COACH INFORMED BIOMECHANICAL ANALYSIS OF THE GOLF SWING

by

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Abstract

Assessing a coach's technical knowledge of a sporting technique can reveal key technical parameters directly associated with a successful performance. Biomechanical analysis of the key technical parameters can reveal information regarding golfer technique to support or provide new knowledge for golf coaching. However, there are few, if any, scientific studies that have used the content of golf coaches' knowledge to guide biomechanical investigation. Therefore, the purpose of this thesis was firstly to identify the key technical parameters that golf coaches associated with a successful golf swing and then to biomechanically analyse these parameters using appropriate data collection and analysis methods. The results of this thesis advance knowledge of golf biomechanics specifically to support future golf coaching.

Qualitative methods were used to determine golf coaches' perceptions of the key technical parameters based on the coaching-biomechanics interface. Five interlinked key technical parameters were identified in conjunction with six descriptors of the technical parameters. Furthermore, even though the swing was commonly analysed at key events, the coaches were also keen to consider the swing as a whole. On comparing the coaches' perceptions to the current golf biomechanical literature it was found that posture was not widely investigated and that it is linked to body rotation; therefore, both these parameters were selected for biomechanical analysis.

Posture included two sub-categories postural balance and postural kinematics which were measured for a group of low handicap golfers. The continuous data analysis technique, principal component analysis (PCA), identified core biomechanical differences in posture parameters and the extent to which golfers differed. This technique also revealed that differences between posture curves occurred throughout the swing. Further correlation analysis revealed strong relationships between the postural balance parameters, $\%COP_{M\text{-}L}$ and $\%COG_{M\text{-}L}$ PC1 scores. The magnitude of thorax flexion and thorax lateral bend throughout the swing was also correlated and deemed to influence body rotation. Moderately strong correlations were observed between the rate of change in thorax lateral bend and clubhead linear velocity.

Body rotation was shown to require 3D analysis, notably, X-factor. PCA also showed differences between golfers' body rotation parameters. Further, correlation analysis identified relationships between golfer posture and body rotation, notably between thorax flexion and upper thorax axial rotation. However, the correlations of body rotation parameters with measures of performance were weak.

Finally, a biomechanical report specifically for golf coaches was developed which aimed to provide feedback on the swing biomechanics describing the key technical parameters. A number of areas for future development in biomechanical reporting were identified.

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To all my family, thank you for being incredibly supportive and understanding, through what must have seemed an eternity for you, but I hope you know that your faith and confidence in me has made this possible. To Steve, thank you for being there for me in my moments of doubt and giving me the encouragement I needed to "just get it done!"

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Publications

Conference Proceedings:

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Smith, A.C., Roberts, J., and Forrester, S. (2013). Using principal component analysis to identify biomechanical features throughout the golf swing. Maths in Sport, Leuven, Belgium. (Oral communication)

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"If you need something to believe in, start with yourself"

Alyson Smith (quoted 5 minutes before my viva)

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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
6DOF	Six degrees of freedom
A-P	Anterior - Posterior
COG	Centre of gravity
COP	Centre of pressure
CV	Coefficient of variation
DOF	Degrees of Freedom
FJC	Functional joint centre
FPCA	Functional principal component analysis
FT	Follow-through
GA	Golf Academy
GCS	Global co-ordinate system
GP	Golf Club Professional
GRF	Ground reaction force
HPA	Horizontal swing plane angle
HSV	High speed video
IMP	Impact
LCS	Local co-ordinate system
MidBS	Mid-backswing
MidDS	Mid-downswing
MidFT	Mid-follow through
M-L	Medial - Lateral
N	National Coach
PC	Principal components
PCA	Principal component analysis
PGA	Professional Golf Association
POSE	Position and orientation
R	Regional Coach
SD	Standard deviation
SJC	Static joint centre
TA	Takeaway
TB	Top of the backswing
VPA	Vertical swing plane angle

Chapter 1 General Introduction

1.1 Introduction

The game of golf requires the golfer to perform a variety of shots, using two core movements; the swing and putt. The golf swing is performed with a number of different clubs, including driver, iron and wedge whereas putting solely requires a putter. Each club is used to fulfil a different purpose during a round of golf. The driver is used for maximising ball displacement, irons are often used for controlled mid-range shots and wedges are used to perform high trajectory or controlled short range shots (Hume et al., 2005). Therefore, the golfer requires a proficient swing in order to perform a variety of successful golf shots. This thesis will focus on the full golf swing using a driver.

The main objectives of a full golf swing are to achieve the required or maximum displacement of the ball whilst maintaining shot accuracy (i.e. towards the intended target direction). The resulting displacement and direction of the golf ball is determined by multiple factors, however the four fundamentals of golf impacts, which would achieve a straight shot and greatest displacement are an impact through the centre of percussion (i.e. point where translational and rotational forces are equal), high clubhead velocity, zero degree face angle and club path. Hay (1993) produced a deterministic model detailing the basic factors that contributed to displacement of the golf ball; however, there were no references to the golfer's technique. Therefore, a modified version of the deterministic model is presented in Figure 1.1 to account for a golfer's technique.

A golfer's technique can be quantified using biomechanical analysis. Biomechanical analysis of sporting technique has become prevalent in recent years and for some elite athletes, and their coach, has become a regular part of training (Smith & Loschner, 2002; Anderson et al., 2005). Biomechanical analysis provides detailed kinematic and kinetic information of a performer's technique for the coach and is suited to elite performers who require this accurate quantitative feedback to inform changes or highlight strengths in an already proficient technique (Lees, 1999; Smith & Loschner, 2002).

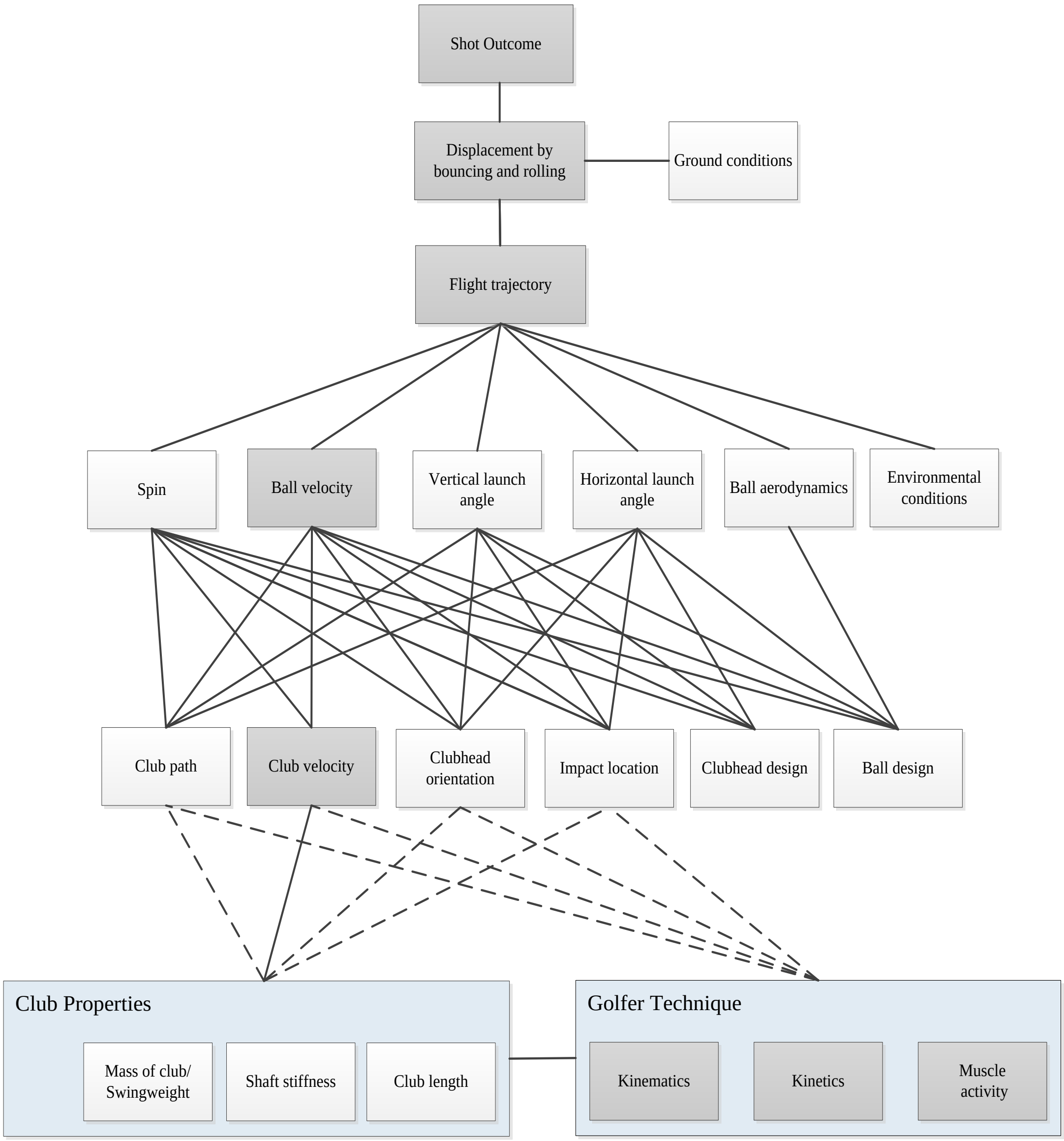


Figure 1.1 Deterministic model of factors contributing to the displacement and direction of the golf ball from a full golf swing adapted from Hay (1993). The grey boxes highlight the path of most golf biomechanical literature. The dashed lines represent theoretical connections which have not been readily investigated.

The initial stage in biomechanical analysis of sporting technique is to identify the key technical parameters which are related to a successful performance (Lees, 1999). Lees et al. (1999) stated three ways that key technical parameters can be identified: using previously established variables which are theory or coach driven; deterministic models; or through statistical analysis of multiple variables (e.g. regression analysis based on correlations with measures of performance). As coaches often guide the technique it is important that there is coherence between biomechanical analysis and coaches' perceptions. Therefore, identifying the key technical parameters of a golf swing using coaches' perceptions could allow better integration of coaching and biomechanical analysis.

The majority of golf biomechanical literature has used deterministic models and statistical analysis to identify the key technical parameters of the golf swing with few key technical parameters of the golf swing guided by coaches' insights, for example, the parameter X-factor. Yet there has been no in depth study that has used coaches' perceptions of the key technical parameters of a successful golf swing in order to guide biomechanical analysis. Once the key technical parameters have been deduced they would need to be biomechanically measured using appropriate analysis techniques. The results of the biomechanical analysis could then be used to examine the effect of the key technical parameters on performance, which may provide new information or confirm already held coaching beliefs regarding a successful golf swing.

1.2 Research Purpose

The purpose of this research were to (i) use golf coaches' perceptions to identify the key technical parameters of a successful golf swing, (ii) to compare the technical parameters to current golf biomechanical literature, (iii) to define suitable methodologies for measuring the chosen key technical parameters and (iv) to biomechanically analyse the key technical parameters to identify differences in golfers technique related to measures of performance. In addition, this research would begin to better integrate golf coaching and biomechanical analysis. The results will help to reinforce existing coaching knowledge as well as lead to new insights to assist future technique development.

1.3 Research Questions

In order to meet the purposes of this research project a number of research questions were proposed.

Q1. What are the key technical parameters that golf coaches' perceive to be important for a successful golf swing?

It is believed that golf coaches have an internal model of a technically successful golf swing (Sherman et al., 2001). The coaching-biomechanics interface has been developed and shown to be effective at gleaning elite coaches' perceptions of the key technical parameters of performance, particularly in sprinting and gymnastics, using qualitative data collection and analysis methods (Irwin & Kerwin, 2007). Therefore, this research will aim to use a qualitative analysis approach, guided by the coaching-biomechanics interface principles, to identify the key technical parameters of a successful elite golf swing.

Q2. How do golf coaches' perceptions of the key technical parameters of the golf swing compare to current golf biomechanical literature?

The next stage of the coaching-biomechanics interface is to compare coaches' perceptions of the key technical parameters to the existing biomechanical literature. This stage of the analysis would allow gaps or similarities between golf coaches' perceptions and the existing golf biomechanical literature to be identified. The results of this stage can then lead to determination of the key technical parameters of the golf swing that required biomechanical analysis, in order to assess their influence on overall golf swing performance. The comparison to the literature could also identify strengths and limitations of current testing methods required to quantify the key technical parameters.

Q3. Are existing biomechanical data collection and analysis methods appropriate for measuring the key technical parameters of the golf swing?

Before the key technical parameters can be examined in detail it is necessary to ensure that the data collection and analysis methods are appropriate. Based on the findings of Q1 and Q2, it should be possible to deduce the suitability of reported data collection and analysis methods by performing comparative studies between methods.

Q4. How can we biomechanically analyse the key technical parameters of individual golfers to support future work in understanding the relationship with performance?

More recent studies have highlighted the need for individual analysis of a golfer's technique as group analysis may mask individual differences (Brown et al., 2011). Therefore, an appropriate statistical analysis tool will be determined to provide a useful platform for comparing individual golfer's techniques. This type of analysis could be used to examine relationships between key technical parameters and examine the parameter throughout the whole swing.

1.4 Overview of Chapters

This thesis has ten chapters consisting of a qualitative study (Chapter 2), literature review (Chapter 3), general methodology (Chapter 4), methodological considerations for posture and body rotations (Chapter 5 & Chapter 7), experimental studies (Chapter 6 & Chapter 8), biomechanical report (Chapter 9) and conclusions including novelty of the research and future research directions (Chapter 10).

Chapter 2: Qualitative researchers are encouraged to approach investigations without preconceptions of the topic area and, therefore, in this thesis the results from the qualitative study are presented before the literature review. The qualitative study was undertaken to determine golf coaches' perceptions of the key technical parameters during the golf swing. A combination of interviews and observations were used to collect the qualitative data which is analysed based on the grounded theory approach. Several key technical parameters are identified and presented.

Chapter 3: This chapter presents a comprehensive review of the current golf biomechanical literature. To aid comparison to the outcomes of the coaches' perception study in Chapter 2, the literature review is structured to align with the results of the key technical parameters identified by the coaches. Initially, the measures of performance are outlined. The biomechanical methods used to measure kinematic and kinetic parameters and associated performance outcomes during the golf swing are critiqued. Each section ends with suggestions for future biomechanical analysis.

Chapter 4: In this chapter, the data collection and analysis methods used to measure golfer kinematics, kinetics and measures of performance are described. Golfer and club kinematics were captured using the Vicon motion analysis system and high speed cameras. Measures of performance were observed using the TrackMan launch monitor. Golfer kinetics were collected using two Kistler force plates. The main objective of each measurement method was to gather accurate and reliable data. The specifications for each piece of testing apparatus are reported. The underlying issues related to data collection and analysis methods were considered to ensure valid and repeatable data.

Chapter 5: Posture was identified as a key technical parameter by golf coaches in Chapter 2 and was not readily investigated in the biomechanical literature (Chapter 3). Therefore, using the general data collection and analysis techniques detailed in Chapter 4, the specific analysis methods used to quantify the biomechanical parameters associated with golf posture are presented. Firstly, the methods used to defined postural kinematics are defined, including the comparison between 2D and 3D trunk kinematics. Secondly, postural balance measures are adapted for the golf swing.

Chapter 6: It was necessary to identify individual differences in golfers' techniques which could be related to measures of performance throughout the swing using appropriate statistical analysis tools. Therefore, principal component analysis was used as a suitable method to identify posture biomechanical differences during the golf swing. The principal component analysis methods are presented in detailed and describe the process for biomechanically interpreting the results. Following this, the relationships between postural kinematic and postural balance using the PCA results are explored. Also, relationships between postural parameters and measures of performance are reported. Finally, the results are compared to the golf coaches' perceptions of posture.

Chapter 7: Body rotation was also identified as a key technical parameter by golf coaches in Chapter 2 and also closely related to posture. Using the general data collection and analysis methods detailed in Chapter 4, the specific analysis methods used to quantify the biomechanical parameters associated with body rotation and in particular the separation between the shoulder and pelvis are presented.

Chapter 8: Principal component analysis is used to identify biomechanical differences in body rotation parameters during the golf swing. The relationships between body rotation parameters, posture and measures of performance are examined. K-means cluster analysis was performed on those relationships that displayed sub-groupings in the golfers' data. Finally, the results are compared to the golf coaches' perceptions of body rotation.

Chapter 9: An example of preliminary biomechanical report is presented which can be used to communicate biomechanical data with golf coaches. The biomechanical parameters included in the report were derived from Chapter 2 to Chapter 8. This Chapter also addresses future improvements and changes which can be made to the biomechanical report.

Chapter 10: The conclusions from this research are presented. The research questions are addressed based on the outcomes of the preceding chapters. The novelty and implications of the research and directions for future research in this golf biomechanics and golf coaching are identified.

Chapter 2 Golf Coaches' Perceptions of Key Technical Swing Parameters

2.1 Introduction

Analysing sporting technique is vitally important for improving and producing stable performances, especially in sports where the participant is under high mental pressure to achieve the correct performance (Buttifield et al., 2009). Sports coaches are required to make accurate and reliable observations of the performer's movement patterns and subsequently improve performance through optimising technique during coaching sessions. The method by which the coach achieves such improvements in technique has been described by Irwin and Kerwin (2007) in a conceptual model of technique (Figure 2.1).

Within this model, it is assumed that for coaches to improve technique they have a well-developed internal model of a technically correct performance (Sherman et al., 2001, Irwin & Kerwin, 2007). For example, Sherman et al. (2001) stated that golf coaches should have an internal model of the characteristics of a technically correct golf swing. The formation of such a model is proposed to be influenced by four aspects; (i) current coaching knowledge, (ii) refinement of already known techniques, (iii) mental picture of skill and (iv) biomechanical understanding of skill. The extent of a coach's technical knowledge, including their biomechanical understanding of the technique is an area that has only recently been explored through the development of the coaching-biomechanics interface (Jones & Hughes, 2007).

The coaching-biomechanics interface aims to discover and understand the content of a coach's technical knowledge regarding a performer's technique. The information gleaned from such insights, through interviews or observations, is then converted into measureable biomechanical parameters that are thought to be directly related to a successful performance. This information can provide new insights into technique, reinforce previously accepted ideas, enhance a coach's technical understanding and assist in optimising performance (Irwin & Kerwin, 2007). Assessing an expert coach's implicit technical knowledge and the sources of such knowledge has been conducted for sports such as gymnastics and sprinting and has provided information to guide biomechanical studies into previously non-investigated areas (Cote et al., 1995a, Thompson et al., 2009).

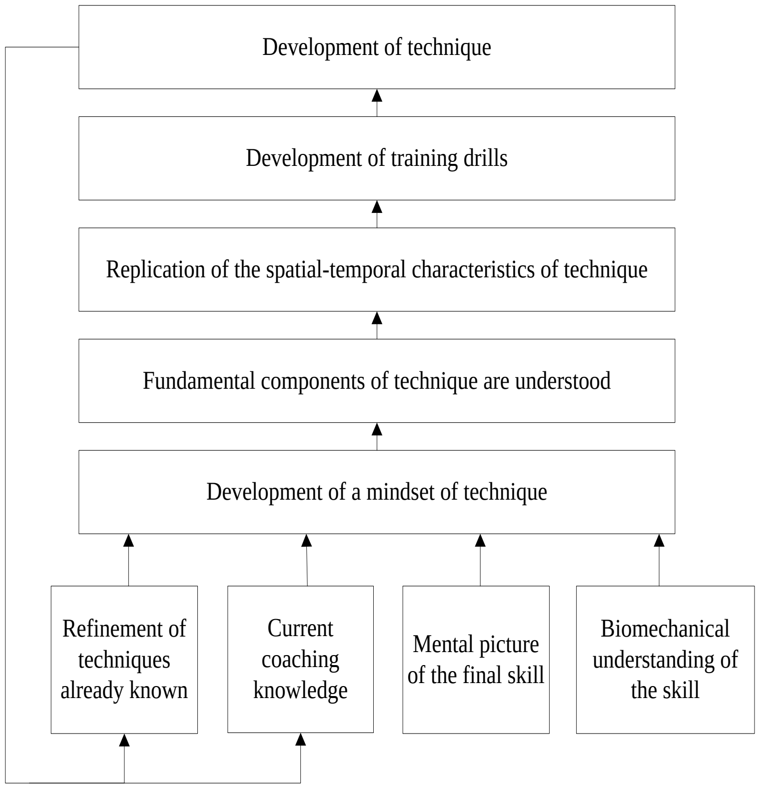


Figure 2.1. Conceptual model of technique reproduced from Irwin and Kerwin (2007)

In golf, few studies have investigated golf coaches' perceptions of swing kinematics. Sherman et al. (2001) reported that amateur and professional coaches showed few differences in their perceptions of ideal golf swing kinematics. In addition, it appeared that, regardless of coaching ability, the coaches seemingly individualized their perception of ideal swing kinematics based on the golfer's expertise and physique. The swing kinematics being analysed, however, were pre-defined by authors as angles between different segments rather than based on the content of the coaches' current technical knowledge. Other studies have attempted to understand how expert golf coaches learn and the sources of this information (Schempp et al., 2007), however this has not been related to the content of their technical knowledge of the golf swing. Despite numerous golf instruction books, there have been few, if any, scientific studies which have investigated the content of a golf coach's technical knowledge. Adlington (1996) provided a personal review of ideal swing technique and biomechanics with the aim to reduce the risk of injury. Similarly, Hume et al. (2005) reported key technical parameters of a golf drive based on a review of the current golf biomechanical literature. Neither review investigated the golf coaches' perceptions of the key technical parameters on a successful golf swing based on the coaching-biomechanics interface.

The purpose of this study, therefore, was to use principles of the coaching-biomechanics interface to identify the key technical parameters that golf coaches associate with a successful golf swing. The term successful was used to define a golf swing that resulted in the intended shot direction and displacement. This purpose would be achieved by addressing the chapter objectives. The first objective was to develop qualitative methods to determine golf coaches' perceptions of key technical parameters. The second objective was to qualitatively analyse the coaches' responses based on the overriding research question for this study of "What are the key technical parameters that golf coaches' associate with a successful golf swing?". The third objective was to identify the key technical parameters which could be compared to current golf biomechanical literature. The term key technical parameter refers to the technical aspects of a golfer's technique that golf coaches believe to be associated with a successful golf swing.

The results of this study are compared to the current golf biomechanical literature (Chapter 3) and the gaps, differences and similarities between the key technical parameters and current biomechanics identified. The outcomes of this process is used to develop the most appropriate methodologies for measuring and analysing the key technical parameters and subsequently identifying biomechanical features in the technical parameters in highly skilled golfers (Chapter 5 - Chapter 8).

2.2 Methods

Qualitative research methods were chosen over quantitative methods for this study as it allowed detailed descriptions and direct quotations to be captured from golf coaches. The qualitative analysis techniques such as interviews and observations would ensure that golf coaches were unrestricted with the use of their own terminology to communicate their perceptions of the key technical parameters.

2.2.1 Participant Selection and Sample Size

Qualitative data collection methods typically rely on relatively small samples of participants who are selected based on the purpose of the research (Patton, 2002). Patton (2002) described these purposefully sampled participants as 'information-rich cases' from which, the researcher can gather in-depth information related specifically to the purpose of the research. This so-called 'purposeful sampling' method has been successfully used by previous studies investigating coaches knowledge (Thompson et al., 2009). Therefore, based on the purpose of this study, recruitment of golf coaches was based on the following criteria: the coach had gained at least a Level 3 Professional Golf Association (PGA) qualification, with Level 4 being the pinnacle of current golf coach education in the UK; the coach had five or more years coaching experience and was currently still actively involved in coaching; and the coach had experience of coaching an elite golfer, for example, a tour level golfer or national level golfer. Golf coaches who met these criteria were contacted through golf coaching specific events, golf coach and academic recommendations and directly through golf courses. Ethical approval for the study was obtained from Loughborough University Ethical Advisory Committee.

The determination of an appropriate sample size was also considered. Patton (2002) recommended that a minimum sample size should be specified based on the information required, the purpose of the study, what will be useful and what can be done with the available time and resources. An ultimatum is presented when a study has a fixed time scale and limited resources as to whether limited information is collected from a large sample size or if greater detail is gained from a smaller sample size giving depth of knowledge (Roberts, 2002). Previous studies with a similar research purpose to that outlined for this study have recruited between seven and seventeen participants (Cote et al., 1995a, Thompson et al., 2009). Cote et al. (1995a) commented that their sample size (17 participants) was consistent with other studies that had reached “theoretical saturation”, in other words, when data from new participants does not contribute any additional information to that already gathered (Biddle et al., 2001). Therefore, it is advised that the study design should be flexible so that the minimum sample size can be increased (Patton, 2002) should theoretical saturation not be reached. For the purpose of this study, a minimum sample size of fifteen golf coaches was initially deemed appropriate given the time and resources available; however, this could be increased if theoretical saturation had not been reached.

2.2.2 Participants

Sixteen golf coaches participated in the study. The participants were aged 24 – 51 years (mean = 39.0 years; SD = 7.6 years) and had an average of 18 years of golf coaching expertise (SD = 8.2 years). In addition, all coaches that participated were highly skilled golfers (i.e. handicap < 0) and several had played golf to a high level before pursuing a career in golf coaching. Summary coaching background information was obtained from the coaches prior to data collection (Table 2.1). The participating coaches were categorised into one of four coaching sectors which were: golf club professionals (GP), national coaches (N), golf academy professionals (GA) and regional coaches (R). Many of the coaches regularly coached elite level golfers whereas the remaining coaches currently coached recreational golfers (i.e. golfers with higher handicaps). Nevertheless, these coaches still had experience of coaching an elite golfer (Table 2.1).

2.3 Data Collection

For qualitative data collection, a combination of data collection methods is advocated (Biddle et al., 2001; Patton, 2002). The main advantage of using a combination of data collection methods is that it allows the strengths of one approach to compensate for the weaknesses of another and, as a result, can increase the validity of data.

Observations have complemented interviews in a number of studies, helping to inform the focus of the proceeding interviews (Gilbourne et al., 1996; Meyer & Wenger, 1998; Biddle et al., 2001). In addition, conducting interviews after the participant has been observed allows for a more in-depth exploration of the key themes identified during the observation (Patton, 2002). Therefore, in this study, a combination of observations and interviews were used to determine the golf coaches' perceptions of the key technical parameters of an elite golf swing.

2.3.1 Observations

Observation involves the recording of events and behaviours which occur in a chosen social setting (i.e. field-setting) related to the research study and "[it] is a fundamental and highly important method in all qualitative inquiry" (Marshall & Rossman, 2006). There are several advantages to using observation as a qualitative analysis method. Observational data can allow the researcher to understand a situation to an extent not possible using only insights of, for example, an interview (Patton, 2002). Similarly, observations can serve to inform subsequent data collections, such as interviews or other studies.

