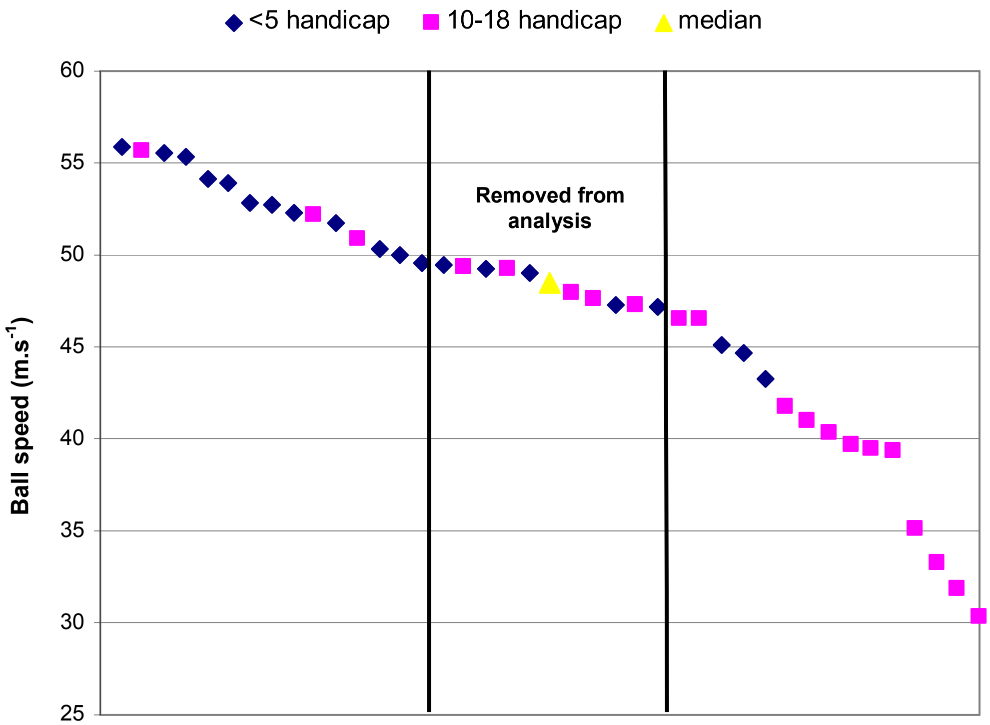


Figure 3.25 Ball speed ($m.s^{-1}$) for each participant with the median value for all the participants and the ten participants removed from analysis shown.

Table 3.3 Anthropometric data for two groups (15 highest ball speeds and 15 lowest ball speeds).

Group	Age	Weight (kg)	Height (cm)	Ball speed ($m.s^{-1}$)	Handicap
15 highest ball speed	27.5 ± 10.0	78.8 ± 7.19	179.94 ± 5.16	52.9 ± 2.1	0.13 ± 6.02
15 lowest ball speed	41.4 ± 18.0	82.31 ± 10.86	176.37 ± 7.04	39.9 ± 5.2	9.67 ± 7.54

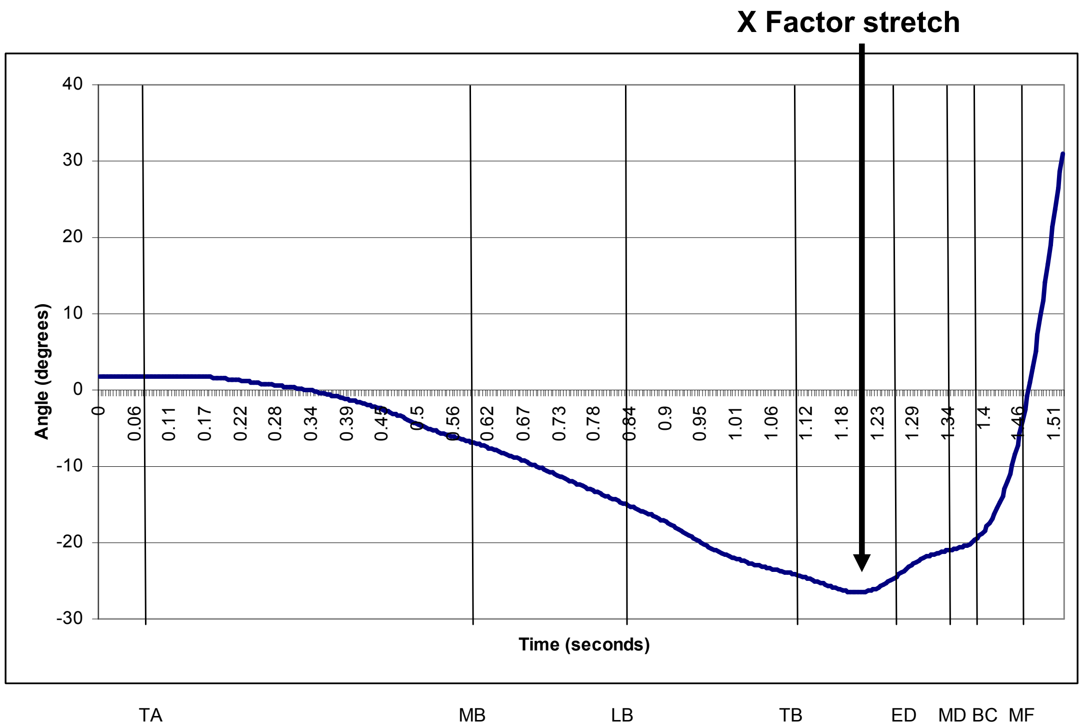
The removal of ten golfers was deemed justifiable; the benefit of having two distinct groups for comparative purposes outweighs the greater statistical power which a larger sample size would give. Inclusion of these participants would have caused the merging of the two groups rendering identification of true differences difficult.

Following the grouping of the participants the motion analysis data was processed. Firstly each participant's static trial was labelled, their body measurements were entered, and an auto label calibration was created. The 'golf' static model was then run on each participant's static trial. The top three trials for each golfer (based on ball speed) were then auto labelled, filtered using the Woltring filter routine (Woltring 1986) with an MSE value of 9 and the 'golf' dynamic model was run to produce angles and angular velocities for all variables assessed. The selection of an MSE value of 9 was based on manufacturer recommendations and pilot work on the effect of MSE values ranging from 5-20 on the data sets residual signal amplitude (Winters 2005).

During some of the trials the forearm and wrist markers were occluded for sections of the trial, due to the closeness of the markers and the speed at which they were moving. This resulted in incomplete data sets for the elbow and wrist angle measurements.

Following this processing eight events during the trial were identified. The eight events are detailed in Table 2.13 and Figure 2.17. Break down of the golf swing into these eight swing events have been detailed and used previously by Ball and Best (2007a, 2007b). These events were identified manually.

The following angles were calculated by the ‘golf’ model of the Vicon motion analysis system: X factor angle, shoulder (flexion/extension, abduction/adduction and internal/external rotation), elbow flexion/extension, wrist abduction/adduction, hip (flexion/extension, abduction/adduction and internal/external rotation), knee flexion/extension and the club shaft angle in the X, Y and Z plane. The angular velocities for the above were also determined. The angles and angular velocities of the above at the eight swing events were selected for statistical analysis of the differences between the two groups. Both the right and left side angles for the shoulder, elbow, wrist, hip and knee were assessed. For the X factor the maximum angle, X Factor stretch and the time of the X factor stretch were also analysed. The X factor stretch is defined as the increase in the X Factor from top of the backswing to early downswing (Figure 3.26).



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 3.26 Graph showing the eight swing events and the X Factor stretch.

As the pressure plate was synchronised with the Vicon system it was possible to identify the participant’s centre of pressure at the eight swing events identified in Vicon Workstation. The data from the pressure plate was exported to Microsoft Excel for analysis. A macro was created to extract the relevant data to allow the calculation of the % centre of pressure in two directions; the direction of the shot (X axis) and perpendicular to the direction of the shot (Y axis) (Figure 3.2). The position of the centre of pressure along the X axis was calculated as a percentage between the two feet. Reference points of 0% (in the front foot) and 100% (in the back foot) were established by averaging where the centre of pressure for each individual foot was located for the first 0.5 s of data collection of each trial. During this initial 0.5 s of data collection the golfers were in a position of ball address.

The position of the centre of pressure in the Y axis was established as a percentage between the heel of the foot which was placed furthest back (0%) and the toe of the foot which was furthest forward (100%) (Figure 3.27).

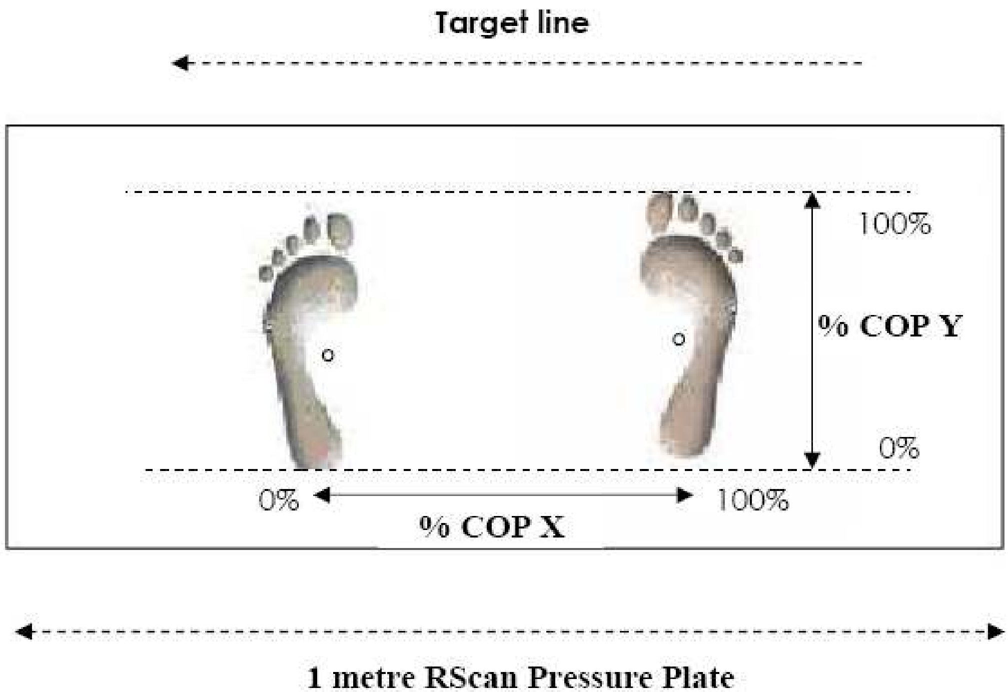


Figure 3.27 Pressure plate showing how % COP X and Y were defined.

Using the time points of the eight key events and the position of the participant's centre of pressure in the X and Y axis it was possible to calculate the velocity of the centre of pressure in the X and Y direction from one swing event to the next. As with the body joint kinematic and golf club swing characteristic data, the results of the top three trials with regard to ball speed were averaged.

3.7 Statistical analysis

Differences between the low and high ball speed groups were statistically analysed using SPSS 15.0 for Windows. One way analyses of variance (ANOVA) were used to assess differences between the groups for the golf club swing characteristics: club speed, clubface angle, swing path, tempo and impact; body joint kinematics: shoulder, elbow, wrist, hip, knee and X Factor angles; % centre of pressure X and Y and centre of pressure X and Y velocity; and golf club kinematics: angles and angular velocities for the golf club in the X, Y and Z plane.

While the present author recognises that some members of the scientific community advocate an adjustment of the p value for multiple comparisons (e.g. Bonferroni adjustment) others clearly do not advocate this approach (Perneger 1998, Hopkins 2009). In the present study as there was a large number of comparisons the Bonferroni adjustment would have resulted in a significant alpha level of $p \leq 0.0003$. The use of the Bonferroni adjustment in the present study was considered too severe, as would alternative adjustment methods, and in order to account for the multiple comparisons in the present study a p value of ≤ 0.01 was considered significant. This significant level has been employed in recent golf research involving multiple comparisons (Ball and Best 2007a, Zheng et al. 2008).

The effect size correlation for each variable was calculated as follows:

$$\eta^2 = \frac{dfh \times F}{dfh \times F + dfe} \qquad \text{(Equation 1)}$$

Where *F* is the test statistic and *dfh* and *dfe* are its degrees of freedom and degrees of freedom for error, respectively.

The following equation (Equation 2) was chosen for calculating effect size correlation for the variables of elbow and wrist angle and angular velocity as there were unequal numbers of participants in each group, and this was the recommended formula for such a situation (Fields 2005).

$$r = \sqrt{\frac{t^2}{t^2 + df}} \qquad \text{(Equation 2)}$$

Where *t* = t statistic and *df* = N – 2 (N = total sample size)

To assess test-retest reliability for the ten participants who completed a retest the intra class correlation coefficient was calculated between all the variables measures on the first test day and the retest day.

Please note sample data from the Pro V swing analyser and pressure plate, and a sample SPSS output can be found in Appendix J Sample Data.

3.8 Limitations

- Both hitting for maximum distance and accuracy are extremely important in golf. Calculating the accuracy of a golf shot is a challenging measure to obtain within an indoor laboratory and was considered beyond the remit of the present study.

- The distance a ball travels is not only determined by ball speed, but by a number of factors (Figure 2.1), including ball spin. While ball spin could not be measured in the present study it is assumed that any differences in ball striking distance between the two groups due to differences in ball spin is smaller than differences in the strike distance due to ball speed.

4 Results

The main aim of this section is to provide results for the between group analysis of the high versus low ball speed groups when hitting for maximum distance with the 5 iron. In addition, as there is limited research on the iron clubs per se this section will also aim to describe the general movement pattern of the participant during the golf swing with the 5 iron club.

The representative graphs provided in this section are from a participant in the high ball speed group (average ball speed 55.5 ms^{-1}). These graphs are presented to indicate the general pattern of the joint angles when hitting for maximum distance with the 5 iron golf club.

4.1 Between group analysis for high versus low ball speed

4.1.1 Golf club swing characteristics

Results from the club swing for the high (52.9 ± 2.1 $m.s^{-1}$) versus low (39.9 ± 5.2 $m.s^{-1}$) ball speed groups can be found in Table 4.1. The high ball speed group were found to generate significantly greater club speed than the low ball speed group (38.2 ± 1.7 $m.s^{-1}$ *vs.* 30.7 ± 2.9 $m.s^{-1}$, $F = 73.5$, $p < 0.001$). At the moment of impact between the club and the ball, the high ball speed group contacted the ball significantly closer to the centre of the club face than the low ball speed group (-0.74 ± 0.68 cm *vs.* -1.95 ± 0.69 cm, $F = 23.5$, $p < 0.001$). No differences were evident between the two groups for clubface angle, swing path angle, tempo or club rotation.

Table 4.1 Group means ± standard deviations for high versus low ball speed groups, for golf club swing characteristics with effect size percentage.

	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
Club Speed (m.s)	**38.2 ± 1.7**	**30.7 ± 2.9**	**< 0.001**	**72.4%**	*
Clubface angle (°)	2 ± 2.53	3 ± 4.91	0.57	1.2%	
Swing path angle (°)	4 ± 3.31	4 ± 1.95	0.82	0.2%	
Tempo (s)	0.95 ± 0.08	1.09 ± 0.21	0.03	15.8%	
Club rotation (deg.in)	2 ± 0.46	1 ± 1.25	0.41	2.5%	
Impact point (cm)	**-0.74 ± 0.68**	**-1.95 ± 0.69**	**< 0.001**	**45.6%**	*

Note: For impact point: 0 = centre of the club face, + = towards the toe of the club face, - = towards the heel of the club face.

4.1.2 Swing duration

Given that a significant difference was found between the tempo of the high versus low ball speed groups (0.95 ± 0.08 s *vs.* 1.09 ± 0.21 s), further analysis of the timing between the eight swing events was carried out to identify where exactly within the swing the differences occurred (Table 4.2). The high ball speed group completed the last two phases prior to ball contact and the phase after ball contact significantly faster than the slow ball speed group: early downswing to mid downswing (0.05 ± 0.01 s *vs.* 0.08 ± 0.02 s, F = 25.9, p < 0.001), mid downswing to ball contact (0.04 ± 0.00 s *vs.* 0.05 ± 0.01 s, F = 31.4, p = < 0.001) and ball contact to mid follow through (0.07 ± 0.01 s *vs.* 0.08 ± 0.01 s, F = 34.7, p < 0.001).

Table 4.2 Group means ± standard deviations (s) for high versus low ball speed groups, for the timing between the eight swing events with effect size percentage.

Time (s)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA - MB	0.42 ± 0.08	0.45 ± 0.05	0.22	5.3%	
MB - LB	0.16 ± 0.04	0.19 ± 0.05	0.06	11.8%	
LB - TB	0.25 ± 0.04	0.29 ± 0.14	0.34	3.2%	
TB - ED	0.19 ± 0.03	0.20 ± 0.05	0.56	1.3%	
ED - MD	**0.05 ± 0.01**	**0.08 ± 0.02**	**< 0.001**	**48.1%**	*
MD - BC	**0.04 ± 0.00**	**0.05 ± 0.01**	**< 0.001**	**52.9%**	*
BC - MF	**0.07 ± 0.01**	**0.08 ± 0.01**	**< 0.001**	**55.4%**	*

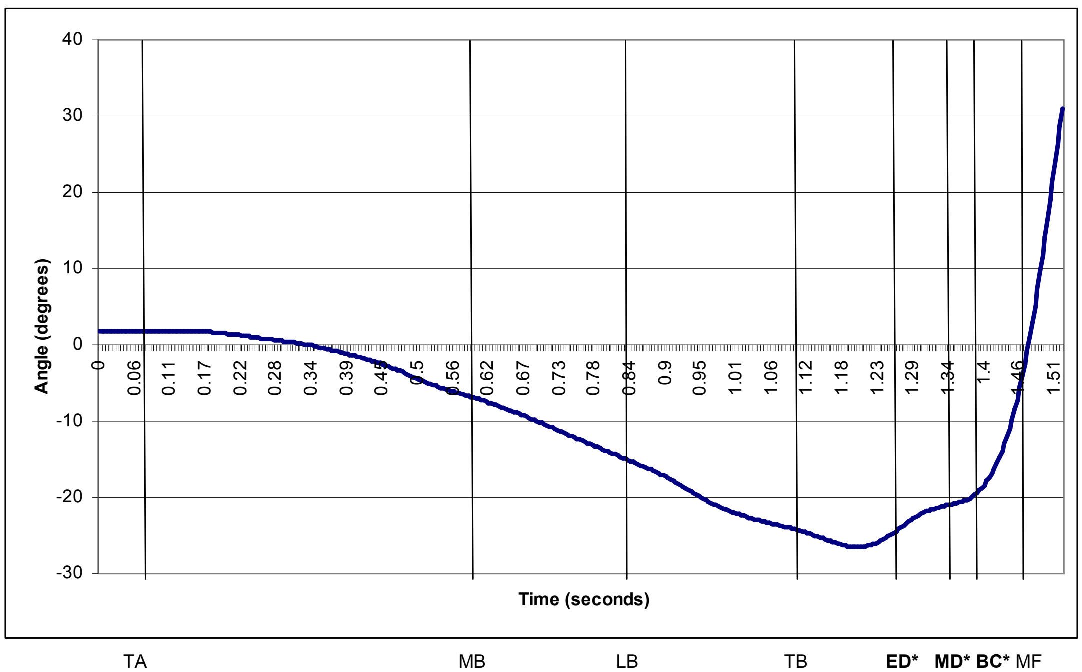
Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.3 Participant kinematics

Definitions for all these angles are provided in Figure 3.10 to Figure 3.19.

4.1.3.1 X Factor angle

Figure 4.1 illustrates a representative graph for the X Factor angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.1 Representative graph for X Factor angle.

For the X Factor angle the high ball speed group were found to have a larger angle at the two swing events prior to ball contact, at ball contact, and at mid follow through (Table 4.3). These differences were early downswing (-42.6 ± 6.3° *vs.* -35.1 ± 6.5°, F = 10.3, p = 0.003) mid downswing (-38.5 ± 6.1° *vs.* -30.4 ± 6.3°, F = 12.7, p = 0.001), ball contact (-36.3 ± 5.3° *vs.* -26.8 ± 7.4°, F = 16.5, p < 0.001) and mid follow through (-15.5 ± 11.2° *vs.* 1.8 ± 13.3°, F = 14.9, p = 0.001). The X Factor stretch which is measured as the increase in the X Factor angle following the event of top of the backswing and the time duration of the stretch were not significantly different for the two groups.

Table 4.3 Group means ± standard deviations for high versus low ball speed groups, for the X Factor angle at the eight swing events, minimum, maximum, stretch and stretch time with effect size percentage.

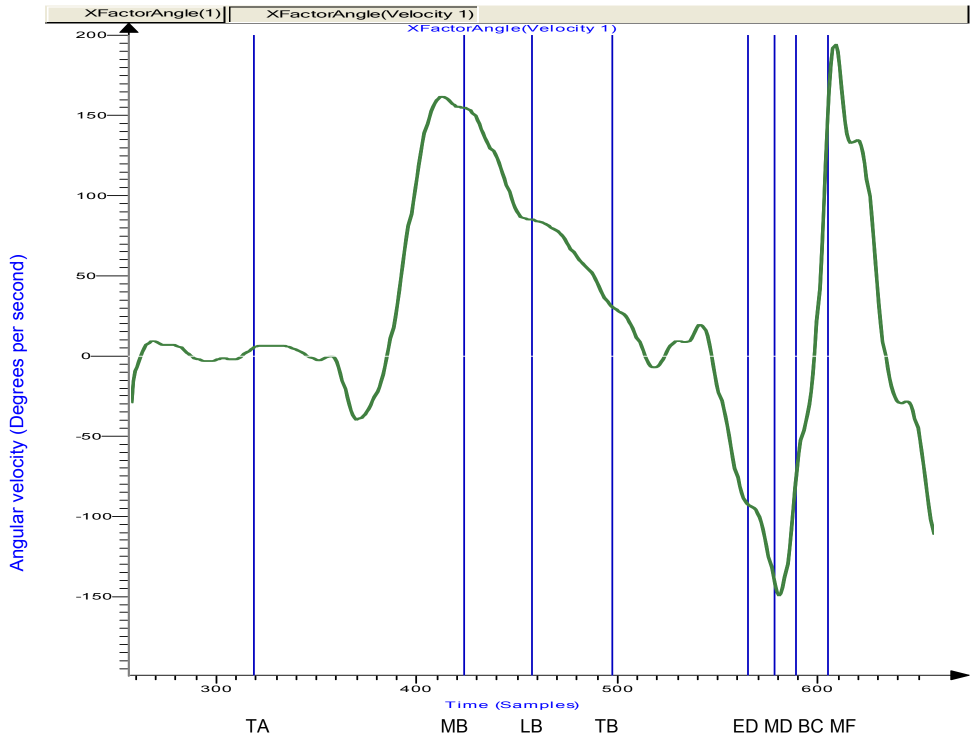
X Factor (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	**-1.7 ± 3.0**	**-1.3 ± 4.8**	**0.81**	**0.2%**	
MB	**-16.2 ± 5.3**	**-16.2 ± 5.4**	**0.98**	**0.0%**	
LB	**-35.3 ± 6.4**	**-32.7 ± 7.6**	**0.32**	**3.4%**	
TB	**-53.8 ± 6.3**	**-48.3 ± 10.5**	**0.1**	**9.6%**	
ED	**-42.6 ± 6.3**	**-35.1 ± 6.5**	**0.003**	**26.9%**	*
MD	**-38.5 ± 6.1**	**-30.4 ± 6.3**	**0.001**	**31.3%**	*
BC	**-36.3 ± 5.3**	**-26.8 ± 7.4**	**< 0.001**	**37.1%**	*
MF	**-15.5 ± 11.2**	**1.8 ± 13.3**	**0.001**	**34.7%**	*
Stretch	-55.1 ± 7.3	-48.7 ± 10.5	0.06	12.0%	
Stretch time (s)[1]	0.07 ± 0.06	0.03 ± 0.03	0.03	16.4%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through, Stretch = increase in the X Factor following TB.

4.1.3.2 X Factor angular velocity

A representative graph for the X Factor angle during the golf swing is shown in Figure 4.2.

[1] Note not all participants were found to have an X Factor stretch and therefore those who did not had an X Factor stretch time of 0s.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.2 Representative graph for X Factor angular velocity.

X Factor angular velocity results were not significantly different between the two groups (Table 4.4).

Table 4.4 Group means ± standard deviations for high versus low ball speed groups, for the X Factor velocity at seven swing events with effect size percentage.

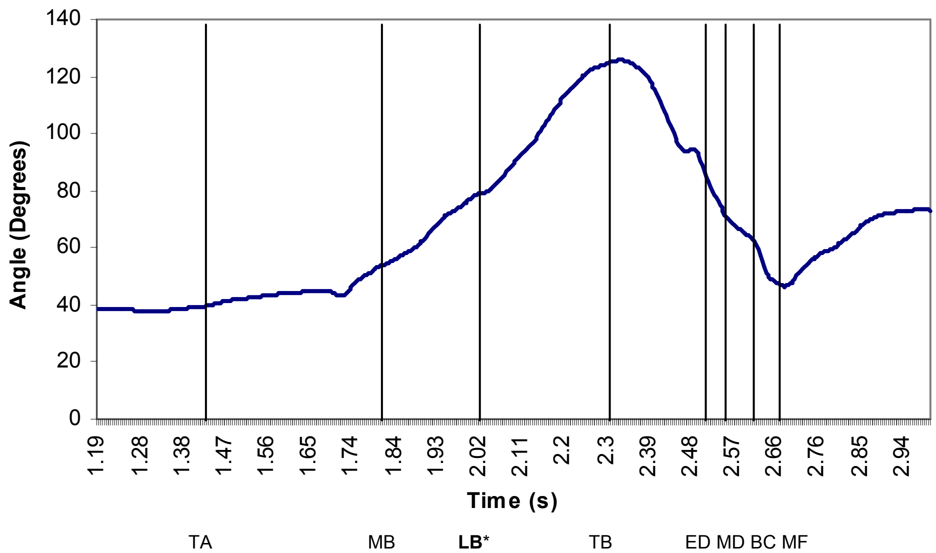
X Factor angular velocity ($deg.s^{-1}$)	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
MB	129.9 ± 31.5	103.75 ± 48.20	0.09	10.0%	
LB	73.3 ± 25.4	69.66 ± 31.06	0.73	0.4%	
TB	23.0 ± 34.0	16.48 ± 21.79	0.54	1.4%	
ED	120.4 ± 63.8	116.48 ± 49.38	0.85	0.1%	
MD	93.9 ± 77.1	40.81 ± 69.39	0.05	12.3%	
BC	47.6 ± 56.4	1.57 ± 49.02	0.02	16.9%	
MF	99.1 ± 132.8	170.7 ± 133.1	0.15	7.2%	

Note: MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.3.3 Shoulder

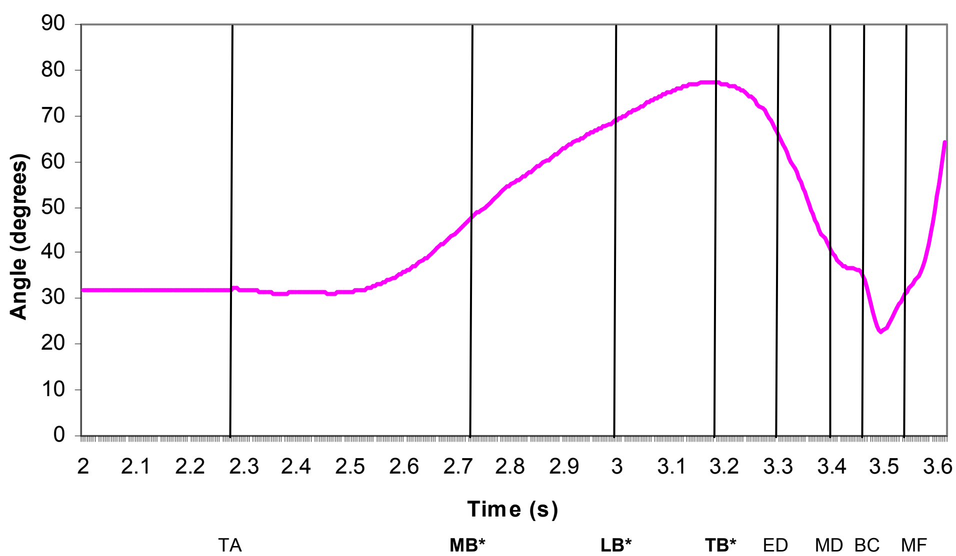
4.1.3.3.1 Flexion/Extension Angle

Figure 4.3 and Figure 4.4 illustrate representative graphs for the left and right shoulders flexion/extension angle during the golf swing.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups (p ≤ 0.01). 0 = neutral; + = flexion; - = extension

Figure 4.3 Representative graph for left shoulder flexion/extension angle during the golf swing.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups (p ≤ 0.01). 0 = neutral; + = flexion; - = extension.

Figure 4.4 Representative graph for right shoulder flexion/extension angle during the golf swing.

Results for left and right shoulder flexion/extension angles can be found in Table 4.5 and Table 4.6, respectively. Left and right shoulder flexion/extension angles were shown to be significantly different between the groups at the event late backswing. The high ball speed group were found to have their left and right shoulders in a significantly greater angle of flexion than the low ball speed group at this event (Left: 78.4 ± 12.3° *vs.* 55.8 ± 17.5°, F = 16.8, p < 0.001, Right: 47.1 ± 9.7° *vs.* 33.9 ± 12.7°, F = 10.0, p = 0.004). In addition, the right shoulder was found to be at a significantly greater angle of flexion for the high ball speed group than the low ball speed group at mid backswing (40.6 ± 10.1° *vs.* 29.4 ± 8.9°, F = 10.2, p = 0.003) and top of backswing (57.3 ± 10.6° *vs.* 44.2 ± 15.9°, F = 7.1, p = 0.01).

Table 4.5 Group means ± standard deviations for high versus low ball speed groups, for left shoulder flexion/extension angle at the eight swing events with effect size percentage.

Left shoulder flexion/extension (°)	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
TA	33.5 ± 8.8	29.1 ± 7.9	0.16	7.0%	
MB	46.9 ± 14.1	32.9 ± 15.6	0.02	19.2%	
LB	**78.4 ± 12.3**	**55.8 ± 17.5**	**< 0.001**	**37.5%**	*
TB	114.1 ± 17	90.6 ± 19.8	0.002	30.2%	
ED	75.1 ± 8.5	68.1 ± 10.9	0.06	12.1%	
MD	55.03 ± 5.41	50.09 ± 10.80	0.13	8.2%	
BC	46.5 ± 4.7	38.7 ± 12.6	0.03	15.4%	
MF	34.5 ± 10.2	23.3 ± 18.2	0.05	13.3%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = flexion; - = extension.

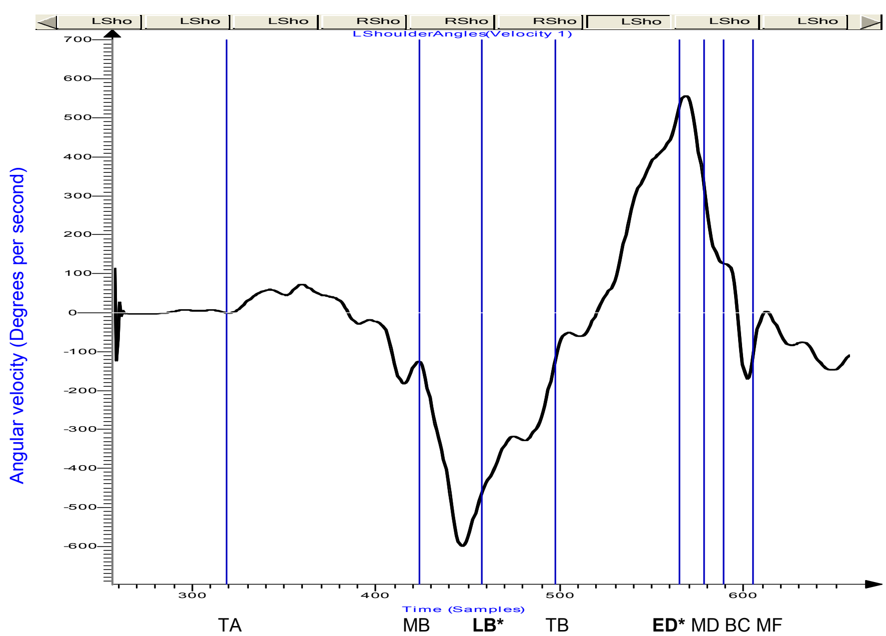
Table 4.6 Group means ± standard deviations for high versus low ball speed groups, for right shoulder flexion/extension angle at the eight swing events with effect size percentage.

Right shoulder flexion/extension (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	34.0 ± 7.6	29.9 ± 6.9	0.13	8.0%	
MB	**40.6 ± 10.1**	**29.4 ± 8.9**	**0.003**	**26.9%**	*
LB	**47.1 ± 9.8**	**33.9 ± 12.7**	**0.004**	**26.4%**	*
TB	**57.3 ± 10.6**	**44.2 ± 15.9**	**0.01**	**20.2%**	*
ED	35.8 ± 8.0	33.9 ± 14.9	0.67	0.7%	
MD	28.8 ± 6.4	25.3 ± 12.8	0.36	3.0%	
BC	31.8 ± 6.7	28.2 ± 9.9	0.26	4.6%	
MF	36.4 ± 12.1	34.1 ± 11.1	0.59	1.1%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = flexion; - = extension.