Table 2.1 Descriptive data of sixteen golf coaches that participated in the qualitative study

Coach ID	No. Years Coaching	Current Coaching Sector	Level of Golfer	Highest Level Golfer Coached	No. Hours Coaching a Week	Coaching Qualification
01	25	GP	Recreational	Professional	35	Level 3 PGA
02	17	GA/N	Elite	Tour	40	Level 3 PGA
03	20	GP	Recreational	Professional	25	Level 3 PGA
04	30	GP	Elite	Tour	45	Level 4 PGA
05	11	N	Elite	Tour	30	Level 3 PGA
06	6	GA	Elite	Tour	25	Level 3 PGA
07	22	GA	Elite	Tour	30	Level 3 PGA
08	15	GP	Elite	Tour	40	Level 3 PGA
09	11	GP	Recreational	National	35	Level 3 PGA
10	31	GP/N	Recreational	Tour	30	Level 3 PGA
11	20	GP/N	Recreational	Tour	20	Level 3 PGA
12	30	N	Elite	Tour	30	Level 4 PGA
13	10	GP	Recreational	Tour	20	Level 3 PGA
14	5	GP	Recreational	Professional	45	Level 3 PGA
15	20	GA	Elite	Tour	40	Level 3 PGA
16	15	N	Elite	Tour	35	Level 3 PGA

GP = golf club professional, GA = golf academy professional, N = national coach, R=regional coach

Another strength of observations is that the researcher may discover information that the participant does not mention due to them being too absorbed in the social setting. The major concern associated with observational data is the threat to validity and reliability. This is due to the potential effects of the observer on what is observed, including the possibility that the participant alters their behaviour because they know they are being observed, also known as the Hawthorne effect (Patton, 2002). To overcome the Hawthorne effect, some researchers use a covert observational style where the participant is unaware that they are being observed, informed consent is not essential and the researcher is a participant in the social setting being observed. This type of observational style has raised ethical concerns given that the participants feel that they are being deceived by the researcher. Conversely, during overt observations the participant is fully informed about the research objectives and the researcher is a complete observer (Patton, 2002). To conduct effective overt observations, the researcher should limit the amount of influence they have on the social setting, for example through keeping a distance between the participant and observer.

In this study, an overt observational style was adopted in a field setting where a typical technical coaching session, led by the golf coach, would take place. A technical coaching session was defined as a session where the golfer would use a driver or long irons and the focus was on the full golf swing. The golfers being coached were requested to be of the highest standard accessible to the coach at the time of the observation, for example, an elite golfer. The coaching sessions lasted between 45 and 120 minutes. A standard video camera (Panasonic, Japan) was used to obtain a record of the coaching session. The video camera was positioned at an appropriate distance from the coach and golfer so that the session could be visually and audibly recorded whilst not interfering with the coaching session (Figure 2.2). In addition, an observer stood near the technical coaching area to record comprehensive field notes of the coaching session. An observation guide was used to organise the field notes into four sections detailing the structure of the session, coach behaviour, technology used and technical analysis of the golf swing (Appendix A). The terms and phrases used by the coach were noted and used during proceeding interviews.

Figure 2.2 Observational set-up for both an indoor and outdoor technical coaching session. Panasonic video camera and laptop positioned away from coaching area.

2.3.2 Interviews

An interview can be used to discover those things which cannot be observed such as thoughts and intentions (Patton, 2002). The purpose of interviewing is to allow insights into an interviewees perspective on a given topic, which are assumed to be meaningful and knowable (Patton, 2002). During an interview, the interviewer has a direct influence over the quality of information obtained and an interviewer must consider the most appropriate interview approach. Patton (2002) identified four types of interview approaches with varying levels of structure, namely, informal conversational interviews, interview guide approach, open-ended interview and closed fixed response interviews. If a structure is too fixed (e.g. closed fixed responses) there may not be an opportunity for probing answers as the interviewer does not stray from a set of predefined questions. Conversely, an unstructured interview (e.g. informal conversational interview) does not have predetermined questions and the direction of the interview is based on the responses of the interviewee. This unstructured approach may increase the relevance of the questions, however it becomes difficult to compare and analyse data if different questions have been used across interviewees. Despite these contrasting approaches they are not mutually exclusive and a combined approach can be used (Patton, 2002). A semi-structured approach, such as the interview guide approach, allows a balance whereby an interview outline can increase the comprehensiveness of the data while remaining flexible enough to explore the interviewee's thoughts.

For this study, following the observation, a semi-structured in-depth interview was conducted with the coach. This approach allows interviews to be partially guided by observational findings whilst still remaining systematic across coaches by using guided unambiguous questions. The interviews were conducted at the same location as the coaching session, therefore increasing the level of comfort for the coach and the probability of attaining high-quality information (Kvale, 2007). To ensure the purpose of the study was addressed an interview guide, divided into two sections, was designed and implemented (Appendix B). The guide provided continuity to the interview, comparability between interviews and has been common practice in previous perception studies (Roberts et al., 2001). The coach was given a brief introduction to the interview purpose and was instructed to answer all questions in relation to a successful elite golfer's swing. The introduction was followed by the first section which focussed on the structure of the technical coaching session. This section included information regarding their coaching behaviour, for example, the position from which they observed the golfer and their use of technology. The second section focussed on their perception of a successful elite golf swing. Each section began with an initial open-ended question, followed by further questioning to explore the coaches response in more detail as to their precise meaning. Any information gleaned from the observations that were not commented on by coaches during initial questioning were also introduced and probed with further questioning. The interviews lasted from between 30 to 45 minutes and were recorded using a Dictaphone (Zoom, Japan) from which verbatim transcripts were produced for data analysis. A pilot observation and interview were conducted to determine the suitability of this methodology. In addition, after completion of the interviews the coaches were asked to provide feedback on the interview technique which informed later interviews.

2.4 Data Analysis

Qualitative data analysis strives to organise and reduce vast amounts of empirical data, for example quotes and observations, into meaningful themes and resulting theories (Walker & Myrick, 2006). There are no standardised methods for analysing qualitative data because each study is unique and therefore the analysis methods used will also be unique (Patton, 2002). Nevertheless, there are approaches for producing meaningful explanations from empirical data. Two popular approaches are (i) deductive analysis and (ii) inductive analysis. Deductive analysis begins with a theory or concept which is then examined by fitting data into the existing theory or model. This method is refuted by some researchers who do not believe that theories should be imposed on data at the outset (Gibbs, 2008). Contrastingly, inductive analysis develops a theory directly from the data and encourages a more analytical approach (Glaser & Strauss, 1977). The widely used grounded theory approach to qualitative data analysis is an inductive methodology used to develop a theory grounded in data. The grounded theory approach involves two main stages; (i) breaking data into meaningful units and (ii) grouping meaningful units with similar meaning into higher order categories (Smith & Cushion, 2006).

Based on grounded theory, an inductive approach to qualitative data analysis was used to identify the professional golf coaches' perceptions of key technical parameters associated with a successful elite golf swing in this study. This approach allowed the technical parameters regarded as important by the coach to emerge from the data and has been successful in studies of similar purpose, for example, when exploring elite sprint coaches' knowledge of sprinting (Jones et al., 2009; Thompson et al., 2009). The QSR-NVivo (QSR International, Australia) qualitative analysis software was used as it allowed all sources of data, for example video and audio, to be collated within a single project. The software also streamlined the coding, comparison and development of key themes from the data.

The inductive analysis of the coaches' data began with transcription of each interview as shown in Figure 2.3. The QSR-NVivo software aided transcription with the ability to reduce playback speed of audio files and by time coding the transcript to help distinguish between interviewee and interviewer. Transcripts were checked for typing errors and misspellings to improve the reliability of the transcription process.

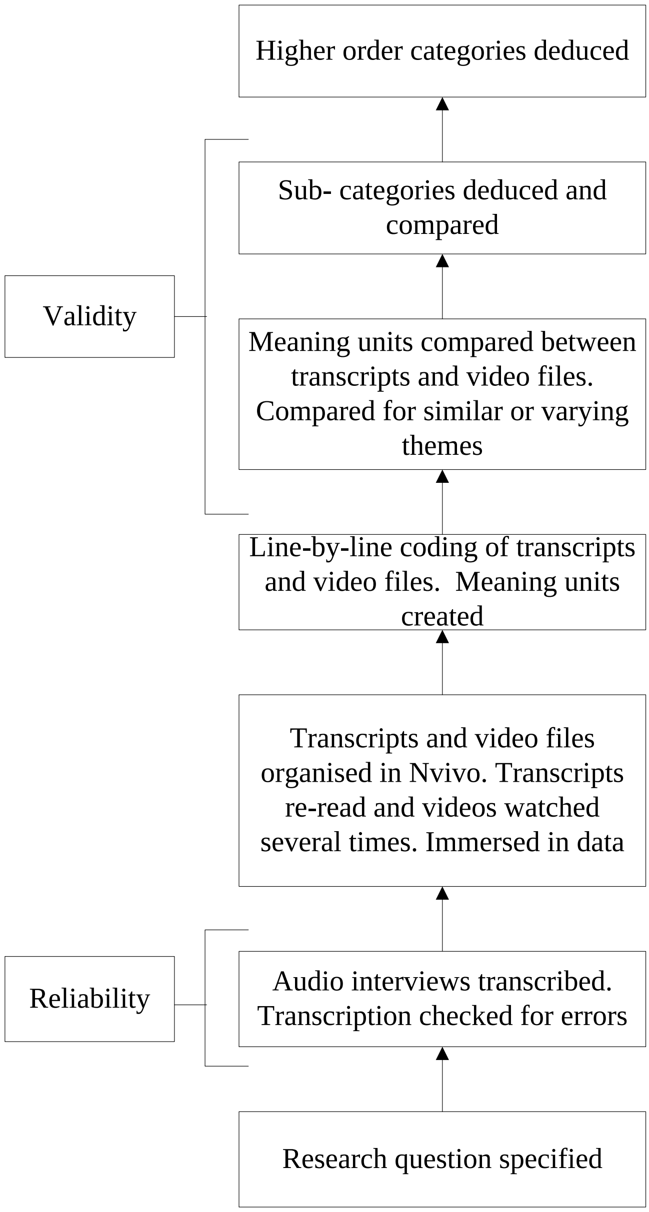


Figure 2.3 Inductive qualitative data analysis approach used in this study based on grounded theory (Patton, 2002)

2.4.1 Initial Coding

Following transcription, it was important to become grounded in the data in order to begin organising data into meaning units based on the content, in a process known as coding (Glaser & Strauss, 1977; Cote et al., 1995b; Walker & Myrick, 2006). Patton (2002) encouraged researchers to focus their coding by trying to answer the proposed research questions and Heath and Cowley (2004) commented that "...the aim is not to discover the theory, but a theory that aids understanding and action in the area of investigation".

In this study, transcripts were initially coded line-by-line which involved highlighting parts of text into meaningful units of data. Many grounded theorists believe line-by-line coding forces the researcher to think analytically and to remain immersed in the data . In addition, line-by-line coding can alleviate researchers preconceptions and prejudices by forcing them to pay closer attention to what the subject has said (Gibbs, 2008). The meaning units may represent an event, an object or action/interaction and should serve an analytical purpose rather than a basic description of a subject's comments (Glaser & Strauss, 1977). For example, Corbin and Strauss (2008) suggested that instead of using the description "reading the schedule" the code should be "information gathering" to provide a more analytical depiction of the data. The line-by-line coding of transcripts was conducted using QSR-NVivo by connecting meaningful units of text (i.e. quotes) to a 'free' node (Gibbs, 2002). A 'free' node was described as an object that represented an idea, theory, dimension or characteristic of the data and was a method of connecting data to a theoretical concept that exemplifies the idea (Gibbs, 2002). The video files from observational sessions of golf coaches were watched on several occasions and excerpts of video were also attached to free nodes within QSR-NVivo. The software also provided additional information such as the number of sources and references attached at a free node.

From this initial coding process, a large number of meaning units were formed which represented numerous ideas or concepts in relation to the proposed research question. The next stage compared meaning units (i.e. free nodes) for similar or varying themes to enable subsequent grouping together into categories.

2.4.2 Higher Level Coding

The meaning units were compared for similarities and differences in themes. This was initially done by considering the title of the meaning unit, the description of the meaning unit and subsequently examining the references (i.e. quotes and video excerpts) attached at that meaning unit. The constant comparison of units ensured a close connection between codes and the data and provided a check for the consistency of coding (Corbin & Strauss, 2008; Gibbs, 2008). The units found to possess similar themes were firstly grouped together into sub-categories. The title of the sub-category needed to adequately define the relationship or theme between meaning units. If sub-categories also shared a common theme these were also grouped together and became branches to an overall higher level category. This process was continued until data saturation was reached and no new information or higher level categories were observed (Walker & Myrick 2006; Gibbs, 2008). Constructing data into a coding hierarchy helped to keep data organised, prevented duplication of categories and provided a basis for the growing conceptual framework (Gibbs, 2002).

The analysis resulted in several higher level categories, sub-categories and associated meaning units. The higher level categories represented the key technical parameters.

2.4.3 Relationships between Categories

Throughout the initial and higher level coding it was apparent that some quotes contained a number of themes and were therefore attached to several higher level categories. For example;

> *If they are set incorrectly in posture they can't work the body correctly because the body action should kind of work almost like a spiral staircase; it should work from left foot to almost right shoulder, around and up, all the way through, so you have to imagine a coiling action spring whereas a lot of people set poorly so they're moving [in] the wrong plane… then part of the reason why their club is moving in a funny fashion is because the body is actually moving incorrectly.*

In this quote, the coach suggests a relationship between three different technical parameters; 'posture', 'club motion' and 'sequential movement of body segments'. Therefore, this quote was coded within three meaning units and these relationships were recorded and acknowledged within the reporting of the key technical parameters by making notes within the NVivo analysis software.

2.4.4 Quality of Results

The quality of data refers to the validity, reliability and generalisability of results (Gibbs, 2008). The quality of results in this study was ensured through a number of measures. The validity of results was improved through use of multiple data collection methodologies and by using the constant comparison approach through analysis. The questions asked during the interviews were unambiguous and did not force or lead the coaches responses; this was confirmed by the feedback given by coaches following the interview process. The constant comparison approach ensured consistency and accuracy during coding and provided a comprehensive data analysis process. In addition, the researcher re-visited a single transcript and made notes on the themes which were then compared to the original coding to ensure coding was consistent and accurate. A second researcher was also given several excerpts of a coach's transcript from the interview and was instructed to carry out line-by-line coding to identify their own meaning units. The meaning units identified by the second researcher were then compared to the original meaning units to ensure that the most appropriate interpretation of the data had been achieved.

2.5 Results

Three elements were discussed by the coaches when describing a successful elite golf swing which were **'Body Motion'**, **'Club Motion'** and **'Ball Flight'** (Figure 2.4). Although coaches were concerned with the 'ball flight', this was to give indirect feedback on the golfer's 'body motion' and 'club motion'. Therefore, ball flight was not explored in detail apart from identifying some of the descriptor words used by coaches to describe ball flight. With further probing, five interlinked key technical parameters were identified; **'Posture'**, **'Body Rotation'**, **'Arm and Wrist Action'**, **'Sequential Movement of Body Segments'** and **'Club Motion'** (Table 2.2, Figure 2.4). In addition, the following six descriptors of performance were often used in conjunction with the technical parameters; **'Powerful'**, **'Accurate'**, **'Consistent'**, **'Repeatable'**, **'Controlled'** and **'Simple'**. These descriptors were separated during analysis due to their importance in defining the aspect of the technical parameter that affected performance. Similarly, the different stages of the swing were also used in conjunction with the technical parameters and as for the descriptors, these were identified separately (Figure 2.4).

The results and discussion is divided into eight sections representing the key technical parameters that emerged during data analysis. Each key technical parameter and stage of the swing is defined within the golf coach's context in order to develop an understanding of the coach's thoughts on the key technical parameters of the golf swing. The inter-related nature of certain technical parameters is also discussed. In the next section, the categories and sub-categories are presented in bold when initially introduced, subsequent reference to them will use apostrophes.

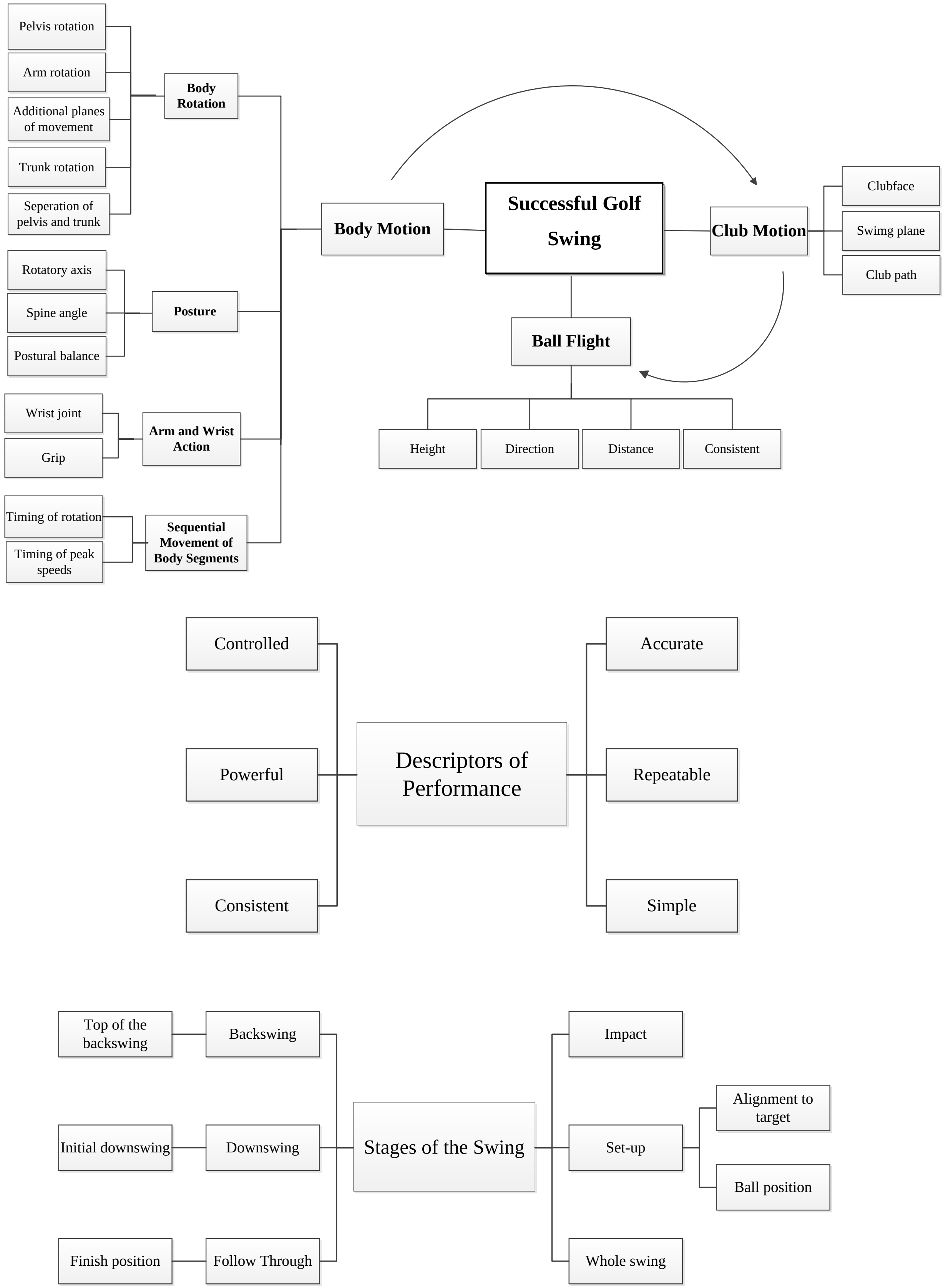


Figure 2.4. Diagram showing the relationship between the elements of a successful golf swing, key technical parameters and sub-categories (bold). The separate diagrams display the descriptors of performance and stages of the swing identified by golf coaches.

Table 2.2. Key technical parameters, sub-categories and meaning units based on the golf coaches perceptions of the key technical parameters of the golf swing.

Key Technical Parameters	Sub-categories	Meaning units
Club motion	Swing plane	- Shaft angle - Shallow/steep - Flat/rounded - Primary/secondary
	Club path	- Angle of attack
	Club face	- Open/closed - Square - Centred strike - Clubhead speed
Posture	Spine angle	- Forward bend - Stability - Centre point - Rotatory axis
	Postural balance	- Centre of gravity - Weight distribution
Body rotations	Trunk (thorax/abdomen) rotation	- Shoulders - Torso - Core
	Pelvis rotation	- Hips
	Separation of pelvis and trunk.	- Disassociation - Resistance - Separation
	Additional planes of movement	- Bend/tilt/sway
Arm and wrist action	Grip	- Natural/Neutral - Strong
	Wrist angle	- Cocking/uncocking - Hinge - Lag
	Arm rotation	- Hand path
Sequential movement of body segments	Timing of movement	- Coil and Uncoil - Force-energy creation
	Timing of peak speed	- Summation of speed

2.5.1 Coaches' Perceptions of a Successful Golf Swing

2.5.1.1 Ball Flight

Many coaches determined a successful golf swing firstly from observing the golfers **'Ball Flight'**. A successful ball flight was described as:

> *Generating the ball flight you want to produce...I've picked a target...I want that ball flight to be straight...and the ball [travels] up and down the target line.*

'Ball flight' was discussed in terms of the 'direction', 'height' and 'distance' of the golf shot. In addition, a consistent ball flight was desirable. From the observational sessions, every coach would define a target with the golfer. Although the coaches used ball flight to determine a successful shot, many coaches acknowledged that the overall ball flight was a result of two other elements; **'Club Motion'**, mainly at impact, which was affected by **'Body Motion'**.

> *You have a face position that matches up to the ball flight you're looking for… you've got effective angle of attack, effective plane, effective speed, those three elements create the ball flight you're looking for and it's repeatable.*

Some of the coaches referred to this chain of analysis as 'working backwards' whereby the analysis of the golf swing was guided by the ball flight and club motion but inevitably was as a result of the body motion:

> *I would be looking at a player's ball flight, how the club is moving out and entering impact, how it's exiting impact and then the things that are influencing that [such as] how the body is working within the swing.*

Through further investigation the body motion and to some extent club motion were the greater focus for coaches during technical analysis of the golf swing and the key technical parameters of these elements were deemed most important:

> *In early years of coaching you would [work] a lot on where the golf club was and how it was delivered...but now you would almost look at the body first to see why the golf club is there.*

2.5.1.2 Descriptors of Performance

There were several words the coaches continually used when discussing the key technical parameters associated with the elements body motion and club motion which were: **'Repeatable', 'Controlled', 'Simple', 'Accurate', 'Powerful'** and **'Consistent'**. During data analysis, it became important to separate these commonly used words as it heightened the understanding of the key technical parameters.

> *Everyone who comes for a lesson says, "I just want to be more consistent"...I've never had anyone come [to] me and say, "I want to hit it 400 yards and I don't care if I find it"...no one has ever said that.*

> *A top class golf swing... has to have repeatability...control and it should blend power and accuracy [so] you're looking for elements that help create those four things, repeatability, control, power and accuracy.*

The terms repeatable, controlled, powerful and simple were often used when discussing key technical parameters of a golfer's technique. The terms consistent and accurate were used when referring to the shot outcome. Although the quotes above use these terms for a general purpose they will be referred to in more detail when discussing the key technical parameters.

2.5.2 Coaches' Perceptions of Stages of Swing

Many golf coaches referred to the key technical parameters of the golf swing at specific stages throughout the swing:

> *First, I would look at address position...then into the backswing to the top, then the start down, moving into impact and from impact to arms straight is follow through, then follow through to finish. So I'd analyse each bit.*

A general consensus amongst coaches was that **'Set-up'** and **'Impact'** were the two most critical stages of the golf swing.

> *First thing to check are the basic fundamentals which are undoubtedly the set-up making sure the foundations are there...without that, there is no point in starting to swing the club.*

The set-up included the ball position, the golfer's alignment to the chosen target and their body position before the golf club was swung. From the observations, all golf coaches and golfers would define a target to which the golfer would aim their golf shots during their coaching session. In addition, some coaches paid particular attention to where the golf ball was positioned relative to the golfer. An incorrect ball position at set-up was linked to changes in a golfer's body movements.

If we're dealing with an elite golfer [a centred strike] should be very easy to attain. Usually something is misaligned in the set up or ball position…like [with the golfer] I just coached, the ball position was too far forward so had to lean forward in his downswing to try and get at the ball.

Ensuring some of the key technical parameters were correct at set-up was very important for coaches and the parameters most often referred to at this stage were **'Posture'** and **'Arm and Wrist Action'**. The particulars of these parameters at set-up will be discussed later in this results section. In addition, a repeatable set-up was advocated by many coaches.

Following the set-up, some coaches referred to the phase **'Backswing'** which culminated when the golfer reached the **'Top of the Backswing'**. The top of the backswing was defined in two different ways by the coaches; the first definition was when the golfer felt they could not rotate their 'shoulders' any further and the second definition was when the club had stopped and then begun moving again.

The end of the backswing would be that tight position where you feel I can't go any further...that's a full shoulder turn

Where the club stops and then starts down...that varies for different people because of flexibility, mobility, build, arm length, injury

Body rotation, posture and **'Sequential Movement'** were often referred to in conjunction with the backswing and for one coach creating a top of the backswing position through these parameters enabled the rest of the swing to work efficiently:

If we can get [the golfer] in a correct position at top of the backswing, everything reacts off the back of that...it's efficient.

Proceeding top of the backswing, the coaches spoke about the **'Downswing'** phase which was initiated by an **'Initial Downswing'** phase or transition phase when the club began moving. For one coach the initial downswing movement was suggested to be the most critical point of the downswing:

I want the initial movement [in the downswing] to be good and once we're on plane there it is very difficult to get off that plane.

The key technical parameters discussed throughout this stage were sequential movement, arm and wrist action, body rotation and motion of the club. The downswing ended at the impact position.

Impact was regarded as a crucial stage during the golf swing. Impact was defined as the point when the club made contact with the golf ball. For one golf coach impact was:

> *The transfer of energy...between club and ball...that is what creates ball flight...where the clubhead is at impact and how your club moves through [impact].*

As impact was regarded to ultimately determine ball flight, the coaches discussed all of the key technical parameters in relation to this stage. Some coaches also believed that the impact position would inevitably be the same across golfers as each golfer would be striving for the same clubhead parameters (e.g. centred strike).

> *All efficient swings are probably quite similar at impact*
>
> *You'll always see the clubhead behind the hands at impact*

Finally, the coaches spoke about the **'Follow Through'** and **'Finish Position'**. The follow through was defined by one coach as the point from impact to the point the arms were straight and the finish position was the when the club finally stopped. Nevertheless, the follow through and finish positions were not widely discussed in relation to the key technical parameters, perhaps due to many coaches only interested in the point to impact.

As aforementioned, whilst coaches acknowledged the need to break the swing into stages in order to technically analyse certain parameters, they still emphasised the need to look at the **'Whole Swing'**.

> *I think there are crucial elements, like set-up, impact...so I do break down elements of it but I try and [have] drills...that help promote motion, movement, rhythm and tempo...I don't like to see players who are transfixed about getting clubs in position, it's a movement.*

The coaches believed that tracing the golfer's movements throughout the swing was equally, if not more important, than solely focusing on specific stages of the golf swing. In addition, one coach highlighted a potential downfall with current biomechanical analysis.

The problem with a lot of the [biomechanical analysis] systems [are] they generally track what it is like at the start or the end of the movement. I don't quite like the idea of that, I like the journey that the body will go on, it is equally important. A lot of systems seem to be there is the top [of the backswing] there is impact but how has that happened...is more important.

2.5.3 Coaches' perceptions of Club Motion

The key technical parameter **'Club Motion'** included three sub-categories, **'Club Path'**, **'Club Face'** and **'Swing Plane'**. Although it has previously been stated that coaching in the past relied too heavily on the club's position, many coaches commented on the importance of club motion.

I'm a big believer in the swing plane and keeping the club swinging on a constant plane around the body…To create a correct impact position you need the correct club path, you need the correct angle of attack and you need a certain degree of clubhead speed and you'd need a very centred strike.

'Swing plane' was defined by coaches as the angle of the club shaft, relative to the horizontal and vertical and would be examined at stages throughout the swing including 'set-up', 'backswing', 'downswing' and 'impact', from a predominantly 'down the line' position.

Swing plane is the angle that the club is swung around the body…it changes from one player to the next…but if we get a good swing plane then [it] controls the angle of attack into the ball.

Plot the clubhead at address and at the position at the top and draw a line between those two points…it should cross through their sternum…The more we get it on that swing plane the less dispersion of the ball initially.

For one coach, swing plane was defined by a specific value for the shaft angle.

Shaft plane is the angle of the shaft at the crucial points in the golf swing…I very much believe golf is a game of 45 degree angles so at the start, club shaft is 45 degrees, or three quarters of a way back the shaft is 45 degrees, coming back down the club shaft is 45 degrees, coming into impact club shaft is 45 degrees.

Several coaches advocated that a golfer should remain on the swing plane throughout the swing and described deviation from the swing plane using words such as ‘shallow’, ‘steep’, ‘flat’ or ‘rounded’. Remaining on the swing plane was deemed to influence other club motion parameters including ‘club face’ and ‘club path’ at impact, which would affect accuracy. The ability to maintain a constant ‘swing plane’ was influenced by ‘body rotation’, ‘posture’, ‘sequential movement’ and ‘arm and wrist parameters’.

> *You will never get a golf swing that will work if it’s off plane, if it’s too shallow, if it’s too steep. If you get the club swung on plane, you will strike the ball well, the angle of attack will be good.*

Conversely, for two coaches the term swing plane was used to aid the explanation for the golfer. These coaches commented that there were different planes throughout the swing and they did not require a golfer to remain on the swing plane for the whole swing, only at impact.

> *It’s a funny one plane, because there’s actually no such thing…the golf swing is more of a rotatory axis but players understand plane…so [the golfer] would believe that it works on the same plane…whereas it can’t there’s going to be different planes.*

For one coach they used the terms ‘primary’ and ‘secondary’ planes to describe the changing planes throughout the swing. Primary plane was defined as the shaft angle at address and secondary plane was defined as the plane created during the backswing when the club was ‘hinged’.

> *Shaft plane is the plane that’s set at takeaway, the primary plane and then secondary plane where he’s working up to, and then they look at the line through the shaft at the ball.*

As aforementioned, the coaches believed that remaining on plane would influence other parameters such as the ‘clubface’ at impact. The ‘club face’ was also strongly related to ‘club path’ and they were both used interchangeably when discussing ideal impact positions. Club path referred to the direction of the path that the clubface was travelling on and clubface referred to the orientation of the clubhead, whilst performed at speed.

> *...the clubhead path, how that is coming into the ball, the direction, the alignment of the clubface, the speed of the swing, the angle of attack and then it’s what most amateur golfer’s miss out, the centered strike.*

For one coach the ability to repeat these characteristics of an impact was deemed to separate amateur golfers from professional golfers.

> *...at the end of the day golf is about the collision between club and ball, that's ultimately what we judge by how repeatable that is...you need the clubhead square on the right angle of attack and repetitively done at speed.*

Some of the most popular words used to describe the club face orientation were 'open', 'closed', 'neutral' and 'square'. The orientation of the clubface was linked to the different types of ball flight, for example, a closed clubface would produce a draw.

Although the orientation of the clubface was deemed critical at impact for generating accurate golf shots, for some coaches the 'club face' orientation was important throughout the swing. The orientation of the clubface was often deemed to be controlled with 'arm and wrist motion'. Nevertheless, this coach believed that if club face orientation was repeatable at stages during the swing then a golfer's body action and impact would 'match' that club face orientation. Finally, the angle of attack or angle of approach, as one coach defined it, was important for generating spin during the golf shot.

> *...you want a fairly steep angle of approach to generate a nice bit of spin and a medium to high swing.*

2.5.4 Coaches' Perceptions of Posture

Fourteen of the sixteen coaches identified **'Posture'** as a key technical parameter of a successful elite golf swing. For many of these coaches, posture was one of the first parameters referred to when asked, 'what technical parameters are vital for a successful elite golf swing?'

Through clarification of the term posture, two sub categories were revealed; **'Spine Angle'** and **'Postural Balance'**. The coaches referred to 'posture' at various stages throughout the swing and therefore regarded 'posture' as both a static and dynamic parameter.

The sub-category 'spine angle' referred to the degree of 'forward bend' or flexion of the trunk/spine to the pelvis during set-up.

[Posture]...is having the correct amount of forward bend to the pelvis and torso, keeping the lumbar and thoracic as neutral as possible so bending forward from the hips, not so much from the knees, or rounded back.

Most coaches regarded the ‘spine angle’ as one rigid segment and only a few coaches would separate the spine angle into different sections including the lumbar and thoracic region of the trunk. Typically, the coaches would analyse a golfer’s spine angle at set-up from a ‘down the line’ position (i.e. right side of right handed golfer facing target).

Achieving the correct ‘spine angle’ at set-up was linked to other technical parameters such as ‘swing plane’ and if ‘posture’ was not correct at set-up then this could have detrimental effects on the remainder of the swing.

If they are set incorrectly in posture they can't work the body correctly... they're moving the wrong plane of movement and then part of the reason why their club is moving in a funny fashion is because the body is actually moving incorrectly.

Another important aspect of ‘spine angle’ was for golfers to maintain this angle throughout the swing. Maintaining the spine angle was reported to prevent any compensatory movements during the golf swing. The idea of ‘matching’ certain golfer movements throughout the swing was also linked to the notion of maintaining the spine angle.

[Posture is] the forward bend...if someone has got a particular forward bend at set-up, let us say 40 degrees of forward bend, then we’re looking at them to have that at the top of the backswing... they’re matching themselves...we’ve not got any funky movements.

Therefore, posture during the swing was about maintaining this spine angle in order to create a rotatory axis which the golfer would rotate around during the golf swing.

[Stable axis] I mean the centre of the golf swing...or the rotatory axis is the spine [and it] should work in a stable fashion...I would advocate a rotation around the top of the spine and that is stability.

Nevertheless, the coach above also stated that the stable axis should move slightly laterally. This statement could be due to this coach’s definition of what constitutes the spine angle or rotatory axis. For example, this coach refers to rotation at ‘the top of the spine' (i.e. thoracic) where as other coaches refer to the whole trunk when discussing spine angle.

Furthermore, some coaches referred to the position of the head when creating a stable axis. When a golfer was viewed to have minimal head movement, they were said to be increasingly stable and able to rotate during the swing.

> *Head position must stay central...if the head position is moving then that's the whole base of the swing gone.*

> *We've done a bit of work...on stabilisers, so his head hardly shifts now, he can work his body far better.*

Maintaining a stable rotatory axis was viewed as important to creating a powerful and efficient swing above other technical parameters such as 'body rotation' and 'club motion'.

> *The guys that are more efficient [and] powerful are the guys that maintain a good centre and rotate around it...not necessarily making massive rotations. We've seen some guys have shorter rotations [hips and shoulders] but they are staying stable...it's about maintaining those postures...to reduce injury and to allow the club to get back to the golf ball more consistently.*

The coaches stressed that by maintaining the rotatory axis the golfer was able to create certain positions with the club in order to create consistent 'club motion', such as a centred strike.

> *If you were to draw a line through somebody's back and one on the front of the head and top of the head and they maintained those points in rotation you'll probably centre the strike pretty well.*

Similarly, having poor posture during set-up and subsequently throughout the swing was suggested to have a detrimental effect on a golfers 'body rotations'.

> *When [the elite golfer] first came [he] stood in terrible posture...so he's out of balance...the shoulders [were] really rounded forward in set-up, so he's almost putting a neck brace on...locking his spine up. So then you'll [see] somebody shift back away from the ball or tip into the ball, so they can't rotate around an axis.*

The comment above also introduced another element of posture which could affect other technical parameters. The notion of creating a stable axis was also linked to the sub category ‘postural balance’.

> *Posture is being in good balance, creating the correct spinal angle. If you’ve spinal angle is not right and if your balance is not right, then there are a lot of counterbalances with the golf swing to try and adjust it.*

Therefore, some coaches argued that the degree of spine angle was as important as creating a balanced position. ‘Postural balance’ was defined statically at set-up as positioning the ‘centre of gravity’ correctly and repeating the position.

> *The reason for posture...is to develop two key balance points...the sternum and the belt buckle...and then be able to move around them.*

From this balanced set-up position, the golfer was deemed to have improved rotational movement which led to improved ‘postural balance’. One coach believed that a combination of poor posture (which was defined as the degree of forward bend of torso to pelvis) and poor ‘sequential movement of body segments’ would lead to poor ‘postural balance’, which ultimately lead to a loss of power and accuracy in the golf shot. Any compensatory movement or counterbalances in the golf swing were as a result of poor postural balance and, for golf coaches, one of the main aims was to simplify the movements during the golf swing.

Another sub-category of ‘postural balance’ was ‘weight transfer’. Some coaches spoke of tracing the golfer’s weight transfer from set-up and through the golf swing. The coaches assessed a golfer’s weight transfer by observing the lower body, in particular the golfer’s feet and poor weight transfer could lead to issues with a golfer’s ball flight.

> *[Posture is when the] body is in a balanced position that enables the club to get moving efficiently and effectively around the body... if somebody’s weight gets too much on the heels it’s going to be very difficult for us to get the correct pitch of the shoulders in the backswing.*

> *If someone is shanking the ball…they’re coming into impact and leaning onto their toes and not clearing the hip, then you can see straight away that their weight is on their toes, so you can just get them kicking their weight back as they hit it.*

2.5.5 Coaches' Perceptions of Body Rotation

When discussing posture the coaches also referred to the key technical parameter **'Body Rotation'.**

> *The reason for posture...is to develop two key balance points...and then be able to move around them, the key then is body motion...are you able to rotate and create the correct force.*

The key technical parameter 'body rotation' encompasses the terms used by coaches to describe the most prevalent movement during the golf swing. Many terms were used when discussing the body segments associated with body rotation. Some coaches would refer to these segments as the 'bigger muscles' as opposed to the 'smaller muscles' which referred to the arms and hands.

> *Encourage...more body rotation, instead of just [the golfers] hands and arms working away from [their] swing independently from [their] body...so the bigger muscles working, rather than the smaller muscles over taking the golf swing.*

Several words were used to communicate the idea of bigger muscle rotations including 'core', 'upper torso,' 'trunk', 'shoulders', 'hips' and 'pelvis'. Nevertheless, the most common words used were 'shoulder' and 'hip' rotations as these were deemed the most appropriate words to communicate clearly with the golfers during coaching sessions.

> *...we don't tend to use upper torso and pelvis at a lesson, it tends to be hips and shoulders. We tend to use upper torso and pelvis when we're talking to the strength and conditioning coaches and the physios. We're all talking different languages which is a bit confusing at times.*

In addition, by using the term 'shoulders' one coach acknowledged that it may lead to inaccurate conclusions regarding rotations due to the additional movement of the shoulders.

> *...there's a lot of independent motion you can create through the shoulders...I'm more interested [in the] trunk and then shoulder stability to that trunk...I'm looking mainly at trunk rotation.*

By taking into account the various terms used to describe 'body rotation', the terms **'Trunk Rotation'** and **'Pelvis Rotation'** will be used to aid clarity.

The rotation of the trunk and pelvis was referred to throughout the swing, from the rotation in the backswing to the rotation through impact. The coaches believed that the rotation of the trunk and pelvis during the backswing was an opportunity to generate a powerful, repeatable and simple swing by producing torque or energy which could then be transferred to the ball at impact.

> *...if there was minimal rotation...you're not going to be able to create as big torque in the backswing, create as much pressure in your right leg, therefore, you're not going to be able to shift that back across through into your left side and transfer that energy back through your arms and your club.*

Only one or two coaches offered preferences for the degree of rotation they would like to see during the swing, whereas other coaches commented that the degree of rotation was golfer specific, depending on elements such as a golfer's degree of flexibility.

> *[At] impact we're looking for the hips to be more turned open than the shoulders, within about 10 degrees...40 degrees with the hips and 35 to 30 degrees with shoulders is fine, as long as we've got the right tilts and right shifts into the left side.*

It was also recognised that 'body rotations' were also influenced by movements within other planes and should not be disregarded:

> *Pelvic rotation... [is] rotation around its mid axis...but it doesn't just rotate...it shifts, it turns, it tilts as well so it's not simple rotation.*

The coaches believed that the separation between the trunk and pelvis was more important than the independent rotations of the segments. Many of the coaches spoke about the 'disassociation', 'resistance', 'storing power' or 'separation' between the trunk and pelvis segments. Others used the coined term 'X-factor' to describe the relationship between the trunk and pelvis.

> *You get a good golfer who is stable...there will be a big difference between the hips and shoulders at the top of the backswing...that is one of the key factors of powerful golf swings, but it's not the key factor, the ability is to be able to separate the hips on the way down from the upper torso and then ... close that*

gap down as quick as we possibly can...that is what we are looking for as far as rotations are concerned.

...the difference between your shoulder turn and the resistance in the legs and how that can create simplicity...then we can start to get the repetition.

Only a few of the coaches spoke about ideal corridors of the degree of rotations. In addition, some coaches suggested that the degree of 'separation between trunk and pelvis' was golfer specific.

...X-factor is important, that you generate some resistance in the body...but the resistance is only relevant to how flexible they are, the more flexible, the more you have to turn to create resistance, the less flexible the less turn to create the same resistance.

When discussing the 'separation between the trunk and pelvis', the coaches also referred to the timing and speed of separation (i.e. timing of rotation and timing of peak speeds respectively) which will be discussed in the section on sequential movement of body segments.

2.5.6 Coaches' Perceptions of Arm and Wrist Actions

Some of the coaches alluded to the importance of **'Arm and Wrist Action'** during the golf swing. The sub-categories of this parameter included the golfer's 'grip' and 'wrist angle'. Grip was often described as fundamental to a successful golf swing and more specifically related to the position of the hands on the golf club grip.

…the grip that a player has must match…their delivery pattern, it must match the clubface they require because of their swing path…if I was pushed on a fundamental it would be the grip.

Several coaches agreed with the statement above and believed that the grip was golfer specific and depended on how the golfer moved throughout the swing. The terms 'neutral' and 'natural' grip were frequently used to describe the position of the hands. A too 'strong' grip was deemed to hinder the golf swing.

…a grip that works for the action, because of the way different people move and different swings, players will grip the golf club differently depending on those factors.

The ‘grip’ was seen as an important determinant of how the wrist, forearm and club moved throughout the swing. The position of the grip was said to affect the ‘wrist angle’.

> *…you want to tend to hold the club, I believe, more in the fingers, so it takes the wrist joint away from the shaft. If the wrist joint is part of the grip…you can’t get much movement in the wrist.*

The coaches would use words such as ‘hinge’, ‘lag’, ‘cocking and uncocking’ and ‘release club’ when discussing ‘wrist angle’. ‘Wrist angle’ was generally discussed from initial downswing phase through to impact. By maintaining a certain wrist angle coaches believed this would ‘stress’ or ‘create pressure’ in the golf club.

> *… you’ve got three power sources…hands and wrists, specifically wrists, then you’ve got your arms and the relationship between the two of them…a good player will create a lot of lag so their arms will come down and they will hold their wrists back…and then there is arms to body and the body itself.*

‘Wrist angle’ appeared to be of secondary importance to such parameters as ‘body rotation’ and, for some coaches, relying on wrist kinematics was associated with inconsistency in the golf swing:

> *…I want the club to come down but I don’t particularly want that to be the fine movements with the hands and arms because under pressure that can vary enormously, whereas creating a hip turn that movement can’t vary as much.*
>
> *…someone with minimal rotation, [I would say to them] you’re going to have to get your speed from somewhere so [you will have to] use your forearms better, your wrists better, your hands better.*

Similarly, one coach did not believe that the arms had a significant role in the golf swing. This coach would expect golfers to maximally ‘cock’ their left wrist from takeaway in order to ‘create loft’ on the club face.

> *…the more I cock that left wrist, the more that shaft [will] bend and that’s what we’re trying to do…you might as well start stressing [the club] on your marks set go, most people they do it on their downswing so they never keep loft on the golf club.*

The wrist uncocking was viewed as the final chain in movements during the downswing, which leads to the final key technical parameter which was sequential movement of body segments.

2.5.7 Coaches' Perceptions of Sequential Movement of Body Segments

As with 'body rotation', there were several aspects associated with the technical parameter **'Sequential Movement of Body Segments'** including **'Timing of Rotation'** and **'Timing of Peak Speeds'**.

The 'timing of rotation' referred to the sequence of body rotations during the golf swing. The swing was initiated at set-up to top of the backswing from the feet to hands and clubs. The descriptive terms such as 'coil and uncoil', 'winds and unwinds' and 'spiral staircase' were used to explain this idea.

> *...the body action should kind of work like a spiral staircase...work from left foot to almost right shoulder around and all the way through...imagine a coiling spring action.*

> *...you generate [club parameters] from the bottom up...coil on the backswing, storing power onto the right side...the power increases as you turn...it derives from the initial movement of the hips beginning the downswing...left foot as anchor...pulls the rest of the body through, so the hips pull through the abs, the abs pull the chest.*

The 'timing of rotations' were suggested to influence golf swing performance through creating 'force', 'power', 'energy' and 'torque' during the backswing. This was then transferred during the downswing through a sequence of body segment movement to improved 'club parameters' such as clubhead speed.

> *...the body winds up or unwinds, and you create torque in your body in the backswing and how your hands and wrists work so it creates some speed in the clubhead, whether you're storing energy at the top of the backswing...that can sort of then bounce back.*

> *...you want to hit the ball further, you look at someone who throws a ball...you're looking for, hips open, pulling shoulders, pulling their arms, pulling their wrists*

The speed of body rotations was also discussed by coaches. In particular, the coaches referred to the timing of peak rotational speeds. The coaches explained that ideally the golfer's proximal segments (i.e. pelvis) would accelerate and reach their peak rotational speed before the more distal segments (i.e. hands). However, the coach admitted that observing this through two-dimensional video was difficult.

> *The summation of speeds...I would like to see the hips, the chest, the arms, the hands stack up and accelerate at the right time, at the right amounts for me to create a centred strike. It's something we can't see on video, so that's...one of the reasons we use 3D.*

The coach above alluded to the magnitude of speed, however, for another coach the appropriate speed was expressed as a ratio between segments and could be related to the rhythm of the swing.

> *[The golfer] needs to be moving at different speeds, clubhead moves the furthest, then the hands and the wrists and the body moves the shortest distance...the body should be working at a pace of one, the arms should be working at a pace of two, hands and wrists four and clubhead at eight.*

2.6 Summary

This chapter has applied the qualitative data collection methods, interviews and observations to determine golf coaches' perceptions of the key technical parameters of a successful golf swing based on the principles of the coaching-biomechanics interface. The coaches defined a successful elite golf swing by three elements, 'Ball Flight', 'Club Motion' and 'Body Motion' with emphasis placed on the latter two. On further probing, five key technical parameters were identified; 'Club motion', 'Posture', 'Body rotation', 'Sequential movement of body segments' and 'Arm and wrist action'. Each technical parameter was further represented by several sub-categories and meaning units. The study also revealed that coaches considered several descriptors of performance, such as power and repeatability, to be indicative of a successful golf swing. Furthermore, many coaches would technically analyse the golf swing at specific stages, however, they acknowledged that more attention should be given to the analysis of the whole swing.

The majority of coaches described posture as the main key technical parameter. Nevertheless, many explanations were offered as to the affect that posture had on performance outcomes. Therefore, the next stage of analysis was to compare the coaches' perceptions of key technical parameters, presented here in, to the current golf biomechanical literature in order to identify the gaps, differences or similarities between the two sources of golf knowledge. The outcomes from this stage are used to help shape subsequent biomechanical studies in this thesis (Chapter 5 & Chapter 7). Furthermore, the outcomes can also be used to inform future studies aimed at informing and supporting golf coaching throughout biomechanical analysis (Chapter 6 & Chapter 8).

Chapter 3 Literature Review

3.1 Introduction

To aid comparison to the outcomes of the coaches' perception study in Chapter 2, the literature review is structured to align with the results of the key technical parameters identified by the coaches. The purpose of this Chapter was to present a comprehensive review of the current golf biomechanical literature. Initially, the measures of performance are outlined and then the biomechanical methods used to measure kinematic and kinetic parameters and associated performance outcomes during the golf swing are critiqued. The specific objectives of this chapter are to provide a comprehensive review of current knowledge on golf biomechanics and to compare with the outcomes of the coaches' perception study to identify similarities, differences and gaps with the current literature. Where appropriate, references to coaches' perceptions are directed to a specific section and page number in the previous chapter. Each section concludes with suggestions for future biomechanical analysis.

3.2 Measures of Performance

This section documents the most common measures of golf swing performance investigated in biomechanical studies.

3.2.1 Shot Distance

Shot distance relates to the maximum driving distance or maximum displacement of the ball. Golf biomechanical studies have often reported maximum clubhead linear velocity, clubhead linear velocity at impact (IMP) or ball velocity as the measures of performance, being related to driving distance. Clubhead and ball velocities have been regarded as the decisive factors in achieving maximum distance of a golf shot (Milburn, 1982; Sprigings & Neal, 2000; Coleman & Rankin, 2005a; Kenny et al., 2008). However, additional club parameters such as angle of attack and the centeredness of the strike will also influence the maximum displacement of the ball (TrackMan, 2010). Using clubhead linear velocity or ball velocity as a measure of performance would satisfy the coaches' desire for a powerful golf swing, however, there were several other measures of performance identified by the coaches, namely accuracy and repeatability that were also important (§2.5.1, p24).

3.2.2 Shot Accuracy

Shot accuracy refers to closeness of the ball to a predefined target (e.g. the pin) with minimal dispersion (i.e. distance from target). Bradshaw et al. (2009) quantified accuracy of golf shots by collating the frequency of shots, as a percentage, that hit a target zone on a net positioned 15 m away. The authors also measured shot dispersion as the mean resultant distance of shots from the target zone. When comparing skilled (handicap range 0 - 1) and unskilled (handicap range 18 - 25) golfers, skilled golfers had greater shot accuracy (86 ± 14.3%) than unskilled golfers (40 ± 20.5%). In addition, as expected, the mean shot dispersion for skilled golfers was less (0.07 ± 0.07 m) than their unskilled counterparts (0.41 ± 0.24 m). The authors did not fully explore the relationship between accuracy and technique but suggested that variability in a golfer's technique could have contributed to differences in golf swing performance. Due to many biomechanical studies taking place in a laboratory it is sometimes difficult to measure performance outcomes such as accuracy. Launch monitors, such as TrackMan (ISG Company, Denmark), can provide an indication of shot accuracy in an indoor laboratory setting, however, final ball position from these devices is estimated.

3.2.3 Repeatability of Measures of Performance

Within this section of the literature review, the term repeatability refers to the variation in a measure of performance between successive golf swings. The repeatability of measures of performance is closely linked to the golf coaches' term consistent which was used when describing shot outcome in the perception study (§2.5.1.2). The repeatability of a golfer's technique will be discussed in later sections as Glazier (2011) comments these are two different types of variability which should have a clear distinction. Variability of measures of performance has received considerably less attention than maximising shot distance (Langdown et al., 2012). Bradshaw et al. (2009) determined the variability of clubhead linear velocity by calculating the coefficient of variation (CV) and standard error of the mean and found that the skilled golfers showed less variability in clubhead linear velocity than unskilled golfers (CV; ~1.7% and ~2.5%, respectively). Furthermore, based on linear regression models, the authors suggested that a golfer's technique, even prior to IMP, could explain differences in the variability of the chosen measures of performance.

Biomechanical studies have attempted to limit shot variability by giving verbal instructions to golfers before testing or detailing the procedures for data acceptance (Table 3.1).

Table 3.1. Verbal instructions given to golfers during biomechanical studies to limit variability due to shot selection

Reference	Instruction	Data Acceptance
Burden et al. (1998)	Not detailed in paper	Longest drive in direction of flag
Egret et al. (2003)	Swing normally based on subjective idea of golfers ideal biomechanical swing	All trials analysed
Mitchell et al. (2003)	No instruction	Data quality and verbal feedback from golfer of successful shot (kinesthetic)
Wheat et al. (2007)	Drive towards a target	Golfers rated shot on 10-point scale (< 7 disregarded)
Myers et al. (2008)	No instruction	Highest ball velocity trials analysed
Meister et al. (2009)	Aim for a straight trajectory with different efforts of golf swing (easy, medium and hard)	Data quality (no marker occlusions)
Moran et al. (2009)	Aim to hit ball straight towards target and as hard as possible	1st, 2nd, 4th and 7th trials analysed
Horan et al. (2010)	Hit usual driver shot as straight as possible	Shots within target line (accuracy)

Langdown et al. (2012) suggested that giving verbal instruction during data collection was good practice as it helped remove variability in data due to shot selection. At the beginning of technical coaching sessions all observed coaches would define a target for the golfer, thereby limiting variability related to shot selection (§2.5.1, p23).

3.2.4 Future Research Recommendations

As the majority of previous biomechanical literature has concentrated on performance outcomes linked to increased driving distance, there is a clear need to incorporate analysis that focuses on additional measures of performance identified as important for golf coaches. Therefore, additional performance outcomes such as shot accuracy and repeatability of measures of performance should be combined with shot displacement measures and their relationship with key technical parameters needs to be ascertained.

3.3 Swing Events

This section identifies the swing events or stages of the swing that authors have used to examine the influence of key technical parameters on golf swing performance, the most notable being top of the backswing (TB) and IMP (Figure 3.1). Other swing events used for analysis include; takeaway (TA), mid-backswing (MidBS), late-backswing, acceleration (Acc), mid-downswing (MidDS), 40 ms to impact (40 ms), impact (IMP), mid follow through (MidFT) and end of follow through (FT) (Figure 3.1). The backswing (green arrows) was from TA to TB and encompassed MidBS and late backswing. The downswing (blue arrows) began from TB until IMP and included Acc, MidDS and 40 ms. However, there are discrepancies between studies when defining some swing events. For example, TB has been defined in several ways: club reaching maximum rotation (Zheng et al., 2008); club reaches most lateral point before changing direction (Burden et al., 1998, Coleman & Rankin, 2005); maximum pelvis rotation (Wheat et al., 2007) and maximum upper torso/shoulder rotation (Neal et al., 1998). The discrepancies in defining the swing events can affect interpretation of some results, such as swing time.