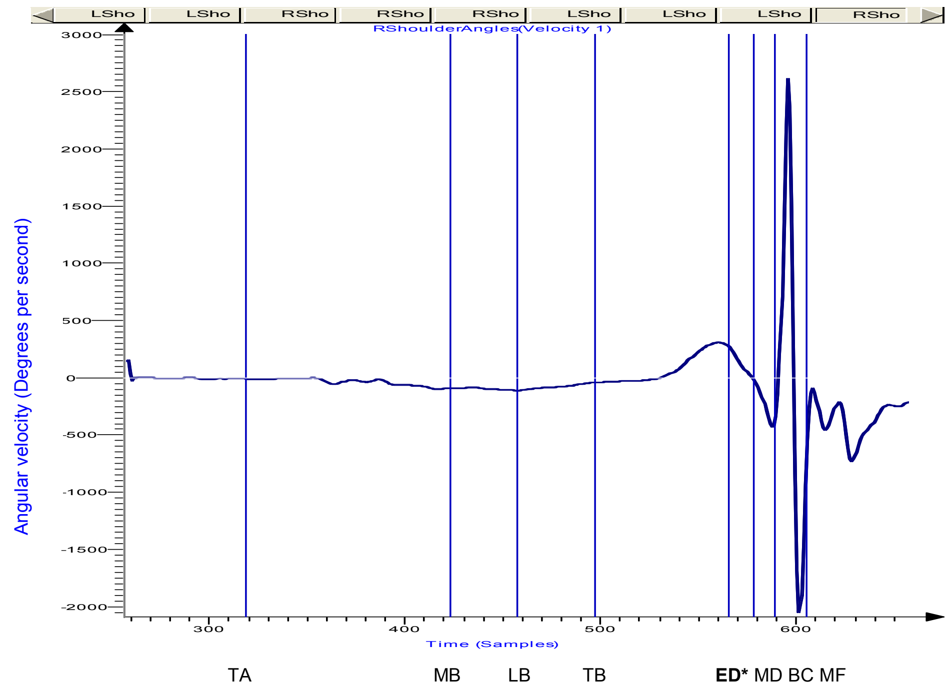
4.1.3.3.2 Flexion/Extension Angular Velocity

Presented in Figure 4.5 and Figure 4.6 are representative graphs for flexion/extension angular velocity for the left and right shoulders during the golf swing.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups (p ≤ 0.01).

Figure 4.5 Representative graph for left shoulder flexion/extension angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.6 Representative graph for right shoulder flexion/extension angular velocity.

For the significant differences seen in the left and right shoulder flexion/extension angular velocities between the groups, the high ball speed group were always found to generate greater angular velocity than the low ball speed group (Table 4.7 and Table 4.8). For both the left and right shoulder the angular velocity was significantly greater for the high ball speed group at early downswing (Left: 494.5 ± 200.3 deg.s^{-1} *vs.* 224.5 ± 119.3 deg.s^{-1}, $F = 19.8$, $p < 0.001$; Right: 206.0 ± 69.3 deg.s^{-1} *vs.* 114.93 ± 71.67 deg.s^{-1}, $F = 12.1$, $p = 0.002$). The left shoulder was also found to have greater angular velocity for the high ball speed group at late backswing (258.2 ± 131.9 deg.s^{-1} *vs.* 150.6 ± 85.4 deg.s^{-1}, $F = 6.9$, $p = 0.01$).

Table 4.7 Group means ± standard deviations for high versus low ball speed groups, for left shoulder flexion/extension angular velocity at seven swing events with effect size percentage.

Left shoulder flexion/extension angular velocity ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	138.2 ± 62.5	91.3 ± 56.5	0.04	14.3%	
LB	**258.2 ± 131.9**	**150.6 ± 85.4**	**0.01**	**20.4%**	*
TB	12.3 ± 57.9	25.8 ± 45.5	0.49	1.8%	
ED	**494.5 ± 200.3**	**224.5 ± 119.7**	**< 0.001**	**42.3%**	*
MD	276.2 ± 124.8	233.7 ± 129.9	0.38	2.9%	
BC	216.0 ± 173.2	239.7 ± 143.3	0.69	0.6%	
MF	66.4 ± 202.5	71.9 ± 131.2	0.93	0.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

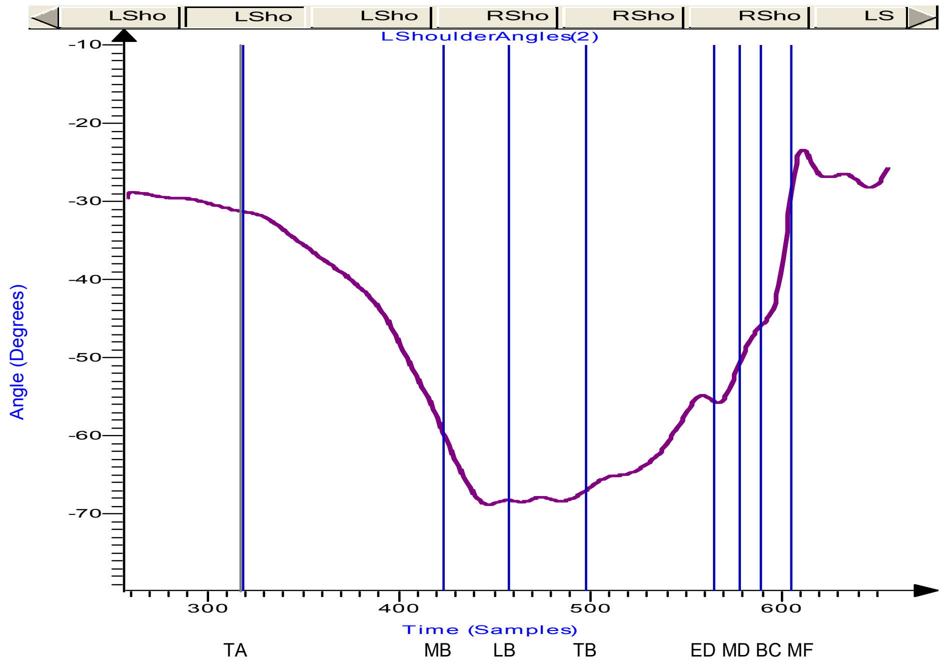
Table 4.8 Group means ± standard deviations for high versus low ball speed groups, for right shoulder flexion/extension angular velocity at seven swing events with effect size percentage.

Right shoulder flexion/extension angular velocity ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	40.4 ± 35.9	13.3 ± 36.2	0.05	13.2%	
LB	58.2 ± 46.8	41.5 ± 43.8	0.33	3.5%	
TB	14.6 ± 33.1	6.1 ± 16.5	0.04	14.6%	
ED	**206.0 ± 69.3**	**114.9 ± 71.7**	**0.002**	**30.9%**	*
MD	62.3 ± 94.3	55.4 ± 93.1	0.84	0.1%	
BC	226.5 ± 120.0	149.9 ± 211.9	0.25	5.0%	
MF	673.7 ± 550.9	298.7 ± 279.6	0.03	16.8%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

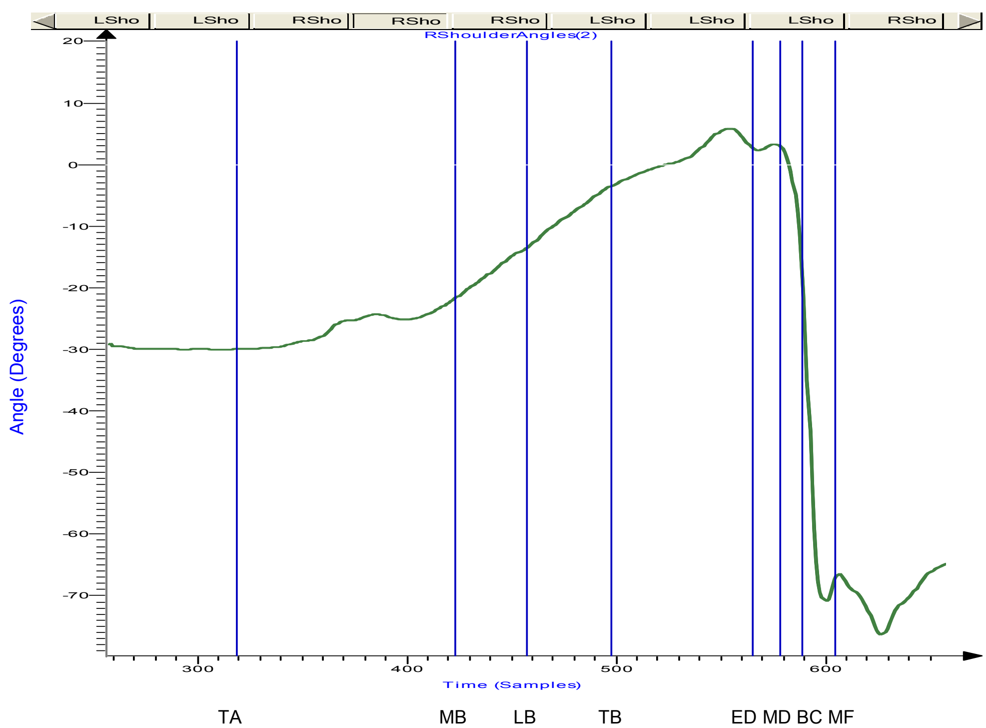
4.1.3.3.3 Abduction/Adduction Angle

Figure 4.7 and Figure 4.8 demonstrate representative graphs for abduction/adduction angle for the left and right shoulder.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.7 Representative graph for left shoulder abduction/adduction angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = abduction; - = adduction.

Figure 4.8 Representative graph for right shoulder abduction/adduction angle.

Results for the left and right shoulder abduction/adduction angle at the eight swing events can be found in Table 4.9 and Table 4.10 respectively. No significant differences were evident between the two groups.

Table 4.9 Group means ± standard deviations for high versus low ball speed groups, for left shoulder abduction/adduction angle at the eight swing events with effect size percentage.

Left shoulder abduction/adduction (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	-6.1 ± 19.7	-19.8 ± 13.6	0.04	14.9%	
MB	-38.6 ± 17.2	-46.5 ± 12.7	0.16	6.9%	
LB	-54.1 ± 17.6	-58.4 ± 10.9	0.43	2.2%	
TB	-60.6 ± 9.9	-62.0 ± 9.8	0.70	0.5%	
ED	-51.7 ± 17.4	-48.4 ± 11.8	0.55	1.3%	
MD	-36.3 ± 18.2	-33.2 ± 11.7	0.58	1.1%	
BC	-16.6 ± 21.8	-20.6 ± 16.2	0.57	1.1%	
MF	-0.6± 19.5	-13.4 ± 14.3	0.05	13.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = abduction; - = adduction.

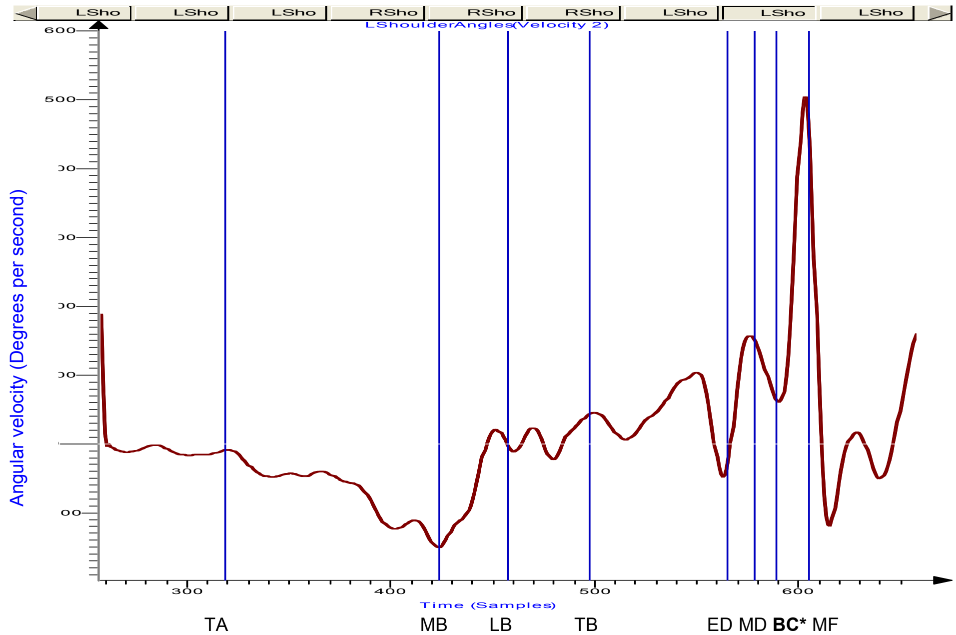
Table 4.10 Group means ± standard deviations for high versus low ball speed groups, for right shoulder abduction/adduction angle at the eight swing events with effect size percentage.

Right shoulder abduction/adduction (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	-8.4 ± 13.8	-12.9 ± 12.8	0.36	3.0%	
MB	0.4 ± 11.9	-3.9 ± 11.9	0.34	3.3%	
LB	3.1 ± 9.5	0.7 ± 13.7	0.58	1.1%	
TB	4.9 ± 9.5	0.2 ± 13.2	0.26	4.5%	
ED	5.7 ± 7.3	1.3 ± 12.2	0.24	4.8%	
MD	1.6 ± 6.1	-1.7 ± 10.8	0.32	3.5%	
BC	-8.7 ± 7.9	-11.9 ± 10.6	0.35	3.1%	
MF	-39.3 ± 15.8	-34.3 ± 14.9	0.38	2.7%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = abduction; - = adduction.

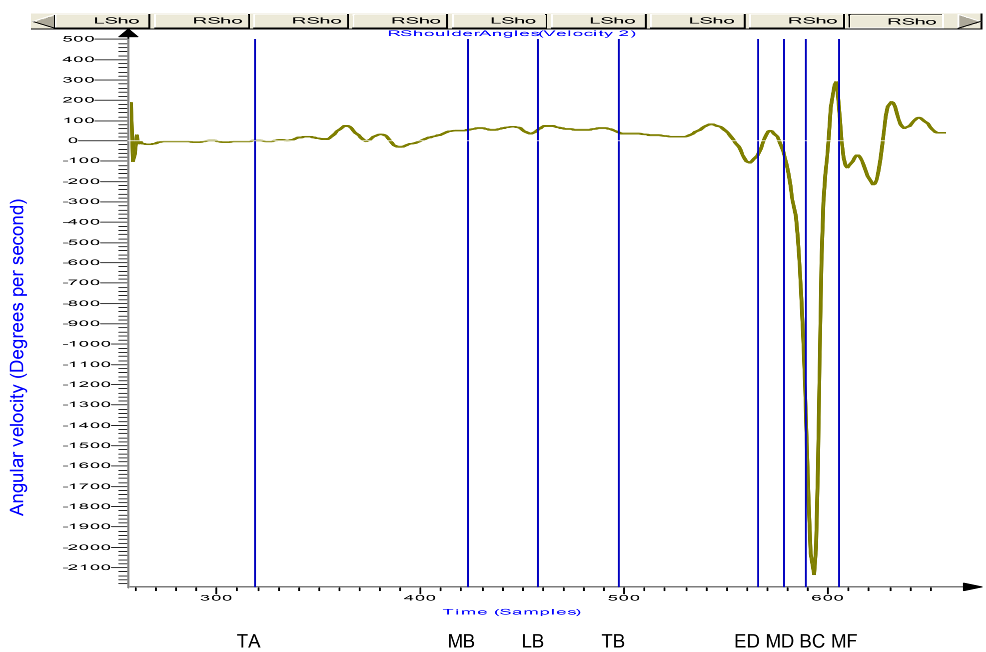
4.1.3.3.4 Abduction/Adduction Angular Velocity

Example graphs for abduction/adduction angular velocity for the left and right shoulders are shown in Figure 4.9 and Figure 4.10.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.9 Representative graph for left shoulder abduction/adduction angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.10 Representative graph for right shoulder abduction/adduction angular velocity.

Only the left shoulder exhibited significant between group differences for abduction/adduction angular velocity (Table 4.11 and Table 4.12). This difference occurred at the event of ball contact with higher angular velocities values seen in the high ball speed group (609.2 ± 304.9 deg.s^{-1} *vs.* 234.8 ± 197.6 deg.s^{-1}, F = 15.6, p = 0.001).

Table 4.11 Group means ± standard deviations for high versus low ball speed groups, for left shoulder abduction/adduction angular velocity at seven swing events with effect size percentage.

Left shoulder abduction/adduction angular velocity (deg.s^{-1})	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
MB	109.0 ± 79.4	78.3 ± 31.6	0.18	6.6%	
LB	74.5 ± 57.5	54.1 ± 45.6	0.30	4.0%	
TB	11.4 ± 23.1	9.1 ± 22.9	0.02	17.5%	
ED	230.2 ± 193.8	189.7 ± 97.7	0.48	1.9%	
MD	384.5 ± 198.0	228.7 ± 137.9	0.02	18.4%	
BC	**609.2 ± 304.9**	**234.8 ± 197.6**	**0.001**	**36.6%**	*
MF	130.5 ± 204.8	66.2 ± 223.9	0.43	2.3%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

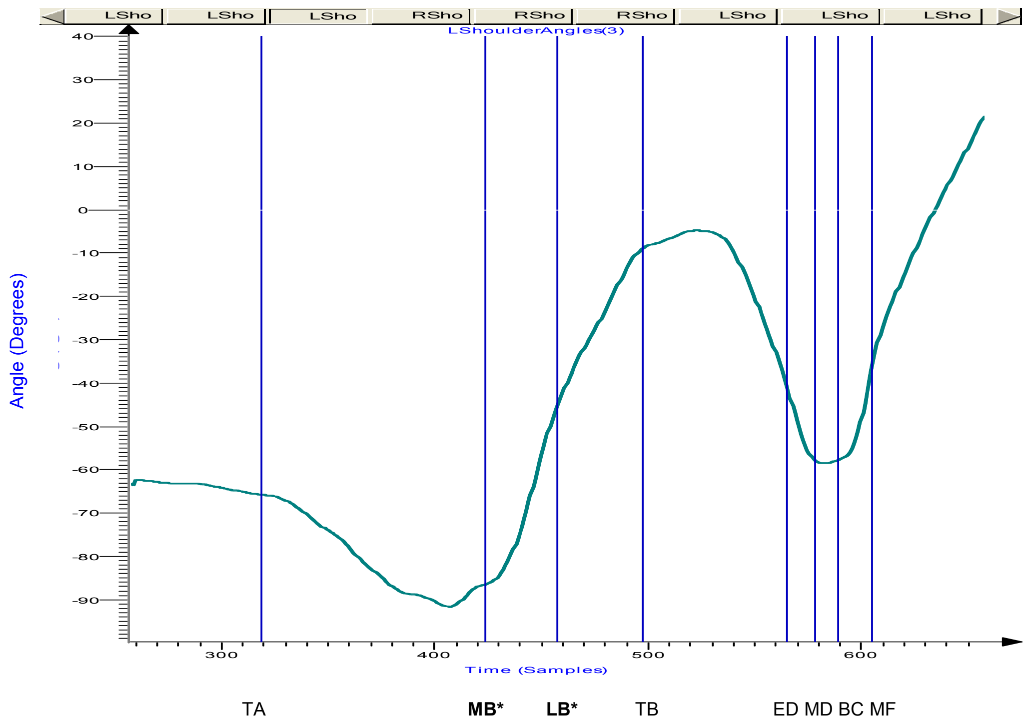
Table 4.12 Group means ± standard deviations for high versus low ball speed groups, for right shoulder abduction/adduction angular velocity at seven events with effect size percentage.

Right shoulder abduction/adduction angular velocity (deg.s^{-1})	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
MB	9.9 ± 56.9	22.7 ± 39.2	0.48	1.8%	
LB	17.1 ± 53.3	15.1 ± 24.6	0.90	0.1%	
TB	6.4 ± 25.1	1.4 ± 25.8	0.41	2.5%	
ED	58.1 ± 95.3	8.3 ± 68.9	0.12	8.9%	
MD	130.6 ± 58.8	74.6 ± 71.7	0.03	16.3%	
BC	490.9 ± 271.2	392.1 ± 228.4	0.30	4.0%	
MF	473.9 ± 870.8	67.3 ± 227.9	0.09	10.2%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

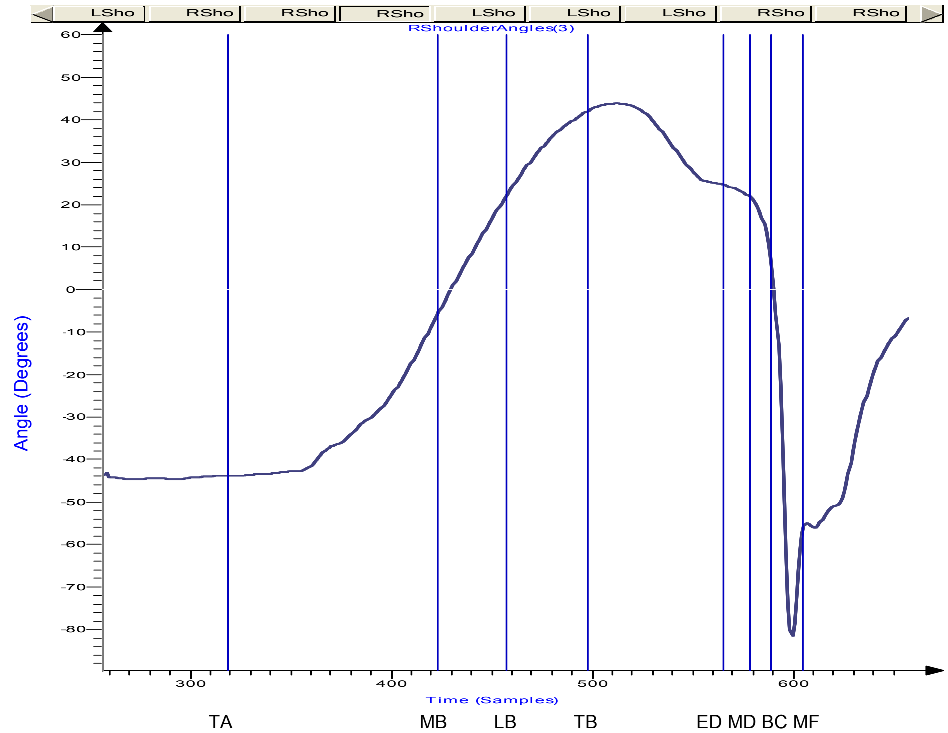
4.1.3.3.5 Internal/External Rotation Angle

Figure 4.11 and Figure 4.12 illustrate representative graphs for internal/external rotation angle for the left and right shoulder during the golf swing.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$). : 0 = neutral; + = external rotation; - = internal rotation.

Figure 4.11 Representative graph for left shoulder internal/external rotation angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.12 Representative graph for right shoulder internal/external rotation angle.

For the left shoulder internal/external rotation angles significant differences between the groups were evident at mid backswing (MB) and late backswing (LB) (Table 4.13). At both events the high ball speed group were found to have their left shoulders less internally rotated than the low ball speed group (MB: -49.5 ± 17.6° *vs.* -66.9 ± 15.2, F = 8.4, p = 0.01; LB: -42.5 ± 15.1° *vs.* -62.9 ± 14.6°, F = 14.6, p = 0.001). No significant differences were evident for the right shoulder internal/external rotation angles (Table 4.14).

Table 4.13 Group means ± standard deviations for high versus low ball speed groups, for left shoulder internal/external rotation angle at the eight swing events with effect size percentage.

Left shoulder internal/external rotation (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	-31.0 ± 19.1	-42.4 ± 14.8	0.08	10.6%	
MB	**-49.5 ± 17.6**	**-66.9 ± 15.2**	**0.01**	**23.0%**	*
LB	**-42.5 ± 15.1**	**-62.9 ± 14.6**	**0.001**	**33.7%**	*
TB	-28.3 ± 20.9	-44.4 ± 17.7	0.03	15.8%	
ED	-51.4 ± 10.9	-52.8 ± 10.3	0.71	0.5%	
MD	-51.8 ± 8.4	-53.6 ± 10.9	0.63	0.8%	
BC	-43.6 ± 12.3	-48.5 ± 13.1	0.30	3.8%	
MF	-25.1 ± 13.1	-31.5 ± 10.9	0.16	7.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. : 0 = neutral; + = external rotation; - = internal rotation.

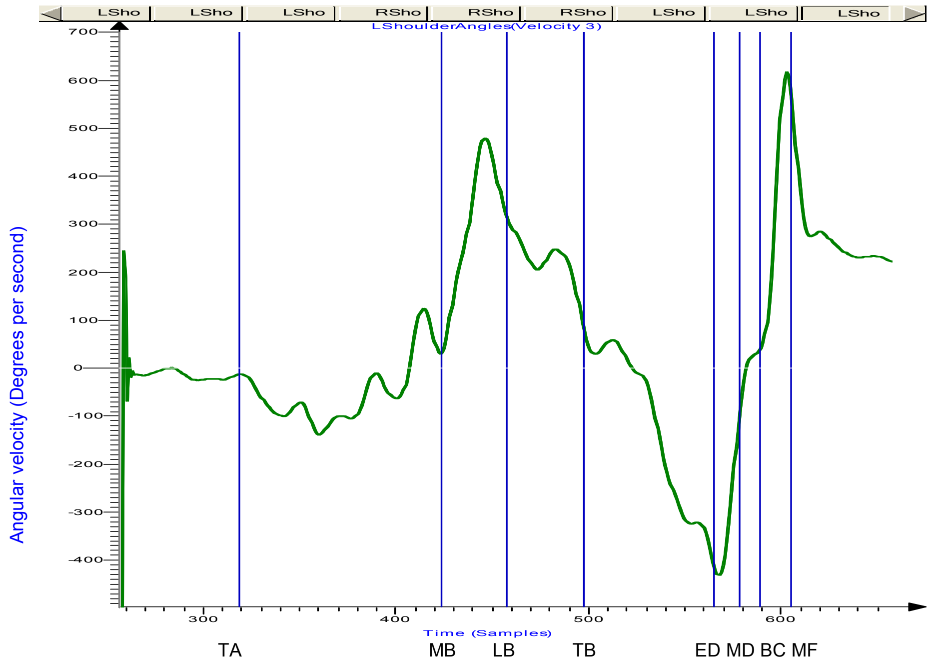
Table 4.14 Group means ± standard deviations for high versus low ball speed groups, for left shoulder internal/external rotation angle at the eight swing events with effect size percentage.

Right shoulder internal/external rotation (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	-16.8 ± 13.5	-21.7 ± 12.6	0.32	3.6%	
MB	3.7 ± 6.9	4.7 ± 8.8	0.73	0.5%	
LB	20.9 ± 8.2	27.4 ± 8.4	0.04	13.7%	
TB	47.1 ± 10.3	52.3 ± 14.6	0.28	4.2%	
ED	24.7 ± 7.9	30.4 ± 8.1	0.06	11.8%	
MD	13.5 ± 8.1	15.2 ± 8.8	0.59	1.1%	
BC	2.7 ± 7.2	-2.7 ± 12.3	0.16	7.0%	
MF	-46.8 ± 18.1	-46.5 ± 14.6	0.97	0.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. : 0 = neutral; + = external rotation; - = internal rotation.

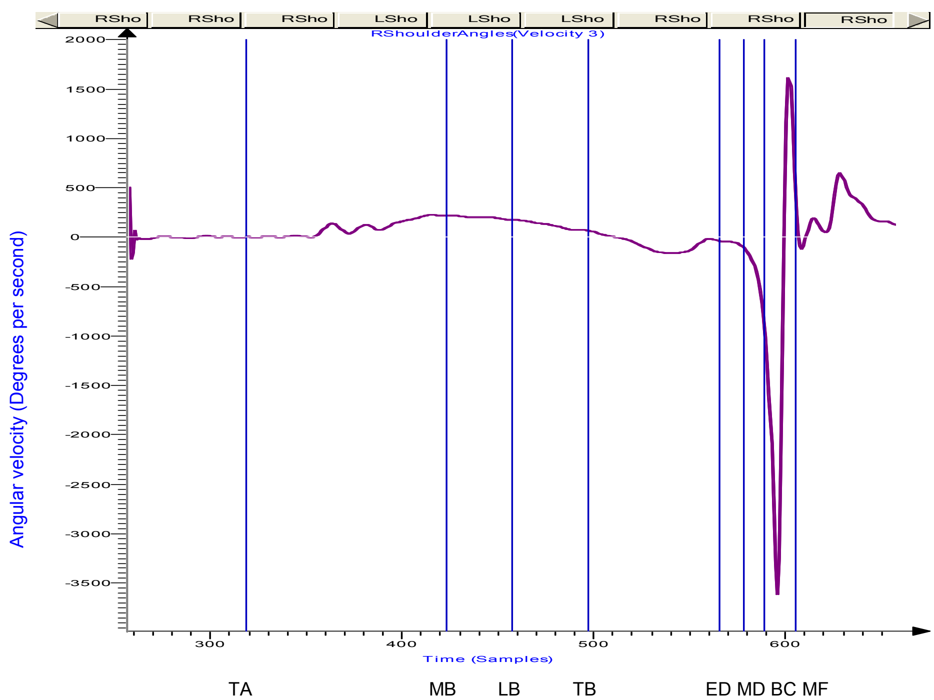
4.1.3.3.6 Internal/External Rotation Angular Velocity

Figure 4.13 and Figure 4.14 demonstrate representative graphs for internal/external angular velocity for the left and right shoulders.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.13 Representative graph for left shoulder internal/external rotation angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.14 Representative graph for right shoulder internal/external rotation angular velocity.

No significant differences were evident between the groups for the left or right shoulder internal/external rotation angular velocities (Table 4.15 and Table 4.16).

Table 4.15 Group means ± standard deviations for high versus low ball speed groups, for left shoulder internal/external rotation angular velocity at seven swing events with effect size percentage.

Left shoulder internal/external rotation angular velocity (deg.s^{-1})	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.05)**
MB	10.2 ± 104.1	9.8 ± 72.2	0.55	1.3%	
LB	114.7 ± 146.1	51.7 ± 75.9	0.15	7.4%	
TB	9.2 ± 58.8	19.3 ± 37.2	0.13	8.3%	
ED	198.0 ± 238.2	36.3 ± 144.4	0.03	15.5%	
MD	111.5 ± 189.2	38.9 ± 155.9	0.27	4.5%	
BC	339.1 ± 300.2	155.5 ± 199.4	0.06	12.4%	
MF	311.2 ± 183.0	312.9 ± 195.3	0.98	0.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.16 Group means ± standard deviations for high versus low ball speed groups, for right shoulder internal/external rotation angular velocity at seven swing events with effect size percentage.

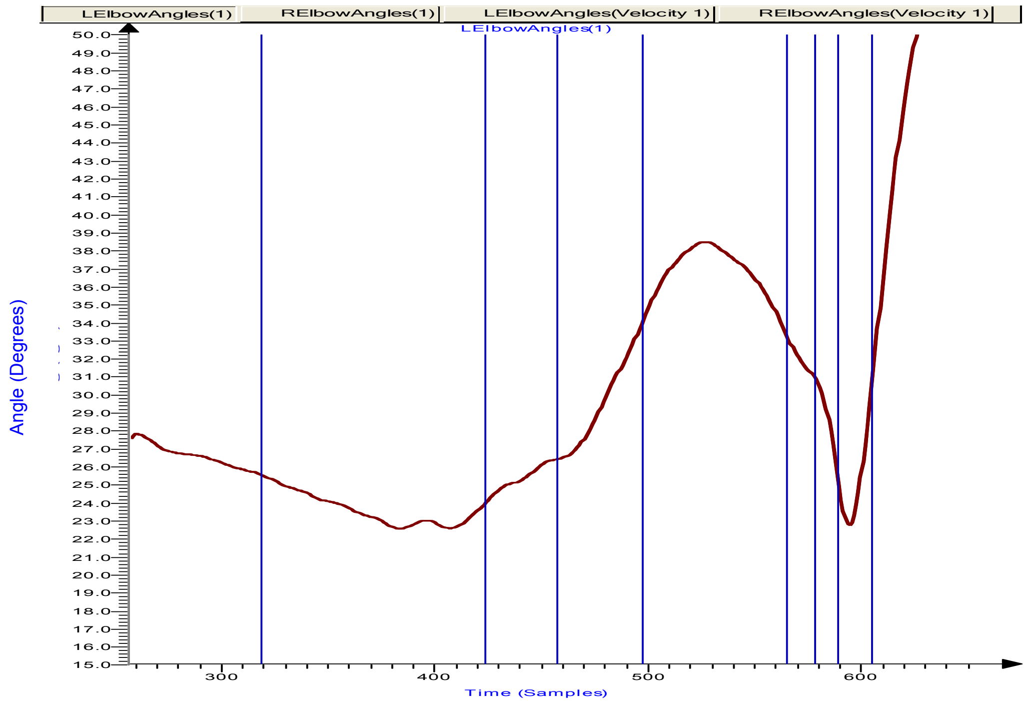
Right shoulder internal/external rotation angular velocity (deg.s^{-1})	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.05)**
MB	91.4 ± 61.4	116.9 ± 44.7	0.21	5.7%	
LB	121.4 ± 33.1	115.6 ± 61.4	0.75	0.4%	
TB	25.8 ± 41.8	1.2 ± 26.3	0.05	14.1%	
ED	239.7 ± 69.5	186.5 ± 96.1	0.10	9.7%	
MD	182.9 ± 74.0	204.5 ± 118.9	0.57	1.2%	
BC	507.5 ± 203.1	587.0 ± 178.8	0.27	4.4%	
MF	522.0 ± 912.7	8.3 ± 275.7	0.04	14.6%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.3.4 Elbow

4.1.3.4.1 Flexion/Extension Angle

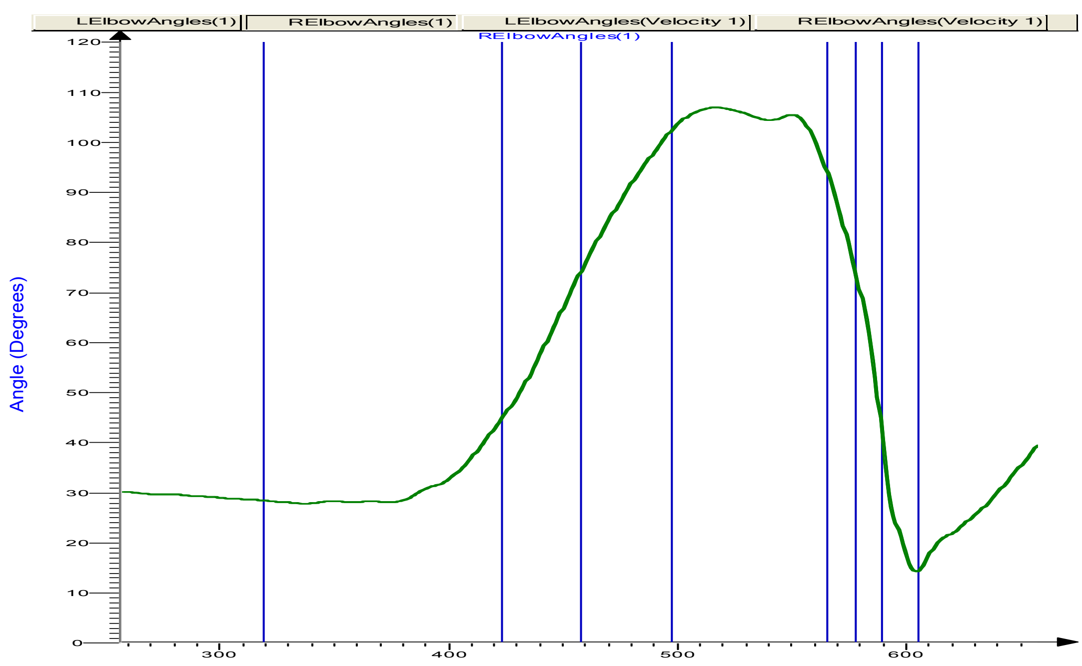
Shown in Figure 4.15 and Figure 4.16 are representative graphs for flexion/extension angle of the left and right elbows.



TA MB LB TB **ED*** MD BC MF

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups (p ≤ 0.01).

Figure 4.15 Representative graph for left elbow flexion/extension angle.



TA MB LB TB ED MD BC MF

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.16 Representative graph for left elbow flexion/extension angle.

A significant difference between the groups was seen in elbow flexion/extension angle for the left elbow at the event of early downswing (Table 4.17). At this event the high speed group were found to have their left elbows in a more extended position than the low ball speed group (32.2 ± 8.6° *vs.* 43.6 ± 8.7°, F = 10.3, p = 0.004). No significant differences were evident between the groups for right elbow flexion/extension angle (Table 4.18).

Table 4.17 Group means ± standard deviations for high versus low ball speed groups, for left elbow flexion/extension angle at the eight swing events with effect size percentage.

Left elbow flexion/extension (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	21.7 ± 5.3	26.7 ± 9.8	0.15	9.4%	
MB	21.2 ± 5.8	29.5 ± 11.3	0.04	18.2%	
LB	26.5 ± 6.4	36.2 ± 11.9	0.03	20.7%	
TB	42.1 ± 10.6	52.3 ± 9.8	0.02	21.5%	
ED	**32.2 ± 8.6**	**43.6 ± 8.7**	**0.004**	**32.1%**	*
MD	28.4 ± 8.1	35.1 ± 9.2	0.08	13.6%	
BC	23.6 ± 7.7	29.4 ± 11.2	0.16	8.7%	
MF	35.0 ± 13.9	47.5 ± 20.7	0.10	11.6%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

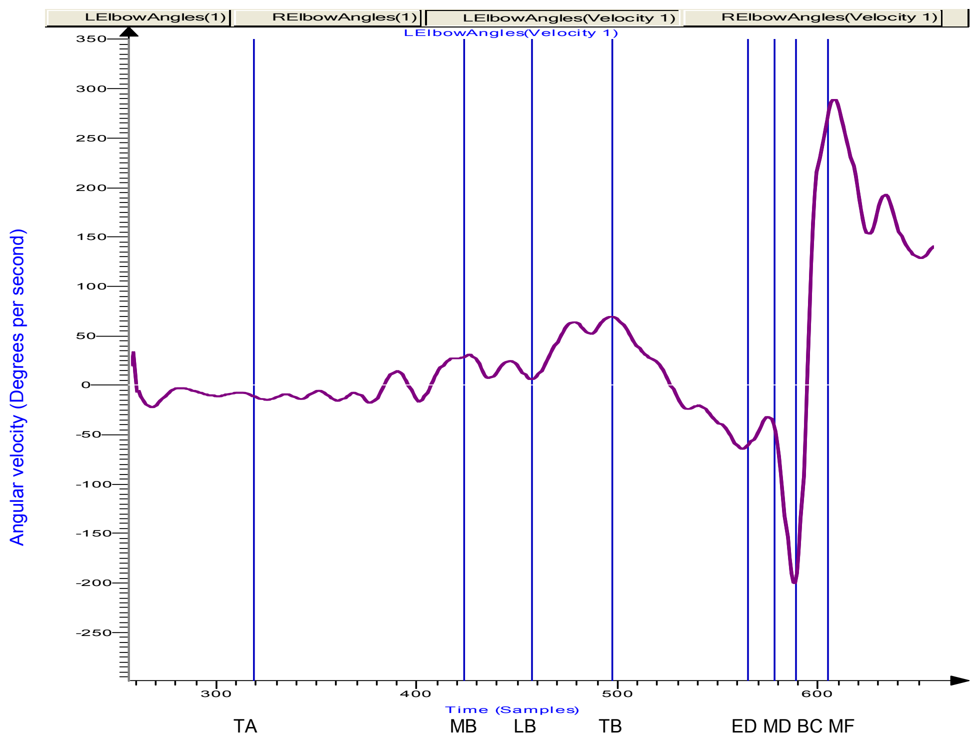
Table 4.18 Group means ± standard deviations for high versus low ball speed groups, for right elbow flexion/extension angle at the eight swing events with effect size percentage.

Right elbow flexion/extension (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	27.8 ± 5.1	29.2 ± 6.9	0.58	1.4%	
MB	45.9 ± 10.4	56.1 ± 10.3	0.02	21.0%	
LB	77.1 ± 10.9	87.6 ± 10.9	0.03	20.0%	
TB	110.5 ± 12.5	115.1 ± 10.9	0.35	4.0%	
ED	96.2 ± 5.5	97.2 ± 7.6	0.73	0.5%	
MD	73.6 ± 6.4	73.4 ± 8.4	0.96	0.0%	
BC	50.6 ± 7.4	46.5 ± 9.0	0.24	6.3%	
MF	24.7 ± 8.1	29.4 ± 9.6	0.21	7.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

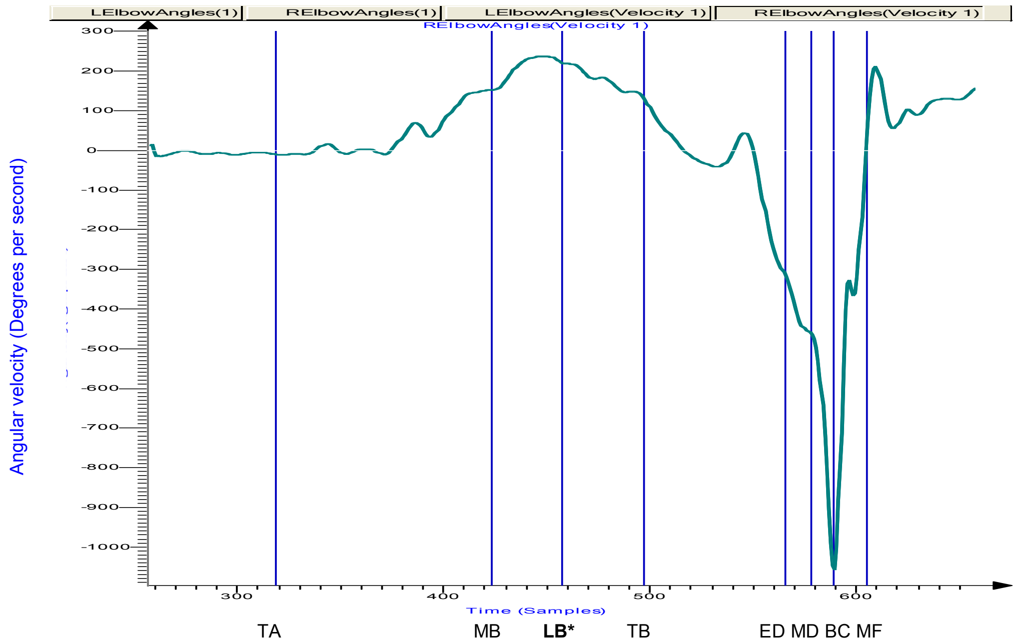
4.1.3.4.2 Flexion/Extension Angular Velocity

Figure 4.17 and Figure 4.18 display representative graphs of flexion/extension angular velocity for the left and right elbows during the golf swing.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.17 Representative graph for left elbow flexion/extension angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups (p ≤ 0.01).

Figure 4.18 Representative graph for right elbow flexion/extension angular velocity.

No significant differences between the groups were found for left elbow flexion/extension angular velocity (Table 4.19). For the right elbow angular velocity was significantly greater at late backswing (211.9 ± 36.8 deg.s^{-1} *vs.* 164.3 ± 43.9 deg.s^{-1}, F = 8.3, p = 0.01) (Table 4.20).

Table 4.19 Group means ± standard deviations for high versus low ball speed groups, for left elbow flexion/extension angular velocity at seven swing events with effect size percentage.

Left elbow flexion/extension angular velocity (deg.s^{-1})	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
MB	19.6 ± 11.7	20.9 ± 8.9	0.75	0.5%	
LB	51.2 ± 29.4	55.1 ± 22.1	0.71	0.6%	
TB	10.4 ± 32.4	7.5 ± 28.7	0.16	8.6%	
ED	83.9 ± 64.0	73.2 ± 49.6	0.64	1.0%	
MD	85.1 ± 62.5	125.9 ± 92.3	0.22	6.4%	
BC	110.9 ± 81.4	78.0 ± 179.1	0.58	1.4%	
MF	271.7 ± 182.8	282.9 ± 137.7	0.86	0.1%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.20 Group means ± standard deviations for high versus low ball speed groups, for right elbow flexion/extension angular velocity at seven swing events with effect size percentage.

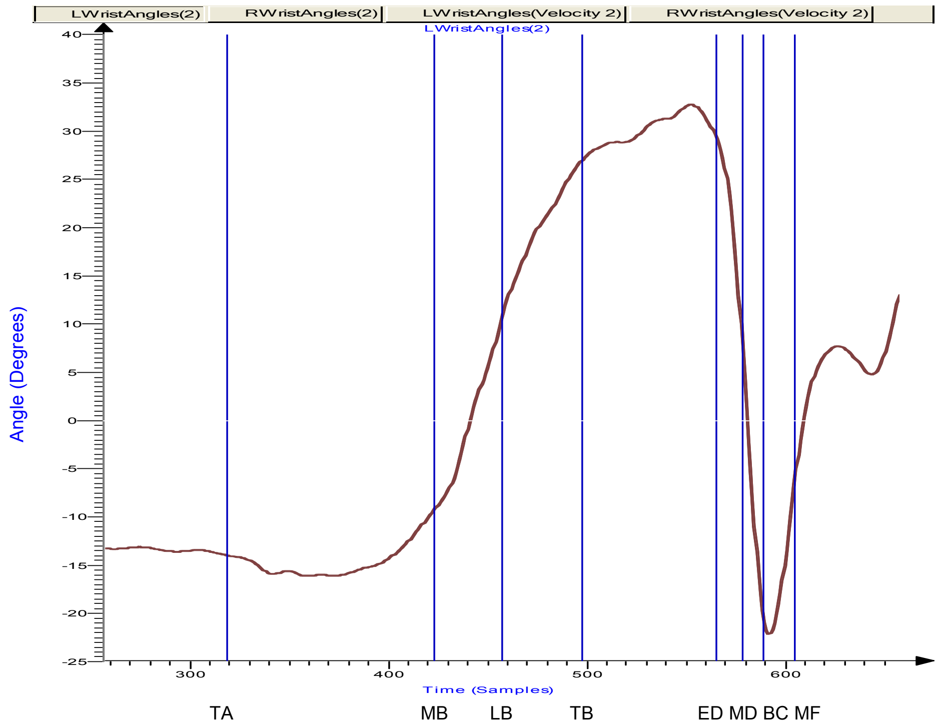
Right elbow flexion/extension angular velocity (deg.s^{-1})	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	145.7 ± 41.2	153.4 ± 38.5	0.63	1.0%	
LB	**211.9 ± 36.8**	**164.3 ± 43.9**	**0.01**	**26.6%**	*
TB	27.2 ± 42.9	10.5 ± 31.7	0.02	21.7%	
ED	329.8 ± 104.7	217.5 ± 116.0	0.02	21.4%	
MD	469.4 ± 96.5	431.8 ± 55.1	0.23	6.2%	
BC	734.9 ± 128.9	647.4 ± 265.1	0.33	4.2%	
MF	93.6 ± 131.0	56.8 ± 143.4	0.52	1.9%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.3.5 Wrist

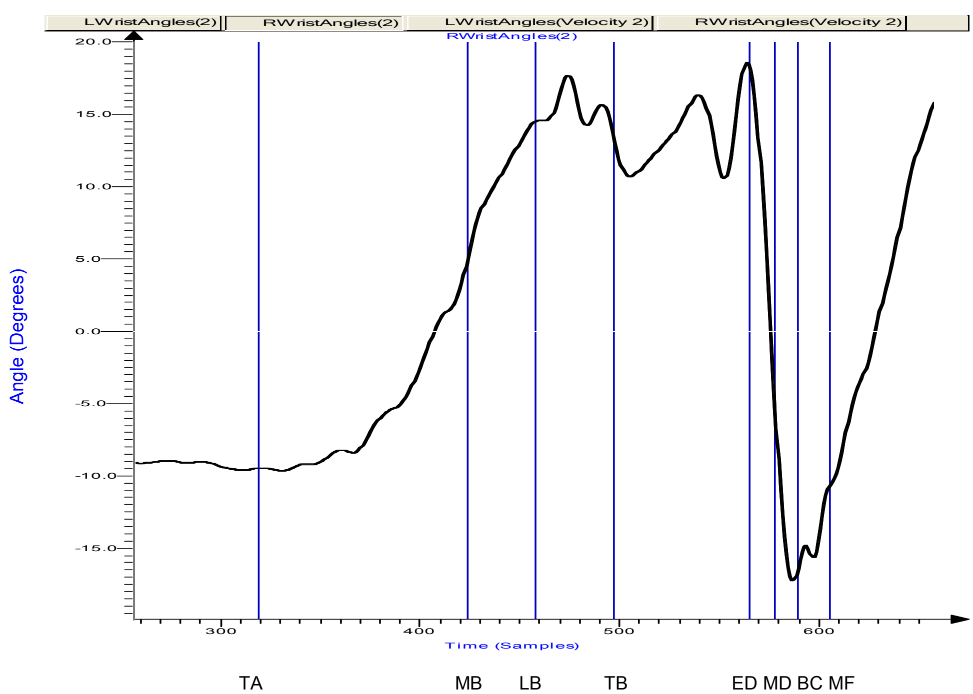
4.1.3.5.1 Abduction/Adduction Angle

Figure 4.19 and Figure 4.20 provide representative graphs for left and right wrist abduction/adduction angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = abduction; - = adduction.

Figure 4.19 Representative graph for left wrist abduction/adduction angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.20 Representative graph for right wrist abduction/adduction angle.

No significant differences were found between the high and low ball speed groups for the left or right wrist abduction/adduction angles (Table 4.21 and Table 4.22).

Table 4.21 Group means ± standard deviations for high versus low ball speed groups, for left wrist abduction/adduction angle at the eight swing events with effect size percentage.

Left wrist abduction/adduction (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	-9.9 ± 8.6	-9.1 ± 8.3	0.83	0.2%	
MB	-2.4 ± 6.9	1.8 ± 7.8	0.19	8.1%	
LB	18.4 ± 8.7	23.4 ± 11.5	0.26	6.1%	
TB	31.3 ± 8.0	32.9 ± 19.3	0.82	0.2%	
ED	27.6 ± 9.5	23.0 ± 15.2	0.42	3.1%	
MD	10.8 ± 6.3	5.7 ± 9.3	0.15	9.6%	
BC	-12.4 ± 6.5	-11.7 ± 6.1	0.81	0.3%	
MF	-5.4 ± 18.8	2.1 ± 16.4	0.32	4.7%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = abduction; - = adduction.

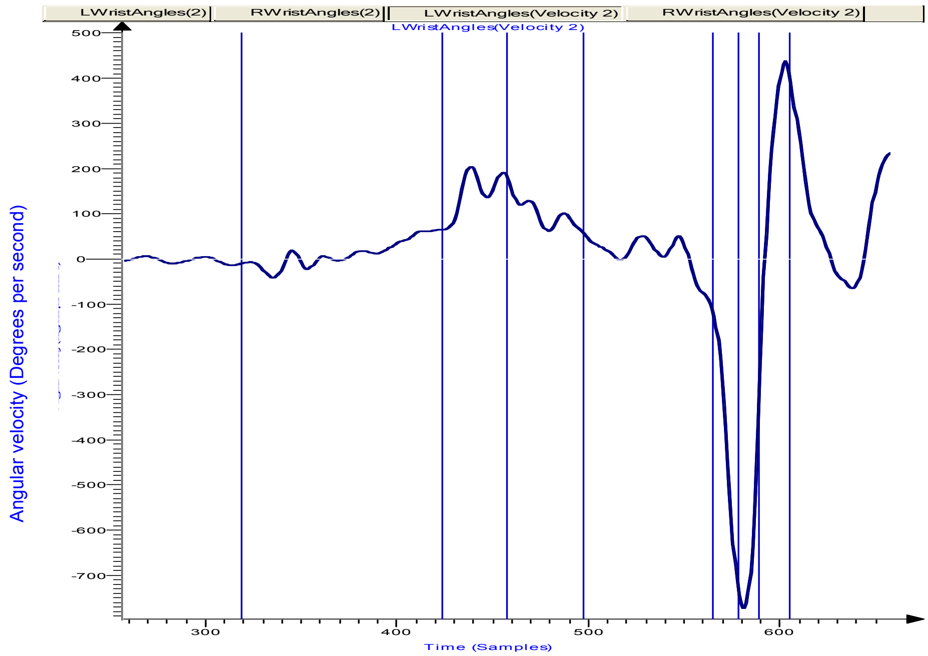
Table 4.22 Group means ± standard deviations for high versus low ball speed groups, for right wrist abduction/adduction angle at the eight swing events with effect size percentage.

Right wrist abduction/adduction (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	-8.4 ± 7.2	-1.9 ± 8.5	0.07	14.6%	
MB	3.2 ± 8.9	12.2 ± 12.1	0.06	15.7%	
LB	22.3 ± 14.9	27.2 ± 16.2	0.47	2.5%	
TB	35.0 ± 21.3	36.5 ± 20.0	0.86	0.1%	
ED	39.2 ± 31.0	36.3 ± 27.7	0.82	0.3%	
MD	9.0 ± 18.9	13.9 ± 15.1	0.49	2.3%	
BC	-12.3 ± 7.4	-5.9 ± 6.2	0.03	19.7%	
MF	-6.1 ± 8.8	-3.5 ± 8.2	0.47	2.5%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = abduction; - = adduction.

4.1.3.5.2 Abduction/Adduction Angular Velocity

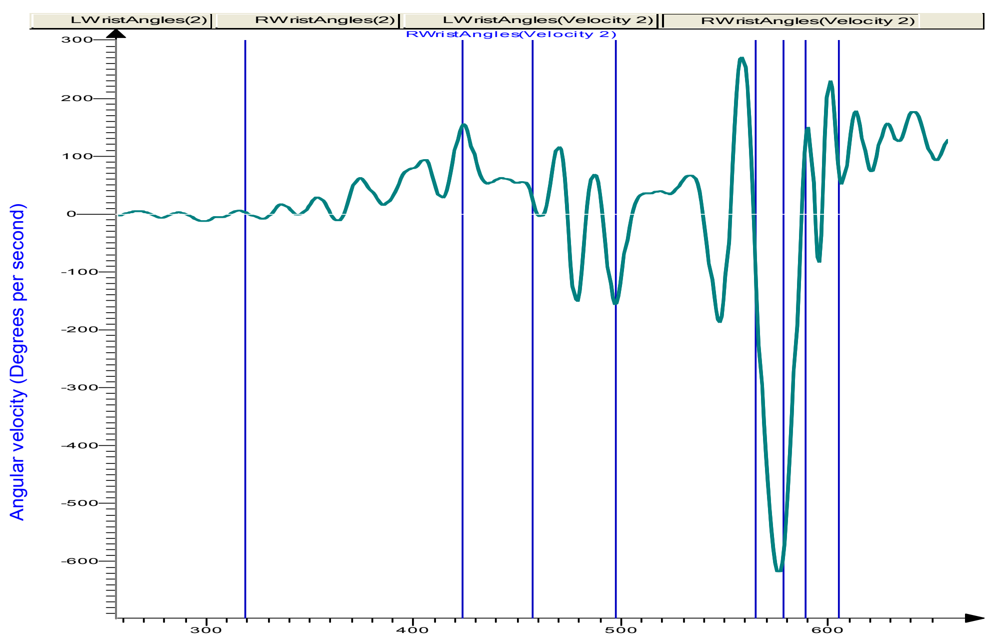
Representative graphs for left and right wrist abduction/adduction angular velocity are provided in Figure 4.21 and Figure 4.22.



TA MB LB TB ED **MD*** BC MF

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.21 Representative graph for left wrist abduction/adduction angular velocity.



TA MB LB TB ED MD BC MF

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.22 Representative graph for right wrist abduction/adduction angular velocity.

Only the left wrist exhibited between group differences for the abduction/adduction angular velocity (Table 4.23 and Table 4.24). This difference occurred at mid downswing (565.2 ± 99.9 $deg.s^{-1}$ *vs.* 376.8 ± 158.8 $deg.s^{-1}$, $F = 10.7$, $p = 0.004$). The high ball speed group generated greater abduction/adduction angular velocity in their left wrists than the low ball speed group.

Table 4.23 Group means ± standard deviations for high versus low ball speed groups, for left wrist abduction/adduction angular velocity at seven swing events with effect size percentage.

Left wrist abduction/adduction angular velocity ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	95.9 ± 40.1	101.3 ± 36.1	0.74	0.5%	
LB	129.5 ± 61.4	93.9 ± 71.9	0.23	6.9%	
TB	16.8 ± 61.4	0.9 ± 20.8	0.22	7.0%	
ED	133.4 ± 97.5	116.1 ± 69.1	0.63	1.2%	
MD	**565.2 ± 99.9**	**376.8 ± 158.8**	**0.004**	**33.8%**	*
BC	308.9 ± 267.5	148.3 ± 186.2	0.10	12.1%	
MF	295.6 ± 287.6	339.7 ± 308.2	0.73	0.6%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.24 Group means ± standard deviations for high versus low ball speed groups, for right wrist abduction/adduction angular velocity at seven swing events with effect size percentage.

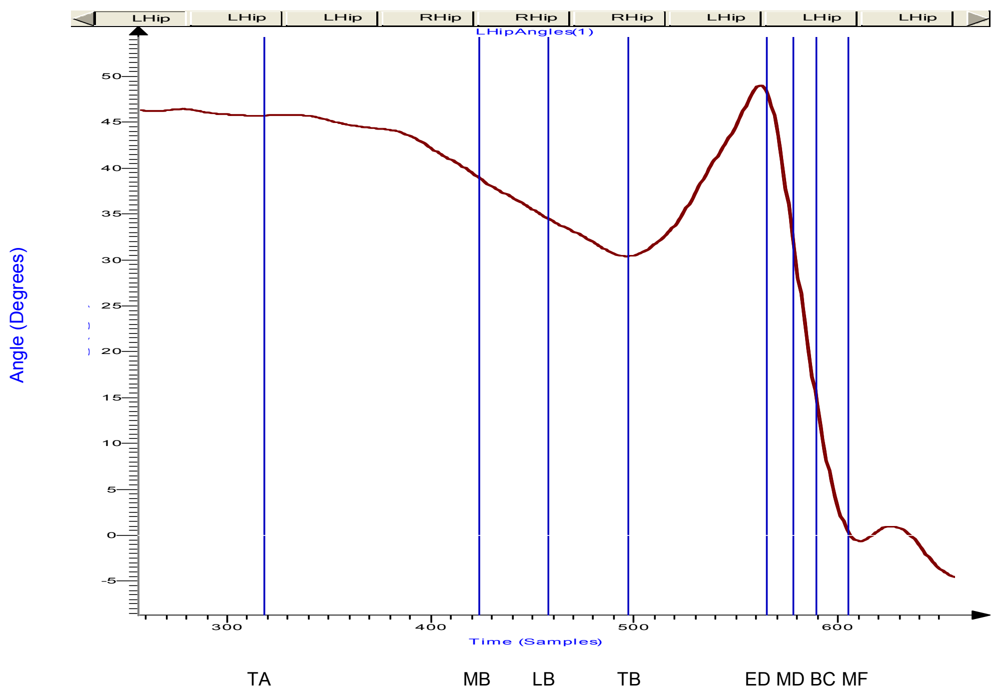
Right wrist abduction/adduction angular velocity ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	102.8 ± 57.5	73.1 ± 48.6	0.19	7.9%	
LB	92.6 ± 93.7	46.4 ± 77.9	0.21	7.4%	
TB	20.7 ± 68.1	17.7 ± 53.8	0.92	0.1%	
ED	95.5 ± 369.9	47.2 ± 173.8	0.68	0.8%	
MD	843.5 ± 628.1	500.8 ± 395.4	0.12	10.9%	
BC	218.8 ± 219.2	223.1 ± 189.9	0.96	0.0%	
MF	163.3 ± 192.6	139.8 ± 127.2	0.73	0.6%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.3.6 Hip

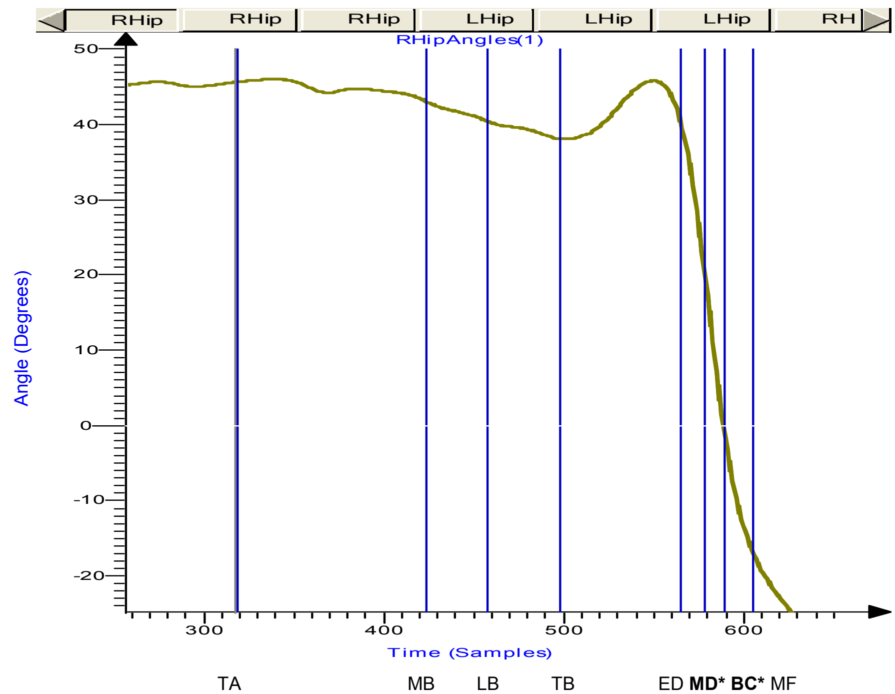
4.1.3.6.1 Flexion/Extension Angle

Figure 4.23 and Figure 4.24 demonstrate representative graphs of the flexion/extension angle for the left and right hips.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = flexion; - = extension.

Figure 4.23 Representative graph for left hip flexion/extension angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \le 0.01$). 0 = neutral; + = flexion; - = extension.

Figure 4.24 Representative graph for right hip flexion/extension angle.

No significant differences were evident between the groups for the left hip flexion/extension angle for any of the eight swing events (Table 4.25). Significant differences in the right hip flexion/extension angle were found at mid downswing and ball contact (Table 4.26). The high ball speed group were found to have their right hips in a less flexed position than the high ball speed group at mid downswing (18.9 ± 9.2° *vs.* 30.2 ± 13.9°, F = 6.8, p = 0.01) and ball contact (2.3 ± 9.4° *vs.* 14.5 ± 13.9°, F = 7.9, p = 0.01).

Table 4.25 Group means ± standard deviations for high versus low ball speed groups, for left hip flexion/extension angle at the eight swing events with effect size percentage.

Left hip flexion/extension (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	38.3 ± 7.7	39.7 ± 9.8	0.67	0.6%	
MB	33.9 ± 7.4	39.0 ± 9.1	0.10	9.3%	
LB	32.7 ± 8.5	37.4 ± 10.2	0.18	6.3%	
TB	35.2 ± 10.7	36.2 ± 14.4	0.84	0.2%	
ED	46.6 ± 6.1	47.3 ± 9.6	0.79	0.2%	
MD	33.8 ± 6.9	39.6 ± 11.1	0.10	9.5%	
BC	21.2 ± 8.8	27.4 ± 10.9	0.10	9.5%	
MF	9.5 ± 9.1	13.8 ± 10.3	0.24	4.9%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = flexion; - = extension.

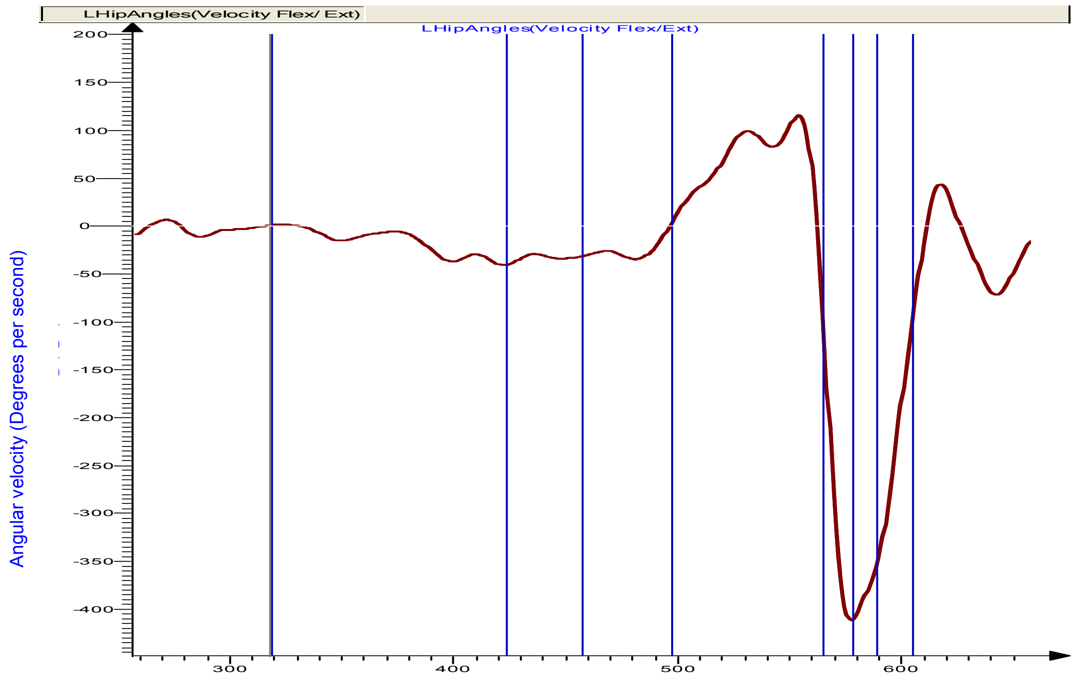
Table 4.26 Group means ± standard deviations for high versus low ball speed groups, for right hip flexion/extension angle at the eight swing events with effect size percentage.