The average swing time, defined from TA to IMP, was not statistically different between the driver (1.08 ± 0.04 sec) and 5-iron (1.09 ± 0.05 sec) (Egret et al., 2003). Nonetheless, a shorter backswing, when using a driver, was proposed to assist in generating faster clubhead linear velocity as observed in elite female golfers (Brown et al,. 2011). Equally, with faster clubhead linear velocity, the inertial forces of the club during the transition phase (defined as from TB through to acceleration phase) would require greater force to initiate the downswing and may indicate the changes in technique between golfers (Brown et al., 2011).

Chu et al. (2010) claimed they used a coach's insight for choosing the swing events for their data analysis. The data was analysed at four discrete points: TB; acceleration (defined as two-thirds of the time elapsed from TB to IMP); 40 ms prior to impact and IMP as these were easily identifiable in each golfer and were considered relevant by golf coaches (Chu et al., 2010). However, the authors provided no details on the information gathered from the golf coaches.

Bradshaw et al. (2009) highlighted the importance of a consistent set-up. The group of skilled golfers had a more consistent stance position, including ball position in stance, trunk angle and clubhead-to-wrist angle than their unskilled counterparts (Bradshaw et al., 2009). In addition, the authors reported that consistency in these specific technical parameters were important in the mid backswing and at TB. However, consistency of these technical parameters throughout the whole swing has not been investigated.

Meister et al. (2009) presented benchmark curves of biomechanical parameters for the whole swing to compare between professional and amateur golfers. From observing the graphs there were noticeable differences between professional and amateurs throughout the swing, however, no statistical analysis was conducted on the overall shapes of the curves only on discrete stages (e.g. impact and maximum values). Recent studies have recognised the limitation with data analysis at key events for biomechanical analysis as a large majority of the signal is unaccounted for during analysis (Donoghue et al., 2008). Hence, functional data analysis techniques have been employed to detect patterns within an entire signal. The application of functional data analysis techniques have proved beneficial for identifying factors of individual performance, which may also be applied to golf (Donà et al., 2009).

The discrepancy in defining some swing events (e.g. TB) was also evident in the coaches' perceptions of swing stages (§2.5.2, p26). The coaches perceptions of the most important swing events was also not fully supported by the literature as some studies did not consider TA and the backswing to be important points when analysing the golf swing (§2.5.2, p25). Nevertheless, the need for more advanced analysis methods which can account for the whole swing was noted by some coaches that emphasised the need for analysis of the whole swing and not only at specific swing events (2.5.2, p26). The suggestion to study the club-player interaction may be echoed in the coaches still regarding club motion as a key technical parameter (§2.5.3, p27); however, more needs to be done to examine the club motion and golfer motion throughout the swing not just at IMP.

3.3.1 Future Research Recommendations

Previous studies have typically performed data analysis on swing events or stages during the golf swing, most notably IMP and TB. The coaches' responses suggest that additional stages of the golf swing warrant investigation, notably at takeaway (§2.5.2).

Also, the limitations identified with analysis at swing events warrants data analysis methods that consider the whole golf swing and may be beneficial in identifying technical differences between golfers or classifying golfers based on their whole swing.

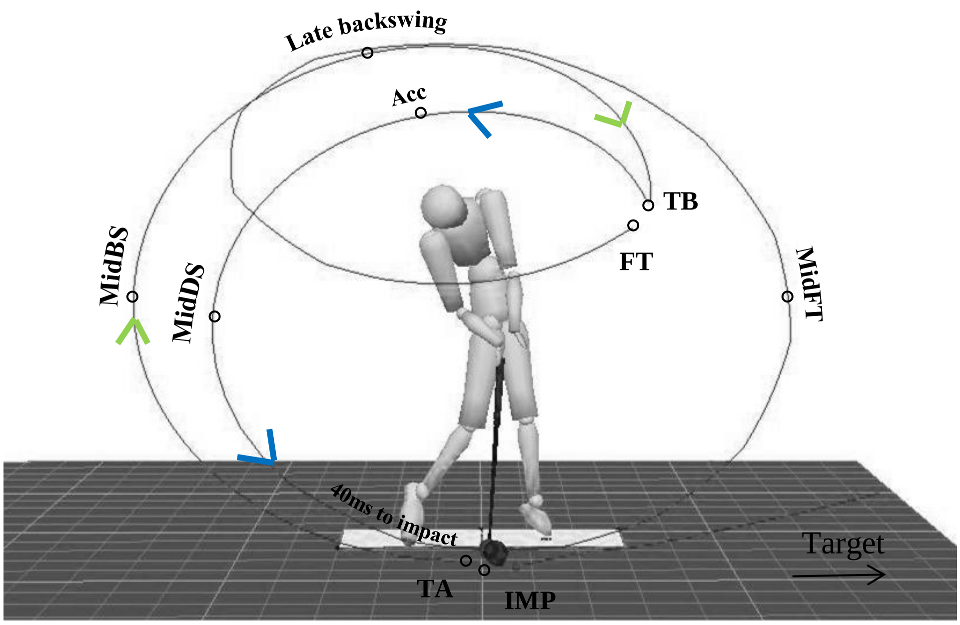


Figure 3.1. Swing events during the golf swing which are often used in biomechanical analysis.

3.4 Club Motion

This section reviews the studies that have investigated parameters associated with the motion of the club throughout the golf swing.

3.4.1 Swing Plane

The swing plane in golf has been represented either as a two segment model (such as arms and club) (Cochran & Stobbs, 1968) or as a single segment model (arm and club separately) (Coleman & Rankin, 2005; Coleman & Anderson, 2007). The notion of a planar golf swing was first established by Cochran and Stobbs (1968), who represented the golf swing as a two segment or alternatively referred to as a double pendulum model which represented the arms and club (Figure 3.2).

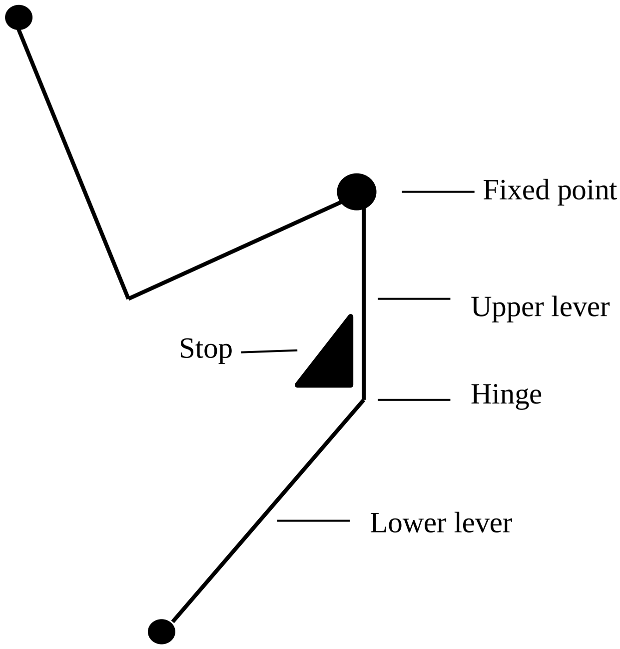


Figure 3.2. Double pendulum model of golf swing as reproduced from Cochran and Stobbs (1968). The fixed point represented a pivot point in the middle of the golfer's chest. The upper lever represented the left arm and lower lever represented the club, connected via the hinge joint which was the passive wrist joint. The hinge joint was restricted by a stop preventing the club moving too far back at TB.

The double pendulum model assumed that the golf swing was planar and the arms and club moved in the same plane throughout the downswing (Coleman & Rankin, 2005). However, more advanced analysis of the golf swing have reported that the club and left arm do not move on a fixed plane throughout the swing (Coleman & Rankin, 2005; Nesbit, 2005; Coleman & Anderson, 2007) (Table 3.2). Initially, Coleman and Rankin (2005) reported that the angle of the left-arm plane (defined by the 7th cervical vertebra (C7), left glenohumeral and left wrist joint) projected onto the yz and xz global reference planes, horizontal and target line angles varied during the downswing for golfers of varying handicap (range 0 – 15) when using a 5-iron (Figure 3.3). All golfers decreased the left-arm plane to the horizontal towards impact (Figure 3.3), thus creating a steeper angle. The authors deemed it undesirable to have the club and left-arm in the same plane as it would affect clubhead linear velocity at IMP, however, no measure of performance was reported.

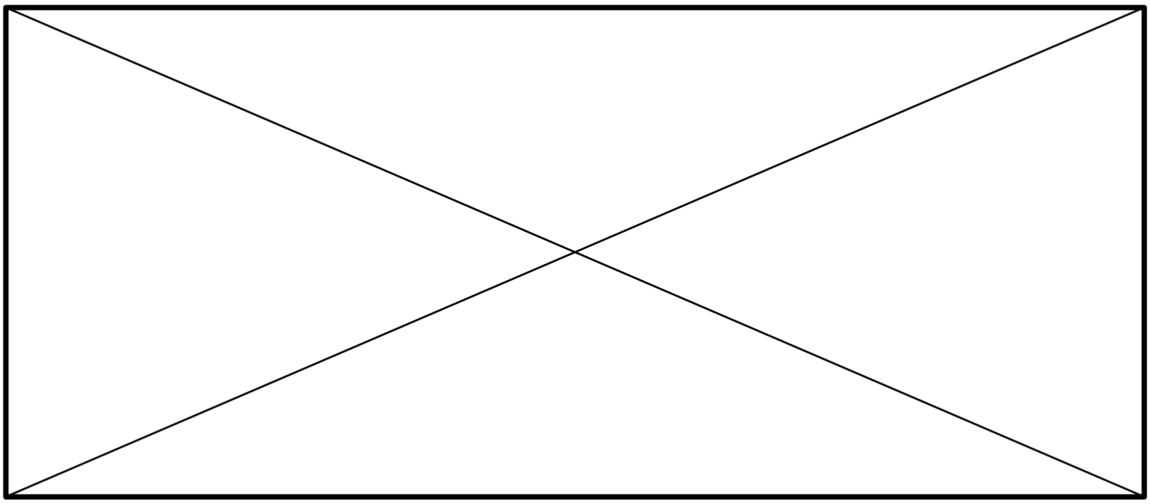


Figure 3.3. Angle between left-arm plane and (a) horizontal plane (α) and (b) target line (β) reproduced from Coleman and Rankin (2005)

A later study by Coleman and Anderson (2007) investigated the coaching term swing plane by examining, in 3D, whether a single fixed plane explained the motion for three different clubs (e.g. driver, 5-iron and pitching wedge) during the downswing. A single "plane of best fit" (which represented the swing plane and was created by a grip marker, shaft and virtual clubhead marker) was fitted for each club and to each golfer during the downswing. The swing plane was then projected onto the global planes and horizontal and target-line angles were calculated (Figure 3.4). The goodness of the swing plane fit was determined by the variance between actual co-ordinate data and data of the plane equation and was used to explain how well the swing plane represented club motion during the downswing. A single swing plane could be fitted to the club motion, however, the goodness of the fit varied within a homogenous group of golfers and between clubs. As expected, the horizontal swing plane angle was significantly different between clubs because of the different club lengths. The swing plane angle relative to the target line was also significantly different between golfers and between the driver and the other clubs (i.e. 5-iron and pitching wedge). The authors offered several reasons for the differences. Firstly, the ball position at set-up is different between the clubs; therefore impact occurs at various stages in the swing arc. Secondly, the type of shot being played (e.g. draw, fade) could have changed their angle, however no measures of performance were reported and shot variability was reduced by instructing golfers to hit a straight shot. Finally, differences in golfers' techniques could have explained the varying target line angles; however, no golfer kinematic or kinetic data was collected.

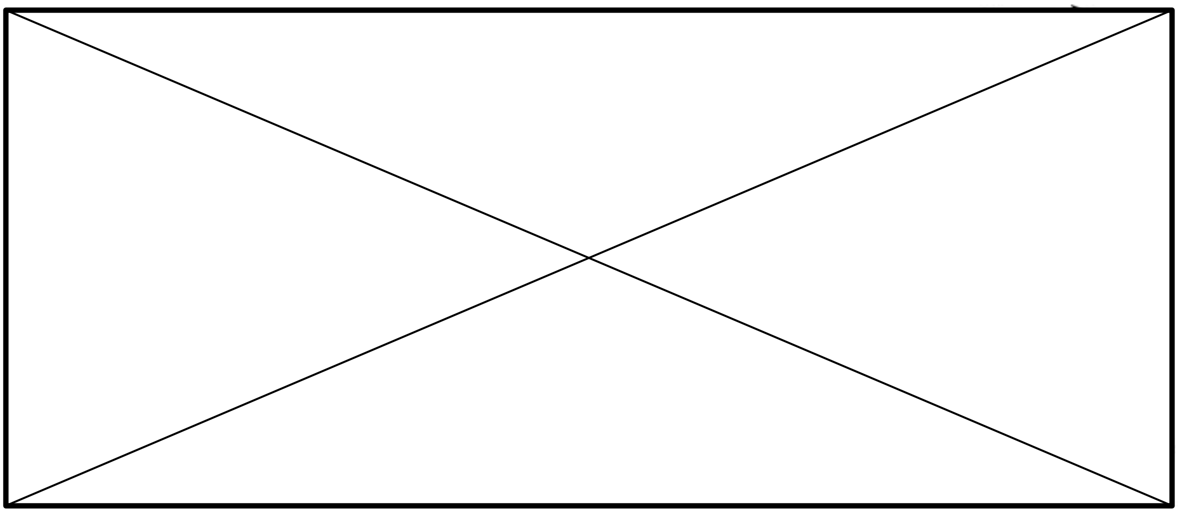


Figure 3.4. Swing plane angle between horizontal (α) and target line (β) defined by Coleman and Anderson (2007).

Due to the varied "goodness of fit" of the single swing plane between golfers, the authors concluded that this model was too simplistic and therefore examined the motion of the club between two consecutive frames of data. This provided a measure of the instantaneous swing plane during the downswing. When examining the instantaneous swing plane, the angle to the horizontal reduced (i.e. steepened) until 70 – 80% of the downswing and then began to increase again (i.e. flatten) for the final 20 – 30% of the swing across the three clubs (Figure 3.5). However, the change in the horizontal angle was less than 10º across clubs. The authors attributed the changes in the horizontal angle to golfer technique; although this was not quantified. There was greater variation in the angle of the swing plane relative to the target line between golfers (driver; -17.2 to 4.1º, 5-iron; 15.8 to 5.1º) but the authors did not comment on the effect these swing plane observations may have on measures of performance (e.g. shot accuracy).

From the outcomes of the coaches' perception study, some of the coaches acknowledged that the golfer and club would move on different planes, confirming the relevance of the investigation by Coleman and Rankin (2005). For the majority of coaches in the coaches perception study, swing plane was used to describe the golf club only (§2.5.3, p28).

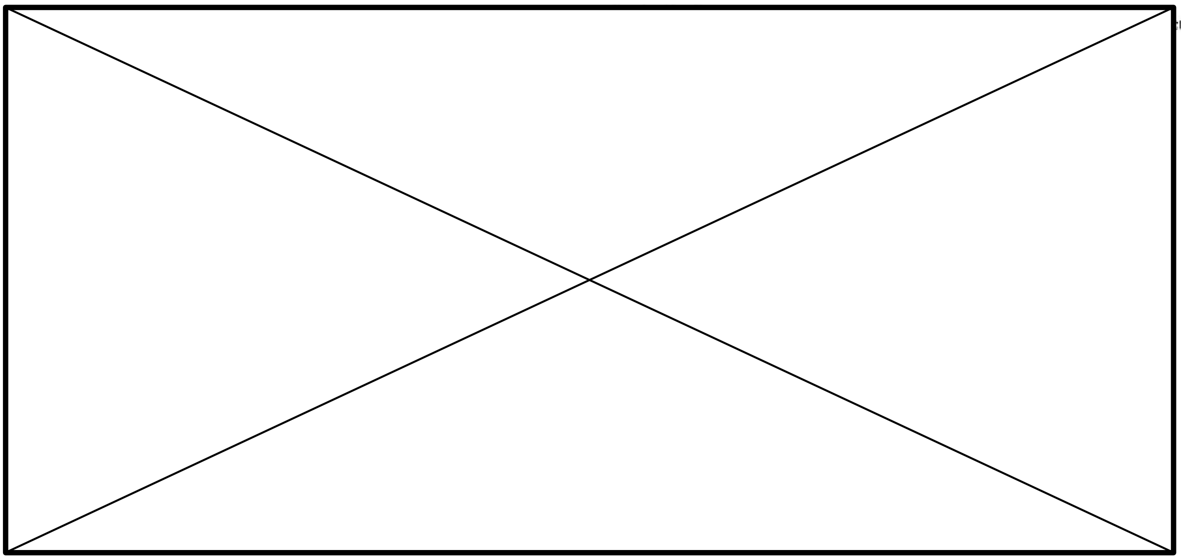


Figure 3.5. Instantaneous swing plane angle in horizontal (a) and target line (b) for a representative golfer and three clubs (Coleman & Anderson, 2007).

The coaches appreciated that swing plane would change between players, but still maintained that the swing required to remain on a specific plane in order to produce accurate and consistent shots. A further shortcoming of coaches perceptions of swing plane was that it was viewed from a down the line position only (Figure 3.3a); negating its 3D nature.

3.4.2 Clubhead Orientation and Direction

This section discusses the measurements that have been taken on club parameters that influence shot distance and shot accuracy, which are predominantly measured at impact. The introduction of launch monitors, such as TrackMan (ISG Company, Denmark); have provided the opportunity to measure a number of parameters that can influence the distance and accuracy of golf shots (Appendix C). Further detail of the club parameter measures and definitions, as defined by TrackMan, can be found in Chapter 4 and Appendix C. Early literature reported that shots hit through the centre of gravity of the clubface, with the clubface and clubhead path orientated in the intended target direction would result in the ball being hit in the intended direction (Hay, 1993). Whilst this is still accepted, the literature from launch monitor companies such as TrackMan states that the initial direction of the ball is influenced by clubhead orientation and clubhead direction (Figure 3.6).

Table 3.2. Biomechanical studies of swing plane

Reference	Plane formation	Angle of Plane	Main Findings
Cochran & Stobbs (1968)	Arms and club (Double Pendulum Model)		- Model used to demonstrate inertia and centripetal forces acting on lower lever to create a well-coordinated downswing if the upper lever was accelerated using the correct force.
Neal & Wilson (1982)	Clubhead and arm (Double Pendulum Model)	Displacement-time of club and arm segment	- X and Z components of club angular velocity were only in constant proportion for the first 100ms. - Plane the club moved through not constant and the motion of the club was not on a single plane.
Coleman & Rankin (2005)	Left-arm plane: C7, left glenohumeral joint, left wrist joint (Upper Pendulum)	Left-arm plane to horizontal and target line. Perpendicular distance on clubhead centre to left-arm plane measured.	- All golfers decreased left-arm plane angle to the horizontal from TB (~ 125 - 145º) to IMP (~ 100º) - Steepening left-arm plane during the downswing as a consequence of left forearm supination. - Maximum rate of steeping similar across golfers, however, occurred at different times - All golfers showed increase in the left-arm plane angle to the target line during late downswing, as a consequence of complex rotation sequence. - Clubhead did not remain on the same plane as left-arm plane. Appears to be an offset between left-arm plane and club shaft at impact, all golfers hit outside (i.e. positive distance from plane) the left-arm plane at IMP.
Nesbit (2005)	Club grip path and clubhead CoM path (Lower Pendulum)	Subjective side view of path grip and clubhead CoM.	- Grip point path and clubhead CoM path not in a fixed plane (difference ~ 10 degrees). - Deflection in the swing plane was affected by swing mechanics. - Magnitude and timing of club shaft deflections varied greatly among subjects.
Coleman & Anderson (2007)	Grip, shaft, toe of pitching wedge, 5-iron, and driver (Plane of best fit/swing plane and continuous swing plane) (Lower Pendulum)	Swing plane to horizontal and target line.	- Difference in swing plane angle between the horizontal were significant between clubs - Driver shallowest horizontal angle (mean 125º and range 121.4 to 129º). - Some golfers fitted a single plane better than others - Significant difference in plane angle to target line for each club. - Most golfers had target line plane angles of less than zero, which the authors suggested would result in a draw shot. - Continuous plane analysis showed angle to horizontal reduced until 70 - 80% of the downswing ("steepening") for all three clubs and increased in the final 20 - 30% ("flattening"). Steepening suggested to be due to trunk rotation, translation left arm abduction. "Flattening" due to wrist ulnar deviation, with forearm supination (left arm) and pronation (right arm). - Continuous plane analysis showed target line below zero (i.e. swing plane to the right of the target line) for 60% then increased through zero towards IMP. - Greater variation between golfers in angle to target line.

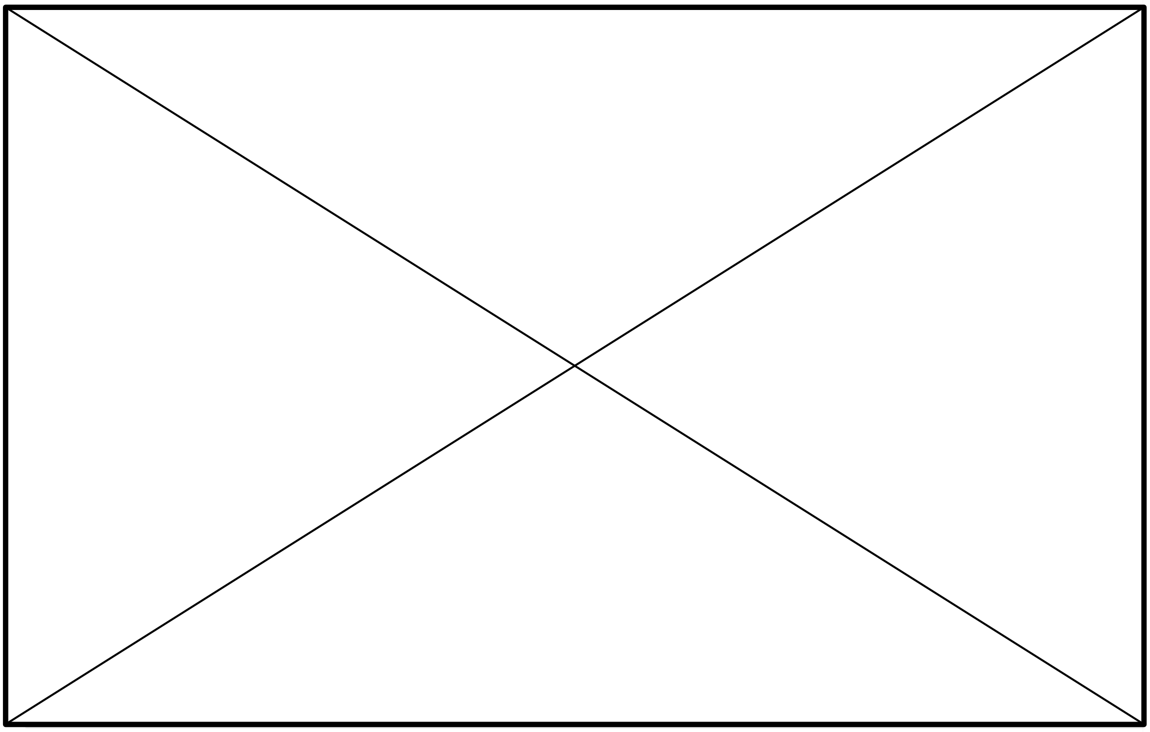


Figure 3.6. (a) Side view and (b) top view of a driver and ball at impact showing TrackMan measured and calculated parameters as reproduced from TrackMan (2010).

Clubhead orientation describes the angle of the clubhead relative to the target line (defined by TrackMan as face angle) and vertical global axis (defined by TrackMan as dynamic loft). Clubhead direction describes the horizontal path the club is travelling on at impact (defined by TrackMan as club path) and the angle the club path is approaching the ball (defined by TrackMan as attack angle). Clubhead orientation accounts for 85% and 75% of initial ball direction for drivers and irons respectively. Conversely, clubhead direction accounted for the remaining 15% and 25% respectively (Tuxen, 2009). Therefore, TrackMan suggest that the most effective way of producing a straight shot are by a club path of 0º, face angle of 0º and centred impact location.

Shot distance is largely influenced by ball velocity, launch angle and spin rate, along with other parameters as included in the deterministic model presented in Chapter 1 and Figure 1.1. From launch monitor data, a greater positive attack angle (4 - 6º) has been reported in professional golfers with more effective drives (i.e. greater displacement). In contrast, the less effective drivers were reported to hit down on the ball approximately 5º. An increased angle of the clubhead path (i.e. attack angle) at IMP has also been reported to positively influence driving distance by Miura (2001). It has also been shown that clubhead linear velocity varies at different locations on the clubhead and therefore would result in lower ball velocities and subsequently shot distance (Ellis et al., 2010). In addition, there are differences in the coefficient of restitution across the club face of a driver which can also affect ball speed during off centre impacts.

An off centre strike on the clubface can also affect the ball's spin axis and subsequently affect the initial direction of the shot and also shot distance (Tuxen, 2009). An off centre strike on the clubface either above or below the clubhead COG leads to a vertical gear effect whereby spin rate can either be decreased or increased. Impacts which are towards the toe or heel of the club face leads to increased side spin due to the gear effect. The gear effect has a greater effect on spin rates when using the driver than irons. Hocknell (2002) showed that better golfers produced less scatter in the impact location on the clubface. Similarly, Williams and Sih (2007) found negative correlations between clubhead speed and handicap and between handicap and vertical impact position on the club face (i.e. lower handicap players swung faster and hit the ball higher on the face).

Betzler et al. (2012) investigated variability in club and ball launch parameters including attack angle, club path, clubhead speed, face angle, impact location and efficiency (i.e. ratio of ball speed to clubhead speed) across golfers of different abilities using a driver. The results reported that Category 1 golfers (handicap plus to 5) were less variable than Category 2 golfers (handicap 6 -12) in all measured clubhead parameters at impact. However, the mean values for some of the club parameters were lower than mean values reported from TrackMan data for tour professional golfers. For example, average attack angle from Tour professionals measured by TrackMan was approximately 4-6° compared to the mean $1.51 \pm 2.49°$ recorded for Category 1 golfers in this study. Interestingly, the authors compared measurement methods between a bespoke motion analysis method (Qualysis) with good repeatability, radar launch monitor (Trackman) and a stereoscopic optical system for measuring club parameters from a golf robot. There were strong correlations between the motion analysis method and radar system for clubhead speed ($r = 99.8\%$, $p < 0.05$), club path ($r = 88\%$, $p < 0.05$), face angle ($r = 80.7\%$, $p < 0.05$) and attack angle ($r = 80.6\%$, $p < 0.05$). However, there were offsets between methods with the motion analysis method both overestimating (face angle (-2.56°)) and underestimating (clubhead speed (0.12 $m.s^{-1}$) and club path (2.27°)) the results from the radar launch monitor. Tuxen (2009) commented on the need for industry standards when comparing data between measurement methods, with values more than two degrees different from that of TrackMan deemed unacceptable. However, there is no gold standard for measuring club and ball parameters.