Right hip flexion/extension (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	36.1 ± 9.4	37.6 ± 10.3	0.69	0.6%	
MB	38.1 ± 9.0	41.1 ± 8.8	0.37	2.9%	
LB	39.3 ± 10.1	41.9 ± 8.9	0.44	2.1%	
TB	41.2 ± 10.9	41.5 ± 10.3	0.94	0.0%	
ED	37.3 ± 7.5	43.1 ± 11.2	0.11	8.8%	
MD	**18.9 ± 9.2**	**30.2 ± 13.9**	**0.01**	**19.7%**	*
BC	**2.3 ± 9.4**	**14.5 ± 13.9**	**0.01**	**21.9%**	*
MF	-10.5 ± 9.5	-0.2 ± 11.7	0.02	19.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = flexion; - = extension.

4.1.3.6.2 Flexion/Extension Angular Velocity

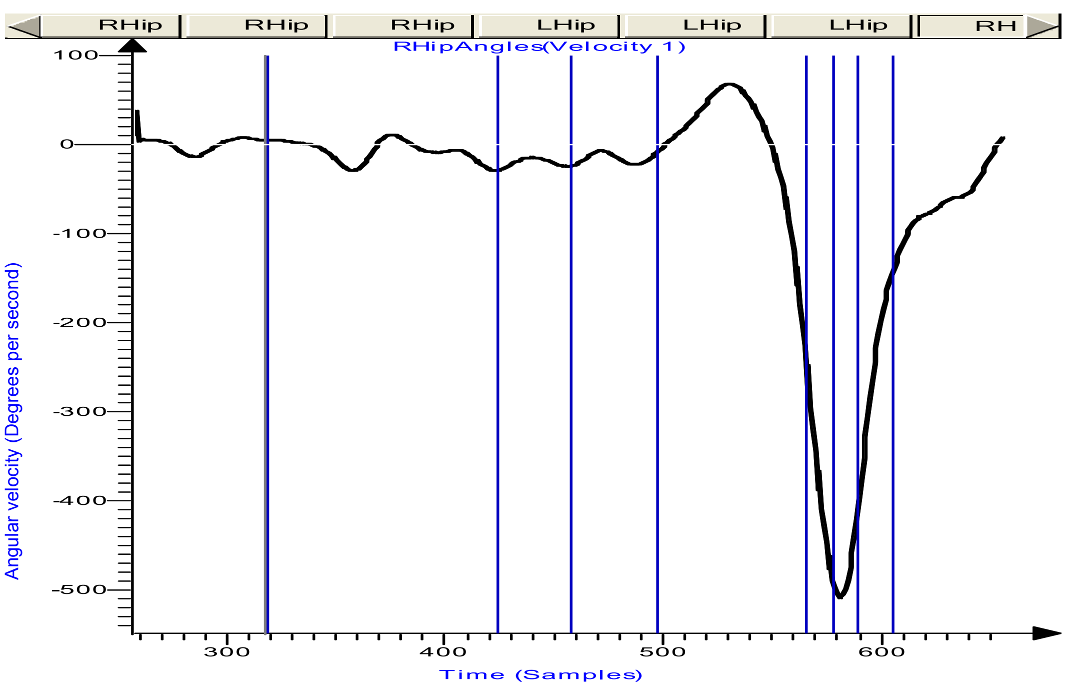
Figure 4.25 and Figure 4.26 show representative graphs for left and right hip flexion/extension angular velocity.



TA MB LB TB ED **MD*** BC MF

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.25 Representative graph for left hip flexion/extension angular velocity.



TA MB LB TB **ED* MD*** BC MF

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.26 Representative graph for right hip flexion/extension angular velocity.

Significant differences in hip flexion/extension angular velocity were found between the groups for both the left and right hip during the downswing (Table 4.27 and Table 4.28). The high ball speed group were found to produce greater angular velocity than the low ball speed group for both the left and right hip at mid downswing (Left: 324.2 ± 107.6 deg.s^{-1} *vs.* 218.4 ± 91.4 deg.s^{-1}, $F = 8.2$, $p = 0.01$; Right: 443.2 ± 115.2 deg.s^{-1} *vs.* 290.4 ± 106.7 deg.s^{-1}, $F = 13.7$, $p = 0.001$) and additionally for the right hip at early downswing (233.5 ± 87.3 deg.s^{-1} *vs.* 77.1 ± 115.9 deg.s^{-1}, $F = 16.7$, $p < 0.001$) .

Table 4.27 Group means ± standard deviations for high versus low ball speed groups, for left hip flexion/extension angular velocity at seven swing events with effect size percentage.

Left hip Flexion/extension angular velocity (deg.s^{-1})	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.05)**
MB	3.4 ± 22.1	5.1 ± 22.7	0.84	0.1%	
LB	10.7 ± 25.1	10.9 ± 31.2	0.98	0.0%	
TB	68.8 ± 48.8	40.4 ± 34.3	0.08	11.0%	
ED	124.3 ± 119.7	11.1 ± 129.6	0.02	18.1%	
MD	**324.2 ± 107.6**	**218.4 ± 91.4**	**0.01**	**23.3%**	*
BC	296.0 ± 62.5	250.7 ± 76.1	0.09	10.1%	
MF	57.9 ± 74.3	76.0 ± 74.2	0.52	1.6%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

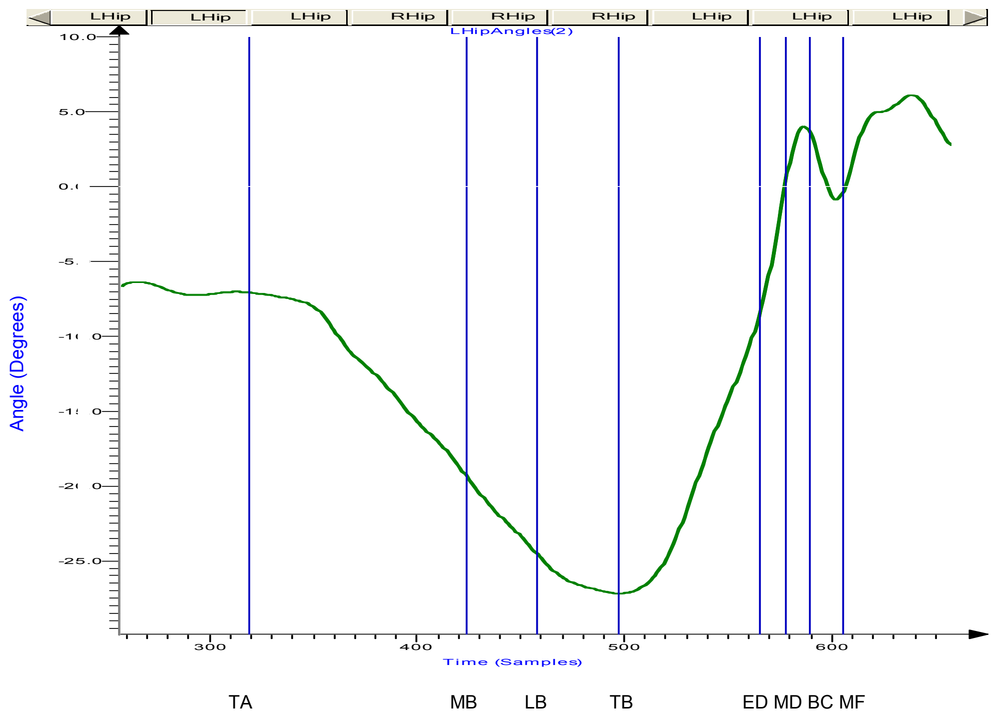
Table 4.28 Group means ± standard deviations for high versus low ball speed groups, for right hip flexion/extension angular velocity at seven swing events with effect size percentage.

Right hip Flexion/extension angular velocity (deg.s^{-1})	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.05)**
MB	4.8 ± 20.2	6.2 ± 17.3	0.83	0.2%	
LB	8.4 ± 16.7	4.0 ± 18.6	0.51	1.6%	
TB	21.8 ± 26.3	18.3 ± 26.4	0.72	0.5%	
ED	**233.5 ± 87.3**	**77.1 ± 115.9**	**< 0.001**	**38.1%**	*
MD	**443.2 ± 115.2**	**290.4 ± 106.7**	**< 0.001**	**33.7%**	*
BC	361.7 ± 115.2	300.7 ± 83.7	0.08	11.1%	
MF	70.5 ± 100.4	88.2 ± 104.4	0.65	0.8%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

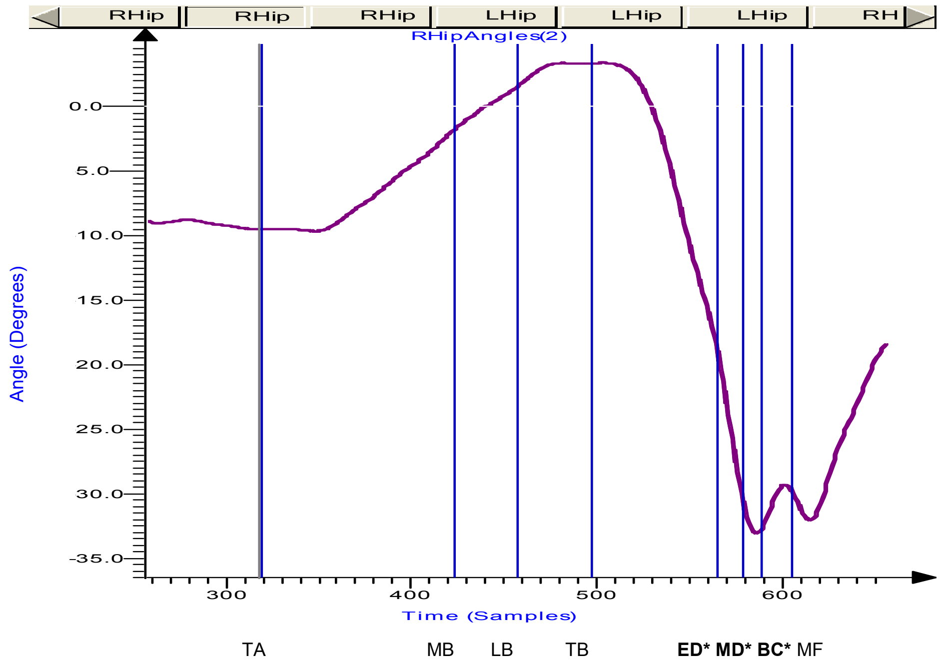
4.1.3.6.3 Abduction/Adduction Angle

Representative graphs of abduction/adduction angle for the left and right hips are demonstrated in Figure 4.27 and Figure 4.28.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups (p ≤ 0.01). 0 = neutral; + = adduction; - = abduction.

Figure 4.27 Representative graph for left hip abduction/adduction angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$). 0 = neutral; + = adduction; - = abduction.

Figure 4.28 Representative graph for right hip abduction/adduction angle.

No significant differences were evident between the groups for left hip abduction/adduction angle at any of the eight swing events (Table 4.29). Significant differences between the groups were evident in right hip abduction/adduction angle towards the end of the downswing (Table 4.30). At the three events early downswing (ED), mid downswing (MD) and ball contact the high ball speed group had their hips in a significantly more abducted position than the low ball speed group (ED: -16.9 ± 6.7° *vs.* -3.9 ± 7.8°, $F = 24.2$, $p < 0.001$; MD: -25.3 ± 5.8° *vs.* -14.2 ± 7.5°, $F = 20.7$, $p < 0.001$; BC: -27.1 ± 5.3° *vs.* -18.5 ± 6.0°, $F = 17.3$, $p < 0.001$).

Table 4.29 Group means ± standard deviations for high versus low ball speed groups, for left hip abduction/adduction angle at the eight swing events with effect size percentage.

Left hip abduction/adduction (°)	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
TA	-12.3 ± 5.6	-10.0 ± 4.8	0.25	4.7%	
MB	-17.7 ± 5.4	-15.4 ± 6.1	0.29	3.9%	
LB	-21.2 ± 6.7	-19.3 ± 6.9	0.46	2.0%	
TB	-21.6 ± 7.8	-19.4 ± 7.7	0.46	2.0%	
ED	-7.9 ± 6.6	-10.3 ± 7.4	0.37	2.8%	
MD	2.9 ± 6.2	-2.6 ± 7.4	0.04	14.9%	
BC	8.9 ± 7.2	3.6 ± 6.5	0.04	13.7%	
MF	11.3 ± 7.5	9.5 ± 6.0	0.46	2.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = adduction; - = abduction.

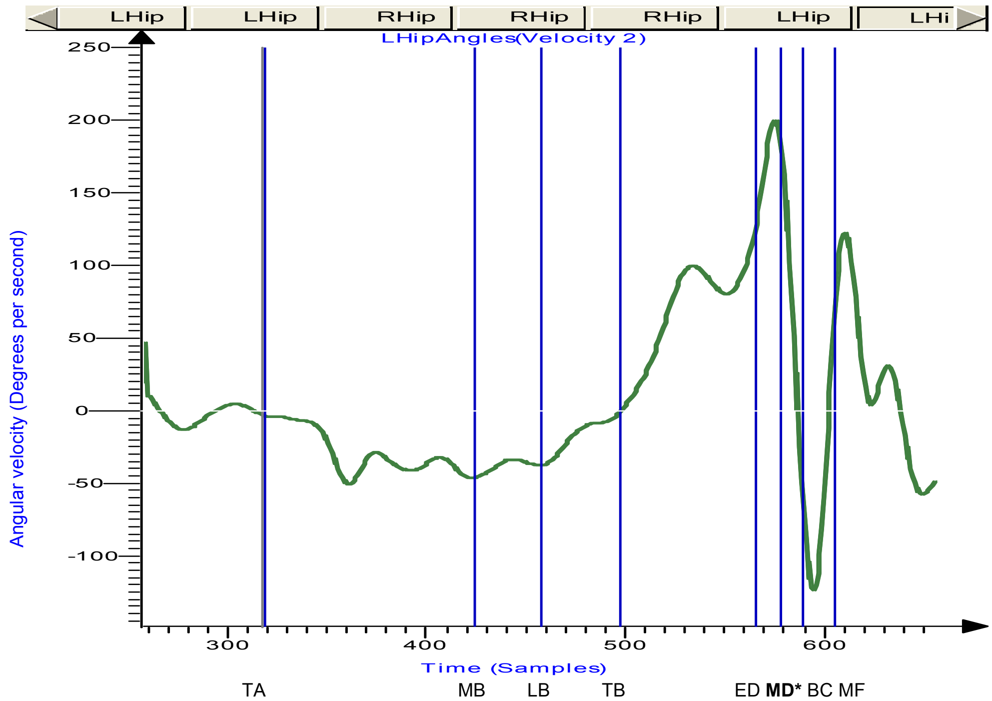
Table 4.30 Group means ± standard deviations for high versus low ball speed groups, for right hip abduction/adduction angle at the eight swing events with effect size percentage.

Right hip abduction/adduction (°)	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
TA	-13.61 ± 4.97	-9.49 ± 4.70	0.03	16.2%	
MB	-6.41 ± 6.94	-1.73 ± 4.33	0.04	14.9%	
LB	0.12 ± 7.16	4.62 ± 4.95	0.06	12.5%	
TB	2.39 ± 8.97	8.05 ± 6.56	0.06	12.2%	
ED	**-16.97 ± 6.65**	**-3.97 ± 7.79**	**< 0.001**	**46.3%**	*
MD	**-25.35 ± 5.8**	**-14.19 ± 7.52**	**< 0.001**	**42.5%**	*
BC	**-27.14 ± 5.26**	**-18.53 ± 6.02**	**< 0.001**	**38.3%**	*
MF	-26.31 ± 5.98	-21.93 ± 7.57	0.09	9.9%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = adduction; - = abduction.

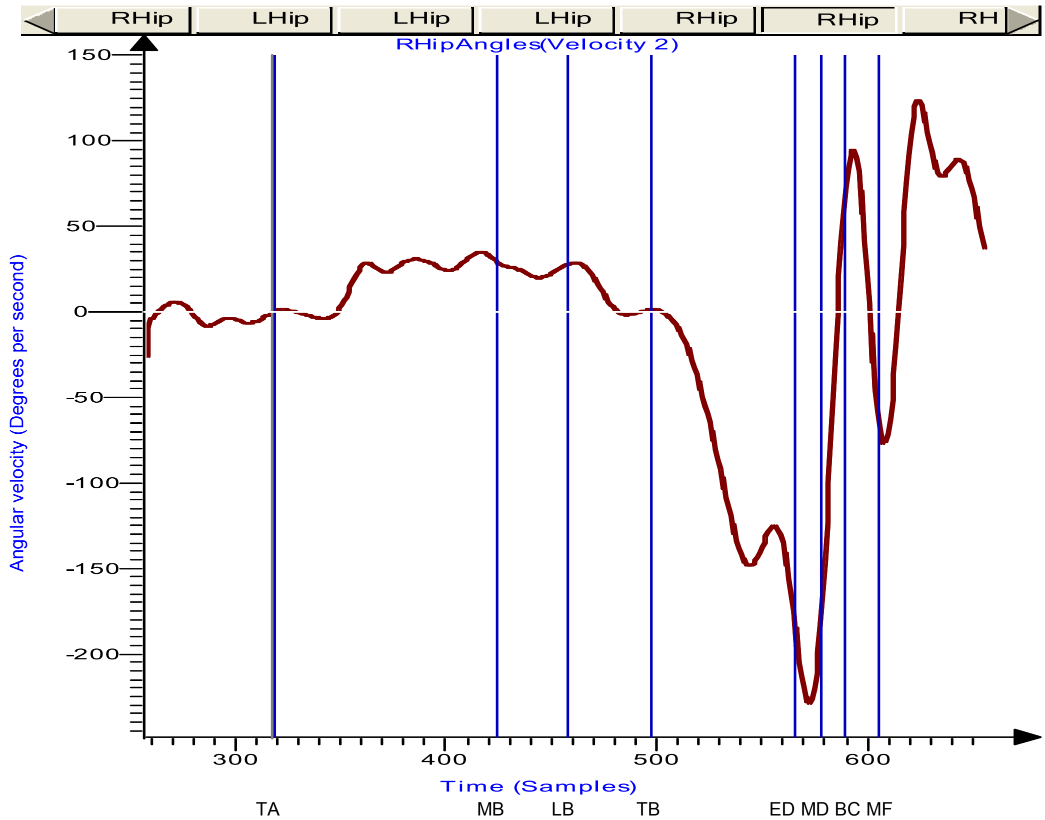
4.1.3.6.4 Abduction/Adduction Angular Velocity

Figure 4.29 and Figure 4.30 provide representative graphs for left and right hip angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.29 Representative graph for left hip abduction/adduction angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.30 Representative graph for right hip abduction/adduction angular velocity.

A between group difference was only found for hip abduction/adduction angular velocity in the left hip (Table 4.31 and Table 4.32). The difference occurred at early mid downswing with the high ball speed group found to produce greater abduction/adduction angular velocity than the low ball speed group (213.8 ± 90.3 deg.s^{-1} *vs.* 131.2 ± 43.1 deg.s^{-1}, F = 10.1, p = 0.004).

Table 4.31 Group means ± standard deviations for high versus low ball speed groups, for left hip abduction/adduction angular velocity at seven swing events with effect size percentage.

Left hip abduction/adduction angular velocity (deg.s^{-1})	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	19.6 ± 25.8	23.5 ± 11.4	0.60	1.0%	
LB	19.9 ± 17.9	16.1 ± 13.9	0.53	1.5%	
TB	19.4 ± 22.5	24.5 ± 28.6	0.60	1.1%	
ED	161.0 ± 68.2	82.8 ± 63.2	0.03	27.6%	
MD	**213.8 ± 90.4**	**131.2 ± 43.1**	**0.004**	**27.2%**	*
BC	91.9 ± 62.9	97.9 ± 62.8	0.80	0.2%	
MF	47.8 ± 37.0	68.8 ± 51.9	0.22	5.4%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

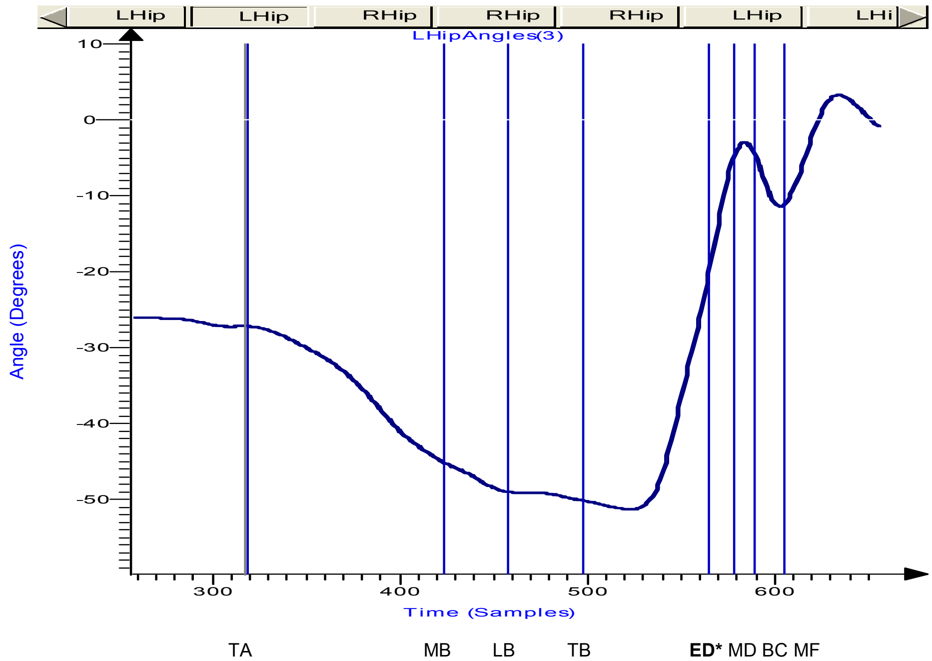
Table 4.32 Group means ± standard deviations for high versus low ball speed groups, for right hip abduction/adduction angular velocity at seven swing events with effect size percentage.

Right hip abduction/adduction angular velocity (deg.s^{-1})	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	40.4 ± 22.1	39.4 ± 20.5	0.91	0.1%	
LB	37.1 ± 37.9	28.1 ± 16.3	0.41	2.6%	
TB	32.1 ± 32.7	13.8 ± 18.2	0.07	11.6%	
ED	160.5 ± 72.7	117.5 ± 61.9	0.10	9.9%	
MD	121.2 ± 72.9	133.2 ± 52.3	0.61	1.0%	
BC	14.7 ± 70.3	38.9 ± 94.2	0.10	9.9%	
MF	39.5 ± 70.9	74.4 ± 62.1	0.17	6.9%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

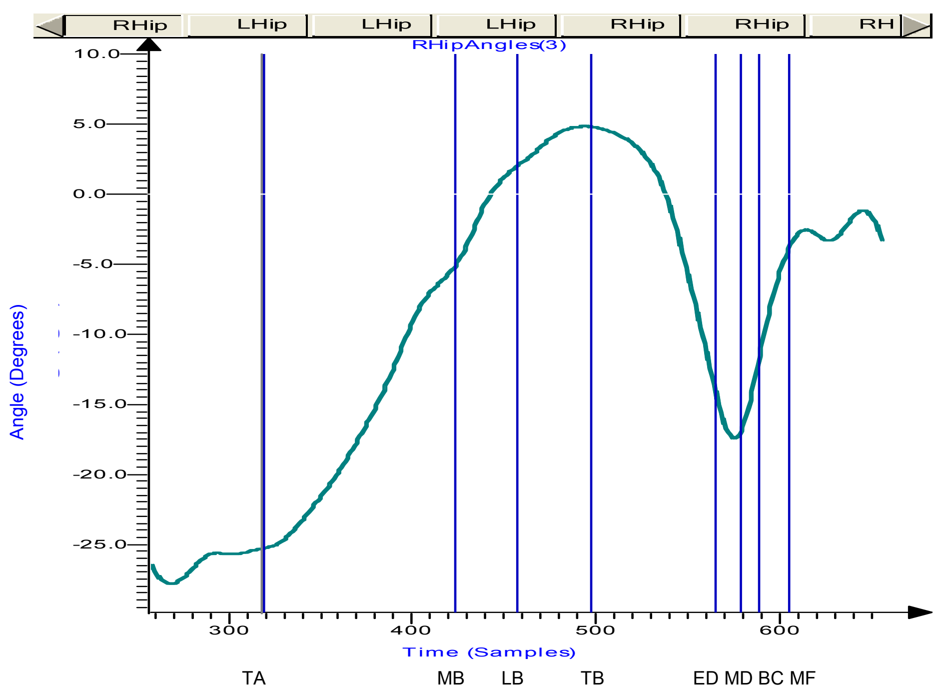
4.1.3.6.5 Internal/External Rotation Angle

Figure 4.31 and Figure 4.32 illustrate representative graphs for internal/external rotation angle for the left and right hips.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups (p ≤ 0.01). 0 = neutral; + = internal rotation; - = external rotation.

Figure 4.31 Representative graph for left hip internal/external rotation angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = internal rotation; - = external rotation.

Figure 4.32 Representative graph for right hip internal/external rotation angle.

Only the left hip exhibited a group difference for hip internal/external rotation angle, this occurred at early downswing. The high ball speed group were found to have their left hips in a less externally rotated position than the low ball speed group (-10.0 ± 7.3° *vs.* -19.0 ± 9.4°, F = 8.6, p = 0.01) at this event.

Table 4.33 Group means ± standard deviations for high versus low ball speed groups, for left hip internal/external rotation angle at the eight swing events with effect size percentage.

Left hip internal/external rotation (°)	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
TA	-3.3 ± 9.4	0.5 ± 7.8	0.24	4.9%	
MB	-21.1 ± 9.7	-19.4 ± 8.1	0.61	0.9%	
LB	-30.0 ± 8.6	-30.1 ± 7.5	0.98	0.0%	
TB	-30.9 ± 7.1	-37.3 ± 9.5	0.65	0.8%	
ED	**-10.0 ± 7.3**	**-19.0 ± 9.4**	**0.01**	**23.4%**	*
MD	1.1 ± 6.1	-0.1 ± 8.3	0.67	0.6%	
BC	0.1 ± 8.6	4.3 ± 9.5	0.21	5.6%	
MF	-6.5 ± 13.7	0.9 ± 8.8	0.09	10.1%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = internal rotation; - = external rotation.

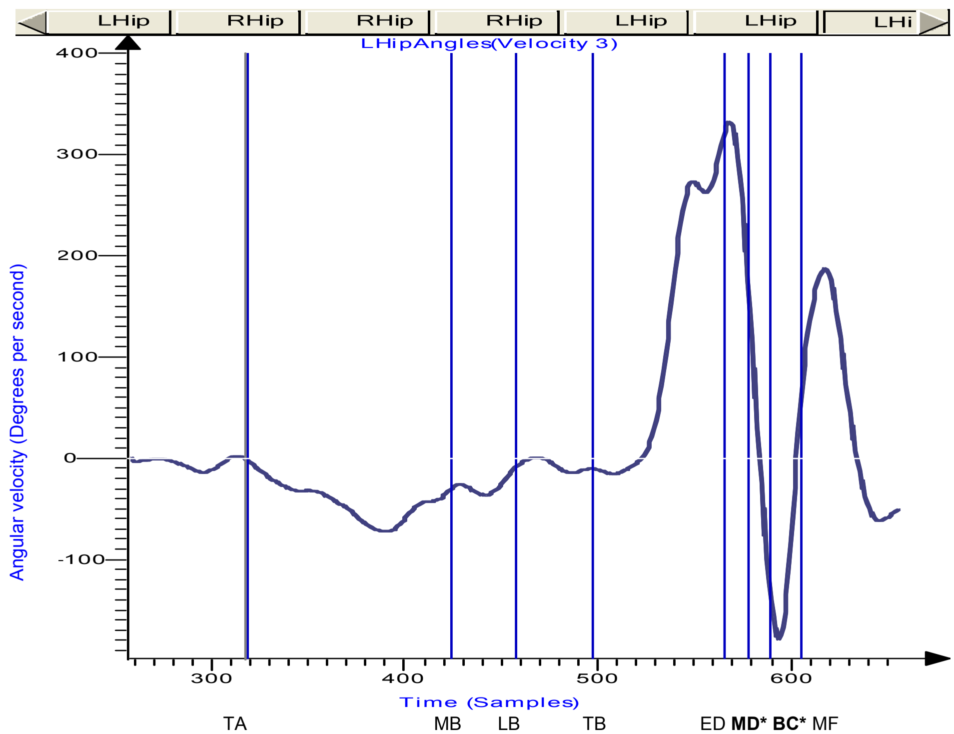
Table 4.34 Group means ± standard deviations for high versus low ball speed groups, for right hip internal/external rotation at the eight swing events with effect size percentage.

Right hip internal/external rotation (°)	**High Ball Speed Group** (mean ± stdev)	**Low Ball Speed Group** (mean ± stdev)	**p value**	**Effect size**	**Significance (* = p ≤ 0.01)**
TA	-3.9 ± 9.0	-4.6 ± 6.8	0.84	0.1%	
MB	9.4 ± 9.6	8.9 ± 7.0	0.88	0.1%	
LB	13.6 ± 11.2	14.9 ± 7.8	0.72	0.5%	
TB	14.7 ± 11.3	16.7 ± 8.8	0.58	1.1%	
ED	-1.5 ± 8.9	2.1 ± 9.2	0.28	4.1%	
MD	-5.8 ± 10.5	-7.6 ± 8.6	0.61	0.9%	
BC	-2.4 ± 11.8	-6.1 ± 10.2	0.36	3.0%	
MF	2.1 ± 12.3	-2.4 ± 9.5	0.27	4.3%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. 0 = neutral; + = internal rotation; - = external rotation.

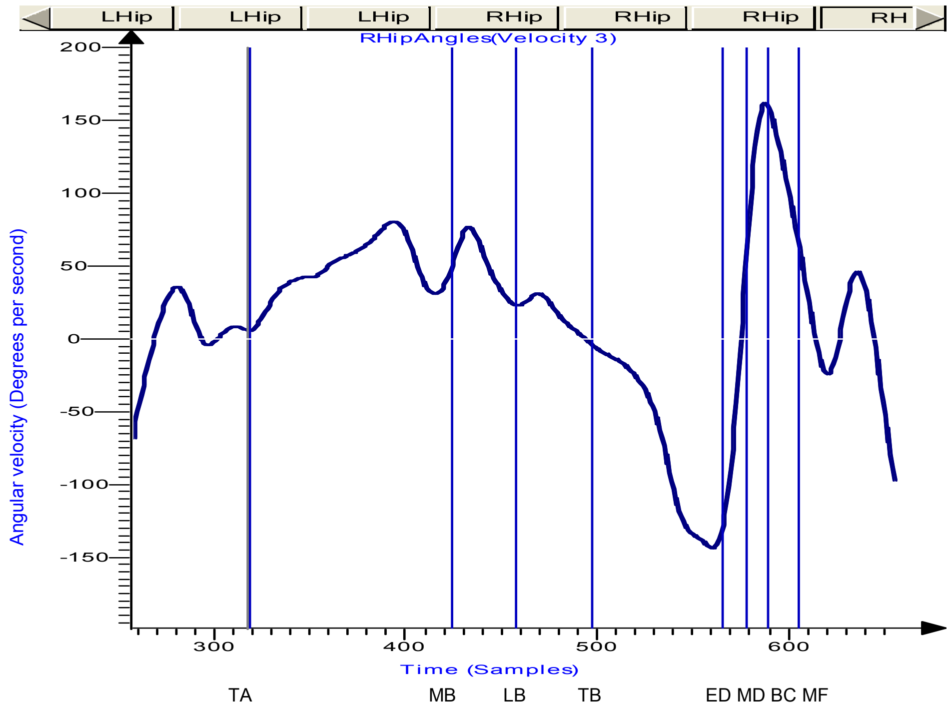
4.1.3.6.6 Internal/External Rotation Angular Velocity

Representative graphs for internal/external rotation angular velocity for the left and right hips during the golf swing can be found in Figure 4.33 and Figure 4.34.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.05$).

Figure 4.33 Representative graph for left hip internal/external rotation angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.34 Representative graph for right hip internal/external rotation angular velocity.

No significant differences in hip internal/external rotation angular velocity between the groups were found to occur in either the left or right hip (Table 4.35 and Table 4.36).

Table 4.35 Group means ± standard deviations for high versus low ball speed groups, for left hip internal/external rotation angular velocity at seven swing events with effect size percentage.

Left hip internal/external rotation angular velocity (deg.s^{-1})	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	74.3 ± 23.8	67.1 ± 22.9	0.41	2.5%	
LB	35.98± 19.6	47.5 ± 22.5	0.16	7.3%	
TB	1.5 ± 51.5	11.1 ± 29.7	0.54	1.4%	
ED	279.0 ± 58.1	234.9 ± 69.7	0.08	11.2%	
MD	95.4 ± 119.0	183.0 ± 106.9	0.05	13.9%	
BC	119.7 ± 156.0	5.5 ± 67.3	0.02	19.9%	
MF	1.3 ± 94.2	14.3 ± 67.2	0.67	0.7%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.36 Group means ± standard deviations for high versus low ball speed groups, for right hip internal/external rotation angular velocity at seven swing events with effect size percentage.

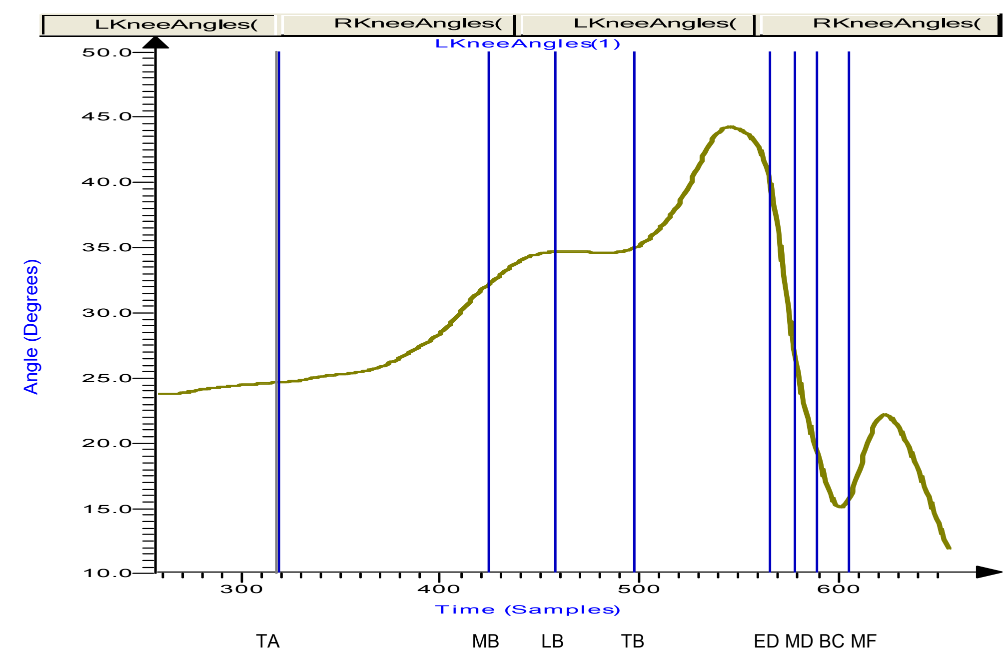
Right hip internal/external rotation angular velocity (deg.s^{-1})	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	30.6 ± 25.7	33.7 ± 17.7	0.70	0.6%	
LB	19.7 ± 16.0	27.6 ± 8.2	0.10	9.5%	
TB	14.6 ± 25.1	23.5 ± 31.2	0.40	2.6%	
ED	157.3 ± 71.3	142.8 ± 75.6	0.60	1.0%	
MD	27.9 ± 107.3	47.3 ± 111.6	0.08	11.2%	
BC	124.2 ± 90.9	86.9 ± 69.8	0.22	5.4%	
MF	9.8 ± 48.6	21.2 ± 92.2	0.28	4.4%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.3.7 Knee

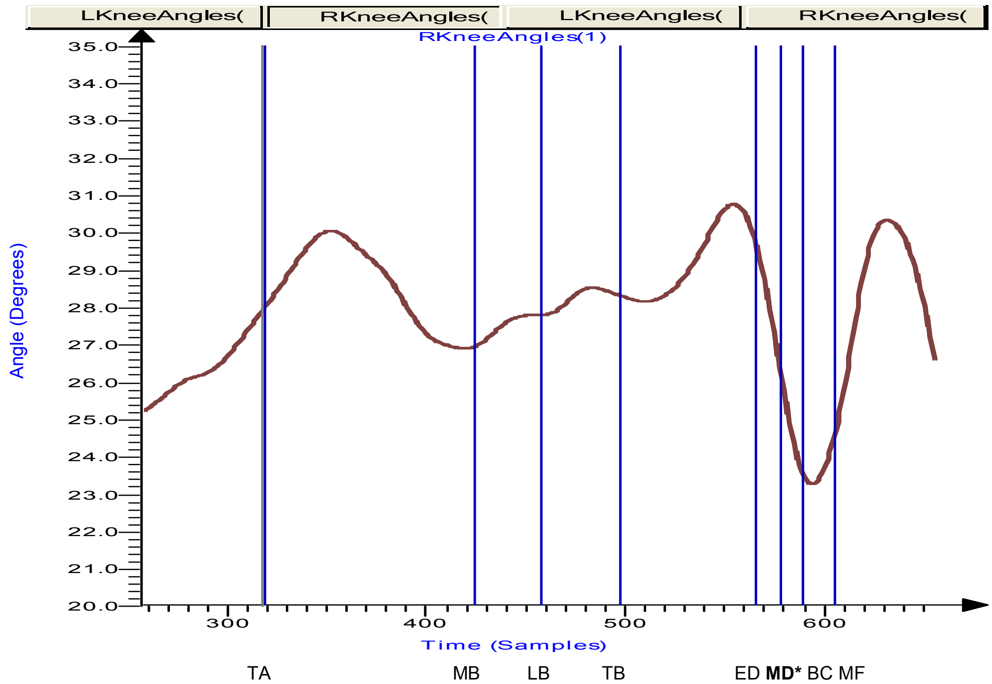
4.1.3.7.1 Flexion/Extension Angle

Figure 4.35 and Figure 4.36 show representative graphs for left and right knee flexion/extension angle for the golf swing.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.35 Representative graph for left knee flexion/extension angle.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.36 Representative graph for right knee flexion/extension angle.

No significant differences were evident between the groups for the left or right knee flexion/extension angle at any of the eight swing events (Table 4.37 and Table 4.38).

Table 4.37 Group means ± standard deviations for high versus low ball speed groups, for left knee flexion/extension angle at the eight swing events with effect size percentage.

Left knee flexion/extension (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	24.7 ± 6.6	23.5 ± 6.1	0.62	0.9%	
MB	30.7 ± 8.3	33.3 ± 6.0	0.33	3.5%	
LB	36.2 ± 8.1	37.5 ± 5.9	0.63	0.8%	
TB	42.6 ± 7.0	39.5 ± 7.2	0.24	5.0%	
ED	38.6 ± 4.5	40.9 ± 4.8	0.18	6.5%	
MD	27.0 ± 6.2	32.2 ± 6.3	0.03	15.4%	
BC	19.7 ± 7.4	23.4 ± 6.8	0.17	6.7%	
MF	17.2 ± 7.4	17.1 ± 6.3	0.97	0.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

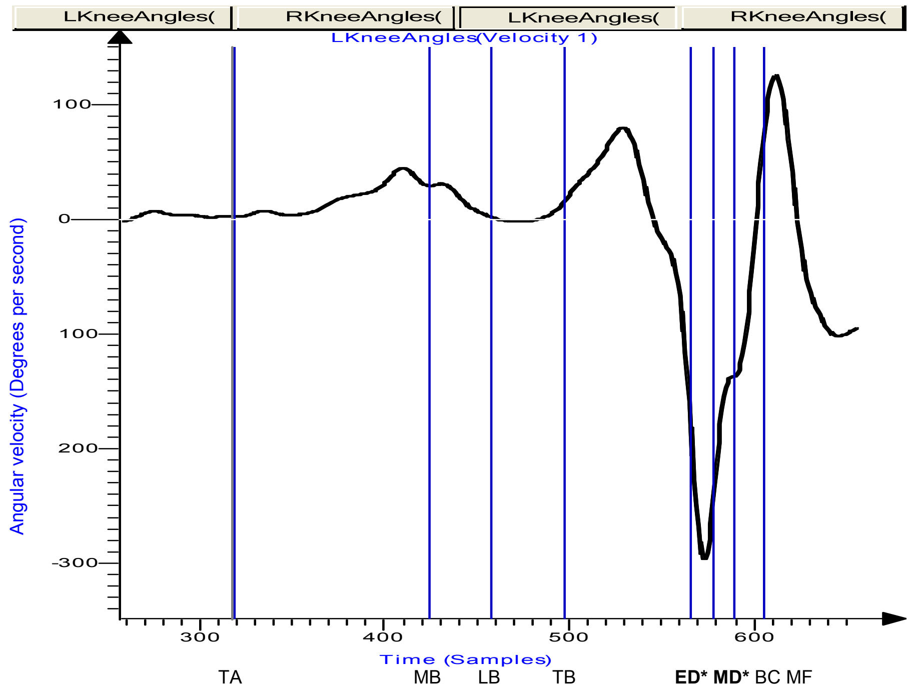
Table 4.38 Group means ± standard deviations for high versus low ball speed groups, for right knee flexion/extension angle at the eight swing events with effect size percentage.

Right knee flexion/extension (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	23.5 ± 7.1	23.6 ± 7.4	0.99	0.0%	
MB	20.0 ± 7.7	23.4 ± 8.8	0.27	4.4%	
LB	21.1 ± 7.7	24.6 ± 8.7	0.26	4.5%	
TB	24.4 ± 7.1	26.3 ± 8.1	0.51	1.6%	
ED	29.9 ± 6.8	31.3 ± 7.9	0.62	0.9%	
MD	26.6 ± 7.7	28.7 ± 9.2	0.51	1.6%	
BC	22.9 ± 9.1	24.2 ± 9.6	0.73	0.4%	
MF	23.4 ± 11.1	23.8 ± 9.9	0.92	0.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

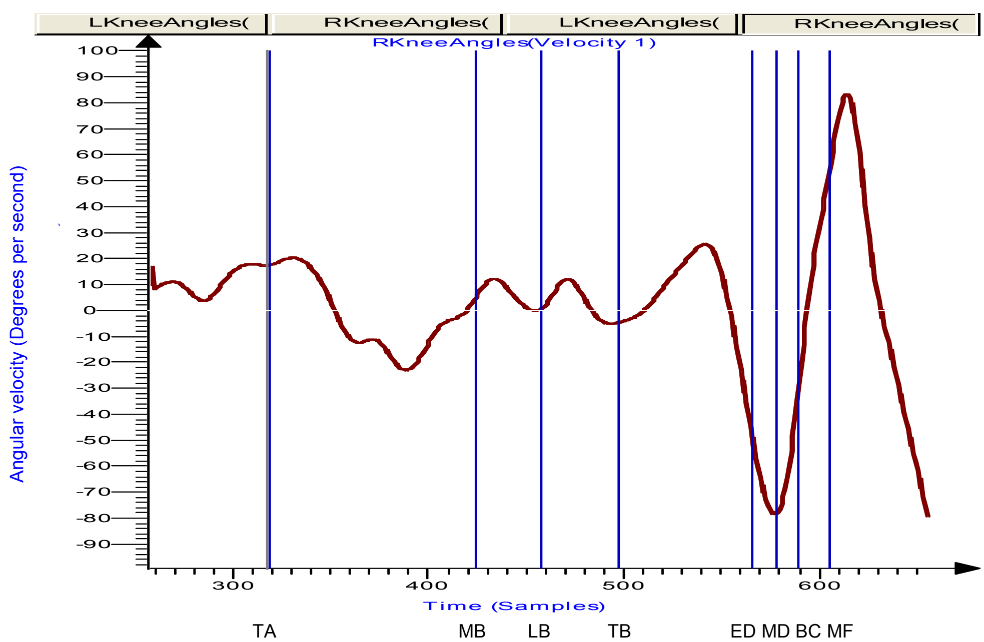
4.1.3.7.2 Flexion/Extension Angular Velocity

Example graphs for left and right knee flexion/extension angular velocity are illustrated in Figure 4.37 and Figure 4.38.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. * indicates significant difference between high and low ball speed groups ($p \leq 0.01$).

Figure 4.37 Representative graph for left knee flexion/extension angular velocity.



Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Figure 4.38 Representative graph for right knee flexion/extension angular velocity.

Between group differences for knee flexion/extension angular velocity only occurred in the left knee (Table 4.39 and Table 4.40). These differences were found to occur at early downswing (ED) and mid downswing (MD). At both events the high ball speed group generated greater angular velocity than the low ball speed group (ED: 164.4 ± 61.5 $deg.s^{-1}$ *vs.* 52.6 ± 68.9 $deg.s^{-1}$, $F = 21.2$, $p < 0.001$; MD: 238.0 ± 75.9 $deg.s^{-1}$ *vs.* 177.3 ± 46.7 $deg.s^{-1}$, $F = 6.8$, $p = 0.01$).

Table 4.39 Group means ± standard deviations for high versus low ball speed groups, for left knee flexion/extension angular velocity at the eight swing events with effect size percentage.

Left knee flexion/extension angular velocity ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	44.4 ± 14.3	37.4 ± 18.9	0.27	4.5%	
LB	22.0 ± 24.9	10.4 ± 23.7	0.19	6.2%	
TB	35.8 ± 31.8	21.6 ± 17.5	0.14	7.8%	
ED	**164.4 ± 61.5**	**52.6 ± 68.7**	**< 0.001**	**44.0%**	*
MD	**238.0 ± 75.9**	**177.3 ± 46.7**	**0.01**	**20.2%**	*
BC	148.0 ± 66.1	158.9 ± 45.1	0.60	1.0%	
MF	52.8 ± 52.1	4.8 ± 53.8	0.02	18.0%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.40 Group means ± standard deviations for high versus low ball speed groups, for right knee flexion/extension angular velocity at the eight swing events with effect size percentage.

Right knee flexion/extension angular velocity ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	1.8 ± 16.6	7.2 ± 19.7	0.19	6.2%	
LB	10.7 ± 9.6	6.9 ± 19.1	0.53	1.5%	
TB	11.8 ± 18.5	16.6 ± 21.9	0.53	1.5%	
ED	13.6 ± 46.7	9.9 ± 56.8	0.24	5.2%	
MD	112.6 ± 84.7	85.1 ± 37.1	0.26	4.6%	
BC	73.9 ± 95.4	74.0 ± 40.9	1.00	0.0%	
MF	54.8 ± 67.1	43.5 ± 70.9	0.66	0.7%	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.3.8 Summary

Table 4.41 and Table 4.42 detail a summary of the significant differences between the groups for joint angles and angular velocities. For the joint angles the most differences were found to occur in the X Factor angle, right shoulder flexion/extension angle and right hip abduction/adduction angle with differences found between the groups at three of the eight swing events. For the differences in angular velocities the high ball speed group were found to have significantly greater angular velocity than the low ball speed group at all significant events.

Table 4.41 Summary of results for participant joint angles.

Angle		TA	MB	LB	TB	ED	MD	BC	MF	Total
X Factor						●	●	●		**3**
Left Shoulder	Flexion/Extension			●						**1**
	Abduction/Adduction									**0**
	Internal/External rotation		●	●						**2**
Right Shoulder	Flexion/Extension		●	●	●					**3**
	Abduction/Adduction									**0**
	Internal/External rotation									**0**
Left Elbow	Flexion/Extension					●				**1**
Right Elbow	Flexion/Extension									**0**
Left Wrist	Abduction/Adduction									**0**
Right Wrist	Abduction/Adduction									**0**
Left Hip	Flexion/Extension									**0**
	Abduction/Adduction									**0**
	Internal/External rotation					●				**1**
Right Hip	Flexion/Extension						●	●		**2**
	Abduction/Adduction					●	●	●		**3**
	Internal/External rotation									**0**
Left Knee	Flexion/Extension									**0**
Right Knee	Flexion/Extension									**0**
Total number of significant differences		**0**	**2**	**3**	**1**	**4**	**3**	**3**	**0**	**16**

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. ● = Significant difference between groups ($p \leq 0.05$).

Table 4.42 Summary of results for participant joint angular velocities.

Angular Velocity		MB	LB	TB	ED	MD	BC	MF	Total
X Factor									**0**
Left Shoulder	Flexion/Extension		●		●				**2**
	Abduction/Adduction						●		**1**
	Internal/External rotation								**0**
Right Shoulder	Flexion/Extension				●				**1**
	Abduction/Adduction								**0**
	Internal/External rotation								**0**
Left Elbow	Flexion/Extension								**0**
Right Elbow	Flexion/Extension		●						**1**
Left Wrist	Abduction/Adduction					●			**1**
Right Wrist	Abduction/Adduction								**0**
Left Hip	Flexion/Extension					●			**1**
	Abduction/Adduction					●			**1**
	Internal/External rotation								**0**
Right Hip	Flexion/Extension				●	●			**2**
	Abduction/Adduction								**0**
	Internal/External rotation								**0**
Left Knee	Flexion/Extension				●	●			**2**
Right Knee	Flexion/Extension								**0**
Total number of significant differences		**0**	**2**	**0**	**4**	**5**	**1**	**0**	**12**

Note: MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through. ● = High ball speed group angular velocity significantly greater than the low ball speed group. ○ = High ball speed group angular velocity significantly smaller than the low ball speed group.

4.1.4 Participant Kinetics

4.1.4.1 Centre of pressure positions

The position of the centre of pressure along the X axis, the target line (Figure 3.27), differed between the groups at two of the later stages of the golf swing: early downswing (35.4 ± 13.1% *vs.* 51.4 ± 17.1%, F = 7.9, p = 0.01) and mid follow through (20.9 ± 11.5% *vs.* 38.8 ± 22.9, F = 6.8, p = 0.01) (Table 4.43). At both events the high ball speed group had their centre of pressure more towards the front foot than the low ball speed group. No differences were seen in the position of the centre of pressure along the Y axis (Table 4.44).

Table 4.43 Group means ± standard deviations for high versus low ball speed groups, for COP X% at the eight swing events with effect size percentage.

COP X%	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	48.6 ± 8.9	48.6 ± 8.9	0.81	0.2%	
MB	79.6 ± 13.8	73.7 ± 13.8	0.26	4.6%	
LB	83.3 ± 12.9	78.3 ± 16.5	0.37	3.0%	
TB	79.6 ± 13.4	79.2 ± 15.9	0.94	0.0%	
ED	**35.4 ± 13.1**	**51.4 ± 17.1**	**0.01**	**22.5%**	*
MD	27.1 ± 16.6	36.7 ± 19.1	0.16	7.1%	
BC	20.6 ± 18.8	36.9 ± 26.5	0.07	11.9%	
MF	**20.9 ± 11.5**	**38.8 ± 22.9**	**0.01**	**20.3%**	*

Note: COP X% = centre of pressure percentage along the X axis, TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.44 Group means ± standard deviations for high versus low ball speed groups, for COP Y% at the eight swing events with effect size percentage.

COP Y%	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	53.2 ± 24.4	62.5 ± 25.2	0.31	3.8%	
MB	62.7 ± 17.0	61.4 ± 21.7	0.86	0.1%	
LB	65.2 ± 14.1	60.7 ± 19.7	0.49	1.8%	
TB	59.1 ± 17.4	56.7 ± 18.4	0.72	0.5%	
ED	37.1 ± 14.3	40.7 ± 15.1	0.52	1.6%	
MD	41.1 ± 15.8	42.2 ± 15.8	0.85	0.1%	
BC	44.1 ± 15.4	43.6 ± 15.8	0.94	0.0%	
MF	45.5 ± 15.8	45.2 ± 19.5	0.96	0.0%	

Note: COP Y% = centre of pressure percentage along the Y axis, TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.4.2 Centre of pressure velocities

No significant differences were evident between the groups for centre of pressure velocities in the X or Y direction (Table 4.45 and Table 4.46).

Table 4.45 Group means ± standard deviations for COP X velocity at the eight swing events with effect size percentage.

COP X Velocity ($m.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA - MB	0.36 ± 0.12	0.24 ± 0.18	0.04	15.0%	
MB - LB	0.17 ± 0.11	0.17 ± 0.11	0.89	0.1%	
LB - TB	0.14 ± 0.11	0.06 ± 0.04	0.02	18.4%	
TB - ED	1.15 ± 0.55	0.65 ± 0.56	0.03	17.3%	
ED - MD	1.21 ± 0.51	0.80 ± 0.57	0.05	13.0%	
MD - BC	1.12 ± 0.63	0.79 ± 0.66	0.19	6.4%	
BC - MF	0.72 ± 0.43	0.56 ± 0.41	0.32	3.6%	

Note: COP X Velocity = centre of pressure velocity in the X axis, TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.46 Group means ± standard deviations for COP Y velocity at the eight swing events with effect size percentage.

COP Y Velocity ($m.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA - MB	0.07 ± 0.06	0.06 ± 0.05	0.58	1.2%	
MB - LB	0.10 ± 0.12	0.09 ± 0.06	0.66	0.7%	
LB - TB	0.08 ± 0.06	0.06 ± 0.08	0.48	1.9%	
TB - ED	0.30 ± 0.19	0.23 ± 0.16	0.24	5.1%	
ED - MD	0.29 ± 0.24	0.30 ± 0.21	0.91	0.0%	
MD - BC	0.27 ± 0.21	0.26 ± 0.15	0.92	0.0%	
BC - MF	0.26 ± 0.17	0.29 ± 0.18	0.63	0.9%	

Note: COP Y Velocity = centre of pressure velocity in the Y axis, TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

4.1.5 Golf club kinematics

The following tables detail the angles and angular velocities for the golf club in the X, Y and Z plane (Table 4.47 to Table 4.52), with no significant difference evident between the groups.

Table 4.47 Group means ± standard deviations for club angle X with effect size percentage.

Club angle X (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
TA	39.4 ± 5.0	38.1 ± 2.3	0.39	2.8%	
LB	-145.5 ± 6.3	-144.6 ± 10.0	0.78	0.3%	
TB	-139.8 ± 24.6	-138.0 ± 29.0	0.86	0.1%	
ED	-143.7 ± 6.4	-147.0 ± 7.4	0.21	5.6%	
BC	35.3 ± 4.2	34.5 ± 2.4	0.54	1.4%	

Note: TA = Take away, LB = Late backswing, TB = Top of backswing, ED = Early downswing, BC = Ball contact.

Table 4.48 Group means ± standard deviations for club angular velocity X with effect size percentage.

Club angular velocity X ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
LB	52.7 ± 44.3	59.0 ± 53.8	0.73	0.4%	
TB	5.9 ± 371.3	9.8 ± 80.9	0.88	0.1%	
ED	349.2 ± 970.5	17.0 ± 79.2	0.21	5.7%	
BC	635.8 ± 1426.8	194.5 ± 177.6	0.26	4.7%	

Note: TA = Take away, LB = Late backswing, TB = Top of backswing, ED = Early downswing, BC = Ball contact.

Table 4.49 Group means ± standard deviations for club angle Y with effect size percentage.

Club angle Y (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	91.2 ± 11.7	90.6 ± 3.2	0.85	0.1%	
LB	174.9 ± 16.5	176.9 ± 1.7	0.65	0.8%	
TB	257.6 ± 9.8	248.0 ± 23.1	0.15	7.5%	
ED	167.4 ± 37.3	176.5 ± 2.0	0.37	3.0%	
MD	94.5 ± 24.0	89.5 ± 2.1	0.44	2.2%	
BC	20.1 ± 22.2	20.1 ± 32.8	0.99	0.0%	

Note: MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact.

Table 4.50 Group means ± standard deviations for club angular velocity Y with effect size percentage.

Club angular velocity Y ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	452.3 ± 493.2	301.1 ± 80.8	0.27	4.5%	
LB	604.6 ± 282.6	575.8 ± 167.5	0.74	0.4%	
TB	33.4 ± 205.4	3.9 ± 18.3	0.50	1.7%	
ED	1478.8 ± 284.3	1114.6 ± 497.2	0.02	18.1%	
MD	1504.2 ± 453.2	1256.7 ± 583.8	0.21	5.7%	
BC	2037.6 ± 608.3	1455.5 ± 8729.2	0.13	8.2%	

Note: MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact.

Table 4.51 Group means ± standard deviations for club angle Z with effect size percentage.

Club angle Z (°)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	93.2 ± 15.0	96.5 ± 11.6	0.52	1.5%	
MD	97.2 ± 30.5	87.4 ± 5.2	0.24	5.0%	
BC	24.4 ± 18.1	16.5 ± 14.6	0.21	5.7%	

Note: MB = Mid backswing, MD = Mid downswing, BC = Ball contact.

Table 4.52 Group means ± standard deviations for club angular velocity Z with effect size percentage.

Club angular velocity Z ($deg.s^{-1}$)	High Ball Speed Group (mean ± stdev)	Low Ball Speed Group (mean ± stdev)	p value	Effect size	Significance (* = p ≤ 0.01)
MB	299.8 ± 224.7	329.0 ± 406.0	0.81	0.2%	
MD	1636.5 ± 1868.5	778.1 ± 259.1	0.10	9.7%	
BC	2986.3 ± 301.8	926.0 ± 4325.2	0.08	11.2%	

Note: MB = Mid backswing, MD = Mid downswing, BC = Ball contact.

4.2 Reliability analysis

Table 4.53 to Table 4.63 provide the calculated intraclass correlation values for all measured variables. Intraclass correlations above 0.7 were considered good, 0.80 – 0.89 very good and > 0.90 high. All of the golf club swing characteristics showed acceptable test retest reliability ranging from 0.77 - 0.99. In addition, the time duration between swing events and all X Factor, shoulder, elbow and knee angle and angular velocity measurements produced acceptable intraclass correlations above 0.7. For the hip angles the majority of the measurements produced at least good intraclass correlations (above 0.7), however, some measures were slightly below 0.7, ranging from 0.61 – 0.67 (left hip flexion/extension at early downswing and mid downswing and right hip internal/external rotation at mid backswing, late backswing and mid follow through). The left hip abduction/adduction angular velocity at mid follow through was the only velocity measurement to produce an intraclass correlation below 0.7 (0.66). None of the left wrist abduction/adduction angle measurements or the right wrist abduction/adduction angle measurements at take away, mid backswing, ball contact and mid follow through produced good reliability. All abduction/adduction angular velocities for the left wrist, except early downswing, produced at least good reliability (≥ 0.7); for the right wrist only the measurement at ball contact produced good reliability. The lower reliability of many of the wrist measurements is most likely due to the high number of markers in close proximity on the wrist and hand.

Centre of pressure measurements in the X direction (front foot to back foot) were above 0.7, except for at take away (0.66) and early downswing (0.67). For the Y direction (heel to toe) the final four swing events were also just below 0.7 [early downswing (0.65), mid downswing (0.69), ball contact (0.69) and mid follow through 0.65)]. The intraclass correlation did not reach the level of 0.7 for the centre of pressure velocity in X direction (front foot to back foot) between the events of late backswing and the top of the backswing (0.66). There were also similarly lower intraclass correlations in the Y direction between the events of take away and mid backswing (0.65) and between early downswing and mid downswing (0.67). For the club measurements in the X direction all intraclass correlation angle measurements were at least 0.7, while for the angular velocity measurements the intraclass correlations were slightly below 0.7 at early downswing (0.65) and ball contact (0.63). Three of the six club angle and angular velocity measurements in the Y direction showed reliability below 0.7 (0.63 -0.68). A possible explanation for these low reliability results for the Y direction measurements is that all the swing events except the top of the backswing were identified based on the club position in the Y direction. Therefore, there was very small variation between subjects for the club angle in the Y direction which when statistically analysed resulted in within-subject measurements appearing relatively large. For the club angle and angular velocities in the Z direction only the angle at mid backswing produced an intraclass correlation above 0.7.

Table 4.53 Intraclass correlation results for golf club swing characteristics.

Golf club swing characteristics	
Club Speed (m.s^{-1})	0.95
Clubface (°)	0.89
Swing path angle (°)	0.78
Tempo (s)	0.99
Rotation (deg.in)	0.87
Impact (cm)	0.77

Table 4.54 Intraclass correlation results for timing between the swing events.

Timing between swing events	
TA - MB	0.75
MB - LB	0.96
LB - TB	0.98
TB - ED	0.93
ED - MD	0.95
MD - BC	0.96
BC - MF	0.92

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.55 Intraclass correlation results for X Factor angles and angular velocities.

Event	X Factor (°)	X Factor Velocity (°.s^{-1})
TA	0.76	
MB	0.71	0.95
LB	0.83	0.98
TB	0.85	0.95
ED	0.87	0.85
MD	0.87	0.91
BC	0.83	0.73
MF	0.71	0.88
Minimum	0.82	
Maximum	0.88	
Stretch	0.99	
Stretch time (s)	0.92	

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.56 Intraclass correlation results for left and right shoulder flexion/extension, abduction/adduction and internal/external rotation angles and angular velocities.

Event	Shoulder Flexion/Extension				Shoulder abduction/adduction				Shoulder Internal/External rotation			
	Left		Right		Left		Right		Left		Right	
	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})
TA	0.89		0.92		0.73		0.71		0.80		0.70	
MB	0.93	0.93	0.92	0.97	0.83	0.72	0.78	0.82	0.91	0.92	0.83	0.83
LB	0.81	0.97	0.97	0.93	0.87	0.81	0.91	0.74	0.88	0.73	0.93	0.81
TB	0.83	0.72	0.98	0.93	0.89	0.76	0.94	0.96	0.79	0.78	0.95	0.84
ED	0.89	0.79	0.97	0.95	0.77	0.90	0.91	0.96	0.85	0.80	0.96	0.90
MD	0.92	0.82	0.95	0.92	0.80	0.70	0.90	0.83	0.91	0.83	0.94	0.93
BC	0.82	0.91	0.96	0.95	0.84	0.93	0.76	0.87	0.73	0.91	0.97	0.94
MF	0.92	0.96	0.75	0.73	0.86	0.81	0.80	0.88	0.89	0.75	0.81	0.70

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.57 Intraclass correlation results for left and right elbow flexion/extension angles and angular velocities.

Event	Elbow Flexion/Extension			
	Left		Right	
	Angle (°)	Angular Velocity ($deg.s^{-1}$)	Angle (°)	Angular Velocity ($deg.s^{-1}$)
TA	0.89		0.92	
MB	0.94	0.95	0.82	0.88
LB	0.94	0.91	0.88	0.94
TB	0.97	0.88	0.96	0.71
ED	0.95	0.70	0.94	0.95
MD	0.93	0.92	0.93	0.87
BC	0.87	0.96	0.95	0.97
MF	0.92	0.98	0.80	0.84

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.58 Intraclass correlation results for left and right wrist abduction/adduction angles and angular velocities.

Event	Wrist abduction/adduction			
	Left		Right	
	Angle (°)	Angular Velocity ($deg.s^{-1}$)	Angle (°)	Angular Velocity ($deg.s^{-1}$)
TA	0.23		0.63	
MB	0.63	0.90	0.06	0.38
LB	0.03	0.73	0.71	0.57
TB	0.43	0.78	0.77	0.09
ED	0.34	0.09	0.89	0.77
MD	0.02	0.90	0.83	0.67
BC	0.09	0.91	0.23	0.83
MF	0.18	0.80	0.52	0.37

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.59 Intraclass correlation results for left and right hip flexion/extension, abduction/adduction and internal/external rotation angles and angular velocities.

Event	Hip Flexion/Extension				Hip abduction/adduction				Hip Internal/External rotation			
	Left		Right		Left		Right		Left		Right	
	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})
TA	0.71		0.74		0.84		0.91		0.71		0.73	
MB	0.70	0.97	0.76	0.78	0.78	0.88	0.90	0.98	0.71	0.95	0.67	0.70
LB	0.71	0.86	0.78	0.90	0.76	0.72	0.91	0.84	0.80	0.96	0.65	0.71
TB	0.82	0.92	0.72	0.87	0.71	0.77	0.91	0.70	0.91	0.98	0.71	0.70
ED	0.61	0.88	0.73	0.95	0.85	0.82	0.91	0.91	0.90	0.93	0.73	0.91
MD	0.65	0.94	0.73	0.88	0.85	0.89	0.95	0.89	0.75	0.95	0.70	0.70
BC	0.70	0.91	0.71	0.90	0.71	0.91	0.93	0.74	0.71	0.84	0.73	0.70
MF	0.72	0.87	0.71	0.93	0.75	0.66	0.86	0.93	0.70	0.92	0.63	0.80

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.60 Intraclass correlation results for left and right knee flexion/extension angle and angular velocities.

Event	Knee Flexion/Extension			
	Left		Right	
	Angle (°)	Angular Velocity (deg.s^{-1})	Angle (°)	Angular Velocity (deg.s^{-1})
TA	0.79		0.84	
MB	0.86	0.96	0.91	0.89
LB	0.87	0.95	0.92	0.93
TB	0.83	0.93	0.86	0.95
ED	0.74	0.93	0.76	0.86
MD	0.73	0.94	0.76	0.71
BC	0.78	0.94	0.71	0.83
MF	0.73	0.90	0.76	0.86

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.61 Intraclass correlation results for centre of pressure measurements in the X and Y direction.

Event	Centre of pressure	
	X	Y
TA	0.66	0.81
MB	0.93	0.70
LB	0.95	0.76
TB	0.95	0.74
ED	0.67	0.65
MD	0.79	0.69
BC	0.88	0.69
MF	0.92	0.65

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.62 Intraclass correlation results for centre of pressure velocity measurements in the X and Y direction.

Event	Centre of pressure velocity ($m.s^{-1}$)	
	X	Y
TA - MB	0.71	0.65
MB - LB	0.96	0.91
LB - TB	0.66	0.98
TB - ED	0.93	0.90
ED - MD	0.91	0.67
MD - BC	0.80	0.92
BC - MF	0.75	0.84

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Table 4.63 Intraclass correlation results for club angles and angular velocities in the X, Y and Z directions.