As aforementioned, clubhead linear velocity is the most frequently reported measure of performance in golf biomechanical studies. Maximum clubhead velocity and clubhead linear velocity at impact have shown strong correlations with some golfer kinematic parameters (Myers et al., 2008; Chu et al., 2010). However, the relationship between club motion parameters such as swing plane, clubhead orientation and club path have not been investigated with golfer kinematic or kinetics. This is surprising given the coaches in this study believed body motion parameters largely affected club motion parameters such as swing plane (§2.5.3, p28). The coaches were also aware of the inter relationship between club path and club face characteristics (§2.5.3, p29) which is supported by launch monitor data such as TrackMan. Similarly, coaches would advocate that clubhead parameters were repeatable at IMP which has also received some support in the biomechanical literature (§2.5.3, p29). Launch monitor data has provided information on club motion; but, how this is achieved through the golfer's body motion is not clearly understood. The lack of studies examining club motion parameters in conjunction with golfer biomechanical data may be due to the difficulty in ascertaining the accuracy of some measurement methods such as launch monitors.

3.4.3 Future Research Recommendations

Future biomechanical studies need to include measures of club motion that can affect both shot distance and shot accuracy. This can be achieved through a combination of extending the motion analysis to include swing plane (left arm and/or club) and launch monitors to gain clubhead and ball parameters. Future studies of club motion should account for golfer kinematics as it may help to explain differences in club motion parameters between golfers. In addition, there is no gold standard for measuring club and ball parameters; therefore there is a need to better understand the accuracy of launch monitor data by comparing to optical based systems.

3.5 Posture

The following section presents literature on golf posture and its relation to measures of performance. However, there are few biomechanical studies that have investigated the effect of posture on measures of performance during the golf swing.

3.5.1 Postural Kinematics

Winter (1995) described posture as "the orientation of any body segment relative to the gravitational vector…an angular measure from the vertical." Therefore, references to the orientation of the body segments from the global vertical axis, will be referred to as postural kinematics. As shown in Table 3.3, different terminology has been used to describe the orientation of the trunk from the global vertical axis when measuring postural kinematics. Therefore, for clarity, the term trunk flexion will be used to describe the orientation of the trunk from the global vertical axis in the sagittal plane. Similarly, the term trunk lateral bend will be used to describe the orientation of the trunk from the global vertical axis in the frontal plane.

Recent methods for measuring postural kinematics in the golf swing have used motion analysis systems, whilst earlier studies used external devices, which utilised gyroscopes and potentiometers (Swing Motion Trainer, SMT) or triaxial electrogoniometers (Lumbar Motion Monitor) (Table 3.3). In the motion analysis studies, trunk flexion and lateral bend were measured from the vertical global axis as a two-dimensional angle of a single rigid trunk segment. Conversely, the studies using external devices measured trunk flexion and lateral bend from a golfer's vertical standing position and often only measured the lower part of the trunk (i.e. the lumbar section). Therefore, the differences in methodologies and different regions of the trunk being analysed could explain differences in the magnitudes of postural kinematics reported in the literature.

Nevertheless, trunk flexion has been acknowledged as a key element of golf posture and was regarded as one of the most important predictor variables of driving ball velocity (Chu et al., 2010). The authors reported minimal changes in the golfer's trunk flexion from TB to IMP (~2 - 3°) and suggested that this angle should remain constant throughout the swing to allow the trunk rotation to be maintained on a plane. In contrast, McTeigue et al. (1994) claimed that trying to maintain constant trunk flexion could cause excessive left side bending and backward bending at TB.

The consistency of trunk flexion at set-up across multiple swings for high and low skilled golfers has also been investigated (Bradshaw et al., 2009). Highly skilled golfers (handicap ~0.3) displayed greater consistency in trunk flexion (i.e. lower coefficient of variation) (1.5 ± 1.1%) and stance width (1.4 ± 0.3%) than lower skilled golfers (4.0 ± 1.5%; 1.9 ± 0.6%, respectively) based on ten 5-iron shots (Bradshaw et al., 2009). The authors suggested that the consistency in trunk flexion at set-up provided a stable base for the execution of the shot and would lead to effective timing and velocity of other technical parameters in the backswing and downswing.

Trunk lateral bend is another key variable in the definition of posture given by Winter (1995). Trunk lateral bend was identified as an important variable at TB (explaining ~25% of the variance in ball velocity) and from the acceleration phase through to IMP (Chu et al., 2010). Between acceleration and IMP, the golfers increased trunk lateral bend from a mean of 8.6 ± 6.0º to 11.7 ± 6.0º, which the authors believed created an upward angle of the club path towards impact (Chu et al., 2010). An increased angle of the club path (i.e. attack angle) at IMP has been reported to positively influence driving distance (§3.4.2). McTeigue et al. (1994) also commented on the greater increase in trunk lateral bend angle towards IMP of tour players compared to amateur golfers. However, there were large differences (of approximately 16º) in the magnitude of trunk lateral bend angle at IMP to the values of Chu et al. (2010). In contrast, Zheng et al. (2008) reported no significant difference in trunk lateral bending between pro golfers (handicap 0 ± 0) and amateur golfers (handicap 3 – 26) and did not regard this parameter as important for distinguishing between pro and amateur golfers. The conflicting results may be due to the different definitions of trunk lateral bend or region of trunk that is analysed (Table 3.3).

The studies summarised in Table 3.3 have treated trunk flexion and lateral bend as separate measures, however, several clinical studies have observed coupled trunk motion during various movements (Huijbregts, 2004; Edmondston et al., 2007). In biomechanical terms, coupled motion describes the association of motion along one axis (either rotation or translation) with another motion about or along a second axis (Huijbregts, 2004). Clinical studies have identified coupled trunk lateral bend as a consequence of trunk axial rotation (Edmondston et al., 2007). Furthermore, Edmondston et al. (2007) anticipated that the magnitude of trunk axial rotation and coupled trunk lateral bend would be affected by the magnitude of trunk flexion from which the movement began. As anticipated, the results revealed that trunk axial rotation and coupled trunk lateral bend were reduced when the movement was initiated with a flexed trunk (Edmondston et al., 2007). The results of the clinical studies could have implications during the golf swing and may indicate that golfer postural kinematics can affect other key technical parameters such as body rotation.

A further derivative of trunk flexion and lateral bend is the timing and magnitude of their velocities which have also been investigated in the literature (Zheng et al., 2008a; Zheng et al., 2008b; Chu et al., 2010). Chu et al. (2010) reported that trunk lateral bend should occur in a short period of time prior to IMP and that early lateral bending could restrict trunk rotation. Similarly, Zheng et al. (2008a) showed that for professional golfers, when using a driver, the timing of maximum trunk lateral bend velocity occurred at approximately 60% of the downswing time. Interestingly, the magnitude of maximum right side trunk lateral bending velocity has been shown to be greater with a 7-iron than a driver (~120 $deg.s^{-1}$ and ~110 $deg.s^{-1}$ respectively) (Lindsay & Horton, 2002). Lindsay and Horton (2002) concluded that the increased right side lateral bending velocity was related to the 7-iron requiring a more vertical swing plane during the downswing than the driver and therefore more lateral motion was created than rotational motion. However, it is unclear from the study as to when the maximum right side trunk lateral bending occurred during the swing and club motion was not directly quantified. Electromyography studies have also confirmed active trunk muscles during the golf swing. A recent review of golf electromyography studies revealed that the right erector spinae was highly activated, especially during the acceleration point (Marta et al., 2012) which supports the finding of increased trunk lateral bend towards impact.

Lateral movement of the trunk was also encouraged following a simplified study of the hub position during the swing with a 3-wood (Sanders & Owens, 1992). Sanders and Owen (1992) defined the hub position as the focal point of the clubhead path. At impact the hub position was approximated to be in line with the left pectoral muscle of right handed golfer. This early study compared the hub movement of elite and novice golfers and also reported chin movement using a single marker. The elite players displayed lateral chin movement towards the back foot during the backswing, reaching maximum displacement after TB and it was positioned behind the ball at IMP. Novice players had a chin position more forward to the ball and lesser displacement during the backswing. The authors concluded by stating that keeping the head still should not be enforced as it prevents lateral movement of the hub during the swing and instead encouraged lateral movement. Alternatively, a more recent study by Horan and Kavanagh (2012) reported low coupling between the head and thorax suggesting golfers used different strategies to control movement. However, this study only analysed the downswing.

The biomechanical definition of posture echoes the coaches description from the perception study as the degree of forward bend in a golfer's spine angle (§2.5.4, p29). The golf coaches believed that maintaining a constant trunk angle throughout the swing, from TA through to IMP, would create consistent club motion (§2.5.4, p32). However, this perception cannot be fully supported by the literature as there are conflicting results and the pattern in trunk flexion has not been formally investigated throughout the whole swing. Previous studies have used ball velocity or clubhead velocity as measures of performance therefore the effect of trunk flexion on other measures of performance, such as shot accuracy, have not been fully investigated. The coaches in the perception study did not discuss expected differences in trunk flexion angle between the driver and long irons, only that the flexion angle remains constant throughout the swing (§2.5.4, p31). In addition, the coaches believed that golfers should have consistent and correct posture at set-up, otherwise it would lead to detrimental club motion and golfer motion (§2.5.4, p32). Whilst this perception has some support from literature, the variability in a golfer's postural kinematics over the whole swing and the effect of posture on other technical parameters, such as body rotation, needs further investigation.

Trunk lateral bending was referred to by only a few coaches when discussing posture during the golf swing (§2.5.4, p31). The contrasting literature, lack of performance related studies and minimal mention by coaches suggests that trunk lateral bend requires further investigation. Nevertheless, coaches alluded to the dependence of body rotations on posture which is partially supported by the clinical study of Edmondston et al. (2007) (§2.5.4, p32). The coaches did not make reference to the timing or velocity of lateral bending, perhaps due to the difficulty in observing such a measure. Nevertheless, the coaches required a stable posture from both a performance and injury perspective; therefore, examining flexion and lateral bend velocities could provide evidence of a golfer's postural stability (§2.5.4, p32). Finally, coaches also suggested that head position contributed to maintaining postural stability throughout the golf swing (§2.5.4, p31); however, there have been conflicting results in the only two previous studies with regards to the role head position has during the swing.

Table 3.3. A summary of references related to posture during the golf swing (driver). Angles, in degrees, are reported at specific swing events (§3.3)

Reference	Terminology	Methods	TA	TB	Acc	40 ms	IMP
Flexion/Extension							
McTeigue et al. (1994)	Lumbar spine forward bend.	SMT[ǂ]	28 ± 2	16 ± 3	-	-	19 ± 2
Lindsay et al. (2002)	Spine/Trunk flexion of thoracolumbar torso	Lumbar motion monitor	28.9 ± 10.9	-	-	-	-
Zheng et al. (2008)	Trunk forward tilt	3D motion analysis	35 ± 4	31 ± 4	-	-	33 ± 3
Chu et al. (2010)	Trunk forward tilt to the global axis (+ve forward)	3D motion analysis	-	22 ± 7	24.2 ± 7.7	23.2 ± 7.9	22.6 ± 7.7
Lateral bend							
McTeigue et al. (1994)	Side bend of lumbar spine	SMT	6 ± 1	3 ± 1	-	-	31 ± 1
Lindsay et al. (2002)	Left/right spine bend of thoracolumbar torso	Lumbar motion monitor	6.9 ± 3.4	-	-	-	-
Zheng et al. (2008)	Trunk lateral bend of shoulder & pelvic vector in frontal plane. (+ve right side bend)	3D motion analysis	13 ± 5	-10 ± 12	-	-	31 ± 5
Chu et al. (2010)	Trunk lateral bend from the global axis	3D motion analysis	-	3.9 ± 7.4	8.6 ± 6	11.7 ± 6	14.4 ± 6.5

[ǂ] SMT (Swing Motion Trainer)

3.5.2 Knee Flexion

Minimal research has been conducted in lower joint kinematics. Egret et al. (2003) is the only study to use knee joint kinematics as measures of a golfers technique between clubs and gender. At set-up, both left and right knee were equally flexed (~18º) regardless of the club. With a driver, left knee flexion was more pronounced than the right knee flexion at TB (~37º vs. ~23º respectively). In a subsequent study, male golfers have also been reported to have greater left knee flexion at TB than females, which was stipulated to increase the swing arc with reduced trunk or pelvis rotation (Egret et al., 2006). Egret et al. (2006) also found wider stance width in male golfers compared to females when accounting for height, however, the effect on any aspect of performance was not discussed.

Some coaches made reference to knee angles when discussing posture (§2.5.4, p32) and it may be of interest to investigate knee motion throughout the swing as it may play a role in maintaining a posture which the coaches would advocate. Similarly, the golfer's stance could be associated with knee flexion.

3.5.3 Postural Balance

Posture is also regarded as a dynamic variable of balance and has been defined as the dynamics of body posture to prevent falling (Winter, 1995). Two common measures associated with postural balance are whole body centre of gravity (COG) and centre of pressure (COP). The previous literature on these topics related to the golf swing is discussed below.

The golfers COG is a weighted average of the COG of each body segment in 3D space and is controlled by the balance control system. Burden et al. (1998) is the only study to report the COG path throughout the golf swing using a driver. The COG displayed a consistent path across all right handed golfers in the backswing but there were differences in COG location at IMP. Initially, the COG moved to the golfers right and maximum displacement (range 3.4 cm - 14.4 cm) was completed before or at TB. This was combined with forward movement of the COG which continued into the downswing and was consistent regardless of hip and shoulder rotations. Approximately 0.1 seconds before IMP, the COG moved to the golfers left (target direction) and forward of the set-up position, but at IMP the COG was different for each golfer. The COG was either in front and left of its position at set-up, behind and left of the set-up position or right and in front of set-up position. There was no clear reason given for this movement of COG and there was no relationship with measures of performance or a golfer's posture (i.e. trunk forward and lateral bend). Centre of gravity investigations of fast bowling in cricket have reported that bowlers who were able to co-ordinate their bowling action with COG deceleration were more likely to generate high ball speeds (Wormgoor et al., 2010).

Centre of pressure is defined as the 2D point location (in the horizontal plane) where the resultant of all ground reaction forces (GRF) act (Winter, 1995). From baseball research, the difference between COP and COG locations (on the horizontal plane) was up to 20 cm at certain phases of the baseball swing (Welch et al., 1995). Furthermore, alignment of these measures determined rotational and linear movements of hitters which, in turn impacted on the bat velocities generated (Welch et al., 1995). Ball and Best (2007a) presented two distinct COP styles observed in the golf swing, 'front foot' and 'reverse foot'. The front foot style was characterised by a balanced position at TA, moving to the back foot (which is the right foot of a right handed golfer) during the backswing then left to the front foot (which is the left foot of a right handed golfer) during the downswing and with the weight predominantly on the front foot at IMP. The reverse foot style was characterised by a shifting of weight to the left from TB through the downswing and then weight was near mid-stance during IMP before moving to the back foot during follow through (Ball & Best, 2007a). Front foot style golfers with greater range of COP_{M-L} movement and increased rate of COP movement to the front foot in the downswing were associated with higher club head velocity. The reverse foot golfers with higher club head velocity had COP measures near mid-stance and greater rate of COP towards the back foot at IMP. The authors stated it was important to identify strategies within each style before links to performance could be deduced. Therefore, it appears that the range and rate of change of COP were points of interest in both COP styles. However, in the 308 golfers examined by Chu et al (2010) only the front foot style, defined using the ratio of vertical GRF between the front and back feet, was observed. Alternatively, the decreasing magnitude of vertical force in the front foot towards impact coupled with an upward translation of the pelvis were stronger predictors of clubhead linear velocity. Therefore, there appears to be disagreement between studies on COP patterns during the golf swing. Nevertheless, Ball and Best (2007b) commented that neither style should be viewed as a technical error as there were no differences in clubhead velocity at impact observed between styles. Instead, it was deemed more important to identify the different strategies used to perform the golf swing in order to make appropriate coaching recommendations. Both these studies only examined part of the notion of postural balance, as variables such as COG and postural kinematics were not examined simultaneously. In addition, perturbations to a normal erect posture (i.e. leaning forward or backwards) during gait has been shown to affect postural responses (i.e. moments) in the hip, knee and ankle based on the inverted pendulum model of balance (Winter, 1995). Therefore, this emphasises the need to collect both kinematic and kinetic data (e.g. GRF data) when examining posture during the golf swing. An area that has not been readily investigated is the ability of golfers to repeat patterns in weight transfer.

The coaches in the perception study also identified the importance of postural balance and discussed the idea in terms of positioning a golfer's COG correctly and their weight transfer (§2.5.4, p32) which echoes Winter's (1995) definition of balance. Often the coaches would make reference to a golfer's postural kinematics as a means of creating a balanced position throughout the swing (§2.5.4, p32). For example, one coach described the need to "match" certain parameters during the golf swing which may be achieved by collecting both kinematic, kinetic and measures of performance.

3.5.4 Future Research Recommendations

Golf posture has only been partially investigated in the biomechanical literature. The variables defining golf posture need to be more completely identified and their effect on measures of performance, such as shot accuracy or repeatability of measures of performance quantified. This may require the development of new methodologies to describe 3D trunk kinematics through multiple segment models. The relationship between postural kinematics and postural balance also needs to be established. Finally, the relationship between posture and other key technical parameters, such as body rotation require investigation.

3.6 Body rotation

This section presents literature regarding trunk and pelvis axial rotation during the golf swing. The term axial rotation refers to motion about the vertical axis of either the local co-ordinate system of a segment or global co-ordinate system.

3.6.1 Pelvis and Trunk Axial Rotation

When reviewing the literature on axial rotation, many terms were used to investigate this parameter, for example, hip, shoulder, trunk, upper torso and thorax. Therefore, to improve clarity in this section the terms trunk and pelvis axial rotation will be used but the terms/definitions from individual studies are presented in Table 3.4.

It is important to present the various terminology, definitions and methodologies used for calculating axial rotation in the literature as it can help interpretation of the results between studies. The majority of previous studies have calculated trunk and pelvis axial rotation as 2D projection angles. These methods include simply using marker positions (e.g. acromion and anterior superior illiac spine (ASIS) markers) to define trunk and pelvis segment vectors (Burden et al., 1998). Two-dimensional axial rotation angles are then calculated by projecting the vectors onto the global co-ordinate system horizontal plane. However, some authors have warned that the complex motions at the shoulder (scapular protraction/retraction) could influence the vector created by the acromion markers and as a result could alter upper rotation angles (Mitchell et al., 2003; Wheat et al., 2007; Myers et al., 2008). Also, in reality, the golfer rotates about an inclined trunk (§3.5.1) and projecting the trunk vector onto the global co-ordinate system horizontal plane could lead to perspective error in axial rotation angle measurements. Similarly, 2D projection angles do not account for the six degrees of freedom of golf swing motion (Horan et al., 2010), hence more recent studies have used 3D measurements to calculate trunk and pelvis axial rotation (Wheat et al., 2007; Horan et al., 2010; Joyce et al., 2010) (Table 3.4).

The golfer's body rotation has been widely investigated within the golf biomechanical literature and is regarded as a key feature in the golf swing (Table 3.4). Many studies have reported pelvis and trunk axial rotational angles at discrete points during the swing including at TA, TB, IMP, mid-downswing, last 40ms prior to impact (Figure 3.1) and the peak magnitudes. The peak magnitudes and magnitudes at these discrete points have been linked to performance outcomes related to increasing shot distance either through subjective interpretation of results (Burden et al., 1998a; Zheng et al., 2008a; Zheng et al., 2008b), correlational analysis (Myers et al., 2008; Meister et al., 2011) or regression analysis (Chu et al., 2010).

Burden et al. (1998) reported that the trunk goes through a greater range of axial motion than the pelvis during the backswing. Peak trunk axial rotation angles have been found to increase linearly as swing intensity increases, leading the authors to suggest that peak trunk rotation was related to driving distance (Meister et al., 2011). At IMP, many of the golfers showed greater axial rotation towards the target than at TA and, unsurprisingly, the authors commented that a golfer's COG pattern was consistent regardless of trunk or pelvis rotations. Professional golfers also exhibited greater trunk rotation at IMP than novice golfers (Meister et al., 2011). Zheng et al. (2008a) similarly noted increased trunk rotation from low handicap to professional golfers at IMP coupled with increases in club angular velocity. However, caution should be raised when comparing these results as the studies used different clubs and definitions of trunk axial rotational angles (Table 3.4).

Benchmark curves of rotational parameters, using 2D projection angles, have highlighted areas of similarities and differences between amateur golfers and their professional counterparts throughout the swing (Meister et al., 2011) (Figure 3.7).

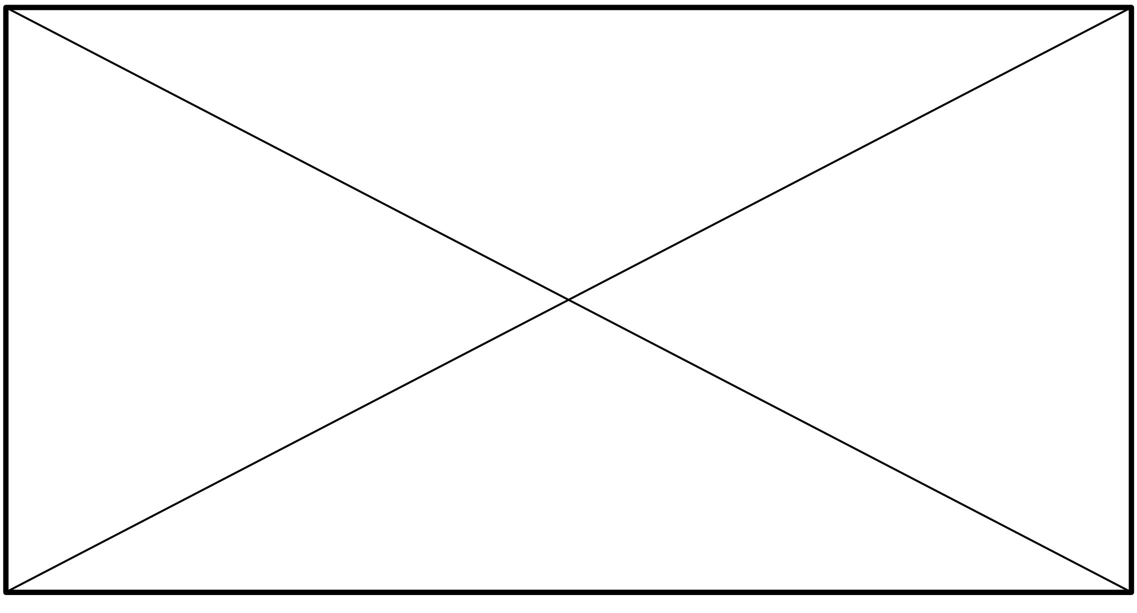


Figure 3.7. Benchmark curves of mean rotational biomechanics of professional and amateurs using a 5-iron (Meister et al., 2011). 100% is impact.

There are also reported differences in rotational parameters between male and female golfers (Zheng et al., 2008b; Horan et al., 2010; Horan et al., 2011). Male golfers showed reduced trunk axial rotation (25.7 ± 8.1° vs. 29.3 ± 11°) and reduced pelvis axial rotation (43.7 ± 10° vs. 49.6 ± 11.9°) at IMP (Horan et al., 2010) and at TB (shoulder rotation; 100 ± 8º vs. 109 ± 7º pelvis rotation;42 ± 7º vs. 49 ± 8º) (Zheng et al., 2008b). These results suggest that the magnitude of axial rotation at these discrete points in the swing did not explain the observed difference in peak clubhead linear velocity between male and female golfers (49.1 ± 3.6 $m.s^{-1}$ and 40.4 ± 3.0 $m.s^{-1}$ respectively). Instead, authors have suggested that the separation between pelvis and trunk axial rotation was more important for power generation (Burden et al., 1998; Chu et al., 2010) .

3.6.2 Pelvis and Trunk Separation (X-factor)

As aforementioned, although body rotation is regarded as a key component to the golf swing, many studies have emphasised that the separation between the trunk and pelvis rotations as more important than the individual segments rotations for producing power during the golf swing (Burden et al., 1998; Chu et al., 2010). The terms thorax-pelvis separation, torso-pelvis separation and X-factor have been used to define the difference in axial rotation between the trunk and pelvis (Table 3.4). For the purpose of this thesis the term X-factor will be used.

Several authors have reported X-factor to be a key technical parameter contributing to golf swing performance outcomes, typically quantified by ball velocity and/or clubhead linear velocity at IMP (Myers et al., 2008; Chu et al., 2010). Despite several studies placing emphasis on X-factor as a key technical parameter influencing performance there appears to be no universally adopted measurement method for X-factor. A number of different methods have been used to determine pelvis and trunk rotation angles and the resulting X-factor from marker positional data (see §3.6.1 and Table 3.4). The X-factor calculated by the 2D projection method would be the angle between the projected pelvis and trunk vectors; however, limitations have been identified with this method as discussed in §3.6.1. Therefore, more recent studies have chosen to use the 3D measurement of X-factor which accounts for the six degrees of freedom of the golf swing motion (Horan et al., 2010). However, there has not been a direct comparison of X-factor magnitude between 2D projection methods and 3D measurement methods until recently (Brown et al., 2013; Kwon et al., 2013). Both studies reported statistically significant differences between X-factor values when using different computation methods. In particular, Kwon et al. (2013) reported substantially larger maximum X-factor values when using the 2D projection method. Although both studies examined 3D X-factor angles, neither study acknowledged the differences due to Cardan rotation orders. In addition, both studies used an homogenous group of ability golfers with handicaps less than 5, therefore, a range of ability golfers may be able to identify differences in computation techniques more readily.

Chu et al. (2010) reported that X-factor at TB explained approximately 25% of ball velocity and the authors suggested golfers should focus on increasing separation between trunk and pelvis in order to increase ball velocity. In addition, maximum X-factor during the downswing has been shown to strongly correlate with ball velocity ($r = 0.54$, $p < 0.05$) and clubhead linear velocity at IMP ($r = 0.86$, $p < 0.05$) (Myers et al., 2008). Furthermore, Myers et al. (2008) reported a moderate correlation between ball velocity and X-factor at TB ($r = 0.55$, $p < 0.05$) but not at IMP. The authors concluded that X-factor at TB and downswing maximum contributed to the rotation velocities of the upper torso and X-factor which, in turn contributed to increased ball velocity. Conversely, Meister et al. (2011) reported statistically significant correlations for X-factor at IMP with clubhead linear velocity ($r = 0.94$, $p < 0.05$). These differing results may be due to the different clubs used in the studies (Table 3.4). Unsurprisingly, several differences have been reported in X-factor magnitude between professional and novice golfer's (i.e. did not have a handicap) (Meister et al., 2011). Professional golfers exhibited greater peak X-factor and greater X-factor at IMP which was coupled with higher 5-iron clubhead linear velocities than novice golfers (35.4 ± 2.1 m.sec^{-1} versus 25.2 m.sec^{-1}). The authors observed that a novice golfer displayed excessive X-factor early in the backswing and proposed that this could lead to injury (Meister et al., 2011) (Figure 3.8). The studies that examined X-factor across shot intensities also reported differences with the magnitude of peak X-factor increasing from easy-to-hard swings and low-to-high ball velocities (Meister et al., 2011).

The difference in X-factor between TB and downswing maximum value (termed X-factor stretch), has been suggested as more important to an effective swing than the maximum X-factor alone (Cheetham & Martin, 2001). It was found that highly skilled golfers (handicap < 0) had an X-factor stretch (13.4º), significantly higher than lower skilled golfers (0.5º). The greater X-factor stretch was considered to contribute to the greater hitting distance for the higher skilled golfers (Cheetham & Martin, 2001). It is important to note that the differences in how TB is defined could affect the value of X-factor at this part in the swing and subsequent X-factor stretch calculations. In addition, the use of 2D X-factor calculation methods may cause inflated X-factor stretch values (Kwon et al., 2013).

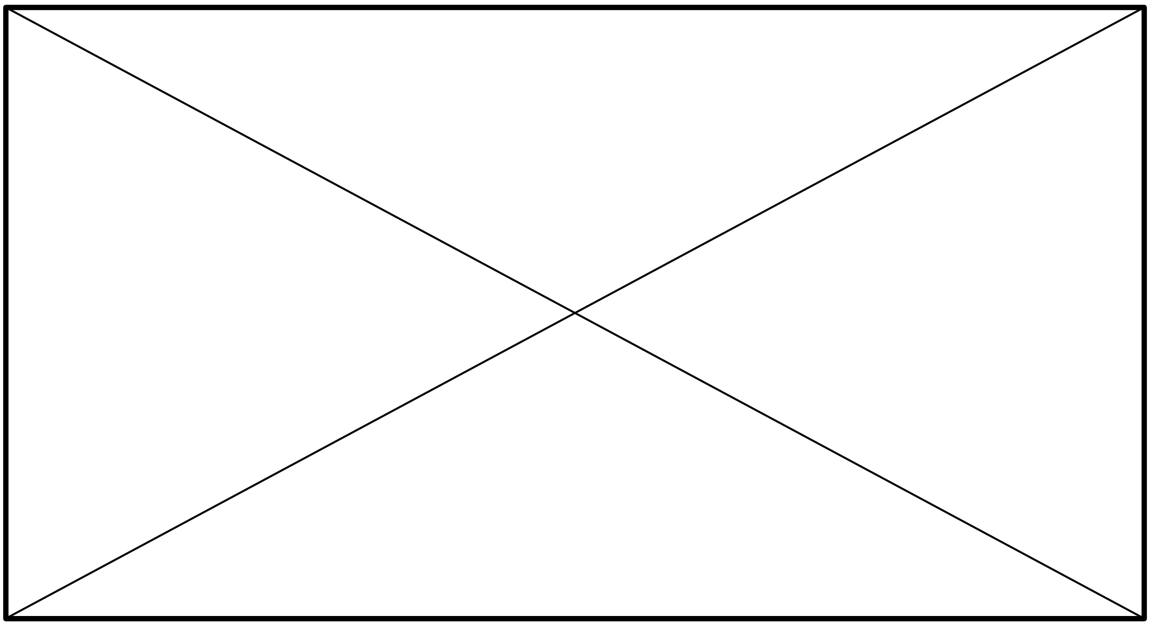


Figure 3.8. Benchmark curves of mean X-factor of professional and amateurs (Meister et al. 2011).

An extension to the idea of X-factor stretch incorporates measures of the rate of stretch during the backswing and rate of recoil during the downswing (Neal, 2008). The rate of stretch and recoil describe the speed with which the trunk and pelvis separate and align providing a measure of rotational power. Golfers with greater driving distance are suggested to display greater maximum rates of recoil (Neal, 2008). Nevertheless, there are limited studies that have investigated this idea further.

The proposed mechanism for increased separation between trunk and pelvis contributing to performance (i.e. X-factor, X-factor stretch) has been related to the increased eccentric loading of the trunk during the backswing which could lead to greater concentric unloading during the downswing (Myers et al., 2008). Burden et al. (1998) theorised that the separation of the pelvis and trunk and timings of rotations would contribute to a stretch-shorten cycle within the spinal rotator muscles, leading to increased trunk acceleration and in turn increased club acceleration leading to greater torque being applied to the golf club. However, no study has quantified the amount of stored energy within these muscles during the golf swing. From electromyography studies, relatively low levels of trunk muscle activity (e.g. abdominal obliques and erector spinae) were reported during TA but increased from TB to IMP on both the right and left side of a right handed golfer (Pink et al., 1993). In direct contrast, studies on female golfers have not provided support for the stretch-shortening mechanism of trunk muscles during the downswing for increasing clubhead linear velocity (Brown et al., 2011). The authors noted that greater X-factor or X-factor recoil velocities could not explain the variance in clubhead linear velocity in all golfers. Therefore, the proposed mechanism for X-factor contributing to performance requires investigation.

The separation between trunk and pelvis was viewed as more important than rotations of individual segments by golf coaches (§2.5.7, p34) which is in agreement with most of the previous biomechanical literature. Some coaches alluded to other important aspects of X-factor, such as rate of recoil (§2.5.7, p34); there have been few studies to investigate this premise.

The consistency of rotational parameters have also been investigated (Bradshaw et al., 2009; Horan et al., 2011; Meister et al., 2011; Tucker et al., 2011). Meister et al. (2011) used the coefficient of variation (CV%) as a measure of consistency in rotational parameters for varying shot intensities (i.e. easy-to-hard). The use of CV% as a measure of variability has been questioned due to it accounting for both methodological and biological variability (Bradshaw et al., 2009) and when applied to small values the CV can become inflated. Nevertheless, peak trunk axial rotation showed greater consistency as shot intensity increased while peak pelvis rotation variability was greater than trunk rotation variability across all shot intensities. In addition, the rotational parameters at IMP displayed larger CV% than the peak values which may be a consequence of consistently identifying the IMP position. In contrast, previous studies have suggested that variability in technique at IMP would be less than at other points of the golf swing (Bradshaw et al., 2009; Penner, 2003). Horan et al. (2011) examined movement variability of rotational parameters using standard deviations (SD) at discrete points (TB, mid-downswing, IMP) and using spanning sets across continuous phases (TB ± 20% downswing time, mid-downswing ± 20% downswing time, IMP ± 20% downswing time) in male and female golfers. Female golfers were reported to have greater axial rotation variability for the pelvis at mid-downswing and IMP and trunk at IMP than males. However, the authors could not explain these differences in variability. These authors also reported that the variability in clubhead trajectory was the same for males and females (Horan et al., 2011) which is partially supported by Meister et al. (2011) who reported minimal variability in clubhead speed as shot intensity increased for professional golfers.

After attaining the correct posture, the coaches in the perception study would encourage body rotation which, using the coaching terminology, related to “hip” and “shoulder” rotations (§2.5.5, p33). The lack of consistency between rotational parameter definitions in the golf biomechanical literature is echoed by the coaches use of multiple terms to describe body rotation (§2.5.5, p34). Whilst some coaches clearly stated they were concerned with trunk rotation others used the term shoulder to describe the same parameter. In addition, although coaches were largely concerned with body rotation they did not discount the effect of movement in other directions such as shifts or translation (§2.5.5, p34). Coaches would also link body rotation to powerful, repeatable and simple swings and therefore it may insinuate they believed body rotation would lead to less variability in the swing (§2.5.5).

3.6.3 Future Research Recommendations

Body rotation is a major component to the golf swing; however, its relationship with other parameters need to be investigated (e.g. posture). Again this will require determination of the most appropriate methodologies to account for rotations and translations about the other axes. Although, body rotation varied at discrete stages, the variability throughout the swing and across golfers needs investigation.

Table 3.4. Summary of literature on axial rotation of pelvis and trunk during the golf swing using 2D projections and 3D methods

Reference	Subjects	Terminology	Method	Definition	Stage	Main Findings/Performance Outcomes
Burden et al. (1998)	- 8 male (handicap 7 ± 1) - Driver	- Hip - Shoulder - Hip - shoulder differential	2D projection Video analysis	- Angle in horizontal plane between hip joint centres and line parallel to target - Angle in horizontal plane between shoulder joint centres and line parallel to target - Angle of the shoulders relative to the hips in the horizontal plane	Whole swing	- Greater range of shoulder rotation than hips. - Sequential rotation of hips and shoulders in excess of 90 degrees during backswing and leading hip rotation in downswing linked to increased clubhead velocity.
Egret et al. (2006)	- 7 male (handicap 6.6 ± 1.7) 5 female (handicap 6.1 ± 3.4) - Driver	- Hip - Shoulder	2D projection Motion analysis	- Angle in horizontal plane created by a line between the greater trochanters and line parallel to target - Angle in horizontal plane created by a line between the acromion and line parallel to target	TA TB IMP	- Shoulder rotation at TB ~ 90º for male golfers - Greater shoulder rotation in female golfers ~ 110º - Female golfers greater hip rotation than males at TB (~ 65º and ~ 38º respectively) - No direct link to performance
Myers et al. (2008)	- 100 males (handicap 8.1 ± 7.3) - Driver	- Upper torso - Pelvis - Torso-pelvic separation - Maximum torso-pelvic separation	2D projection Motion analysis	- Angle between upper torso segment (not clearly defined) and global x-axis (parallel to target direction) - Angle between pelvis segment (not clearly defined) and global x-axis (parallel to target direction) - Difference between the upper torso rotation angle and pelvic rotation angle at the top of the backswing. - Maximum difference between the upper torso rotation angle and pelvic rotation angle during downswing represented x-factor stretch	TB MID Last 40ms IMP	- Torso-pelvic separation (maximum and at TB) contributed to increased upper torso rotation velocity and torso-pelvic separation velocity in downswing which contributed to increased ball velocity
Zheng et al. (2008a)	- 72 golfers Tour pro to high handicap (handicap 0-21) - Driver	- Trunk axial rotation - Shoulder-to-hip separation	2D projection Motion analysis	- Angle between the vector of the pectoral girdle and the vector of the pelvic girdle in the transverse plane.	TA TB IMP	- Greater trunk rotation for pro than high handicap golfers. - At IMP magnitude of trunk rotation increased from high handicap to tour pro. - Maintaining shoulder-to-hip separation throughout swing characteristic of higher skilled golfers - Greater trunk rotation for pro and low handicap associated with a lower trunk rotation velocity.

Reference	Subjects	Terminology	Method	Definition	Stage	Main Findings/Performance Outcomes
Zheng et al. (2008b)	- 25 female LPGA tour 25 male PGA tour - Driver	- Trunk axial rotation - Shoulder orientation - Pelvis orientation	2D projection Motion analysis	- Angle between the vector of the pectoral girdle and the vector of the pelvic girdle in the transverse plane. Referred to as shoulder-to-hip separation. - Shoulder vector projected to the floor plane (parallel to target) - Pelvis vector projected to the floor plane (parallel to target)	TA TB IMP	- Greater shoulder and pelvic orientation (9 and 7º) for LPGA than PGA - Greater change in shoulder and pelvis orientation from TB to IMP for LPGA than PGA but less 'uncoiling' effect - Similar X-factor between LPGA to PGA at TB described as the coiling effect and mechanism for creating a 'power' swing - LPGA more pelvic rotation that PGA at IMP. - X-factor magnitude converted into power less for LPGA (no explanation given)
Horan et al. (2010)	- 19 male (handicap < 4) 19 female (handicap <4) - Driver	- Thorax axial rotation - Pelvis axial rotation - Thorax-pelvis separation	Motion analysis 3D	- Angular rotation of thorax segment z-axes relative to the LCS based on position of the heel markers. - Angular rotation of pelvis segment z-axes relative to the - - LCS based on position of the heel markers. - Difference between thorax and pelvis axial rotation projected onto a horizontal plane.	TB IMP Max.	- Female greater thorax and pelvis axial rotation at IMP - Lesser magnitude of thorax rotation reported than previous studies, due to methodological differences therefore, results not affected by out of plane motion - No difference in X-factor between males and females - Body rotation considered in combination with postural parameters, velocities, translations and motor control. All contributed to the increased clubhead linear velocity
Chu et al. (2010)	- 308 golfers (266 males, 42 females) handicap 8.4 ± 8.4 - Driver	- Upper torso - Pelvis - X-factor	Motion analysis	- Positive for rotating forward, 0º for neutral position. No definition given for upper torso - Positive for rotating forward, 0º for neutral. No definition given for pelvis - Separation between the upper torso and pelvis.	TB ACC. Last 40ms IMP	- X-factor important at TB than pelvis or thorax rotation - Generates greater power - Increased leading knee flexion linked to improved pelvis backward rotation. - Included analysis of movement in other planes and velocities
Joyce et al. (2010)	- 1 male golfer (handicap 7) - Driver	X-factor	Motion analysis 3D	- Separation of the hip-shoulder alignment at the top of the downswing. - Shoulder segment was through the left and right acromion process and T10	TA IMP FT	- ZYX cardan rotation order (lateral bending,flexion/extension,axial rotation) selected

Reference	Subjects	Terminology	Method	Definition	Stage	Main Findings/Performance Outcomes
Horan et al. (2011)	- 19 male (handicap < 2) 19 female (handicap <3) - Driver	- Thorax axial rotation	3D Motion analysis	- Angular rotation of thorax segment z-axes relative to the LCS based on position of the heel markers. - Thorax defined by four markers (suprasternal notch,xiphoid process,C7 and T10)	TB MID IMP TB, MID, IMP ± 20%	- Females greater variability for pelvis axial rotation at MID and IMP and thorax axial rotation at IMP. - Thorax-pelvis coupling greater variability at TB associated with transitional movement
Meister et al. (2011)	- 15 male golfers (10 pro) (5 amateur handicap 4-30) - 5-iron	- Pelvis - Upper-torso - X-factor	2D projection Motion analysis	- Line defined by right and left acromion superior iliac spines (ASIS) - Line defined by the right and left acromion processes. - Angle between the pelvis and upper-torso projected into the horizontal plane.	Whole swing Max. IMP	- Measure of consistency of rotational biomechanics - O-factor, S-factor and X-factor highly consistent in professional golfers based on coefficients of variation - Increase in clubhead speed at impact, peak X-factor, X-factor at impact and peak upper-torso rotation, therefore important for power generation - Upper-torso contributes to X-factor more than pelvis.

3.7 Arm and Wrist Kinematics

This section provides details of those studies that have investigated the influence of arm (including upper and forearm) and wrist kinematics on performance during the golf swing.

3.7.1 Wrist Kinematics

Within the literature wrist angles (Milburn, 1982; Zheng et al., 2008a; Zheng et al., 2008b), wrist angular velocities (Zheng et al., 2008a; Zheng et al., 2008b) and wrist torques (Sprigings & Neal, 2000) have been reported throughout the golf swing. Early double pendulum models of the golf swing, modelled the left wrist as a simple hinge joint and wrist-cock angles were reported. Wrist-cock angles represent radial deviation and wrist-uncocking is wrist adduction or ulnar deviation (Figure 3.9). Cochran and Stobbs (1969) considered the wrist-cock angles during the downswing and reported the wrist as pivotal to increasing clubhead linear velocity.

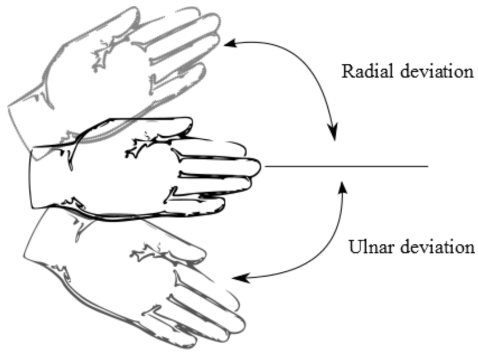


Figure 3.9. Wrist radial and ulnar deviation reported as cocking and uncocking angles in golf biomechanical literature (Milburn 1982)

Milburn et al. (1982) supported this finding as they reported a delay in the uncocking of the wrists would result in greater production of peak wrist angular velocity in accordance with the theory of proximal-to-distal sequencing. However, if wrist uncocking began too early it resulted in a loss of clubhead speed. The authors reported that wrist angles remained constant for the first part of the downswing (approximately 60º to 70º), increased during transition and finally increased to almost 180º at IMP (180º being the neutral position) which signified that the hands were leading the clubhead. More recent studies have also reported left wrist angles at IMP close to 180º in professional golfers (165 ± 4º) (Zheng et al., 2008b). Significant differences were also noted between professional and higher handicap amateur golfers in left wrist angles at IMP (165 ± 4º vs. 156 ± 9º), maximum left wrist velocity (1085 ± 338 $deg.sec^{-1}$ vs. 662 ± 249 $deg.sec^{-1}$) and timing of maximum left wrist velocity in the downswing (88 ± 4% vs. 83 ± 5%). The study by Fedorcik et al. (2012) measured significantly larger radial deviation wrist angles in the lead arm for higher handicap golfers, but did not present any measures of performance. Nevertheless, these results suggest that professional golfers reached maximum left wrist angular velocities closer to IMP than amateur golfers and delayed the release of their wrist. Left wrist hinge angles and wrist hinge velocity measured during the downswing have also been related to ball velocity at IMP. It has been reported that approximately 35% of ball velocity was explained by wrist hinge angle (35.3 ± 13º, 0º was neutral position) 40ms prior to impact (Chu et al., 2010). The negative relation between wrist angle velocity and ball velocity suggested that rapid wrist motion in the 40ms before IMP was advantageous. However, none of the above studies accounted for movement at the wrist in other planes including flexion/extension or pronation/supination. The potential reason for this could be due to the difficulty in quantifying wrist motion using current motion analysis techniques.

From simulation studies, it was proposed that a well-timed wrist torque, during the downswing, could increase clubhead velocity by 9% at IMP (Sprigings & Neal, 2000). The applied wrist torque began shortly after the natural uncocking of the wrists due to the centrifugal force (radial component) of the club. This well-timed wrist torque echoes simulation studies conducted by Miura (2001) who investigated the effect of an inward pull of the golf club at IMP on the clubhead velocity. The theoretical phenomenon under investigation was parametric acceleration, which states that if the pivot point of a rotating mass is moved in the opposite direction to the centrifugal force of the mass, the kinetic energy of the mass could increase. Using the golf swing as an example, the authors found that the radial component of the hands (414 N) was largely due to the centripetal force of the club. The clubhead could not be accelerated by additional tangential force applied with the hands as the arm was decelerating at IMP and the additional tangential force would disturb natural motion of the club. The only necessary action for the golfer was to oppose the large centrifugal force and if this did not occur the club would move radially and decrease clubhead velocity. Nevertheless, from emulation of the golf swing it was found clubhead velocity could increase with the pull motion initiated 0.04 seconds before impact. When observing an expert golfer the authors recorded an altered trajectory of the hand path. The co-ordinated rotation of shoulder, pelvis and lifting of the left side of the body was proposed to generate the inward pull motion. However, no biomechanical data was collected to confirm these observations. The change in hand path (i.e. hub path) has been noted in kinematic studies where by the hub path had a non-constant radius (i.e. non-circular path), a shifting centre of rotation and was individualised across golfers (Nesbit & Mcginnis, 2009). However, there was a pattern in the changing hub radius between golfers. The maximum radius occurred near TB, and the minimum radius happened during mid-backswing, with all golfers experiencing a sharp reduction in hub radius at impact as discussed by Miura (2001). Optimising the hub path of a scratch golfer to a non-circular path resulted in lower kinetic loading but with increased clubhead velocity (Nesbit & Mcginnis, 2009). In addition, the reduced radius of the hub path towards impact has been suggested to give an impression of a delayed wrist release (Nesbit, 2005).

Coaches were keen for players to “cock” their wrists and to time when their wrist uncocked (§2.5.6, p36). Some coaches referred to wrist kinematics as a power source (§2.5.6, p36), which is supported by the biomechanical literature that has reported the importance of wrist kinematics on generating clubhead linear velocity. Much of the literature has focused on wrist kinematics during the downswing and into IMP, however, for one coach wrist kinematics were important during the backswing (§2.5.6, p36). Although the coaches did not allude to the importance of the hand path during the swing, this may be due to the difficulty in observing such a measure with computer modelling or biomechanical analysis.

3.7.2 Grip

Grip has been deemed important for resulting wrist motion during the golf swing (Cochran & Stobbs, 1968). Cochran and Stobbs (1968) reported a simplified version of grip force versus wrist angle test and found that wrist motion was hindered by a high grip force (> 320 N). Similarly, reductions in grip force due to the position and orientation of wrist and forearm are also evident (Mogk & Keir, 2003). Nevertheless, the force applied at the grip must be able to overcome or balance centrifugal forces of the golf club (Miura, 2001). Despite all golfers needing to overcome the centrifugal force of the club, individual golfer grip force profiles have been reported (Komi et al., 2008). Trends appeared within the data, for example, overall grip force was close to minimum at IMP and left hand total force was always greater than that for the right hand. Komi et al. (2008) also reported individual finger forces and peak left thumb forces occurred before and after IMP. However, links to performance and golfer kinematis were not investigated.

Grip was often described as fundamental to the golf swing by coaches (§2.5.6, p35). The coaches would require a grip to match a golfer's swing (§2.5.6, p35) which is partially supported by the study of Komi et al. (2008) that recorded individual golfer grip force profiles, but there was no measure of golfer kinematics.

3.7.3 Arm Kinematics

Arm movement during the golf swing has received less attention than wrist movement. Zheng et al. (2008a) reported arm kinematics during their analysis of the golf swing which included measures of upper arm-trunk and elbow flexion angles. The only significant difference was greater left elbow flexion in high handicap golfers compared to professional or lower handicap golfers. The higher handicap golfers also exhibited lower elbow flexion velocity. The differences in arm kinematics were suggested to be associated with the golfer's ability to effectively change club orientation through IMP. Furthermore, Horan et al. (2011) observed decreasing variability in hand and club trajectories towards IMP in both male and female golfers which was proposed to be crucial for regulating IMP characteristics. However, neither study had measures of clubhead orientation. EMG studies have recorded active pronator teres muscles in both trail and lead arm during the golf swing (Farber et al., 2009). The pronator teres muscle activity was higher in the trail arm of amateur golfers and higher in the lead arm of professional golfers. The difference in pronator teres activity was linked to the prevalence of elbow injuries between the two groups of golfers and there was no suggestion of differences in technique causing changes to activity despite kinematic data showing differences in arm kinematics. For example, in tennis, increased forearm rotation has been linked to the generation of greater racket head speed (Elliott et al., 1996).

3.7.4 Future Research Recommendations

The role the arms and wrists play in regulating club parameters such as clubhead orientation needs further study. In addition, the lesser variability shown in arm kinematics at IMP need to be linked to clubhead orientation and direction.

3.8 Sequential Sequencing of Body Segments

This section presents literature on some of the observed sequences of body motion throughout the golf swing. In particular, the magnitudes and timings of differences between pelvis and trunk axial rotation angles are discussed.

3.8.1 Proximal to Distal Sequencing

The term proximal-to-distal sequencing refers to an ordered sequence of body segment movements during a sporting action. The proximal-to-distal sequencing of body segments has been reported in sports such as tennis, baseball and cricket and a substantial amount of research has been conducted for the golf swing (Table 3.5). Several proximal-to-distal sequencing principals have been measured including joint/segment rotational angles (Burden et al., 1998), joint/segment angular velocities (Teu et al., 2006; Cheetham et al., 2008; Neal et al., 2008; Chu et al., 2010; Tinmark et al., 2010; Horan et al., 2010; Vena et al., 2011b), kinetic energy (Anderson, 2006; Kenny et al., 2008; Ferdinands, 2011), muscle activity (Hirashima et al., 2002) and torques (Hirashima et al., 2008). The body segments most often included in proximal-to-distal golf studies are the pelvis, trunk, left arm (forearm and upper arm), hands and clubhead. The proposed mechanisms include a reversal of joint torques which increases the speed of the distal segments or that proximal deceleration is caused by the acceleration of distal segments (Marshall & Elliott, 2000). With the plethora of parameters being investigated, a number of calculation methods have been used to measure proximal-to-distal sequencing (Table 3.5). Marshall and Elliott (2010) raised caution when interpretating some proximal-to-distal sequencing research due to the calculation methods that were used. The authors noted that some 2D calculation methods neglected rotation about the longitudinal axis, which could result in inaccurate support for the proximal-to-distal sequencing. For example, they showed that it was essential to consider the longitudinal axis of the upper arm and forearm in the development of racquet head speed in a squash forearm or tennis serve (Marshall & Elliott, 2010). Furthermore, either both or individual measurements of the magnitude (which refers to the peak values) and/or timing (which refers to the instant when peak values occur) of proximal-to-distal sequencing principals have been reported in support or against the theory of proximal-to-distal sequencing during the golf swing (Table 3.5).

In golf research, attaining the maximum clubhead linear velocity before IMP has been linked to a loss of shot distance (Milburn, 1982). Therefore, ensuring maximum clubhead linear velocity is timed correctly, is vital for golf swing performance. The ability to produce maximum clubhead linear velocity is proposed to be the end of a chain of sequenced movements. Putnam (1993) acknowledged that the most frequently used principal to define proximal-to-distal sequencing was the summation of speed principal. The summation of speed principal states that in order to achieve maximum speed at the most distal segment then the movement should begin with the more proximal segments. Each segment begins movement at the instant of greatest speed of the preceding segment and that the maximum speed of a segment should be greater than that of which it follows. Furthermore, it has been noted that the speed of proximal segments diminishes by the time the most distal segment reaches maximum speed.

Milburn et al. (1982) was the first study to examine the summation of segmental velocities in the golf swing using the double pendulum model (Figure 3.2). A delay in the wrist uncocking was deemed advantageous to the production of peak angular velocity at the wrist, which is in agreement with Putnam (1993) proposed mechanism for the proximal-to-distal sequence. However, this study was based on a simplified two dimensional model of the golf swing which has since been shown to be inadequate (Marshall & Elliott, 2000). More recent studies have also shown support for the proximal-to-distal sequencing pattern during the golf swing using three-dimensional motion analysis (Cheetham et al., 2008; Neal et al., 2008; Tinmark et al., 2010). Both the magnitude and timing of the examined sequencing principal have been reported to follow the proximal-to-distal sequence (Table 3.5). Cheetham et al. (2008) suggested that practitioners would use these sequencing patterns as a measure of a golfer's efficiency and they noted that elite golfers exhibited greater magnitudes for pelvis, trunk, arm and club rotational velocities compared to amateurs, except for pelvis deceleration. Elite golfers also showed consistent timings of peak rotational velocities between swings, which was deemed to contribute to high clubhead linear velocity (Cheetham et al., 2008). Nevertheless, no significant differences were reported for timing parameters between elite and amateur golfers.

Table 3.5. Summary of studies examining the proximal-to-distal sequencing of body segments during the golf swing.