Event	Club					
	X		Y		Z	
	Angle (°)	Angular Velocity ($deg.s^{-1}$)	Angle (°)	Angular Velocity ($deg.s^{-1}$)	Angle (°)	Angular Velocity ($deg.s^{-1}$)
TA	0.71					
MB			0.68	0.63	0.94	0.48
LB	0.95	0.90	0.72	0.68		
TB	0.90	0.71	0.90	0.70		
ED	0.71	0.65	0.67	0.72		
MD			0.73	0.67	0.44	0.45
BC	0.83	0.63	0.66	0.70	0.50	0.52

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact.

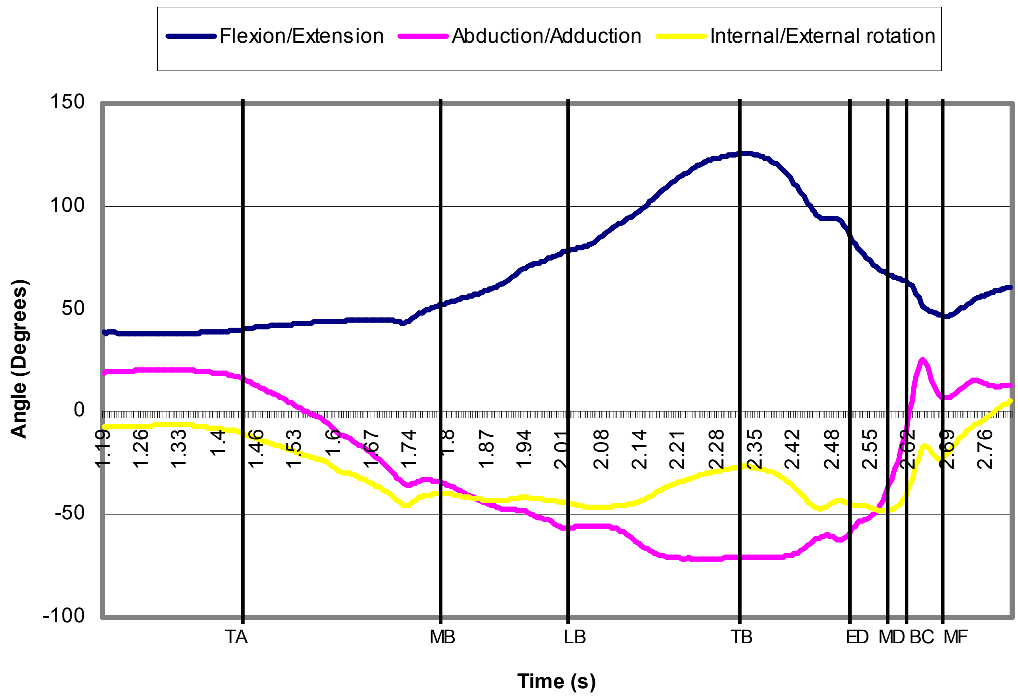
4.3 General description of joint actions

4.3.1 X Factor

Figure 4.1 illustrates a representative graph for the X Factor angle. The X Factor angle describes the relative rotation of the shoulders with respect to the hips (Figure 3.19). As the participant moved from their take away position their hips rotated more away from the direction of the target than their shoulders, this is indicated by the slight decrease in the X Factor angle between take away and mid backswing. Towards mid backswing the shoulders then started to rotate more away from the direction of the target than the hips which caused the sharp increase in the X Factor angle until the top of the backswing. The further increase in the X Factor angle termed the “X Factor stretch” early in the downswing (between the top of backswing and early downswing events) was caused by the faster rotation of the hips in the direction of the target than the shoulders. The subsequent sharp decrease in the X Factor angle from the events of early downswing to mid follow through was caused by an increase in the speed of rotation of the shoulders in the direction of the target relative to the hips.

4.3.2 Shoulder

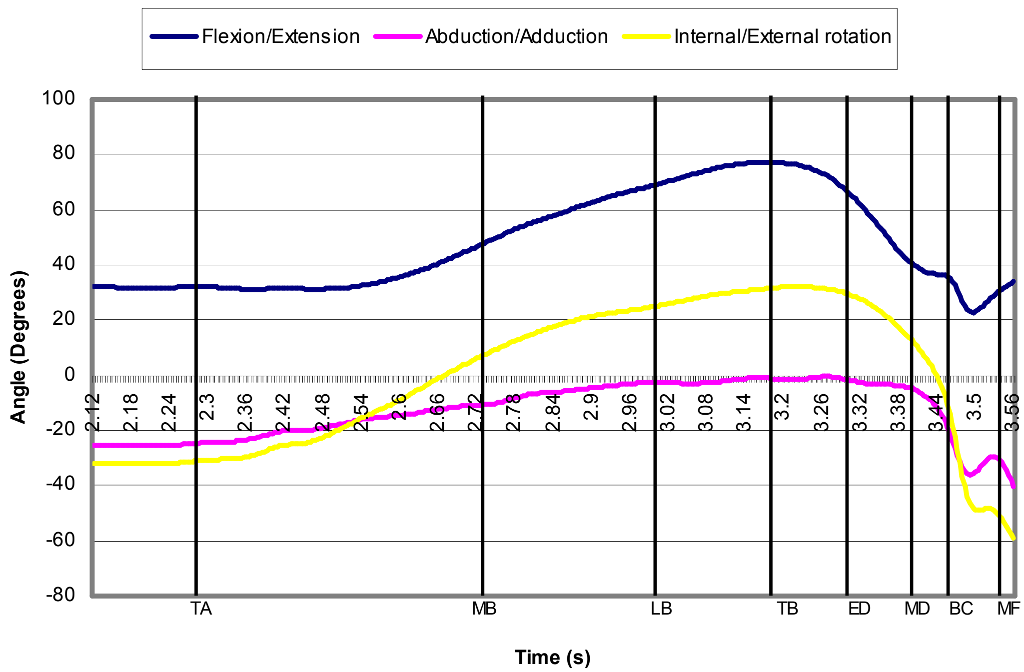
Figure 4.39 shows a representative graph for the movement of the left shoulder about the 3 axes (flexion/extension, abduction/adduction and internal/external rotation). In the take away position the participants had their left shoulder in a flexed, adducted and slightly internally rotated position. To bring the club to its horizontal position at the event of mid backswing the left shoulder slightly increased its flexion and largely increased its adduction and internal rotation as the participant started to bring their left arm across their body. To further raise the club to its vertical position at late backswing the left arm moved further across the body; this was achieved through rapidly increasing its flexion, further increasing its adduction and maintaining its internal rotation. To bring the club to its position behind the head at the top of the backswing the left shoulder continued to be rapidly flexed, it was further adducted and its internal rotation was slightly decreased. During the downswing the shoulder rapidly extended, returning close to its initial position (at take away) by mid follow through. A rapid decrease in adduction began half way between the top of the backswing and mid downswing, as the left arm returned back across the body to bring the club back to contact the ball. By ball contact the abduction/adduction angle is approximately 0°, meaning it is in a neutral position. Following ball contact the left arm rapidly moved into an abducted position and then rapidly decreased up to the event of mid follow through. In relation to the shoulder internal/external rotation an initial increase in internal rotation following the top of the backswing was evident and continued until half way between the events of top of the backswing and early downswing after which internal rotation is maintained until the event of mid downswing. Following mid downswing there was a rapid decrease in internal rotation which assisted in bringing the clubface in line to contact the ball. Following ball contact internal rotation decreased and then started to increase prior to the event of mid follow through.



Note: TA = take away; MB = mid backswing; LB = late backswing; TB = top of backswing; ED = early downswing; MD = mid downswing; BC = ball contact; MF = mid follow through. For flexion/extension: 0 = neutral; + = flexion; - = extension; abduction/adduction: 0 = neutral; + = abduction; - = adduction; internal/external rotation: 0 = neutral; + = external rotation; - = internal rotation.

Figure 4.39 Representative graph for left shoulder flexion/extension, abduction/adduction and internal/external rotation angles.

Figure 4.40 shows a representative graph for the movement of the right shoulder about the 3 axes (flexion/extension, abduction/adduction and internal/external rotation). It was found, as expected, that the left shoulder (Figure 4.39) utilised a greater range of motion in the flexion/extension and abduction/adduction angles compared to the right shoulder; as the club is rotated to the right side of the body during the backswing and therefore the left arm needs to use a greater range of movement than the right arm.



Note: TA = take away; MB = mid backswing; LB = late backswing; TB = top of backswing; ED = early downswing; MD = mid downswing; BC = ball contact; MF = mid follow through. For flexion/extension: 0 = neutral; + = flexion; - = extension; abduction/adduction: 0 = neutral; + = abduction; - = adduction; internal/external rotation: 0 = neutral; + = external rotation; - = internal rotation.

Figure 4.40 Representative graph for right shoulder flexion/extension, abduction/adduction and internal/external rotation angles.

At the take away position the right shoulder is in a flexed, adducted and internally rotated position. The flexed position was maintained until half way to the event of mid backswing after which flexion increased. Between the events of take away and mid backswing there was a reduction in both adduction and internal rotation, with the shoulder changing to an externally rotated position by mid backswing. All three angles continue to increase with all three reaching close to their maximum value at the top of the backswing as the club was brought to its position behind the head. Following the top of the backswing there was a decrease in both flexion and external rotation in order to return the club to contact the ball with the shoulder returning to an internal rotation position (approximating the take away position) by ball contact. The shoulder remained in an approximately neutral position in respect to abduction/adduction from the top of the backswing to early downswing after which it became slightly adducted up to mid downswing and then rapidly adducted as ball contact approached. Following ball contact all three angles continued their previous pattern until half way between the events of ball contact and mid follow through at which point their movement changed to the opposite direction.

4.3.3 Elbow

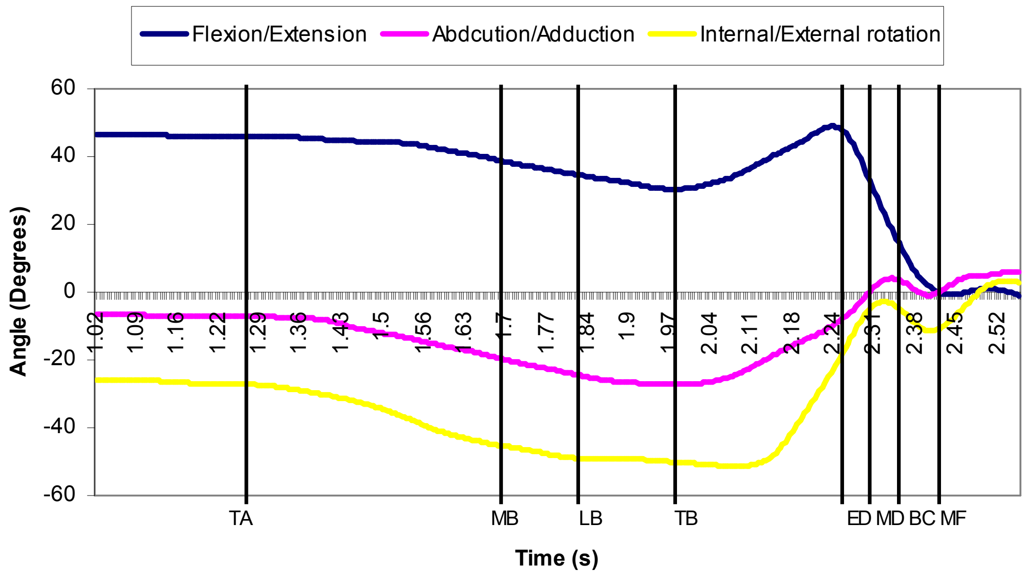
Shown in Figure 4.15 and Figure 4.16 are representative graphs for flexion/extension angle of the left and right elbows. The left elbow utilised a small range of movement during the swing. At the take away position it is in a flexed position and approximately maintained that position until just prior to mid backswing, after which a rapid small increase in flexion occurred until its maximum was reached in between the top of the backswing and early downswing. After this maximum value was reached the elbow began to extend as the club was returned to contact the ball. The elbow initially continued to extend following ball contact and then flexed rapidly as the club reached the mid follow through event. The right elbow angle at take away was similar to the left elbow; this angle was maintained initially and then the elbow rapidly flexed until the top of the backswing, as the club was moved from its initial position at take away to its position behind the head at the top of the backswing. Maximum flexion occurred around the top of the backswing and shortly after the top of the backswing the elbow extended rapidly to aid in returning the club to contact the ball, reaching its most extended position around mid follow through.

4.3.4 Wrist

Figure 4.19 and Figure 4.20 provide representative graphs for left and right wrist abduction/adduction angle. The left wrist was in an adducted position at take away and prior to the event of mid backswing it started to rapidly decrease changing to an abducted position between the events of mid backswing and late backswing, which assisted in raising the club to its vertical position at late backswing. An increase in abduction continued, reaching a maximum close to early downswing. Following this maximum, a rapid decrease in abduction was seen with the wrist changing to an adducted position between mid downswing and ball contact, as the club is returned to make contact with the ball. The wrist continued to adduct reaching its maximum adducted position at approximately ball contact. Following ball contact there was a rapid decrease in adduction as mid follow through was approached. The right wrist followed a similar pattern as the left wrist, however, it used less range of movement. It started in an adducted position at take away and rapidly changed to an abducted position prior to mid backswing. Slight fluctuations occurred between late backswing and early downswing after which there was a rapid decrease in abduction. The wrist position changed to an adducted position around mid downswing and reached a maximum adduction at approximately ball contact after which the wrist rapidly reduced its adduction.

4.3.5 Hip

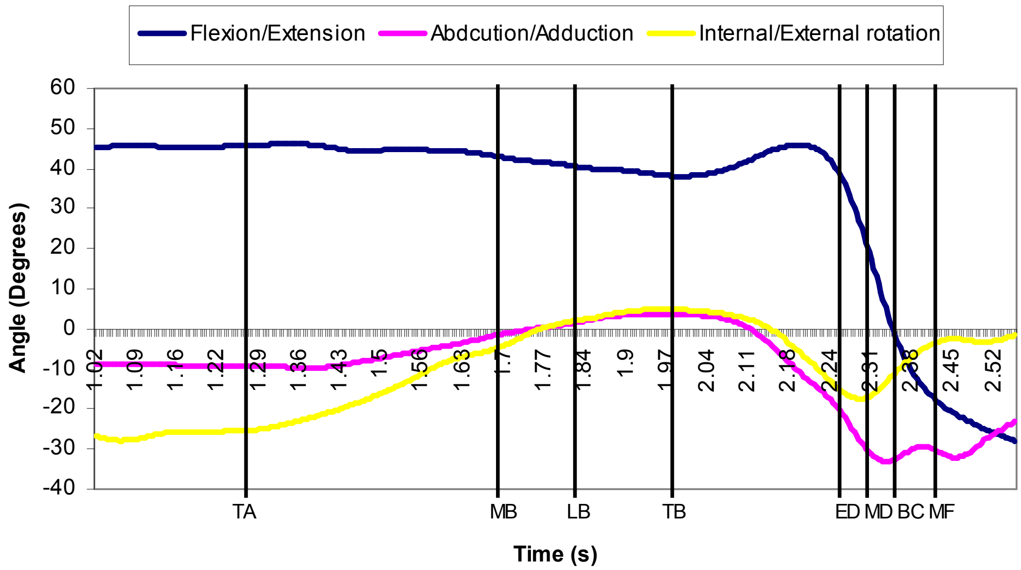
Figure 4.41 and Figure 4.42 show representative graphs for the movement of the left and right hip about the 3 axes (flexion/extension, abduction/adduction and internal/external rotation). At take away the left hip was in a flexed, abducted and externally rotated position. From take away to the top of the backswing there was a slight decrease in hip flexion along with a slight increase in abduction and external rotation, to allow the pelvis to rotate away from the direction of the target during the backswing. Following the top of the backswing the hip flexed, reaching a maximum at approximately early downswing. The left hip then rapidly extended to aid weight transfer in the direction of the target. Hip abduction reduced following the top of the backswing reaching a neutral position at approximately mid downswing, as the pelvis rotated back in the direction of the target. The hip then adducted slightly until ball contact after which it returned to a neutral position by mid follow through. Following the top of the backswing the hip maintained its externally rotated position until half way to the early downswing position after which it reduced, reaching a minimum between mid downswing and ball contact, again due to the pelvis's rotation back in the direction of the target. Following ball contact the hip increased its external rotation until approximately mid follow through.



Note: TA = take away; MB = mid backswing; LB = late backswing; TB = top of backswing; ED = early downswing; MD = mid downswing; BC = ball contact; MF = mid follow through. For flexion/extension: 0 = neutral; + = flexion; - = extension; abduction/adduction: 0 = neutral; + = adduction; - = abduction; internal/external rotation: 0 = neutral; + = internal rotation; - = external rotation.

Figure 4.41 Representative graph for left hip flexion/extension, abduction/adduction and internal/external rotation angles.

The right hip started in a flexed, abducted and externally rotated position at take away. Its flexion followed a similar pattern to the left hip up until early downswing after which it rapidly reduced reaching a neutral position at approximately ball contact. As the swing continued to mid follow through the hip changed to an extended position, as the pelvis continued to rotate in the direction of the target. Half way towards mid backswing the right hip's abduction started to reduce, with the hip changing to an adducted position between mid and late backswing. The hip reached its maximum adduction at approximately the top of the backswing, the event when the pelvis is in its most rotated position away from the direction of the target. Following the top of the backswing a reduction in adduction was evident with the hip changing to an abducted position half way between the top of the backswing and early downswing, as the pelvis rotated back towards the direction of the target. The hip then rapidly abducted reaching a maximum at approximately ball contact, due to the pelvis's rapid rotation and after ball contact abduction reduced slightly. Following take away the hip's external rotation reduced reaching a neutral position between mid and late backswing. It then changed to a slightly internally rotated position reaching its maximum at approximately the top of the backswing. After the top of the backswing as the pelvis rotated back towards the target, internal rotation reduced, changing to an externally rotated position prior to early downswing, and continued to externally rotate up until mid downswing. External rotation then reduced reaching an approximately neutral position by mid follow through.



Note: TA = take away; MB = mid backswing; LB = late backswing; TB = top of backswing; ED = early downswing; MD = mid downswing; BC = ball contact; MF = mid follow through. For flexion/extension: 0 = neutral; + = flexion; - = extension; abduction/adduction: 0 = neutral; + = adduction; - = abduction; internal/external rotation: 0 = neutral; + = internal rotation; - = external rotation.

Figure 4.42 Representative graph for right hip flexion/extension, abduction/adduction and internal/external rotation angles.

4.3.6 Knee

Figure 4.35 and Figure 4.36 show representative graphs for left and right knee flexion/extension angle for the golf swing. The left knee started in a flexed position at takeaway and its flexion increased gradually until the top of the backswing. Following the top of the backswing there was a rapid increase in flexion as the pelvis was rotated back in the direction of the target. The knee reached its minimum flexion close to mid follow through. For the right knee there was an initial rapid increase in flexion from takeaway followed by a rapid decrease up until mid backswing due to the initial rotation of the body away from the direction of the target. Following mid backswing the knee flexed slightly, until half way between the top of the backswing and early downswing, after which it rapidly increased reaching a maximum just prior to early downswing. This was due to the initial rotation of the pelvis back in the direction of the target following the top of the backswing. Following early downswing there was a rapid decrease in flexion until ball contact, as the knee extended to aid weight transfer to the front foot. Following ball contact the knee flexed rapidly as the pelvis continued to rotate towards the target resulting in the back foot lifting its heel off the ground and the back foot internally rotating (towards the direction of the target).

5 Discussion

The aim of the present study was to determine if golfers with different skill levels when using the 5 iron club to achieve maximum distance would show differences in joint and club kinematics and weight transfer during the swing. The present study divided 30 participants into two groups of 15 representing high ball speed (52.9 ± 2.1 $m.s^{-1}$) and low ball speed (39.9 ± 5.2 $m.s^{-1}$) groups. Participants were grouped in this manner in order to distinguish skill level in terms of shot distance (as there is a positive relationship between ball speed and shot distance) with the 5 iron club. There are few studies on the iron clubs that have examined the effect of skill level on participant or club kinematics or kinetics, therefore, where appropriate studies that have examined the effect of skill level using the driver club will be included for comparative purposes. Practical implications for the findings of the study will also be proposed.

No previous studies examining skill level in iron clubs were found that used ball speed to group their participants, as used in the present study. Golfing handicap would appear to be the most frequently used means of grouping golfers. As previously discussed (pg.75), handicap may not be the most appropriate means of grouping participants in a study which isolates one aspect of the golf game, in this case the 5 iron golf swing when hitting for maximum distance, as handicap is calculated from many aspects of the golf game (including driving, putting and chipping). Ball speed is perhaps a more appropriate indicator of golfing performance with the 5 iron club.

With regard to golf club swing characteristics (Table 4.1) two significant differences were evident between the high and low ball speed groups: club speed and impact point. It was found, as expected, that the high ball speed group generated greater club speed at impact than the low ball speed group (38.2 ± 1.7 $m.s^{-1}$ *vs.* 30.7 ± 2.9 $m.s^{-1}$), as the speed of the golf club is the greatest determining factor of the speed of the ball. No previous studies were found that examined club speed in participants of varying skill level using iron clubs.

The results for impact point showed that the high ball speed group hit the ball significantly closer to the centre of the clubface than the low ball speed group (-0.74 cm *vs.* -1.95 cm, where a negative value indicates the impact point is towards the heel of the club head). No past research was located that examined impact point. The closer to the centre of the clubface that the ball is hit the greater the amount of energy transferred to the ball and therefore the greater the ball speed generated. The ability of the participant to hit the golf ball with the centre of the club face is determined by their ability to control the movement of the club in the frontal plane. As there are a large number of biomechanical degrees of freedom associated with controlling this movement it is difficult to identify which joint actions are responsible for this significant difference between the groups.

For the remaining four of the golf club swing characteristics analysed (clubface angle, swing path angle, tempo and club rotation) no significant differences were evident between the groups, indicating that these characteristics may not be performance determining factors in the iron club golf swing. Only two of these characteristics, clubface angle and tempo, were found to be discussed in previous research. The results from the present study show slightly smaller clubface angles (high ball speed group 2 ± 2.53° and low ball speed group 3 ± 4.91°) than that reported by Williams and Sih (2002) for the 5 iron club (5.07 ± 6.23°). A possible explanation for this could be that their participants consisted of 28 golfers with a wide range of handicap (0-36), they were not separated by skill level as in the present study. This possible explanation is supported by the slightly higher standard deviation reported by Williams and Sih (2002), indicating larger variation in results within their participants than in the present study.

No previous research examined the differences in tempo between skill levels for the iron club. However, McTeigue et al. (1994) and Barrentine et al. (1994) examined if differences occurred between different skill levels in tempo using the driver club. McTeigue et al. (1994) reported that the professional and senior professional golfers completed their golf swings significantly faster than the amateurs (1.09s and 1.03 s *vs.* 1.28 s, respectively). Barrentine et al. (1994) found that their professional and low handicap golfers completed their downswing significantly faster than the high handicap golfers (0.281 ± 0.04 s and 0.278 ± 0.04 s versus 0.331 ± 0.04 s, respectively) and the total swing time was significantly faster for the professional golfers compared to the high handicap golfers (1.087 ± 0.12 s *vs.* 1.272 ± 0.25 s).

Further analysis of the tempo in the present study was conducted using the motion analysis system which allowed the identification of the timing between the eight swing events (see Table 2.13 and Figure 2.17). The high ball speed group were found to complete from the events of early downswing through to mid follow through significantly faster than the low ball speed group (Table 4.2). Zheng et al. (2008) and McTeigue et al. (1994) were the only studies found that detailed the tempo breakdown during the golf swing for different skill level golfers, however, they both used the driver club opposed to the 5 iron used in the present study. Similar between skill level differences were reported for the timing between mid downswing and ball contact by Zheng et al. (2008) as in the present study with both their professional and low handicap golfers using less time than their high handicap golfers (0.045 ± 0.008 s and 0.044 ± 0.006 s vs. 0.058 ± 0.014 s). McTeigue et al. (1994) detailed their results for professional, senior professional and amateur golfers during the backswing (0.80 s, 0.75 s and 0.91 s, respectively) and downswing (0.29 s, 0.28 s and 0.38 s, respectively). As reported previously, McTeigue et al. (1994) found that the professional and senior professional golfers completed the whole of the golf swing significantly faster than the amateurs, however, no such significant difference between the groups were reported when the swing was broken into the backswing and downswing phases. Zheng et al. (2008) also compared the timing between the events of take away and mid backswing and in contrast to the present study where no significant difference was evident between the groups found their higher skilled golfers completed it significantly faster than the lesser skilled golfers (0.37 ± 0.08 s *vs.* 0.46 ± 0.12 s). Two previous studies were located that reported timing values for the iron clubs (Nagao and Sawada 1973, Barrentine, Fleisig and Johnson 1994), which allows for comparisons to be made with the absolute values of the present study. These two studies divided the swing into two phases: backswing and downswing. In order to allow direct comparison between these two studies and the present study, for the present study the backswing was calculated as the sum of the time between the events of take away and the top of the backswing (high ball speed 0.83 ± 0.11 s *vs.* low ball speed 0.93 ± 0.18 s) and the downswing was calculated as the sum of the time between the events of top of the backswing and ball contact (high ball speed 0.28 ± 0.04s *vs.* low ball speed 0.33 ± 0.05). These results from the present study are comparable with those found by Barrentine et al. (1994) (backswing 0.82 ± 0.15 s; downswing 0.29 ± 0.05 s) and Nagao et al. (1973) (downswing 0.22 s).

In summary, the findings from the golf club swing characteristics showed that the participants in the high ball speed group generated their greater ball speed through greater club speed, impacting the ball closer to the centre of the club face and using less time to complete the later stages of the swing (from the events of early downswing to mid follow through) than the low ball speed group. The following analysis of the biomechanics of the participants will aim to identify the kinematic and weight transfer performance determining factors that produced greater ball speed.

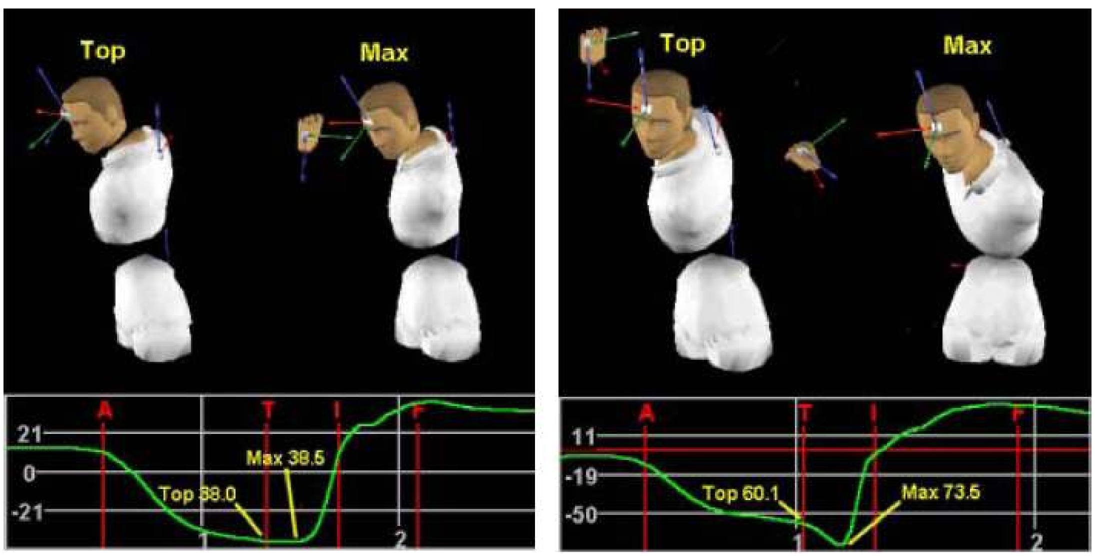
No significant differences were found between the groups for X Factor angle or angular velocity at the first four swing events which combine to form the backswing: takeaway, mid backswing, late backswing and top of backswing (Table 4.3 and Table 4.4). No previous studies were found that examined differences in skill level for the X Factor angle or angular velocity at the first three events for the iron club. Two studies were found that examined the X Factor angle at take away when using the driver club, they found no significant difference between the different skill levels they assessed (McTeigue et al. 1994, Zheng et al. 2008). Cheetham et al. (2001) was the only previous study found to examine the X Factor angle when using an iron club. Their study measured the X Factor at the fourth swing event, the top of backswing and made a comparison between two groups of different skill levels. Similar to the present study no significant difference was found between their highly skilled and less skilled golfers (48° vs. 44°, respectively) and the magnitude of their results were comparable to the present study (high ball speed 51.9 ± 4.8° *vs.* low ball speed 47.9 ± 9.9°). In contrast, studies that examined the differences in skill level for the X Factor angle when using a driver found differences at the top of the backswing (Myers et al. 2008, Zheng et al. 2008). Myers et al. (2008) found their high ball velocity (75.4 ± 4.4 $m.s^{-1}$) group had a greater X Factor angle than their low (55.7 ± 2.7 $m.s^{-1}$) and medium (65.6 ± 3.7 $m.s^{-1}$) ball velocity groups and Zheng et al. (2008) found that their professional golfers had a greater X Factor angle than their high handicap (21.3 ± 3.8) golfers. For the X Factor angular velocity no previous studies were located that examined it at any of the four events of the backswing (takeaway, mid backswing and late backswing and top of backswing).

Analysis of the X Factor angle during the downswing in the present study established significant between group differences (Table 4.3). At the events of early downswing (ED), mid downswing (MD) and ball contact (BC) the high ball speed group were found to have a significantly greater X Factor angle than the low ball speed group (ED: 45.1 ± 5.8° *vs.* 37.5 ± 7.6°; MD: 39.1 ± 5.4° *vs.* 30.8 ± 5.8°; BC: 36.4 ± 5.7 *vs.* 30.0 ± 6.3°). No such significant differences were evident between the groups for X Factor angular velocity during the downswing (Table 4.3). These results from the present study suggest that the X Factor angle at the top of the backswing may not be the most important phase for the X Factor angle. It may be the ability of the golfer to maintain a larger X Factor angle throughout the downswing that contributes to producing higher ball speeds. No previous studies using an iron club have examined this, however, a recent study using the driver club examined the differences in the X Factor angle and angular velocity between four groups of different skill level [Professional, low handicap (0-7), mid handicap (8-14) and high handicap (15+)] (Zheng et al. 2008). Their results showed that the professionals and low handicap groups were both found to have a significantly greater X Factor angle than the mid and high handicap groups at ball contact (24 ± 10° and 22 ± 6° *vs.* 15 ± 5° and 9 ± 9°, respectively). The authors suggested that higher flexibility and better control of trunk muscles in the higher skilled golfers may be the reason for this difference; however they did not provide justification for this. The magnitude of the X Factor angles at ball contact for the driver club reported by Zheng et al. (2008) were found to be less than those reported in the present study for the 5 iron club (high ball speed 36.4 ± 5.7° vs. low ball speed 30.0 ± 6.3°). A possible explanation for this difference between the driver and 5 iron club could be that the driver club is longer and has a heavier club head than the 5 iron club. This would lead to greater inertia during the downswing with the driver club which may cause the upper body to rotate faster relative to the hips than it would when using the 5 iron club.

Zheng et al. (2008) did not report values for X Factor angular velocity at specific swing events, instead they reported its maximum value during the downswing with no significant differences evident between the groups for the maximum X Factor angular velocity or the time of this maximum. In contrast Watanabe et al. (1999) analysed the golf swing of 22 amateur golfers using the driver club and found that improvements in performance could be achieved by increasing X Factor angular velocity. The only other previous research located that examined X factor angular velocity was a training study conducted by Lephart et al. (2007) that examined the benefit of an eight week golf specific exercise program on golfing performance. Results showed a significant increase in X Factor angular velocity at what they defined the acceleration phase (two thirds of the time between the top of backswing and ball contact) following the exercise program (203.6 ± 78.5°.s^{-1} vs. 236.7 ± 68.5°.s^{-1}). They also found a small increase in the X Factor angle at the top of the backswing; however this did not reach statistical significance (-49.8 ± 7.6° vs. -53.5 ± 5.6°). Their golf specific exercise program which aimed to promote stability of the lower body and to increase mobility of the upper body was found to increase club head velocity, ball velocity and total distance. It should be noted that this study by Lephart et al. used the driver club, however, it is likely that increasing the X Factor angle and X Factor angular velocity through a golf specific exercise program could benefit golfers in increasing their ball velocity and total distance with the iron clubs.

No significant difference was found between the groups in the present study for the X Factor stretch. In contrast, Cheetham et al. (2001) found their higher skilled golfers had a significantly greater stretch than the lesser skilled golfers (57° vs. 50°, respectively) when using the 5 iron club. The authors reported absolute X Factor stretch values, however, were comparable to those found in the present study (High ball speed 53.5 ± 5.7° *vs.* Low ball speed 48.5 ± 9.9°). Cheetham et al. (2001) described the faster rotation of the hips than the shoulders in the highly skilled golfers during the start of the downswing as the cause of the significantly greater X Factor stretch. The authors proposed that the benefit of the X Factor stretch was the utilisation of the stretch shortening cycle; however, the results of the present study don’t support this. Additional to the finding of no significant difference between the groups for the X Factor stretch in the present study the finding of no significant difference between the groups for X Factor angular velocity at early downswing further suggests no difference between the groups in their utilisation of the stretch shortening cycle. A greater initial muscle contraction velocity during the concentric phase (at early downswing in the case of the golf swing) is believed to result from the use of the stretch shortening cycle (Miyaguchi and Demura 2006). However, this is not to say that the stretch shortening cycle does not occur or is not important, as it clearly does occur. The issue is whether the skill differences influence the effectiveness of the stretch shortening cycle.

Although Cheetham et al. (2001) did not discuss the X Factor angle during the downswing following the X Factor stretch they provided graphical representation of the X Factor angle throughout the golf swing for a highly skilled and less skilled golfer (Figure 5.1).



(a) (b)

Figure 5.1 The X Factor angle for a less skilled (a) and highly skilled (b) golfer: (A) Take away (T) Top of the backswing (I) Ball contact (F) End of follow through. Taken from Cheetham et al. (2001).

They stated that the negative values of the X Factor angle represented a closed X Factor angle, meaning the shoulders were rotated more away from the direction of the target than the hips. From their graphs they showed that the X Factor angle was close to 0° at impact, indicating that the shoulder and hips were close to parallel at impact. These findings contradict the results of the present study in which the shoulders were never found to be more rotated towards the target than the hips during the downswing (from the event of the top of the backswing to the event of ball contact). A possible explanation for the differences in results between the present study and Cheetham et al. (2001) is that in the present study the X Factor angle was calculated using motion analysis as the differential angle between the shoulder and the hips while Cheetham et al. (2001) used two 6 degree of freedom sensors placed on the back (at the third thoracic vertebrae) and the pelvis to calculate the X Factor angle. It is possible that the two different measurement systems are not measuring exactly the same functional angle.

The summation of all the individual joint velocities determines the overall end velocity of the golf club head which effects ball speed. It is the concentric phase impulse that determines the final angular velocity of each joint and this is mainly determined by the neuromuscular output of the muscles crossing each joint. The neuromuscular output is in part affected significantly by the use of the stretch shortening cycle and the joint range of motion [impulse-momentum relationship (see Equation 3)] employed. The stretch shortening cycle which was previously defined and described in the literature review section (pg.21), utilises a rapid eccentric contraction (at the top of the backswing) to enhance force output from the muscle during the concentric phase. Previous research has shown that the greater the speed of the stretching and the sooner the muscle is contracted after stretching the greater the enhancement(Cavagna, Dusman and Margaria 1968, Bosco, Komi and Ito 1981, Wilson, Elliott and Wood 1991).

The impulse-momentum relationship is defined as:

$$Tt = I(\omega_f - \omega_i) \qquad \text{(Equation 3)}$$

where T = Torque; t = time; I = moment of inertia; ω_f = final angular velocity; ω_i = initial angular velocity.

For the golf swing at the start of the downswing the velocity is 0 (ω_i = 0), therefore the formula becomes:

$$Tt = I\omega_f$$

$$\therefore \omega_f = \frac{Tt}{I}$$

This shows that in order to generate high end velocity (ω_f) it would be advantageous to increase the time (t) of the golf swing. It is important to note, however, that increasing the time of the golf swing by simply completing the swing more slowly will not increase end velocity. In order to successfully increase the end velocity of the golf swing the time taken to complete the swing should be increased by increasing the range of motion of the joints involved in the golf swing.

Both of these two mechanisms (stretch shortening cycle and impulse-momentum relationship) are utilised during the golf swing, however, maximising one will decrease the effectiveness of the other. The stretch shortening cycle utilises a rapid stretch of the muscle during the eccentric phase to generate enhancement in the concentric phase. If the eccentric phase is too long or requires too great a motion about the given joint, the mechanisms which cause the enhancement from the stretch shortening cycle (e.g. storage and reutilisation of elastic energy, increased force at the start of the concentric contraction, neural reflex potentiation and altered properties of the contractile machinery) are negatively affected. In contrast the impulse-momentum relationship utilises greater range of motion about a joint to generate greater end velocity. Support for this inverse relationship between the two mechanisms has been shown by Moran and Wallace (2007). They found increases in jump height with increasing eccentric loading (drop jump > counter movement jump > static jump) supporting the stretch shortening cycle mechanism. However, when they examined the effect of different knee joint range of movement at the start of the propulsive phase for each jump (70° *vs.* 90°) they found significantly greater enhancements from the stretch shortening cycle for a smaller range of movement (70°) compared to a larger range of movement (90°) at the knee joint. For example, similar jump heights were produced in the 90° counter movement jump as in the 70° drop jump, even though the counter movement jump used a smaller amount of eccentric loading.

As discussed previously from the results of the X Factor stretch and X Factor angular velocity at early downswing in the present study it is unclear if there is an effect of skill level on the utilisation of the stretch shortening cycle. It is possible that some participants in the high ball speed group maximise the utilisation of the stretch shortening cycle while others maximise the utilisation of the impulse-momentum relationship. It is possible that maximising one or other of these two mechanisms may mask whether between skill differences occurred or not.

Previous studies with iron clubs have not examined the movement of the individual shoulder joints choosing instead to examine the rotation of both the right and left shoulders together (torso rotation) (Lindsay, Horton and Paley 2002, Egret et al. 2003). This does not allow for full analysis of what actions are occurring at the individual shoulder joints during the golf swing. The present study examined the right and left shoulder independently and described the movement of each shoulder about 3 axes (flexion/extension, abduction/adduction and internal/external rotation), the results for which have not been previously reported for the 5 iron club.

Results for left and right shoulder flexion/extension angles (Table 4.5 and Table 4.6) showed that the higher ball speed group flexed their right shoulders more than the low ball speed group during the backswing (at events mid backswing, late backswing and top of backswing) and their left shoulders more at late backswing, thereby utilising a greater range of motion in the backswing. This appears to have allowed the high ball speed group to produce greater extension angular velocity in both shoulders at early downswing. The greater range of movement used by the high ball speed group may indicate that they more effectively utilised the impulse-momentum relationship mechanism (described previously in relation to the X Factor) to generate greater angular velocity. However, the results also suggest the possible utilisation of the stretch shortening cycle by the high ball speed group: with a greater angular velocity of the left shoulder by the high ball speed group evident at late backswing. Higher velocities during the backswing increase eccentric loading, which increases the potential for enhancement in the concentric phase (downswing) through the stretch shortening cycle (Cavagna, Dusman and Margaria 1968, Bosco, Komi and Ito 1981, Wilson, Elliott and Wood 1991), as evident by the significantly greater angular velocity during early downswing for the high ball speed group.

For the shoulders abduction/adduction angle no significant differences were evident between the groups (Table 4.9 and Table 4.10). The only significant difference evident between the groups was for the left shoulder angular velocity at ball contact, with the high ball speed group found to generate significantly greater angular velocity than the low ball speed group.

For the shoulders internal/external rotation angle the high ball speed group were found to use less rotation of their left shoulders than the low ball speed group during the backswing (Table 4.13). A possible benefit for this lesser range of movement by the high ball speed group during the backswing is enhanced utilisation of the stretch shortening cycle. A small range of movement during the eccentric phase increases the potential for enhancements in the concentric phase (Moran and Wallace 2007). Another possible benefit of this lesser range of motion for the high ball speed group is an increased possibility of returning the club head to the ball at a more optimal orientation. By maintaining the club orientation as close to the take away position as possible there is a lesser chance of inaccurate impact between the club head and ball. This proposed explanation for the high ball speed groups lesser shoulder rotation would be further reinforced if there was a significant difference between the groups for club face angle, however no such difference was found. In contrast to the present study where no significant difference was evident between the high and low ball speed groups for right shoulder internal/external rotation angle at the top of the backswing (47.1 ± 10.3° *vs.* 52.3 ± 14.6°), research by Zheng et al. (2008) with the driver club found significant differences between their groups. Their professional golfers were found to have a significantly greater angle than both mid and high handicap golfers (66 ± 11° *vs.* 47 ± 24° and 46 ± 17°) and the low handicap golfers also had a significantly greater angle than the high handicap golfers (61 ± 15° vs. 46 ± 17°). A possible explanation for these contrasting results is the different club and participant groupings used in the study by Zheng et al. (2008) compared to the present study (driver vs. 5 iron, and participants grouped by handicap vs. participants grouped by ball speed).

The high ball speed group were found to keep their left elbows more extended than the low ball speed group at early downswing and no significant differences were evident between the groups for the right elbow (Table 4.17 and Table 4.18). The benefits of keeping the left arm straight during the swing have been discussed in general literature describing golf technique (Bunn 1972, Broer 1973, Maddalozzo

1987). The postulated benefit of this is the more extended a golfer keeps their arms the greater the velocity the club head is capable of generating since the club head travels through a longer arc in a given time and therefore moves faster (Broer 1973) (see Equation 4).

$$v = \omega . d \qquad \text{(Equation 4)}$$

where v = linear velocity; ω= angular velocity; r = radius of rotation. This formula shows that it is possible to increase linear velocity by increasing the radius of rotation (e.g. by extending the elbow). The only previous study that examined elbow flexion used the driver club (Zheng et al. 2008). Reasonably comparable results between Zheng et al. (2008) and the present study are evident (Table 5.1), with the variation likely due to the differences in club shaft length of the driver and 5 iron clubs.

Table 5.1 Comparison of elbow flexion (°) results in the present study with Zheng et al. 2008.

Study	Participants	TA		TB		BC	
		Left	Right	Left	Right	Left	Right
Present study	(1) 15 High ball speed	21.7 ± 5.3	27.8 ± 5.1	42.1 ± 10.6	110.5 ± 12.5	23.6 ± 7.7	50.6 ± 7.4
	(2) 15 Low ball speed	26.7 ± 8.8	29.2 ± 6.9	52.3 ± 9.8	115.1 ± 10.9	29.4 ± 11.2	46.5 ± 9.0
Zheng et al. 2008	(1) 18 Professionals	31 ± 4	48 ± 6	58 ± 9	130 ± 8	34 ± 6	40 ± 5
	(2) 18 Low handicap	30 ± 5	45 ± 7	60 ± 12	129 ± 11	31 ± 8	42 ± 9
	(3)18 Mid handicap	32 ± 10	47 ± 6	64 ± 13	129 ± 9	35 ± 6	39 ± 13
	(4) 18 High handicap	36 ± 6	52 ± 9	67 ± 14	128 ± 12	45 ± 8	41 ± 13
						* (1) vs. (4)	
						(2) vs. (4)	
						(3) vs. (4)	

Note: TA = take away; TB = top of backswing; BC = ball contact. * = significant difference between groups ($p < 0.05$).

A combination of actual golfer data collection (Milburn 1982, Neal and Wilson 1985, Robinson 1994, Nesbit 2005) and mathematical modelling studies (Jorgensen 1970, Pickering and Vickers 1999, Sprigings and Mackenzie 2002) using the driver club suggest that during the golf swing, the wrist angle and wrist angular velocity prior to ball impact are important contributors to ball velocity and driving distance. These studies support the theory that delayed wrist uncocking contributes to high club head velocity. Wrist "uncocking" is wrist adduction (ulnar deviation) from an abducted (radial deviated) position. It was shown by Neal and Wilson (1985) with four professional and two low handicap golfers using the driver, that rapid wrist uncocking appeared to begin between 100ms and 80ms prior to impact. The above studies suggested that delayed uncocking of the wrists improved club head speed by varying amounts. For example, Sprigings and Mackenzie (2002) reported that delaying the wrist uncocking contributed a 1.6% increase in club head speed (44.7 $m.s^{-1}$ *vs.* 44.0 $m.s^{-1}$), which they stated was approximately 40% less than the increase reported in Pickering and Vickers (2.5%) and Jorgensen (2.9%). Only one study (Budney and Bellow 1982) compared different skill levels using an iron club. They found that professionals achieved greater wrist velocity following uncocking than amateurs at ball contact for all the iron clubs (3 iron, 6 iron, 9 iron and pitching wedge). While in a club comparison study by Nagao and Sawada (1973) it was found that for the driver club the participants maintained their wrist in a cocked position during the downswing and rapidly uncocked before ball contact and for the 9 iron the cocked position was not maintained and from approximately the middle of the downswing it uncocked. Consistent with the findings of Nagao and Sawada (1973), results from the present study found no significant differences between the groups for left wrist cock angle. Greater angular velocity of the left wrist for the high ball speed group was found at mid downswing, which possibly contributed to their greater club head speed. No previous research using the iron clubs was found to report absolute values to allow comparison with the present study. Recent research by Zheng et al. (2008) provided left and right wrist angle data for driver at take away, top of the backswing and ball contact, however, it is not possible to compare their results to the present study as they measured the wrist angle as the angle between the forearm and the club shaft, while the present study measured it as the angle between the forearm and the hand. It should be noted however that wrist movement is difficult to measure due to the high number of markers in close proximity on the wrist. This is supported by the findings in the present studies reliability analysis which show none of the left wrist angle measurements at the eight swing events to be reliable and the right wrist measurements could not be considered reliable at four of the eight swing events.

Similar to the shoulders, measurement of hip movement in the literature has generally described the movement of both hips together (pelvic rotation). The present study examined the rotation of the right and left hip independently with the movement described in relation to the 3 axes (flexion/extension, abduction/adduction and internal/external rotation). Of all the significant differences evident between the high and low ball speed groups for the assessed joints (shoulder, elbow, wrist, hip and knee), the top three when ranked by effect size were the right hip abduction/adduction angle at early downswing, mid downswing and ball contact (46.3%, 42.5% and 38.3% respectively); indicating the importance of hip movement in distinguishing between the two groups. The right hip was significantly more abducted for high ball speed group than the low ball speed group. Given that the distance between the feet does not change greatly during the golf swing, an increase in the abduction angle in the right hip would suggest a subsequent decreased abduction/increased adduction angle in the left hip. However, no significance differences were found between the groups at these swing events. These differences in the right hip angles between the groups resulted in the high ball speed group moving their hips more in the direction of the target during the downswing than the low ball speed group. This finding can be further explained by examining the centre of pressure (COP) results. The high ball speed group was found to have their COP more towards the front foot than the low ball speed group (35.4% versus 51.3% respectively) at early downswing, indicating that they were indeed moving their body in the direction of the target.

The right hip for the high ball speed group was also found to be more extended at mid follow through which is likely to aid in the transfer of weight to the front foot and also due to the rotation of the pelvis towards the direction of the target. It is unclear why the high ball speed group was found to have their left hip less externally rotated than the low ball speed group at early downswing. They appeared to use a similar range of movement from top of backswing to early downswing but the angles at the start and end differed. Greater left and right hip flexion/extension angular velocity was evident for the high ball speed group at mid downswing. This ability to generate higher velocities early in the concentric phase (downswing) by the high ball speed group possibly contributed to their greater club head speed by their more enhanced utilisation of the stretch shortening cycle than the low ball speed group. The increased velocity of the hips early in the downswing also possibly indicates the high ball speed group's superior use of proximal to distal sequencing as they reached higher velocity of the proximal segment (hips) early in the concentric movement which possibly led to their higher velocity at the distal segment (club head).

Table 5.2 details a comparison between the knee flexion/extension angles recorded in the present study and that of Egret at al. (2003). The results are comparable with a maximum difference of approximately 6°. In the present study no significant differences between the high and low ball speed groups were evident. Greater left knee angular velocity was evident in the high ball speed group at early and mid downswing. Since the left foot remains on the ground during the golf swing, the increased velocity may be indicative of the high speed golfers moving their hips more towards the target than the low ball speed group.

Table 5.2 Comparison of present study knee angle (°) results with Egret et al. 2003.

Study	Participants	TA		TB		BC	
		Left	Right	Left	Right	Left	Right
Present study	15 high ball speed	24.7 ± 6.6	23.5 ± 7.1	42.6 ± 7.0	24.4 ± 7.1	19.7 ± 7.4	22.9 ± 9.1
	15 low ball speed	23.5 ± 6.1	23.6 ± 7.4	39.5 ± 7.2	26.3 ± 8.1	23.4 ± 6.8	24.2 ± 9.6
Egret et al. 2003	7 golfers handicap (0.4 ± 1.1)	18 ± 7.5	17.6 ± 6	36.5 ± 7.6	19.1 ± 3.4	17.6 ± 7.5	24.5 ± 8.4

Note: TA = take away; TB = top of backswing; BC = ball contact

No significant differences were evident between the groups for the golf club kinematics examined.

5.1 Summary

No difference in the timing of the backswing was evident between the groups, however, the high ball speed group were found to complete the downswing significantly faster than the low ball speed group. They were also found to impact the ball closer to the centre of the club face than the low ball speed group. For the X Factor angle the high ball speed group were found to have a greater angle at early and mid downswing and ball contact, suggesting the benefit of maintaining a large X Factor angle generating high ball speed. The high ball speed group also utilised greater flexion of the shoulders during the backswing and early in the downswing, which lead to their greater shoulder angular velocity. The high ball speed group also utilised less internal/external rotation of the shoulder which was likely to aid in the optimal orientation of the club face at ball contact. They were also found to extend their left arms more at early backswing creating a greater arc for the club head to travel through and therefore generating greater velocity. The importance of hip movement in distinguishing between the high and low ball speed groups was indicated by the large effect sizes evident between the group for right hip abduction/adduction angle at early and mid downswing and at ball contact. The high ball speed group utilised a greater range of right hip extension and abduction which is thought to have contributed to their centre of pressure being more towards the front foot at early downswing. This is believed to have benefited the golfers as greater weight transfer during the downswing allows more force to be generated by their body in the direction of the target. Subsequently, this greater force generated by the body in the direction of the target can be transferred to the club head to allow greater ball speed generation. No differences were evident between the groups for the golf club kinematics examined. Two mechanisms are proposed to explain the greater generation of ball speed in the high ball speed group (stretch shortening cycle and the impulse momentum relationship) and these are discussed in relation to the results for the individual joint kinematics.

5.2 Practical Implications

It is likely that having a large X Factor angle at the top of the backswing, and then maintaining that large X Factor angle during the downswing could benefit golfers in increasing their ball launch velocity when hitting with the 5 iron club for maximum distance. It could benefit golfers to increase their shoulder flexion during the backswing to allow greater generation of shoulder angular velocity and also by increasing shoulder flexion at ball contact the arc the club head travels through increases and as a result the club head velocity can increase. By minimising the longitudinal rotation of the club head during the swing through minimising the internal/external rotation of the shoulders it is possible to aid the optimal orientation of the club face at ball contact. In relation to the arms, greater ball velocity may be generated by maintaining the left arm as straight as possible throughout the swing, as this would increase the arc the club head travels through and therefore increase its velocity. A greater transfer of weight from the back to the front foot from early downswing through to ball contact brought about by greater movement of the hips in the direction of the target and a greater extension of the right hip, allows greater force generation in the direction of the target which can be transferred to the club to produce greater ball velocity.

6 Conclusion

The biomechanical performance determining factors of the 5 iron golf swing when hitting for maximum distance were identified through analysis of the joint kinematics and weight transfer of the skilled (high ball speed group) and lesser (low ball speed group) golfers. No significant differences were evident between the two groups for the club kinematics examined. The high ball speed group took less time to complete their downswing than the low ball speed group and contacted the ball closer to the centre of the club. In general, the high ball speed group utilised a greater range of movement in the shoulders and hips leading to greater angular velocities at these joints and subsequently greater club head and ball speeds. The high ball speed group also utilised greater shoulder flexion and elbow extension to create a greater arc for the club head to travel through thus generating greater club head speed. The importance of hip movement in distinguishing between the high and low ball speed groups was indicated by the large effect sizes evident between the high and low ball speed groups for a number of hip measurements. These differences in hip movement between the groups is thought to have contributed to the high ball speed groups centre of pressure being more towards the front foot at early downswing than the low ball speed group.

Additionally, results from the present study allowed for the general description of the joint actions of the 5 iron golf swing when hitting for maximum distance.

7 Future Research

- The present study statistically identified a number of very important biomechanical performance determining factors when hitting for maximum distance with the 5 iron golf club. Future research should investigate the best coaching/instructional methods for changing these performance determining factors and the subsequent effect of these changes on performance (ball speed).

- In terms of identifying the biomechanical performance determining factors for a 5 iron club, or in fact any iron club, it is clear that there is a dearth of research. Future research should therefore address this.

- Previous research has generally examined the golf swing at the events of take away, top of backswing and ball contact, the present study illustrates the benefit of examining more events as important significant differences between the two groups were established and therefore future studies should include more swing events in their research.

- The present study discussed the possible inappropriate use of handicap to group participants as handicap is calculated from overall playing (including driving, chipping and putting) and proposed that grouping by ball speed may be more suitable in research when examining one particular aspect of the golf game.

- Future research should aim to combine kinematic and kinetic analysis of the golfer and club, as in the present study, to gain a more complete understanding of the golf swing.

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9 Appendix

Appendix A Ethics Application

Dublin City University

RESEARCH ETHICS COMMITTEE

APPLICATION FOR APPROVAL OF A PROJECT INVOLVING HUMAN PARTICIPANTS

Application No. *(office use only)* DCUREC/2007/ ☐☐☐

Period of Approval *(office use only)* ....../....../...... to ....../....../....

This application form is to be used by researchers seeking ethics approval for individual projects and studies.

The **signed original and an electronic copy** of your completed application must be submitted to the DCU Research Ethics Committee. *Applications must be completed on the form; answers in the form of attachments will not be accepted, except where indicated. No handwritten applications will be accepted.* **Research must not commence until written approval has been received from the Research Ethics Committee.**

PROJECT TITLE **Biomechanical analysis of the golf swing.**

PRINCIPAL INVESTIGATOR(S) **Dr. Kieran Moran**

Guidelines to Applicants

1.1 PRINCIPAL INVESTIGATOR(S): *Supervisors and co-supervisors of student projects are Principal Investigators. PhD and Doctoral students can be listed as Investigators.*

2.0 PROJECT OUTLINE: *Provide a brief outline of the project, aims, methods, duration, funding, profile of participants and proposed interaction with them. This description must be in everyday language that is free from jargon. Please explain any technical terms or discipline-specific phrases.*

2.1 LAY DESCRIPTION: *Provide a brief outline of the project, including what participants will be required to do. This description must be in everyday language which is free from jargon. Please explain any technical terms or discipline-specific phrases. (No more than 300 words).*

2.2 AIMS OF AND JUSTIFICATION FOR THE RESEARCH: *State the aims and significance of the project (approx. 400 words). Where relevant, state the specific hypothesis to be tested. Also please provide a brief description of current research, a justification as to why this research should proceed and an explanation of any expected benefits to the community.* ***NB – all references cited should be listed in an attached bibiliography.***

2.3 PROPOSED METHOD: *Provide an outline of the proposed method, including details of data collection techniques, tasks participants will be asked to do, the estimated time commitment involved, and how data will be analysed. If the project includes any procedure which is beyond already established and accepted techniques please include a description of it. (No more than 400 words.)*

2.4 PARTICIPANT PROFILE: *Provide number, age range and source of participants. Please provide a justification of your proposed sample size. Please provide a justification for selecting a specific gender.*

2.5 MEANS BY WHICH PARTICIPANTS ARE TO BE RECRUITED: *Please provide specific details as to how you will be recruiting participants. How will people be told you are doing this research? How will they be approached and asked if they are willing to participate? If you are mailing to or phoning people, please explain how you have obtained their names and contact details. This information will need to be included in the plain language statement. If a recruitment advertisement is to be used, please ensure you attach a copy to this application.*

3.3 POTENTIAL RISKS TO PARTICIPANTS AND RISK MANAGEMENT PROCEDURES*: Identify, as far as possible, all potential risks to participants (physical, psychological, social, legal or economic etc.), associated with the proposed research. Please explain what risk management procedures will be put in place.*

3.6 ADVERSE/UNEXPECTED OUTCOMES: *Please describe what measures you have in place in the event that there are any unexpected outcomes or adverse effects to participants arising from involvement in the project.*

3.7 MONITORING: *Please explain how you propose to monitor the conduct of the project (especially where several people are involved in recruiting or interviewing, administering procedures) to ensure that it conforms with the procedures set out in this application. In the case of student projects please give details of how the supervisor(s) will monitor the conduct of the project.*

3.8 SUPPORT FOR PARTICIPANTS: *Depending on risks to participants you may need to consider having additional support for participants during/after the study. Consider whether your project would require additional support, e.g., external counseling available to participants. Please advise what support will be available.*

4.0 INVESTIGATORS' QUALIFICATIONS, EXPERIENCE AND SKILLS: *List the academic qualifications and outline the experience and skills relevant to this project that the researchers and any supporting staff have in carrying out the research and in dealing with any emergencies, unexpected outcomes, or contingencies that may arise.*

5.2 HOW WILL THE ANONYMITY OF THE PARTICIPANTS BE RESPECTED? *Please bear in mind that where the sample size is very small, it may be impossible to guarantee anonymity/confidentiality of participant identity. Participants involved in such projects need to be advised of this limitation.*

5.3 LEGAL LIMITATIONS TO DATA CONFIDENTIALITY: *Participants need to be aware that confidentiality of information provided can only be protected within the limitations of the law - i.e., it is possible for data to be subject to subpoena, freedom of information claim or mandated reporting by some professions. Depending on the research proposal you may need to specifically state these limitations.*

6.0 DATA/SAMPLE STORAGE, SECURITY AND DISPOSAL: *For the purpose of this section, "Data" includes that in a raw or processed state (e.g. interview audiotape, transcript or analysis). "Samples" include body fluids or tissue samples.*

8.0 PLAIN LANGUAGE STATEMENT: *Written information in plain language that you will be providing to participants, outlining the phases and nature of their involvement in the project and inviting their participation. Please note that the language used must reflect the participant age group and corresponding comprehension level.*

9.0 INFORMED CONSENT FORM: *This is a very important document that should be addressed by participants to researchers, requiring participants to indicate their consent to specific statements, and give their signature.*

FOR FURTHER INFORMATION AND NOTES ON THE DEVELOPMENT OF PLAIN LANGUAGE STATEMENTS AND INFORMED CONSENT FORMS, PLEASE CONSULT THE DCU REC WEBSITE: WWW.DC.IE/RESEARCH/ETHICS

1. ADMINISTRATIVE DETAILS

THIS PROJECT IS:
(tick as many as apply)

☐ Research Project
☐ Practical Class
☒ Student Research Project
(please give details)
  ☒ Masters ☐ Undergraduate
  ☐ PhD

☐ Funded Consultancy
☐ Clinical Trial
☐ Other - *Please Describe:*

Project Start Date: 1/4/07 **Project End date: 1/10/07**

1.1 INVESTIGATOR CONTACT DETAILS *(see Guidelines)*

PRINCIPAL INVESTIGATOR(S):

TITLE	*SURNAME*	*FIRST NAME*	*PHONE*	*FAX*	*EMAIL*

OTHER INVESTIGATORS:

TITLE	*SURNAME*	*FIRST NAME*	*PHONE*	*FAX*	*EMAIL*
Ms.	Aoife	Healy	01-7008470		aoife.healy26@mail.dcu.ie

FACULTY/DEPARTMENT/SCHOOL/ CENTRE:

1.2 WILL THE RESEARCH BE UNDERTAKEN ON-SITE AT DUBLIN CITY UNIVERSITY?

☒ YES ☐ NO *(If NO, give details of off-campus location.)*

1.3 IS THIS PROTOCOL BEING SUBMITTED TO ANOTHER ETHICS COMMITTEE, OR HAS IT BEEN PREVIOUSLY SUBMITTED TO AN ETHICS COMMITTEE?)

☐ YES ☒ NO *(If YES, please provide details and copies of approval(s) received etc.)*

DECLARATION BY INVESTIGATORS

The information contained herein is, to the best of my knowledge and belief, accurate. I have read the University's current research ethics guidelines, and accept responsibility for the conduct of the procedures set out in the attached application in accordance with the guidelines, the University's policy on Conflict of Interest and any other condition laid down by the Dublin City University Research Ethics Committee or its Sub-Committees. I have attempted to identify all risks related to the research that may arise in conducting this research and acknowledge my obligations and the rights of the participants.

If there any affiliation or financial interest for researcher(s) in this research or its outcomes or any other circumstances which might represent a perceived, potential or actual conflict of interest this should be declared in accordance with Dublin City University policy on Conflicts of Interest.

I and my co-investigators or supporting staff have the appropriate qualifications, experience and facilities to conduct the research set out in the attached application and to deal with any emergencies and contingencies related to the research that may arise.

Signature(s):

Principal investigator(s): ____________________________ ____________________________

Print name(s) in block letters: ____________________________ ____________________________

Date: ____________________________ ____________________________

2. PROJECT OUTLINE

2.1 LAY DESCRIPTION *(see Guidelines)*

Golf is a popular sport worldwide; it is played by 10-20% of the adult population in most countries. There is a limited amount of information on the movement of the golfer or the golf club during the golf swing. Therefore there is a need to investigate this.

Participants will visit the Biomechanics lab in DCU and perform 20 golf swings on a once off basis. Participants will be required to dress in shorts and perform their golf swings hitting the ball into a net. They will be required to have reflective markers (spheres) attached to a number of sites on their body with double sided tape. The participants' movements will be recorded by a 12 camera motion analysis system which is used to determine the movement of the limbs. The movement of the golf club will be recorded by a movement sensor attached to the shaft of the golf club and movement sensors on the ground.

2.2 AIMS OF AND JUSTIFICATION FOR THE RESEARCH *(see Guidelines)*

Aim 1: To compare and contrast the movement patterns of low handicap (<5) and high handicap (>10) golfers.

Brief Background:

McLaughlin and Best (1994) believed that although there is a high volume of literature relating to the golf swing, the application of scientific quantitative method to golf is limited. Farrally et al. (2003) pointed out that recent research hasn't made a significant advance on the work of Cochran and Stobbs (1968). They believe that we are a long way from understanding the complex movement pattern of the golf swing. This study will add to the limited scientific quantitative data on the golf swing. There is in addition little research detailing the kinematics of the golf club during a golf swing. Club head velocity is usually the only measurement of the club that is recorded. This study aims to detail the kinematics of the golf club during the golf swing using a novel sensor placed on the golf club shaft.

2.3 PROPOSED METHOD *(see Guidelines)*

40 participants will be asked to visit the Biomechanics lab once. Participants' skill level will be determined by their self reported handicap and they will be assigned to either the low handicap (<5) or high handicap (>10) group.

39 reflective markers will be placed over selected anatomical landmarks on the participants. The use of reflective markers will not cause any disturbance to the golf swing or cause any discomfort to the participants. A Vicon motion analysis system (Oxford Metricx, UK) will record the motion of the markers. The system consists of twelve cameras placed around the golf swing area, which emit infrared light that is reflected back to the cameras by the markers. This allows calculation of the co-ordinate data of the markers and hence the subjects body segments. A MTx (miniature inertial 3 DOF Orientation Tracker) sensor (Xsens Technologies, Netherlands) placed on the shaft of the golf club will record the movements of the golf club throughout the swing.

After performing their usual pre-game warm-up participants will be required to perform 20 golf swings with a 5 iron club, hitting the ball into a net. The subjects will be hitting the ball from a golf swing analysis mat located on the ground (Golftek Inc., USA) which will record ball launch and golf swing data. The measurements obtained form the recordings will be analysed and movement kinematics calculated. The participants will then perform their usual post-game warm down.

The session will take no longer than 1 hour.

While the participants will be recorded with cameras, these cameras will only record the reflective markers and not the features of the participants.

2.4 PARTICIPANT PROFILE *(see Guidelines)*

Participants will be sourced from the University and from local golf clubs. 20 low handicap (<5) and 20 high handicap golfers (>10) will be recruited. All participants must be male, right handed and injury free.

Egret et al. (2006) found differences in the kinematics of the golf swing between men and women. Therefore, to increase homogeniality only one gender will be recruited. Males will be recruited in this instance because there appears to be more male golfers in DCU, than female. A statistical power analysis indicated that 17 participants will be needed in each group. Allowing for drop out and possible incomplete data sets 20 participants will be recruited.

2.5 MEANS BY WHICH PARTICIPANTS ARE TO BE RECRUITED *(see Guidelines)*

2.6 PLEASE EXPLAIN WHEN, HOW, WHERE, AND TO WHOM RESULTS WILL BE DISSEMINATED, INCLUDING WHETHER PARTICIPANTS WILL BE PROVIDED WITH ANY INFORMATION AS TO THE FINDINGS OR OUTCOMES OF THE PROJECT?

2.7 OTHER APPROVALS REQUIRED *Has permission to gain access to another location, organisation etc. been obtained?. Copies of letters of approval to be provided when available.*

☐ YES ☐ NO ☒ NOT APPLICABLE

(If YES, please specify from whom and attach a copy. If NO, please explain when this will be obtained.)

2.8 HAS A SIMILAR PROPOSAL BEEN PREVIOUSLY APPROVED BY THE REC?

☐ YES ☒ NO

(If YES, please state both the REC Application Number and Project Title)

3. RISK AND RISK MANAGEMENT

3.1 ARE THE RISKS TO SUBJECTS AND/OR RESEARCHERS ASSOCIATED WITH YOUR PROJECT GREATER THAN THOSE ENCOUNTERED IN EVERYDAY LIFE?