Reference	Terminology	Purpose	Sequencing Parameter	Parameter Calculation Method	Evidence for Sequencing and Additional Findings
Milburn (1982)	Summation of segmental velocities	Examine double pendulum model of the downswing	- Arm angular velocity/acceleration - Wrist angular velocity/acceleration (club relative to arm) - Clubhead linear velocity	- Differentiation of linear kinematics	- Delay in wrist uncocking was advantageous to the production of peak wrist angular velocity - Delay allowed the acceleration of the proximal segment to reach peak value
Burden et al. (1998)	Sequential pattern of rotation	Determine the pattern of hip and shoulder rotations	- Hip rotation angle - Shoulder rotation angle	2D projected vectors	- **Timing** of peak pelvis rotation before shoulder rotation. - Hips began rotating before shoulders in downswing. - **Magnitude** of peak shoulder rotation greater than pelvis rotation angle - Allowed an eccentric-concentric sequence of the spinal rotator muscles (i.e. stretch-shortening cycle)
Anderson et al. (2006)	Segmental sequencing of kinetic energy	Explore transfer of speed through kinetic energy (KE)	- Hip KE - Torso KE - Arm KE - Club KE	- Sum of rotational and translational KE	- **Magnitude** of KE increased from proximal-to-distal - **Timing** of peak KE same for hips, torso and arms - Timing of club peak KE later in downswing - Summation of speed principal not supported
Teu et al. (2006)	Kinematic chain	Method for analysis of angular velocity using dual Euler angles	- Hand angular velocity (ulnar/radial abduction,flexion/extension) - Forearm angular velocity (pronation/supination,flexion/extension) - Upper arm angular velocity (retroversion/anterversion,adduction/abduction,internal/external rotation) - Torso rotational velocity	Dual Euler angle algorithms	- Identified importance of wrist uncocking (16%), external rotation of the upper arm (11.6%) and supination of the forearm (9.7%) to achieving high clubhead speed. - Dual Euler angle method more appropriate and less prone to errors than other methods and could ascertain the contribution of segmental rotations to the clubhead linear velocity.
Cheetham et al. (2008)	Kinematic sequence	Compare magnitude and timing of kinematic sequence	- Rotational acceleration and deceleration (pelvis,thorax, arm and club) - Peak rotational speed - Timing of peak rotational speed - Change in rotational speed between segments	- Pelvis & thorax angular velocity vectors resolved into each LCS. Rotational speed represented as velocity around vertical axis. - Angular velocity of arm-club around a normal to the instantaneous swing plane	- **Magnitude** of angular velocity increased from: pelvis, thorax, arm, club - **Timing** of peak angular velocity sequence should be: pelvis, thorax, arm, club - Measure of swing efficiency - Elite golfers displayed greater magnitudes for the parameters studied except pelvis deceleration - Consistent timing of the peak angular speeds was shown in elite golfers

Reference	Terminology	Purpose	Sequencing Parameter Studied	Parameter Calculation Method	Evidence for Sequencing and Additional Findings
Kenny et al. (2008)	Segmental sequencing of kinetic energy (KE)	Investigate the transfer of speed using model data where kinetic energy was the outcome measure	- Peak kinetic energy - Timing of peak kinetic energy	- Forward and inverse dynamic modelling	- **Magnitude** of peak KE increased sequentially from proximal-to-distal segments for both driver and 7-irons. No significant differences in KE between clubs - **Timing** of peak KE was subject specific pattern for peak KE. Does not support PDS
Neal et al. (2008)	Body segment sequencing and timing	Compare differences in sequencing and timing of segment velocities between well timed and mistimed shots	- Resultant peak angular velocity (Pelvis, Upper Torso, Arm, Forearm, Hand) - Timing of peak velocity - Timing between peaks	- Angular velocities reported with respect to the LCS. - Resultant angular speed was calculated. - Hand linear and angular velocity calculated	- **Magnitude** of peak angular velocity followed sequence from pelvis-to-hand for well-timed and mis-timed shots. - **Timing** of peak velocity followed a proximal-to-distal sequence, however upper torso and arm timings were similar (only 3ms between peaks). - Qualitatively, in mistimed shots the pelvis reached peak speed earlier in the downswing and was greater than in well-timed shots. - Consistent to coaching observations, upper torso unable to "catch-up" to pelvis.
Chu et al. (2010)	Kinetic chain	Identify variables important to driving ball velocity.	- Upper torso rotation velocity - Wrist hinge velocity - Pelvis rotation velocity - X-factor velocity	No calculation methods for velocities presented.	- Upper torso (UT) rotation velocity most important predictor at acceleration point in the swing. - Supported kinetic chain theory that peak UT rotation velocity occurred before impact so that energy can be transferred to the club at impact. - Timing of leading arm "release" should be delayed
Horan et al. (2010)	Proximal-to-distal pattern	Present detailed 3D kinematics of thorax and pelvis to compare between male and female golfers	- Thorax and pelvis angular velocity	- Poisson equation: angular velocity matrix of each segment with respect to LCS was calculated by multiplying differentiated rotation matrix by inverse of rotation matrix	- Males greater thorax axial rotation, thorax and pelvis tilt (right), thorax and pelvis tilt (posterior) velocities. - Contribution of lateral thorax tilt velocity to overall golf movement pattern not been investigated. - Magnitude of lateral thorax tilt velocity marginally lower than axial rotation velocity, not evident in the pelvis. - Considering resultant velocity the thorax will move faster than the pelvis due to lateral tilt velocity therefore there will be an overall a proximal-to-distal sequence.

Reference	Terminology	Purpose	Sequencing Parameter Studied	Parameter Calculation Method	Evidence for Sequencing and Additional Findings
Tinmark et al. (2010)	Kinematic sequence	Identify a proximal-to-distal sequence (PDS) for maximal and submaximal shot distance	- Angular speed for pelvis, torso and hand - Times of maximum and minimum angular speeds	- Angular velocity calculated by finite difference of rotation matrix with respect to the laboratory reference frame and is independent of the choice of the LCS for each segment. - Resultant angular velocity	- **Magnitude** of peak angular speed increased from proximal to distal segments. - **Timing** of peak angular speed followed proximal-to-distal sequence - PDS characteristics of max- and sub-maximal distance shots (i.e. driver to 40m wedge shots). However, require kinetic data to confirm PDS impact on accuracy - Suggested mechanism was the interaction torques used to generate clubhead speeds.
Vena et al. (2011b)	Kinematic sequence	Gain better understanding of rotational components of the golf swing using instantaneous screw axis theory	- Left arm, shoulders and pelvis angular velocity - Time of peak angular velocity - Magnitude of peak	- Instantaneous screw axis (ISA) theory. Angular velocity at each segment relative to ISA	- **Magnitude** of peak angular velocity increased from proximal-to-distal segments - **Timing** of peak segment velocity followed a proximal-to-distal sequence for 2 of 5 golfers - Peak angular velocity of arm segment and overall sequencing varied between golfers. - Pelvis and shoulder angular velocity increase to maximum and decrease before impact transmit momentum to distal segments - Consistent angular velocity within subjects - Method effective as a measure of the kinematic sequence. - No link to performance outcome

Tinmark et al. (2010) observed the proximal-to-distal sequencing in the magnitude and timing of peak angular velocity for shots with low and high clubhead linear velocities (i.e. wedge shots to 40m and driver respectively). The magnitude of peak angular velocities also increased from partial shots to full shots across the group of golfers. The authors do not report whether these findings were statistically significant and instead suggest that observing the proximal-to-distal sequence in slower shots may improve accuracy as hypothesised by Hirashima et al. (2007).

Neal et al. (2008) also investigated the proximal-to-distal sequencing of the principles; peak angular velocities, timing of peak angular velocity and lag times between the timings of peak angular velocity, between two shot types (i.e. subjectively rated well-timed and mis-timed shots). The group averages displayed the proximal-to-distal sequence in the measured principles for both well-timed and mis-timed shots, however, they were not statistically different between groups despite the two types of shots being significantly different for both shot distance and shot accuracy (defined as the lateral distance from the ball to the target line on landing). The authors suggested that the differences in performance outcomes (i.e. shot distance and shot accuracy) between well-timed and mis-timed shots could be explained by changes in other club parameters such as centeredness of strike or clubhead orientation (e.g. attack angle) that have also been proposed to affect performance (§3.4.2) rather than body sequencing changes. Furthermore, the authors suggested that the golfers rated their well-timed and mis-timed shots based on subjective opinions of feel, sound and centeredness of strike rather than on body sequencing. As aforementioned, a proximal-to-distal sequence was shown in the group mean data for the measured principles, however, from qualitatively examining the angular velocities for a single golfer, it is clear that they do not follow the proximal-to-distal sequence in the timing of peak angular velocities between segments (Figure 3.10). Therefore it is unclear how the authors concluded that the proximal-to-distal sequence was typical for all golfers, even from this homogenous group of golfers (Neal et al., 2008). This finding is similar to studies that have investigated segmental sequencing of kinetic energy for the golf swing which report a sequential pattern for magnitudes of kinetic energy but not the timings of peak kinetic energy magnitudes (Table 3.5).

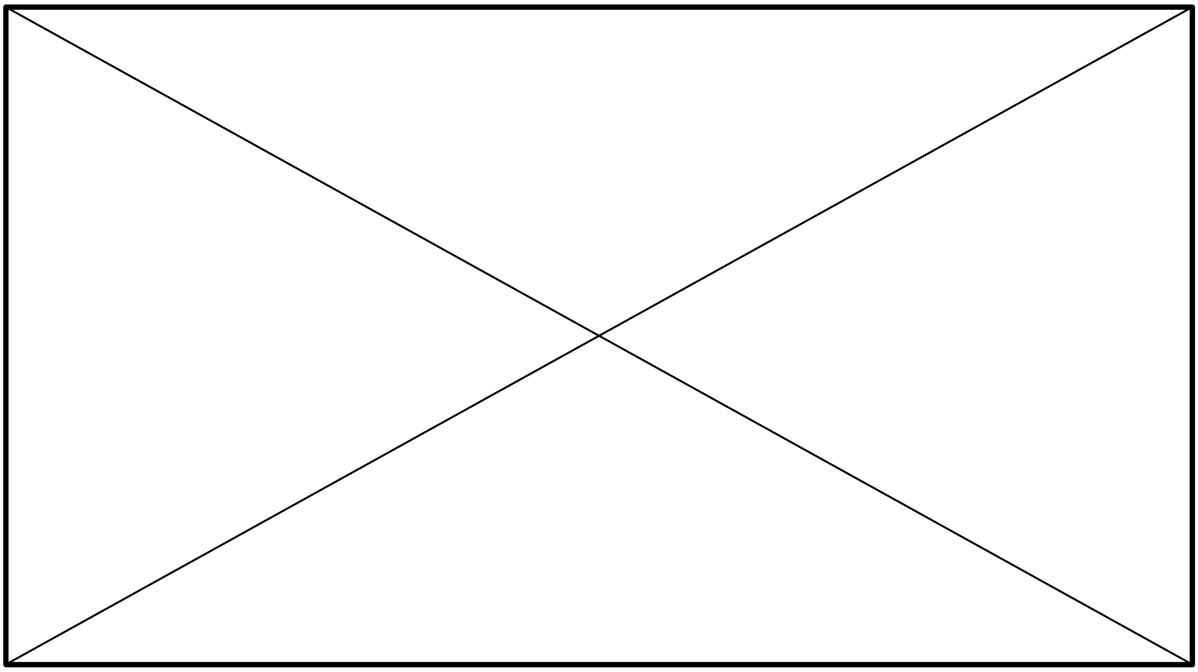


Figure 3.10. Examples of well-timed and mis-timed shot for a single golfer (Neal et al., 2008)

The potential problem of generalising the pattern of proximal-to-distal sequencing across golfers was also shown by Vena et al. (2011). By using the instantaneous screw axis theory it was found that the magnitudes of peak angular velocity increased from proximal-to-distal segments (i.e. pelvis – shoulders - left arm), however the timing of the peak velocity only followed the proximal-to-distal sequence for two of the five golfers analysed. Near bell shaped angular trunk and pelvis velocity curves for four of the five golfers were reported, which is in keeping with previous findings that suggest that the speed of proximal segments diminishes before distal segments (Vena et al., 2011). However, the angular velocity of the arm segment displayed greater variation across golfers, which the authors concluded was due to two components contributing to the motion of the left arm (i.e. rotation about the glenohumeral joint and supination of the wrist) which as mentioned earlier other studies do not consider when reporting angular velocity (Marshall & Elliott, 2010). Therefore, the instantaneous screw axis method for computing angular velocity was suggested to be representative of joint motions that have dominant axes of rotation. However, the verification of the ISA method was performed against differentiated Euler-cardan angles which may not have the same anatomical meaning because Cardan rotations are typically selected on the basis of anatomical interpretation (Lees et al., 2010).

Golf coaches spoke about a sequence of body movements from TA through to IMP as a means of creating powerful swings. The coaches discussed the sequence of body movement in terms of the sequence of rotations and the sequence of peak speeds, which is in keeping with biomechanical literature that has reported magnitudes and timings of peak rotational velocities, rotational angles, kinetic energy and torques (§2.5.7, p37). In addition, coaches were concerned with the timing of initial rotations, for example in terms of timing of accelerations. The coaches also believed that the sequential movement created torque, power, and energy during the golf swing, however, this is still not fully investigated in biomechanical literature (§2.5.7, p37). The coaches also associated a sequential movement with creating an ideal centred strike which could relate to the accuracy and distance of a golf shot (§2.5.7, p38). However, much of the literature has focused on the relationship between sequential movement and shot distance. The coaches seemed to regard the sequential movement as inherent within every golfer's swing (§2.5.7, p37) which from biomechanical literature has not been confirmed during inspection of individual golfer data.

3.8.2 Future Research Recommendations

The methodologies used to quantify X-factor requires attention as current literature has defined this angle in many ways. In addition, much of the current research has analysed X-factor at discrete stages in the swing and there appears to be a need to investigate this parameter throughout the whole swing and to observe and compare patterns for individual golfers. The proposed mechanism of X-factor contributing to performance (clubhead linear velocity at IMP) also needs examining. Whilst, the proximal-to-distal sequencing of segments during the swing is key for coaches and biomechanical studies, the contrasting results across studies means that other parameters may also be important. Therefore, sequential movement also needs to account for parameters such as posture. Finally, sequential movement is associated with generating power during the swing, however, the variability in sequencing and effect on other elements of performance require quantification.

3.9 Summary

This chapter has presented the most current golf biomechanical literature whilst structured into sections that followed the key technical parameters identified by golf coaches. Much of the previous golf biomechanical research has been guided by previous studies or using regression analysis. Whilst some studies make reference to coaches' coaching ideas and the biomechanical outcome, the coaching ideas have not been formally gathered. Several limitations with the data collection and data analysis methods used to measure some of the key technical parameters were identified. Few golf biomechanical studies had examined the relationship between key technical parameters and there was a heavy focus on increasing club head velocity. Therefore, the relationship between golfer kinematics/ kinetics and other measures of performance has been largely unresolved, perhaps due to the difficulty in collecting performance data in the laboratory. In addition, much of the data analysis had been performed at specific swing events that were predefined at the beginning of the study and very few studies had treated the swing as a whole movement.

The key technical parameter, posture, had received relatively little attention in the golf biomechanical literature, despite the coaches who were interviewed identifying posture most frequently as a key technical parameter. The literature on posture was limited to 2D analysis of spine angle and therefore did not account for movement in other directions. Furthermore, this 2D spine angle was actually a representative of the whole trunk angle and did not treat the trunk as multi segment. As aforementioned, the relationship between posture and other key technical parameters such as body rotation was not readily investigated. Therefore, the following chapters will address the limitations of data collection and analysis methods for studying golf posture and body rotation. Following which, the biomechanical features and relationship between posture and body rotation will be examined.

Chapter 4 General Methods

4.1 Introduction

The purpose of this chapter were to present the data collection and analysis methods used to measure golfer kinematics, kinetics and measures of performance in this thesis. Golfer and club kinematics were captured using the Vicon motion analysis system and high speed cameras. Measures of performance were measured using the TrackMan launch monitor. Golfer kinetics was collected using two Kistler force plates. The specifications for each piece of testing apparatus are reported. The objectives for this chapter were to be able to collect and process data that would allow the research questions three and four to be addressed.

4.2 Data Collection

This section details the testing equipment, calibration procedures and where appropriate, the accuracy measurements for each piece of testing equipment used to collect data on the golfer, club and their performance.

4.2.1 Experimental Set-Up

Testing took place in an indoor laboratory as it allowed repeatable conditions between golfers and testing environments (Figure 4.1). Golfers used their own clubs, golf glove, golf shoes and all golfers used the same brand golf ball (Titleist, ProV1). Golfers hit from an artificial golf mat (1.5 m x 1.5 m) into a net positioned approximately 4m away; a vertical pole placed behind the net provided a target line (Figure 4.2). Thirteen Vicon cameras were used to capture the golf swing. Eleven cameras (1 - 11) were mounted with clamps onto a railing surrounding the laboratory. The remaining cameras (12 - 13) were mounted on tripods, camera 12 was positioned anterior to the golfer and camera 13 was positioned to the left of the target line but slightly offset from the target line to improve tracking of trunk markers and during follow through. This created a 6 m x 6 m x 3 m capture volume. Two Kistler force plates were positioned in the centre of the capture volume and the global co-ordinate system (GCS) from where all marker trajectories were measured was set in the middle of the two force plates (Figure 4.2). In accordance with TrackMan instructions, the launch monitor was positioned 3 m away from the ball position along the GCS x-axis, in a straight line from the target and through the ball position during a golfer's set-up and was placed at the same height as the golf mat. A reflective dot was placed on the golf ball, with the dot facing away from the launch monitor when golfers struck the ball with an iron and towards the unit with the driver. In order to measure ball spin, the ball must perform at least 2 full revolutions before hitting the net therefore it is important to orientate the ball in such a way to account for the different ball speed and spin rates generated with each club. The high speed video (HSV) camera was also positioned along the x-axis approximately 4 m from the golf mat. The height of the HSV camera was adjusted so that the golfer’s hands during set-up were approximately in the centre of the cameras field of view.

Figure 4.1 Indoor laboratory set-up

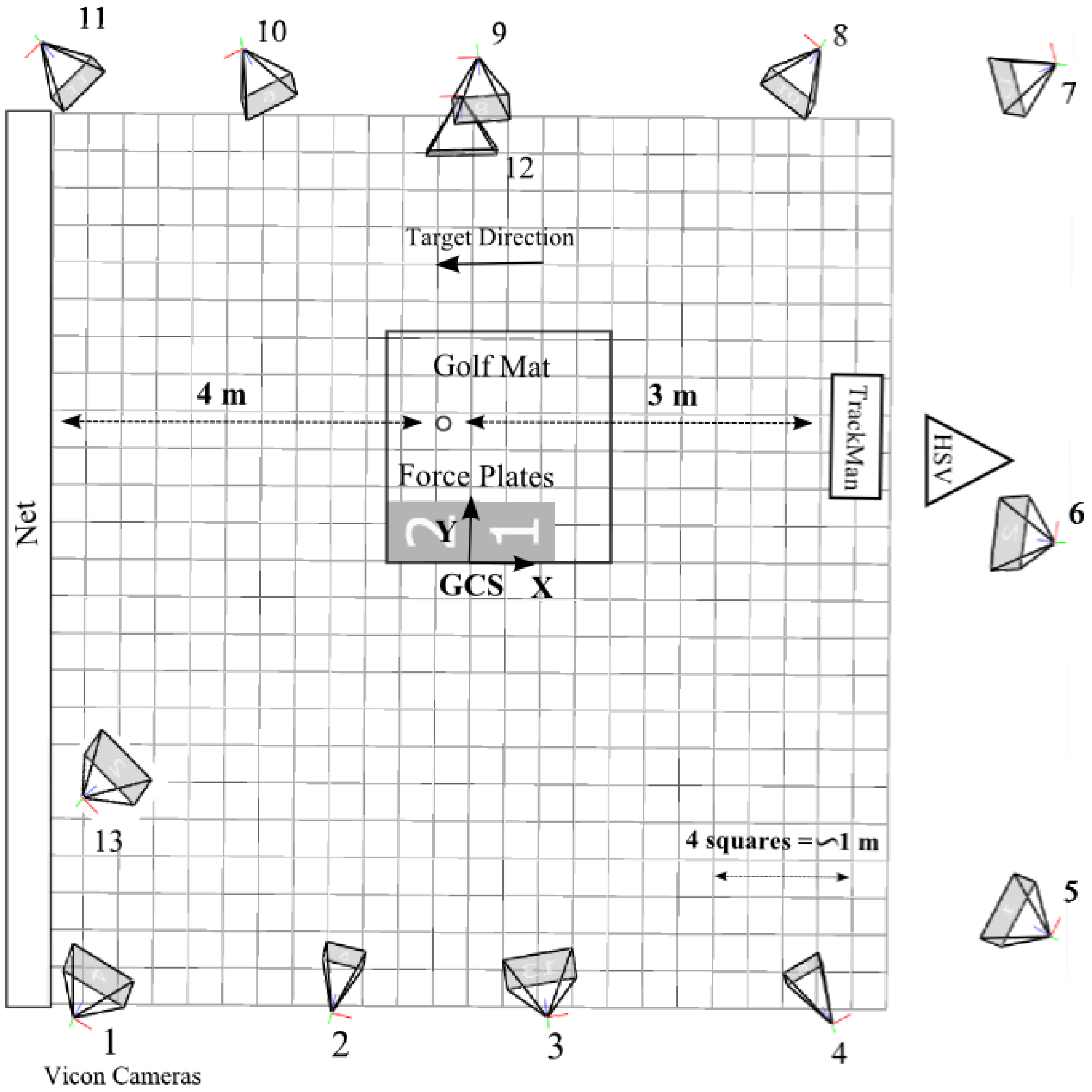


Figure 4.2. Plan view of experimental set-up showing the Vicon camera positions (1 – 13), force plates (FP 1 & 2), high speed camera (HSV) and TrackMan launch monitor (TrackMan). The global co-ordinate system (GCS) origin, x-axis and y-axis are shown. The z-axis was perpendicular to the x-y plane (with +ve upwards).

4.2.2 High Speed Video

High speed video of the golf swing was captured in the sagittal plane using a Photron Fastcam (SA1, Photron, San Diego) operating at 250 Hz and the shutter speed was 1/sampling frequency. Vicon and high speed video were collected synchronously using an external manual trigger. The high speed video was principally used as a visual reference to compare against collected kinematic data using Vicon.

4.2.3 Launch Monitor

The TrackMan launch monitor (ISG Company, Denmark) was used to capture the motion and orientation of the clubhead along with ball launch conditions and resulting shot trajectory of each golf swing (Figure 4.3).

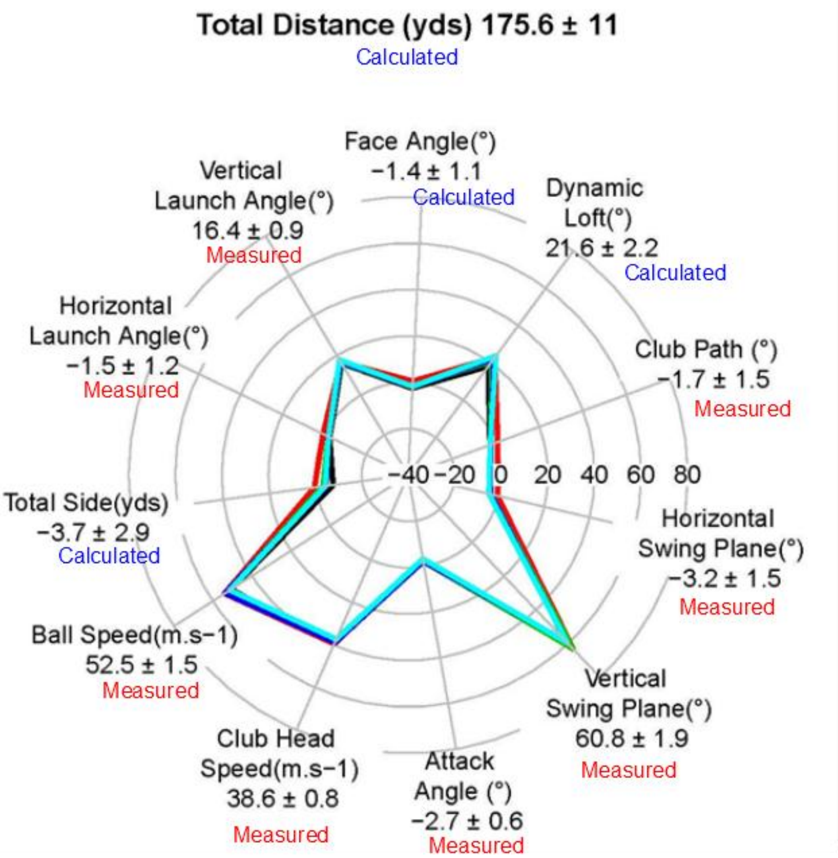


Figure 4.3. TrackMan parameters (measured or calculated) presented as a radial plot.

The TrackMan launch monitor uses a phased array Doppler radar device when measuring the ball flight and a more detailed explanation of the technology is presented in Appendix C (Trackman, 2003). The TrackMan definitions for the measured and calculated clubhead parameters and measurement accuracy for the parameters are also presented in Appendix C. The measured parameters included clubhead linear velocity, vertical swing plane, horizontal swing plane, attack angle, club path, ball velocity and spin rate.

The suitability of measuring clubhead linear velocities and ball velocities in this thesis using the TrackMan launch monitor were assessed by comparing data captured simultaneously using both the Vicon motion analysis system and TrackMan launch monitor. Data was collected for five golf swings from ten randomly selected golfers using both their own 5-iron and driver. A marker was placed on the hosel of the clubs to calculate maximum clubhead linear velocity using the Vicon motion analysis system, sampling at 250 Hz (Figure 4.4). A piece of retro-reflective tape was also placed on the golf ball to calculate initial ball velocities as the derivative of ball positional data using Vicon. The first derivative of ball positional data averaged across the 2^{nd}, 3^{rd} and 4^{th} frames, after impact, was defined as ball velocity. The mean difference between measurements of clubhead linear velocity and ball velocity from Vicon and TrackMan were calculated.

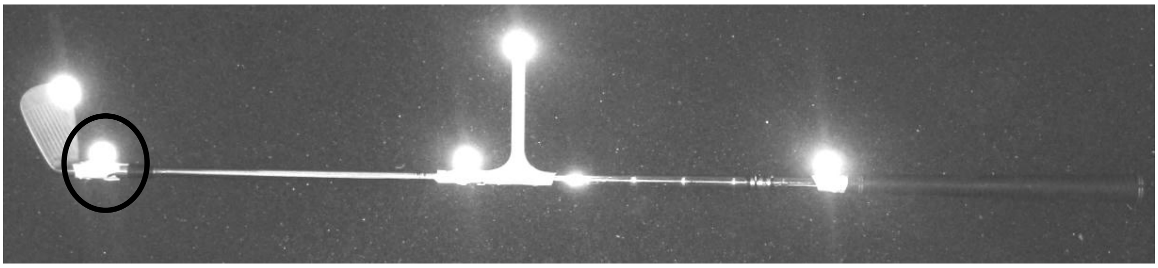


Figure 4.4. 5-iron with marker placements. The circle highlights the hosel marker used to calculate clubhead linear velocity using Vicon.