☒ YES ☐ NO *If YES, this proposal will be subject to full REC review*

If NO, this proposal may be processed by expedited administrative review

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3.2 DOES THE RESEARCH INVOLVE:

	YES	NO
• use of a questionnaire? (attach copy)?	☒	☐
• interviews (attach interview questions)?	☐	☒
• observation of participants without their knowledge?	☐	☒
• participant observation (provide details in section 2)?	☒	☐
• audio- or video-taping interviewees or events?	☐	☒
• access to personal and/or confidential data (including student, patient or client data) without the participant's specific consent?	☐	☒
• administration of any stimuli, tasks, investigations or procedures which may be experienced by participants as physically or mentally painful, stressful or unpleasant during or after the research process?	☐	☒
• performance of any acts which might diminish the self-esteem of participants or cause them to experience embarrassment, regret or depression?	☐	☒
• investigation of participants involved in illegal activities?	☐	☒
• procedures that involve deception of participants?	☐	☒
• administration of any substance or agent?	☐	☒
• use of non-treatment of placebo control conditions?	☐	☒
• collection of body tissues or fluid samples?	☐	☒
• collection and/or testing of DNA samples?	☐	☒
• participation in a clinical trial?	☐	☒
• administration of ionising radiation to participants?	☐	☒

3.3 POTENTIAL RISKS TO PARTICIPANTS AND RISK MANAGEMENT PROCEDURES *(see Guidelines)*

The event being carried out is a standard golf swing activity. It will place stress on the body above that of normal daily activities (e.g. walking). However, as the participants will have regurly performed this action on a weekly/monthly basis there is no increased risk of injury than they are usually accustomed too. To limit the small potential for injury, the participants will undertake a warm up prior to the activity and a warm down after the activity. As they are performing the golf swing in a lab setting they will hit the golf balls into heavy duty golf netting (Tildenet, Ireland) which will prevent the ball from rebounding back and injuring the participant.

As with all exercise testing there is a risk of health implications such as a risk of Myocardial Infarction (heart attack), heart arrhythmias and even death. The risk of these however will be very small and reduced even further by excluding subjects with a history of heart disease or other medical conditions that may contraindicate exercise participation.

3.4 ARE THERE LIKELY TO BE ANY BENEFITS (DIRECT OR INDIRECT) TO PARTICIPANTS FROM THIS RESEARCH?

☐ YES ☒ NO *(If YES, provide details.)*

3.5 ARE THERE ANY SPECIFIC RISKS TO RESEARCHERS? *(e.g. risk of infection or where research is undertaken at an off-campus location)*

☐ YES ☒ NO *(If YES, please describe.)*

3.6 ADVERSE/UNEXPECTED OUTCOMES *(see Guidelines)*

3.7 MONITORING *(see Guidelines)*

3.8 SUPPORT FOR PARTICIPANTS *(see Guidelines)*

3.9 DO YOU PROPOSE TO OFFER PAYMENTS OR INCENTIVES TO PARTICIPANTS?

☐ YES ☒ NO *(If YES, please provide further details.)*

4. INVESTIGATORS' QUALIFICATIONS, EXPERIENCE AND SKILLS *(Approx. 200 words – see Guidelines)*

5. CONFIDENTIALITY/ANONYMITY

5.1 WILL THE IDENTITY OF THE PARTICIPANTS BE PROTECTED?

☒ YES ☐ NO *(If NO, please explain)*

IF YOU ANSWERED YES TO 5.1, PLEASE ANSWER THE FOLLOWING QUESTIONS:

5.2 HOW WILL THE ANONYMITY OF THE PARTICIPANTS BE RESPECTED? *(see Guidelines)*

5.3 LEGAL LIMITATIONS TO DATA CONFIDENTIALITY: *(Have you included appropriate information in the plain language statement and consent form? See Guidelines)*

☒ YES ☐ NO *(If NO, please advise how participants will be advised .)*

6 DATA/SAMPLE STORAGE, SECURITY AND DISPOSAL *(see Guidelines)*

6.1 HOW WILL THE DATA/SAMPLES BE STORED? *(The REC recommends that all data be stored on campus)*

Stored at DCU ☒
Stored at another site ☐ **(***Please explain where and for what purpose)*

6.2 WHO WILL HAVE ACCESS TO DATA/SAMPLES?

Access by named researchers only ☒
Access by people other than named researcher(s) ☐ **(***Please explain who and for what purpose)*

Other : ☐ **(***Please explain)*

6.3 IF DATA/SAMPLES ARE TO BE DISPOSED OF, PLEASE EXPLAIN HOW, WHEN AND BY WHOM THIS WILL BE DONE?

7. FUNDING

7.1 HOW IS THIS WORK BEING FUNDED?

The work is being funded by Enterprise Ireland under the Sister Project run by Trinity College Dublin.

7.2 PROJECT GRANT NUMBER (If relevant and/or known)

7.3 DOES THE PROJECT REQUIRE APPROVAL BEFORE CONSIDERATION FOR FUNDING BY A GRANTING BODY?

☐ YES ☒ NO

7.4 HOW WILL PARTICIPANTS BE INFORMED OF THE SOURCE OF THE FUNDING?

They will not be informed about the source of funding.

8. PLAIN LANGUAGE STATEMENT *(Approx. 400 words – see Guidelines)*

Attached

9. INFORMED CONSENT FORM *(Approx. 300 words – see Guidelines)*

Attached

10. CHECKLIST

Please check that all supplementary information is attached to your application (in both hard and soft copy). If questionnaire or interview questions are submitted in draft form, a copy of the final documentation must be submitted for final approval when available.

	ATTACHED	NOT APPLICABLE
Bibliography	☒	☐
Recruitment advertisement	☒	☐
Plain language statement/Information Statement	☒	☐

Informed Consent form	☒		☐
Evidence of external approvals related to the research	☐		☒
Questionnaire	☐ draft	☒ final	☐
Interview Schedule	☐ draft	☐ final	☒
Debriefing material	☐		☒
Other	☐		☒

Please note:

1. Any amendments to the original approved proposal must receive prior REC approval.

2. As a condition of approval investigators are required to document and report immediately to the Secretary of the Research Ethics Committee any adverse events, any issues which might negatively impact on the conduct of the research and/or any complaint from a participant relating to their participation in the study

Please submit the **signed original, plus an electronic copy** of your completed application to:
Ms. Fiona Brennan, Research Officer, Office of the Vice-President for Research
(fiona.brennan@dcu.ie, Ph. 01-7007816)

Appendix B Email and poster recruitment advertisements

Dear _________,

I am a postgraduate student in the Department of Health and Human Performance at Dublin City University under the supervision of Dr. Kieran Moran. I am currently conducting research on the movement pattern of the golfer and the golf club during the golf swing.

We are looking for volunteers to participate in the study. Volunteers must be male golfers, right handed, with a handicap of <5 or >10.

As a participant in this study, you would be asked to perform 20 golf swings with a 5 iron golf club in a laboratory setting. This will be preceeded by a warm up and followed by a warm down. Your performance will be recorded by high speed cameras, a sensor placed on the shaft of the golf club, and sensors in the mat from which the golf balls will be hit. The total duration, including the set up, the warm up, the test, and the warm down, should take no more than 60mins.

For more information about this study, or to volunteer for this study,
please contact:
Aoife Healy,
Department of Health and Human Performance,
at
01-7008470
Email: aoife.healy26@mail.dcu.ie

Department of Health and Human Performance

Dublin City University

PARTICIPANTS NEEDED FOR RESEARCH IN GOLF

We are looking for volunteers to take part in a study on the movement pattern of the golfer and the golf club during the golf swing. Volunteers must be **male**, **right handed** and have a **handicap of <5 or 10-18**.

> As a participant in this study, you would be asked to perform 25 golf swings with your own 5 iron golf club in a laboratory. This will be preceeded by a warm up and followed by a warm down. Your performance will be recorded by high speed cameras, a sensor placed on the shaft of the golf club, and sensors in the mat from which the golf balls will be hit. The total duration, including the set up, the warm up, the test, and the warm down, should take no more than 60mins.

For more information about this study, or to volunteer for this study, please contact:
Aoife Healy
Department of Health and Human Performance
at
01-7008470
Email: aoife.healy26@mail.dcu.ie

Appendix C Plain Language Statement

Plain Language Statement

I. **Introduction to the Research Study:**

Title: Biomechanical Analysis of the Golf Swing

Department: School of Health and Human Performance, Faculty of Science and Health.

Investigators: Aoife Healy (01- 7008470) and Dr Kieran Moran (01-7008011).

II. **Details of what involvement in the Research Study will require:**
You will be required to perform 20 golf swings with a 5 iron golf club. This will be preceeded by a warm up and followed by a cool down. Your performance will be recorded by high speed cameras, a sensor placed on the shaft of the golf club, and sensors in the mat off which the golf balls will be hit. The total duration, including the set up, the warm up, the test, and the cool down, should take no more than 60mins.

III. **Potential risks from involvement in the Research Study:**
The event being carried out is a standard golf swing activity. It will place stress on the body above that of normal daily activities (e.g. walking). However, as you will have regurly performed this action on a weekly/monthly basis there is no increased risk of injury than you are usually accustomed too. To limit the small potential for injury, you will undertake a warm up prior to the activity and a warm down after the activity.
As with all exercise testing there is a risk of health implications such as a risk of heart attack and even death. The risk of these however will be very small and reduced even further by excluding participants with a history of heart disease or other medical conditions that may increase the risk of injury associated with exercise participation.

IV. **Benefits from involvement in the Research Study:**
There are no benefits to the participants from the study, however, participants will be provided with the results of the study.

V. **Confidentiality of data:**
Dublin City University will protect all the information about you and your part in this study within the limitations of the law. Your identity and personal information will not be revealed, published or used in future studies and all data will be destroyed five years after collection. However, the study's findings will form the basis of a postgraduate thesis.

VI. **Destruction of data:**
All data collected for this research study will be destroyed after five years.

VII. **Involvement in the Research Study is voluntary**

If you do agree to take part in the study, you may withdraw at any point. There will be no penalty if you withdraw before you have completed all stages of the study. Involvement/non-involvement in this study will not affect your relationship with DCU in any way.

If participants have concerns about this study and wish to contact an independent person, please contact:

The Secretary, Dublin City University Research Ethics Committee, c/o Office of the Vice-President for Research, Dublin City University, Dublin 9. Tel 01-7008000

Appendix D Physical Activity Readiness Questionnaire

Physical Activity Readiness Questionnaire (Par-Q)

For most people physical activity should not pose any problem or hazard. The Par-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them.

Common sense is your best guide in answering these questions. Please read them carefully and check **YES** or **NO** opposite the question if it applies to you. If a question is answered with **YES**, ***please use the available space to explain your answer and give additional details.***

1. Has a doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor? ☐**YES** ☐ **NO**

2. Do you feel pain in your chest when you do physical activity? ☐**YES** ☐ **NO**

3. In the past month, have you had chest pain when you were not doing physical activity? ☐**YES** ☐ **NO**

4. Do you lose your balance because of dizziness or do you ever lose consciousness? ☐**YES** ☐ **NO**

5. Do you have a bone or joint problem that could be made worse by a change in your physical activity? ☐**YES** ☐ **NO**

6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition? ☐**YES** ☐ **NO**

7. Do you know of any other reason why you should not do physical activity? ☐**YES** ☐ **NO**

Name: ______________________________

Signature: ___________________________

Date: ______________________________

Appendix E Informed consent form

DUBLIN CITY UNIVERSITY
RESEARCH - INFORMED CONSENT FORM
School of Health and Human Performance

Investigators: Aoife Healy B.Sc. and Dr. Kieran Moran

I. Research Study Title: Biomechanical Analysis of the Golf Swing

II. Introduction to this study:
Golf is a popular sport worldwide; it is played by 10-20% of the adult population in most countries. There is a limited amount of information on the movement of the golfer or the golf club during the golf swing. Therefore there is a need to investigate this.

III. I am being asked to participate in this research study. The study has the following purposes:
(1) To compare and contrast the movement patterns of low handicap and high handicap golfers.

IV. Confirmation of particular requirements as highlighted in the Plain Language Statement:

Please complete the following (Circle Yes or No for each question)
Have you read or had read to you the Plain Language Statement
Yes/No
Do you understand the information provided?
Yes/No
Have you had an opportunity to ask questions and discuss this study?
Yes/No
Have you received satisfactory answers to all your questions?
Yes/No

V. This research study will take place at the:
Biomechanics Laboratory, School of Health and Human Performance, Dublin City University

VI. This is what will happen during the research study:
You will be required to perform 20 golf swings with a 5 iron golf club club. This will be preceeded by a warm up and followed by a warm down. 39 reflective markers will be placed on selected sites on your body. Your performance will be recorded by high speed cameras, a sensor placed on the shaft of the golf club, and sensors in the mat from which the golf balls will be hit. The total duration, including the set up, the warm up, the test, and the warm down, should take no more than 60mins.

VIII. My confidentiality will be guarded:
Dublin City University will protect all the information about me and my part in this study within the limitations of the law. My identity or personal information, will not be revealed, published or used in future studies and all data will be destroyed five years after collection. The study findings will form the basis for preparation of a postgraduate thesis, academic publications, conference papers and other scientific publications.

IX. If I have questions about the research project, I am free to call:
Dr. Kieran Moran at telephone no.: 01 7008011

X. Taking part in this study is my decision. If I do agree to take part in the study, I may withdraw at any point. There will be no penalty if I withdraw before I have completed all stages of the study. Involvement/non-involvement in this study will not affect your relationship with DCU in any way.

XI. Signature:
I have read and understood the information in this form. My questions and concerns have been answered by the researchers, and I have a copy of this consent form. Therefore, I consent to take part in this research project entitled:

Signed:
____

Name in block capitols:
____

Witness:
____

Date:
____

This Informed Consent form was officially approved by the DCU Research Ethics Committee on:

____/____/____

Official DCU Stamp:

Appendix F Anthropometric data required for Vicon motion analysis system

Subject measurements for Vicon motion analysis system

Mass: The mass of the subject in kilograms

Height: The height of the subject in centimetres.

Leg length: Measured from the ASIS to the medial malleolus.

Knee width: Measurement of the knee width about the flexion axis.

Ankle width: Measurement of the ankle width about the medial and lateral malleoli.

Shoulder offset: The vertical distance from the centre of the glenohumeral joint to the marker on the acromion clavicular joint.

Elbow width: The distance between the medial and lateral epicondyles of the humerus.

Wrist width: It is the distance between the anterior (palm side) and posterior (back) side of the wrist in the anatomical position.

Hand thickness: The distance between the dorsal and palmar surfaces of the hand.

Appendix G Definitions for marker placement on the participant

GOLFER model (45 markers - 41 markers on golfer, 4 on golf club)

Head markers
LFHD – left temple
RRHD – right temple
LBHD – back of head roughly at same level as the front head markers
RBHD - back of head roughly at same level as the front head markers

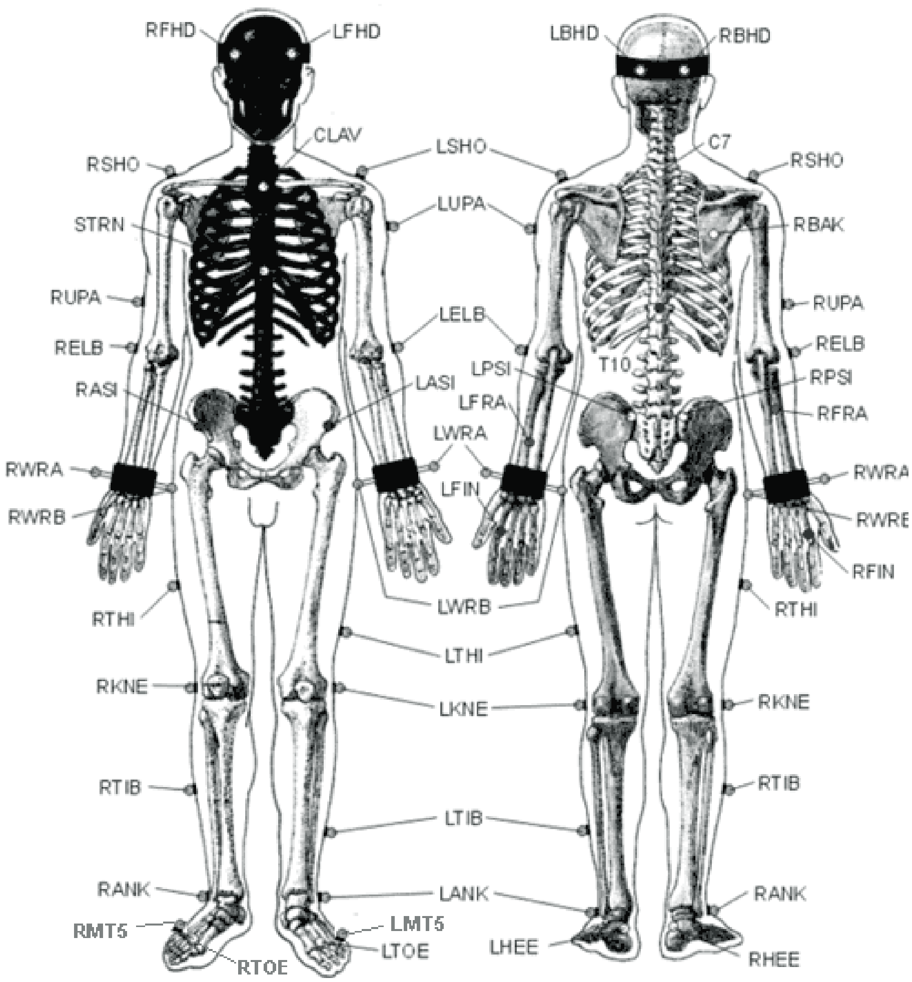
Torso markers
C7 – spinous process of the 7th cervical vertebrae. C7 is most prominent vertebra, felt at the base of the neckwhen the chin is rested on the chest.
T10 - spinous process of the 10th thoracic vertebrae. Approximately in the centre of the spine, more or less at the same height as the lower end of the breast bone. The marker position is located by finding the inferior angle of the scapula. Move horizontally across to the vertebrae, this should be T7. Get the subject to slump forward and count down to T10.
CLAV – jugular notch where the clavicles meet the sternum
STRN – Xiphoid process of the sternum
RBAK – middle of the right scapula

Arm markers
LSHO – Acromio-clavicular joint
LUPA – between the shoulder and elbow markers (placed asymmetrically with RUPA)
LELB – lateral epicondyle approximating elbow joint axis
LFRA – between elbow and the wrist markers (placed asymmetrically with RFRA)
LWRA – wrist bar thumb side. Bar should be just above the wrist joint. Care must be taken so that the band does not move around the wrist during movement.
LWRB – wrist bar pinkie side
LFIN – just below the head of the second metacarpal
Pelvis markers
LASI – placed directly over the left anterior superior iliac spine
RASI - placed directly over the right anterior superior iliac spine
LPSI – placed directly over the left posterior superior iliac spine
RPSI - placed directly over the right posterior superior iliac spine (slight bony prominences that can be felt immediately below the dimples)

Leg markers
LTHI – placed on the lower lateral 1/3 of the thigh, just below the swing of the hand, although height is not critical. (The antero-posterior placement of the marker is critical for correct alignment of the knee flexion axis. Try to keep the marker off the belly of the muscle, but place the thigh marker at least two marker diameters proximal of the knee marker. Adjust the position of the marker so that it is aligned in the plane that contains the hip and knee joint centres and the knee flexion/extenxion axis.) (placed asymmetrically with **RTHI**)

LKNE – lateral epicondyle of the knee (the point about which the lower leg appears to rotate)
LTIB – similar to the thigh markers, these are placed over the lower 1/3 of the shank to determine the alignment of the ankle flexion axis. (should line in the plane that contains the knee and ankle joint centres. The ankle joint axis between the medial and lateral malleoli, is externally rotated by between 5 and 15 degrees with respect to the knee flexion axis. The placement of the shank marker should reflect this.) (placed asymmetrically with **RTIB**)
LANK – lateral malleolus
LHEE – placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker.
LTOE – placed over the 2nd metatarsal head
LMT5 - placed over the 5th metatarsal head

Golf Club
OBJ1 – Placed near the base of the grip on the golf shaft.
OBJ2 and **OBJ3** – spaced along the shaft of the golf club.
OBJ4 – placed on a solid metal bar at the top of the club shaft.



Appendix H Golftek Pro V Swing analyser measurement definitions

Golftek Pro V Analyser - Definitions

Ball speed – Horizontal speed of the ball ($m.s^{-1}$)

Clubhead speed – the speed the club was traveling in the impact area ($m.s^{-1}$)

Clubface Angle – the angle of the clubface at the moment of impact. This is expressed as an Open, Square or Closed angle. That angle is measured in 1 degree increments with relation to the target line.

Swingpath angle – the horizontal approach of the club moving into the impact zone, this zone is defined as the area 6" prior to impact up to the moment of impact. This angle is expressed as Straight, Inside-Out or Outside-In, and is measured in 2 degree increments. These angles are also in relation to the target line.

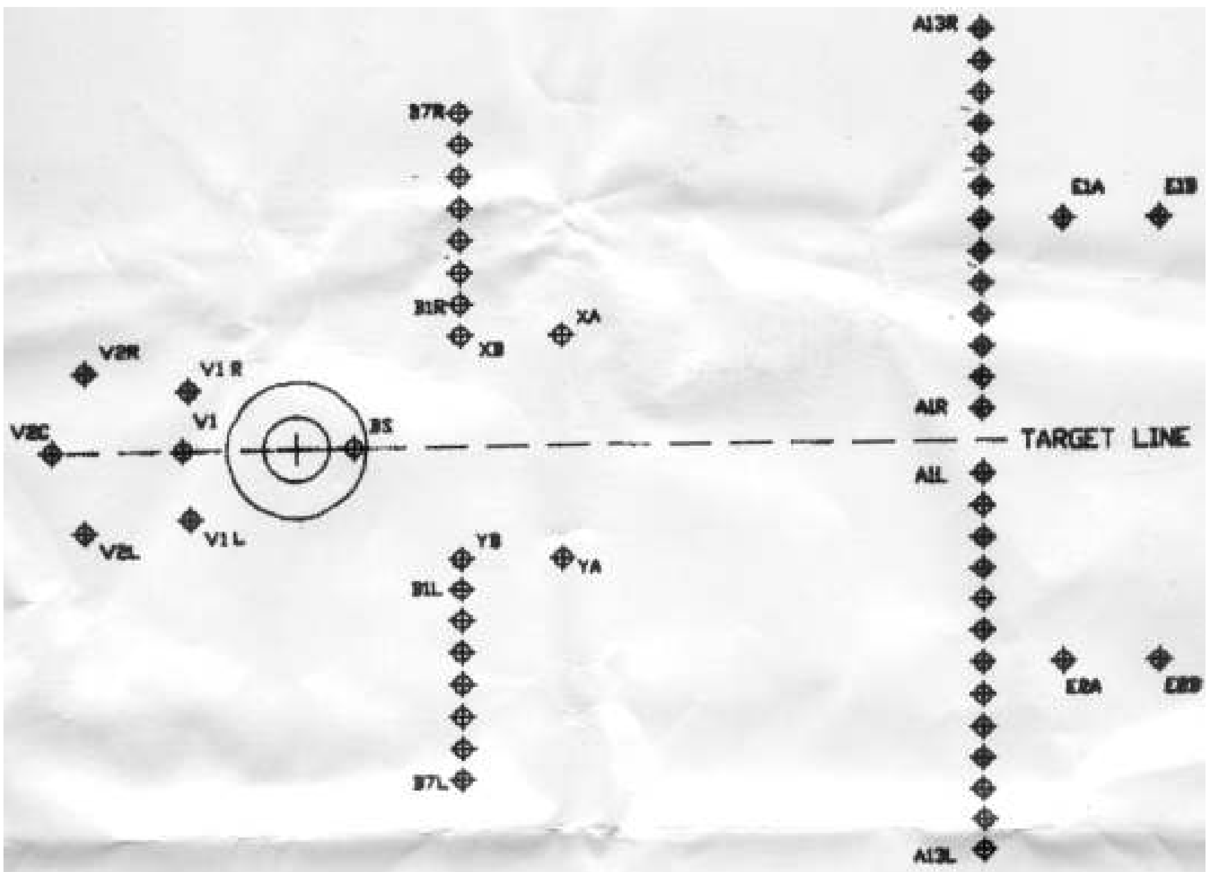
Impact – the indicates (in 0.25 inch increments) how far off-center the ball was struck.

Tempo – total time to complete the swing, from the moment of take away to the moment of impact (s).

Rotation – the measures how quickly the clubface is rotating (or rolling) through the impact area. This value is displayed in degrees per inch. Higher rotations rates indicate excessive rotation which could cause a loss of accuracy in the player's shots. Clubface rotation is affected by the player's wrist rotation and the flex of the shaft.

SHF (Solid Hit Factor) – the solid hit factor is a ratio of Clubhead Speed vs. Ball Velocity. Each club has an optimum SHF where the energy from the club is imparted to the ball with very little loss. In a Driver that number is 1.4 i.e. if the driver is traveling at 100mph when it strikes the ball, and the ball is struck on the exact sweet spot, the ball will then leave the clubhead at about 140mph. the number changes with the irons, the 5 iron is 1.3. The SHF is intended to be the basis for comparing how solid a person hits one club versus another.

Appendix I Golftek Pro V Swing analyser measurement calculations



All sensors are infra-red phototransistors and normally conduct a photocurrent because of the light provided by the overhead lamp. When the sensors are shadowed by a club or ball during the swing, the photocurrent is considerably decreases and this condition is detected using various computer scans during the swing. The sensors are connected to integrated circuit comparators which converts current changes into output voltage changes which are detected by a microprocessor within the system. In the standby mode between swings, the microprocessor and its counters are inactive. However, when a moving club passes over the enable sensor (E1A and E1B or E2A and E2B) at a speed faster than 10 mph, the electronic system starts to measure and process all the digital data.

1. Sensors E1A, E2A, E1B and End E2B are used to enable the circuitry.
2. Sensors YA, YB, XA, XB measure the Clubface Angle.
3. Sensors V1, V1L, V1R, V2, V2L, and V2R measure Ball Carry (Ball Velocity).
4. Sensors B1R - B7R measure Clubface Impact point for right handed golfers.
5. Sensor Line A1R - A13R and B1R - B7R measure right-hand Clubhead Speed and Path
6. Sensor B1L-B7L measure Clubface impact point for left-hand golfers.
7. Sensor Line A1L – A13L and B1L – B7L measure left-hand Clubhead Speed and Path.
8. Sensor BS is used to detect the ball on the tee.

Clubhead speed: A moving club first passes over the A line of sensors (26) and then the B line (16). Sensors in the A line start a counter in the processor and sensors in the B line stop the count. The formula:

$V = dfc/n$

is used to calculate clubhead speed. (d = distance between sensor line (7.16 inches), fc = clock frequency, n = final count)

Ball speed: This is measured in the same way as clubhead speed using the V1 sensors to start a counter and the V2 sensors to stop the count. The distance between V1 and V2 is 1.4 inches.

Clubface Angle: The clubface sensors at impact are XB and YB. A counter is initiated when the first of these two sensors is shaded and is stopped when the second is shaded. The tangent of clubface angle (θ) is:

$\tan^{-1} \theta = dc/z$

The count is a function of the horizontal distance the clubhead travels between the two sensors (dc), z = the distance between the XB and YB sensors (1.4 inches). The dc term is defined by:

$dc = vn/fc$

where v is the measured clubhead speed. Clubface angle is also calculated 1 inch before impact to allow us to determine clubhead rotation just prior to impact.

Note: If the X sensor is shaded first, clubface is closed; id the Y sensor is shaded first, clubface is open.

Swing path: The individual sensors in both the A line and the B line are spaced 0.25 inches apart. Since the distance between the two lines is 7.16 inches, each sensor is equivalent to 2 degrees of swing path. The value of swing path can be determined by the difference in the position of unshaded sensors in line B versus line A. For example, if line A shows sensors A9 – A13 unshaded, and the line B shows B3 – B7 unshaded, the club swing path would be 6 degrees outside- in.

Impact Point: The Prografix software has a club selection menu that includes club head size. Four types of irons and two types of woods can be selected. The average size for each type club has been pre-programmed into the processor. During the swing, the number of B line sensors shaded indicates the position of the toe of the club at impact with 0.25 inch accuracy. As club head size is known, the point of contact between ball and clubface can be calculated.

Appendix J Sample Data

Sample data for one participant from Pro V swing analyser

Club number	Club speed m/s	Ball speed m/s	Clubface (deg)	Swingpath (deg)	Impact	Tempo (sec)	Rot (deg/in)	SHF
5I	37.5	52.1	Open 5°	In-Out 2°	1.27cm- Heel	0.88	2	1.39
5I	37.5	51.5	Open 7°	In-Out 2°	1.91cm- Heel	0.87	2	1.37
5I	38.1	53.6	Open 4°	In-Out 2°	1.27cm- Heel	0.85	2	1.41
5I	38.4	50.3	Open 10°	In-Out 2°	1.91cm- Heel	0.84	2	1.31
5I	37.2	44.5	Open 8°	In-Out 2°	2.54cm- Heel	0.85	2	1.2
5I	37.8	53.6	Open 4°	In-Out 4°	1.27cm- Heel	0.84	1	1.42
5I	37.5	51.5	Open 8°	In-Out 2°	1.91cm- Heel	0.85	2	1.37
5I	37.8	52.1	Open 6°	In-Out 4°	1.91cm- Heel	0.83	2	1.38
5I	38.1	52.1	Open 7°	In-Out 2°	1.91cm- Heel	0.83	2	1.37
5I	38.1	51.8	Open 8°	In-Out 2°	1.91cm- Heel	0.84	2	1.36
5I	37.8	50.6	Open 8°	In-Out 2°	1.91cm- Heel	0.84	2	1.34
5I	38.1	54.3	Open 4°	In-Out 2°	1.91cm- Heel	0.85	2	1.42
5I	38.7	54.9	Open 3°	In-Out 2°	1.27cm- Heel	0.85	2	1.42
5I	38.4	53.9	Open 5°	In-Out 2°	1.27cm- Heel	0.87	2	1.4
5I	38.1	53.3	Open 5°	In-Out 2°	1.27cm- Heel	0.84	1	1.4

Sample centre of pressure in the direction of the shot (X axis) data calculated using macro for one participant.

File #	Trial #	TA	MB	LB	TB	ED	MD	BC	MF
Patient name: BF	1	58.81	85.96	91.50	83.70	41.85	52.91	50.81	32.21
Patient name: BF	2	51.91	81.27	87.98	80.30	45.65	60.68	49.54	29.87
Patient name: BF	3	56.76	83.55	89.03	81.74	40.43	57.29	48.73	36.32
Patient name: BF	4	54.16	86.35	93.11	86.01	39.91	46.01	33.83	14.12
Patient name: BF	5	52.27	85.17	90.08	83.92	37.77	45.40	33.45	12.90
Patient name: BF	6	60.58	55.55	56.77	76.66	85.73	85.31	85.53	83.90
Patient name: BF	7	58.27	88.99	91.73	86.87	44.02	47.02	44.37	24.74
Patient name: BF	8	55.21	83.65	89.05	83.55	43.05	53.32	47.11	34.19
Patient name: BF	9	55.40	81.80	86.39	80.38	43.81	55.18	45.99	24.50
Patient name: BF	10	54.84	83.66	86.17	83.36	43.65	53.62	46.12	26.96
Patient name: BF	11	61.35	84.47	91.96	84.96	41.27	52.92	41.27	24.44
Patient name: BF	12	48.05	83.22	86.06	78.36	40.71	49.13	39.03	20.64
Patient name: BF	13	55.16	81.29	87.15	76.65	41.03	56.71	44.88	28.56
Patient name: BF	14	61.13	88.71	92.69	87.99	48.33	47.56	41.78	22.80
Patient name: BF	15	57.14	86.15	91.59	84.82	46.96	59.13	45.54	23.18

Note: TA = Take away, MB = Mid backswing, LB = Late backswing, TB = Top of backswing, ED = Early downswing, MD = Mid downswing, BC = Ball contact, MF = Mid follow through.

Sample SPSS output - One way analyses of variance (ANOVA) used to assess differences between the groups for left knee angle at swing event 1

Univariate Analysis of Variance

Between-Subjects Factors

		N
Bspeed_G	1.00	15
	2.00	15

Descriptive Statistics

Dependent Variable: LKNEE_1

Bspeed_G	Mean	Std. Deviation	N
1.00	24.6877	6.59205	15
2.00	23.5411	6.06951	15
Total	24.1144	6.25321	30

Tests of Between-Subjects Effects

Dependent Variable: LKNEE_1

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	9.861(a)	1	9.861	.246	.624	.009
Intercept	17445.090	1	17445.090	434.530	.000	.939
Bspeed_G	9.861	1	9.861	.246	.624	.009
Error	1124.117	28	40.147			
Total	18579.068	30				
Corrected Total	1133.978	29				

a R Squared = .009 (Adjusted R Squared = -.027)

Parameter Estimates

Dependent Variable: LKNEE_1

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval		Partial Eta Squared
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound
Intercept	23.541	1.636	14.389	.000	20.190	26.892	.881
[Bspeed_G=1.00]	1.147	2.314	.496	.624	-3.593	5.886	.009
[Bspeed_G=2.00]	0(a)	.	.	.	.	.	.

a This parameter is set to zero because it is redundant.