For clubhead linear velocity, the TrackMan launch monitor recorded greater maximum clubhead linear velocities than the Vicon motion analysis system for both the driver and 5iron respectively (2.1 ± 1.2 $m.s^{-1}$ and 1.6 ± 0.7 $m.s^{-1}$) (Figure 4.5). Pearson correlation was strong for clubhead linear velocity measured by Vicon and TrackMan for the driver ($r = 0.93$, $p < 0.01$) and for the 5-iron ($r = 0.99$, $p < 0.01$). Initial ball velocities were consistently greater with the TrackMan launch monitor than the Vicon motion analysis system for both driver and 5iron (2.2 ± 6.1 $m.s^{-1}$ and 5.7 ± 5.4 $m.s^{-1}$ respectively) (Figure 4.5). This was especially evident when recording ball velocities using a 5-iron.

The difference between velocities recorded using Vicon and TrackMan may be due to a number of reasons. Betzler et al. (2006) commented that the differences in clubhead linear velocities between the launch monitor and motion analysis system were due to the different positions used to measure the variable, which is in agreement with this study. As aforementioned, TrackMan claims to measure from the centre of the clubface whereas the marker used to calculate clubhead linear velocity in Vicon was placed on the hosel of the club thereby reducing the length of the radii from the centre of rotation (i.e. shaft axis) and decreasing measured clubhead velocity (Ellis et al., 2010). In addition, Vicon captured data at a sampling frequency of 250 Hz, therefore there was a data point approximately every 0.18 m at peak velocity which may be too low a resolution for highly accurate velocity estimates. The differences in ball velocity may in part be due to the rotation of the golf ball, as Vicon may have missed some portions of the data due to poor marker visibility and too low a sampling frequency. This resulted in gaps in the data having to be filled with Vicon and could lead to underestimation of ball velocity.

The TrackMan launch monitor will be used in this thesis to report club and ball parameters such as clubhead linear velocity. The agreement with the Vicon measurements suggests that the system adequately measures some club parameters. To evaluate the true accuracy of ball launch monitors a more thorough investigation would have been required by comparing measured TrackMan parameters to an optical based system. However, it should be noted that only those parameters measured by TrackMan (identified in Appendix C) will be considered during data analysis.

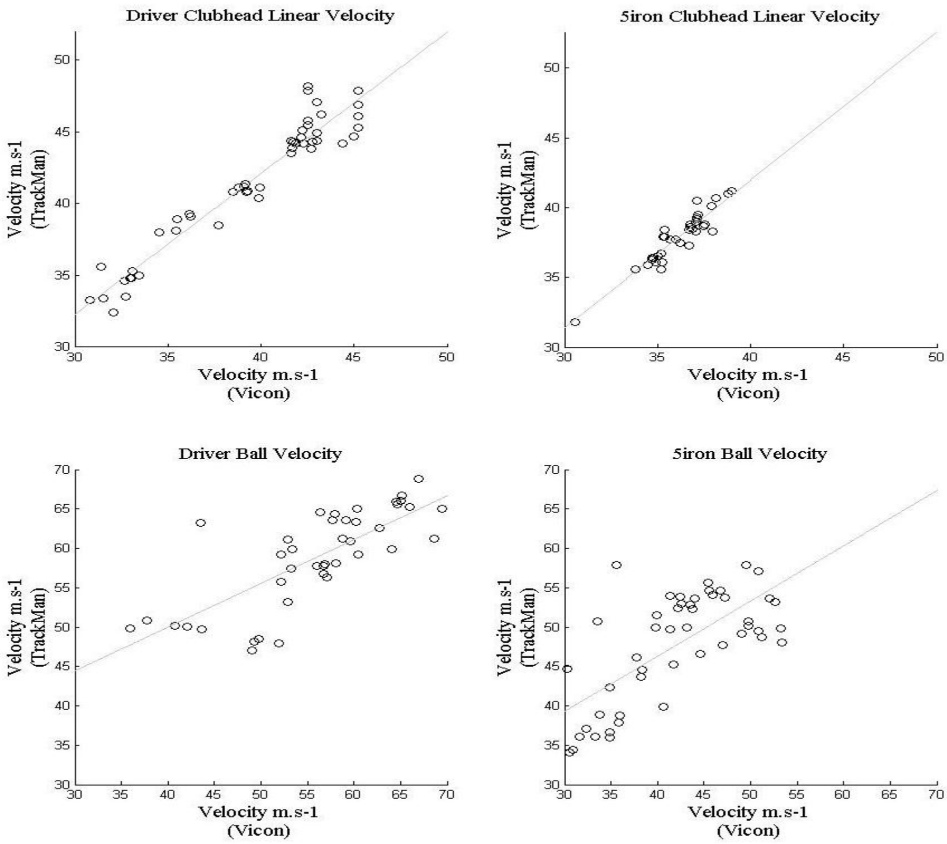


Figure 4.5. Scatterplots showing clubhead linear velocity and ball velocity for both driver and 5iron when measured using Vicon and TrackMan. The line of best fit is also plotted.

4.2.4 Force Plate

Ground reaction forces (GRF) were collected using two 0.6 m x 0.4 m Kistler force plates (Kistler, 9281CA), one under each foot of the golfer. Each force plate contains three layers of piezoelectric crystals that are situated in each corner of the force plate. The deformation of the piezoelectric sensors results in a change in electrical charge and in turn is used to calculate force in three directions (i.e. medial - lateral (x), anterior - posterior (y) and vertical (z) (Figure 4.2)). The sensors are initially calibrated in each direction by the manufacturers. Two sections of golf mat, equal to the size of the force plates and assumed to be rigid, were securely attached to the surface of the force plates using double-sided adhesive tape. Before each trial a further calibration procedure was carried out which involved recording the force when only the golf mat was in contact with the force plate and defining this as the zero force level.

The GRF were sampled using the Vicon Nexus software at 1000 Hz and synchronized with the kinematic data. The GRF for each force plate were recorded and combined for a measure of overall GRF. The combined GRF was used to determine overall COP and force within the GCS.

4.2.5 Vicon Motion Analysis System

The Vicon MX system (Oxford Metrics Ltd) was used to capture the golfer and club kinematic parameters in three-dimensions. The Vicon motion analysis system is a passive system, where by retro-reflective markers attached at specific anatomical locations are recorded using infra-red cameras. The retro-reflective markers are identified in each camera from the reflected light emitted from a ring of powerful infrared light emitting diodes (LED's) that surround the camera. A 2D circle is fitted to the marker and along with the 2D circles from other cameras a Vicon generated algorithm is applied to reconstruct 3D marker positions.

To capture the movement with high precision using a cameras full resolution, the T40 (2352 x 1728 pixels) and T20 (1600 x 1280 pixels) cameras can operate at sampling frequencies of 370 Hz and 500 Hz respectively, but are capable at capturing up to 2000 Hz at reduced resolution. Previous golf studies have used sampling frequencies between 200 Hz and 500 Hz when using a 3D motion analysis system (Betzler et al., 2006; Zheng et al., 2008a;Horan et al., 2010; Meister et al., 2011); however, increasing sampling frequencies can affect the precision of data due to a decrease in spatial resolution because of decreased clarity of markers. Therefore, the capture volume size also needs to be considered when selecting sampling frequency. The capture volume was defined by the thirteen Vicon camera positions, as shown in Figure 4.2. Given the large capture volume and the high speed movement being captured the chosen sampling frequency was 250 Hz in order to provide a trade-off between capture volume, temporal resolution and spatial resolution. At 250 Hz the T20 cameras would have a resolution of 800 x 640 pixels and for a clubhead travelling at 45 $m.sec^{-1}$ there would be a data point in view every 0.18 m. Other important camera parameters include threshold, strobe, gain and circularity which were set based on Vicon manual recommendations (Vicon, 2002).

4.2.5.1 Calibration

Before capturing data, the Vicon motion analysis system required dynamic calibration. Once all unnecessary reflective objects had been removed from the capture volume, a wand fitted with five Vicon markers, situated at known distances apart, (Figure 4.6) was moved through the capture volume and the Nexus software calibrated the cameras by searching for the wand markers in each camera's view. A measure of the cameras accuracy was produced (i.e. camera residual) once each camera had captured 1000 frames. The camera residual was the root mean square of the distance between two rays; the first was a ray from the centre of the strobe ring to the centroid of the marker and the second was a reflection of the ray from the marker centroid to the camera lens (Roosen, 2006). A lower camera residual error (< 0.25 mm) signified a more accurate 2D contribution by that camera and an improved calibration procedure. If any residual was > 0.25 mm the calibration process was repeated until an adequate camera residual was calculated. The camera residuals in Table 4.1 were typical of a calibration process conducted during data collection. Following calibration, the capture volume origin was set, which was the (0, 0, 0) global co-ordinate system (GCS) and direction of the x, y and z axes from which marker positions were measured (Figure 4.2).

Table 4.1. Mean ± SD camera residuals for a typical Vicon calibration

Camera Number	Residual (mm)
1	0.17
2	0.20
3	0.13
4	0.17
5	0.12
6	0.20
7	0.24
8	0.17
9	0.20
10	0.19
11	0.17
12	0.17
13	0.20
Mean ± SD residual	0.18 ± 0.03

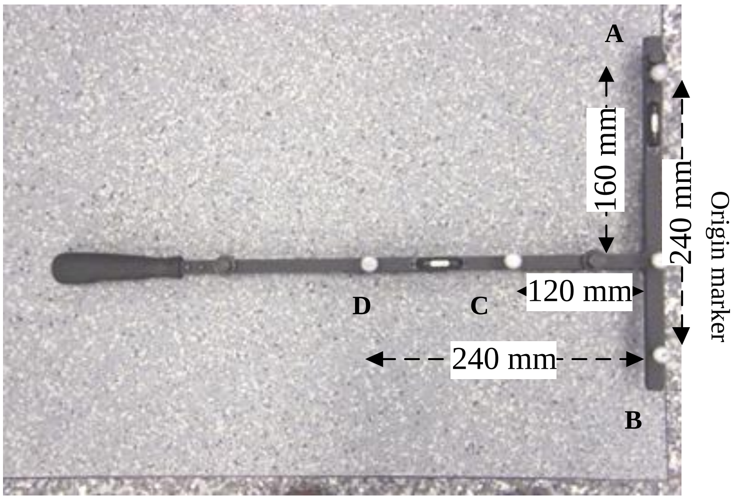


Figure 4.6. Vicon 5-marker calibration wand with origin marker labelled and other markers (A, B, C, D) at known distances relative to the origin marker. All markers were at the same height in the z-direction.

4.2.5.2 Vicon Measurement Accuracy

Previous studies have reported that a Vicon system, similar to that used in this thesis, measured angles on a rotating plate within 1.4º and reported a maximum error in angular measurements of 4.6º (Richards, 1999). In addition, the Vicon system was reported to measure the distance between two markers within 0.062 cm. Nevertheless, the results of accuracy studies conducted on one Vicon motion analysis system may not generalise to all Vicon motion analysis systems due to differences in the number of Vicon cameras used and the positioning of cameras. Therefore, the accuracy of each system should be defined. The accuracy of angular measurements was determined for the Vicon Nexus motion analysis system used during this thesis.

Following Vicon calibration, the rigid calibration wand was used to collect six trials at 250 Hz. The calibration wand was used because the retro-reflective markers are attached to the wand at known distances from the origin marker and the wand is set at a 90º angle (Figure 4.6) (Vicon, 2008). The six trials consisted of both static and dynamic trials. For the static trial the wand was placed on the floor in the x-y plane in the middle of the capture volume. During the dynamic trials the wand was moved along the GCS x-axis (medial - lateral), y-axis *(*anterior - posterior) and z-axis (up - down) throughout the capture volume.

The length and angle calculations were similar to those of Richards (1999). The length of the vector created between markers A and B was measured for each frame of the trial. The measured distances were then averaged across the trial and the known distance (240 mm) was subtracted in order to obtain a mean absolute error. The root mean square error (RMSE) was used as an indication of the repeatability associated with the distance measurement for each trial:

$$RMSE = \sqrt{\sum \frac{(m-d)^2}{n}}$$

where *m* is the measured distance and *d* is the mean measured distance and *n* is the number of data points. The measured angle between the origin, A and C markers was measured using Vicon during the trials and RMSE and absolute error were calculated as above (Table 4.2 and Table 4.3).

Table 4.2. Measured length between two markers (A & B) attached to the wand and positioned 240 mm apart.

Trial Details	Mean measured length (mm)	RMSE (mm)	Mean absolute error (mm)
Static	239.94	0.01	-0.06
Dynamic x-direction	239.98	0.24	-0.02
Dynamic y-direction	240.12	0.51	0.12
Dynamic z-direction	239.94	0.25	-0.06
Rotated	239.81	0.15	-0.19
Mean ± SD	239.96 ± 0.1	0.23 ± 0.1	-0.04 ± 0.1

Table 4.3. Measured angle between markers A & C attached to the wand creating a 90º angle

Trial Details	Mean measured angle (º)	RMSE (º)	Mean absolute error (º)
Static	89.78	0.01	0.22
Dynamic x-direction	89.89	0.08	0.11
Dynamic y-direction	89.73	0.25	0.27
Dynamic z-direction	89.78	0.16	0.22
Rotated	89.94	0.05	0.06
Mean ± SD	89.82 ± 0.1	0.11 ± 0.1	0.18 ± 0.1

The mean measured lengths across all trials were typically 0.1 mm less than the actual distance except for the dynamic y-direction where the mean measured length was 0.1 mm greater than the actual length. The RMS values of this measurement were 0.51 mm. Therefore, it can be deemed that the Vicon system was able to record length very accurately which is similar to results found by Richards (1999). The mean measured angle across all trials was within 0.3º less than the actual angle. As before, the dynamic trial in the y-direction displayed the greatest RMS error value (0.25º). The angle was measured between a marker positioned close to the origin (i.e. C), therefore using the marker D may have improved these angles further. Nevertheless, these values are lower than those reported by Richards (1999) who reported RMS error values for Vicon of up to 4.6º. Therefore, it can be concluded that the Vicon motion analysis system used in this thesis is capable of repeatedly measuring distances and angles within 0.2 mm and less than 0.3º throughout the capture volume.

4.2.5.3 Golfer Marker Set

Marker sets must provide adequate marker visibility, avoid marker occlusions throughout the movement, not interfere with performance, allow automatic or manual labelling of markers during processing, be distributed over the largest possible area of a segment and be appropriately placed to reconstruct the movement of the athlete to a suitable level of accuracy and precision (Wright, 2008). Some golf specific problems arising from current marker sets include marker occlusions due to the golfer's body position throughout the swing (Wright, 2008). Despite golfer marker sets needing to meet certain specifications, there appears to be no standardised golfer marker sets used between studies. The Vicon plug-in-gait marker set was adapted in this thesis and consisted of sixty-three 14 mm diameter reflective markers, which were placed on the golfer at specific anatomical locations (Figure 4.7) and five markers, including one wand marker, were placed on the golfers own clubs (Figure 4.4). The Table 4.4 contains a list of the golfer marker set. The additional markers placed around the hip joints (e.g. LTH1, LTH2, LTH3) were in accordance with Begon et al. (2007) for determining functional hip joint centres. The additional markers placed around the shoulder joint (e.g. RSHO, RUP1, RUP2) were based on recommendations by Rettig et al. (2009a) for determining functional shoulder joint centres. Selected anthropometrics were also measured which included the golfer’s height, weight, shoulder width (anterior-posterior direction), shoulder joint offset (distance from LAC to LSHO) and inter ASIS distance (distance between LASI and RASI). The later three measurements were used as part of the golfer model determination and were measured using callipers.

The repeatability in kinematic data due to the variability of skin mounted markers placements has been recognised as a source of error for 3D motion analysis (e.g. running: (Farber et al., 2002)). Therefore, the between-day and between-tester repeatability of selected golfer kinematics were compared to investigate the effect of marker placement (Smith et al., 2010). The between-day kinematic day appeared to be more consistent than between-tester data; therefore the same tester will be used to apply markers throughout this thesis.

4.2.6 Data Collection Instruction

All golfers gave their informed consent and ethical clearance was obtained from Loughborough University Ethical Advisory Committee. Before data collection, each golfer performed several warm up swings at their own discretion with a club of their choice. Unless stated elsewhere, golfers were instructed to address the ball in their normal stance position and to hit a full shot as accurately as possible (i.e. towards the target) with either the driver or 5-iron. This instruction aimed to help eliminate the variability in a golfer’s swing due to shot selection (§3.2.3, Langdown et al., 2012) and was similar to instructions given in previous studies (§3.2.3). Following each shot, golfers were asked to subjectively rate how good the shot felt based on their individual capabilities on a 10-point scale; the highest ratings for each golfer was deemed representative of a golfers better shot. Golf shots with a rating of 8 or more were accepted for data analysis as these were deemed representative of a typical golf shot for that golfer.

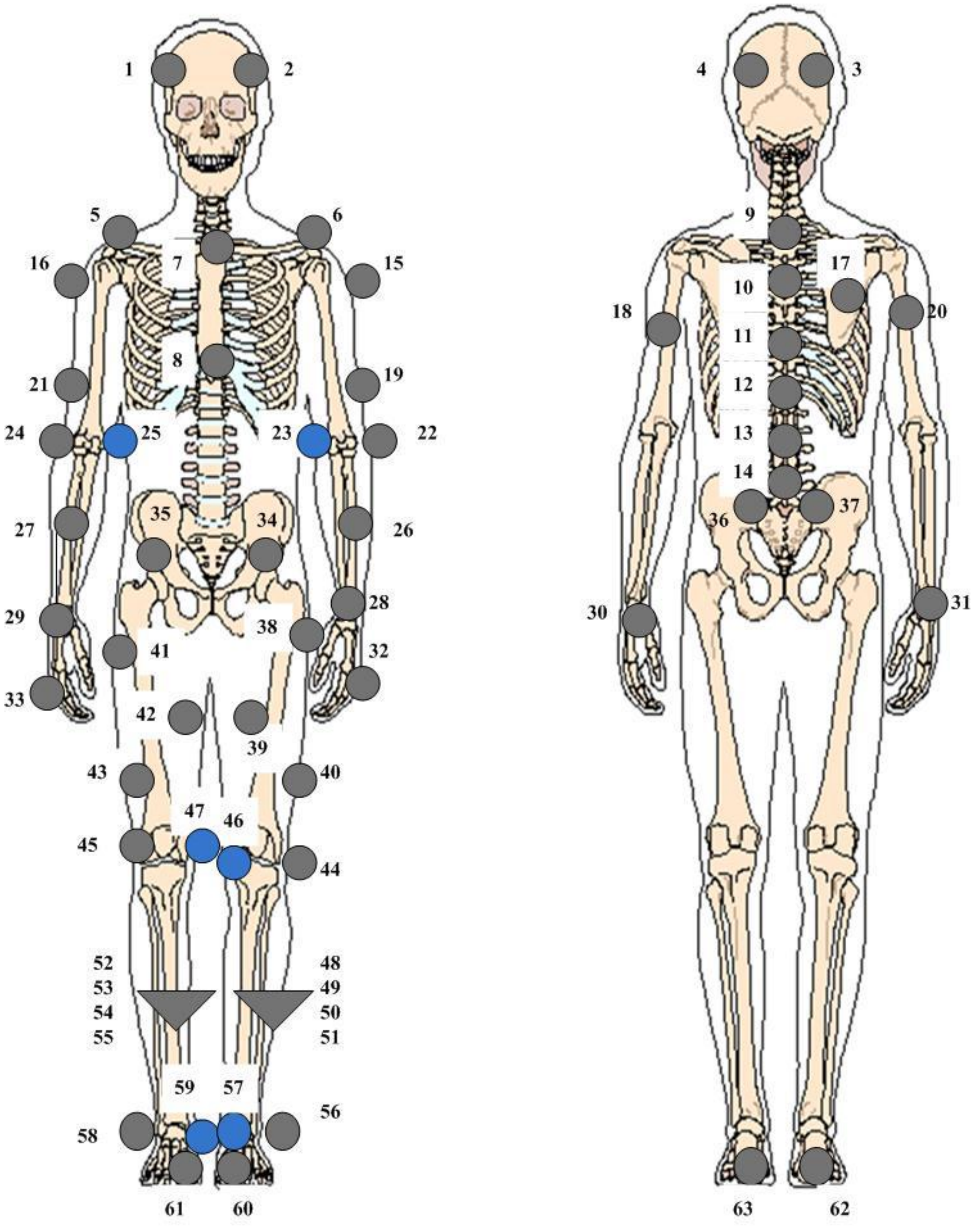


Figure 4.7. Golfer marker set. Blue markers used for static calibration. Triangle represents cluster marker set on shank.

Table 4.4. Golfer marker set including marker names, definitions and anatomical placements

Marker	Definition	Anatomical placement
RFHD[1]	Right front head	Right temple
LFHD[2]	Left front head	Left temple
RBHD[3]	Right back head	Right back of head
LBHD[4]	Left back head	Left back of head
RAC[5]	Right acromion	Bony prominence of right shoulder
LAC[6]	Left acromion	Bony prominence of left shoulder
CLAV[7]	Clavicle	Top of the breast bone
STRN[8]	Sternum	Base of breast bone
C7[9]	7th cervical vertebrae	Prominent vertebrae at base of neck
T2[10]	2nd thoracic vertebrae	Two vertebrae below C7
T8[11]	8th thoracic vertebrae	Two vertebrae above T10
T10[12]	10th thoracic vertebrae	Centre of mid-back
L4[13]	4th lumbar vertebrae	One vertebrae above L5
L5[14]	5th lumbar vertebrae	Last vertebrae above sacrum
LSHO[15]	Left shoulder	Lateral side of left shoulder at shoulder joint centre level
RSHO[16]	Right shoulder	Lateral side of right shoulder at shoulder joint centre level
RBAK[17]	Right back	Right back over right scapula
LUP1[18]	Left upper arm 1	Posterior side of left upper arm
LUP2[19]	Left upper arm 2	Lateral side of left upper arm above epicondyle
RUP1[20]	Right upper arm 1	Posterior side of right upper arm
RUP2[21]	Right upper arm 2	Lateral side of right upper arm above epicondyle
LLELB[22]	Left lateral elbow	Left lateral elbow epicondyle
LMELB[23]	Left medial elbow	Left medial elbow epicondyle
RLELB[24]	Right lateral elbow	Right lateral elbow epicondyle
RMELB[25]	Right medial elbow	Right medial elbow epicondyle
LFA[26]	Left forearm	Posterior side of left forearm
RFA[27]	Right forearm	Posterior side of right forearm
LRAD[28]	Left radius	Left radial epicondyle
RRAD[29]	Right radius	Right radial epicondyle
LULN[30]	Left ulna	Left ulna epicondyle
RULN[31]	Right ulna	Right ulna epicondyle
LHA[32]	Left hand	Dorsum of left hand below head of 2nd metacarpal
RHA[33]	Right hand	Dorsum of right hand below head of 2nd metacarpal
LASIS[34]	Left anterior superior illiac spine	Bony prominence of the left anterior superior iliac
RASIS[35]	Right anterior superior illiac spine	Bony prominence of the right anterior superior iliac
LPSIS[36]	Left posterior superior iliac spine	Bony prominence of the left posterior superior iliac
RPSIS[37]	Right posterior superior iliac spine	Bony prominence of the right posterior iliac
LTH1[38]	Left thigh 1	Lateral side of left thigh ≈ 0.1m under greater trochanter
LTH2[39]	Left thigh 2	Medial side of left thigh between vastus medialis and rectus femoris
LTH3[40]	Left thigh 3	Left vastus lateralis tendon
RTH1[41]	Right thigh 1	Lateral side of right thigh ≈ 0.1m under greater trochanter
RTH2[42]	Right thigh 2	Medial side of right thigh between vastus medialis and rectus femoris

Marker	Definition	Anatomical placement
RTH3[43]	Right thigh 3	Right vastus lateralis tendon
LLK[44]	Left lateral knee	Left lateral knee epicondyle
RLK[45]	Right lateral knee	Right lateral knee epicondyle
LMK[46]	Left medial knee	Left medial knee epicondyle
RMK[47]	Right medial knee	Right medial knee epicondyle
LSK1[48]	Left shank 1	Lateral side of left shank
LSK2[49]	Left shank 2	Lateral side of left shank
LSK3[50]	Left shank 3	Lateral side of left shank
LSK4[51]	Left shank 4	Lateral side of left shank
RSK1[52]	Right shank 1	Lateral side of right shank
RSK2[53]	Right shank 2	Anterior side of right shank
RSK3[54]	Right shank 1	Lateral side of right shank
RSK4[55]	Right shank 1	Lateral side of right shank
LLA[56]	Left lateral ankle	Left lateral malleolus
LMA[57]	Left medial ankle	Left medial malleolus
RLA[58]	Right lateral ankle	Right lateral malleolus
RMA[59]	Right medial ankle	Right medial malleolus
LTOE[60]	Left toe	Dorsum of left foot below 2nd metatarsal
RTOE[61]	Right toe	Dorsum of right foot below 2nd metatarsal
RHEEL[62]	Right heel	Posterior side of right heel
LHEEL[63]	Left heel	Posterior side of left heel

Table 4.5. Club marker set including marker names, definitions and placements

Marker	Definition	Placement
OBJ1	Grip	Below club grip
OBJ2	Shaft	Middle of shaft
OBJ3	Clubhead	Hosel of clubhead
OBJ4	Wand shaft marker	Middle of shaft
OBJ5	Clubhead	Toe of clubhead

4.3 Data Processing

This section describes the procedures that are used to process the collected kinematic and kinetic data.

4.3.1 Reconstruction and Labelling

Following data collection, the marker positions were reconstructed using the Vicon Nexus software. Some of the reconstruction settings were adjusted (e.g. marker movement speed, quality) to yield the best reconstruction of data without reconstructing noise such as the reflection from the shaft of some irons (Table 4.6).

Table 4.6. Vicon data reconstruction parameters

Reconstruction Properties	Setting
Marker Movement Speed	7
Model Rigidity	3
Quality/Speed	4

After reconstruction of the data, the trials were labelled using Vicon Nexus in accordance with the marker set used (Table 4.4). Initially, a static trial of the golfer stood in the anatomical position with all markers clearly visible was labelled, followed by automatic labelling of dynamic trials. Each labelled trial was then checked to ensure occluded markers were relabelled and gaps in marker trajectories were filled using spline fills or by copying the trajectory of a marker moving on the same rigid segment. Care was taken to select the most appropriate gap filling technique through visual inspection as a spline fill was not adequate for large gaps (i.e. marker trajectory missing for more than 10 frames) and therefore mirroring trajectories of markers on the same segment was deemed more appropriate.

4.3.2 Golfer Model Segment Definitions

The marker positions were used to define a whole body golfer model in order to calculate kinematic data. Visual 3D (C-Motion, USA) software was used to build the golfer model. To achieve this, a static trial was required along with at least three tracking markers attached to each segment in both the static and subsequent dynamic trials. Providing these requirements of Visual 3D were met, the position and orientation of every segment could be computed.

The marker set reported in §4.2.5.3 was used to initially create a seventeen segment golfer model including; head, trunk, pelvis, left thigh, right thigh, left shank, right shank, left foot, right foot, left upper arm, right upper arm, left forearm, right forearm, left hand, right hand, golf club shaft and golf clubhead (Figure 4.8). Visual 3D assumes that segments are rigid objects (i.e. they do not deform when force is applied and inter marker distances are invariant), segments are implicitly linked (e.g. segments are not constrained) and that each segment is defined by a local co-ordinate system (LCS) based on a right handed Cartesian co-ordinate system (C-Motion, 2011).

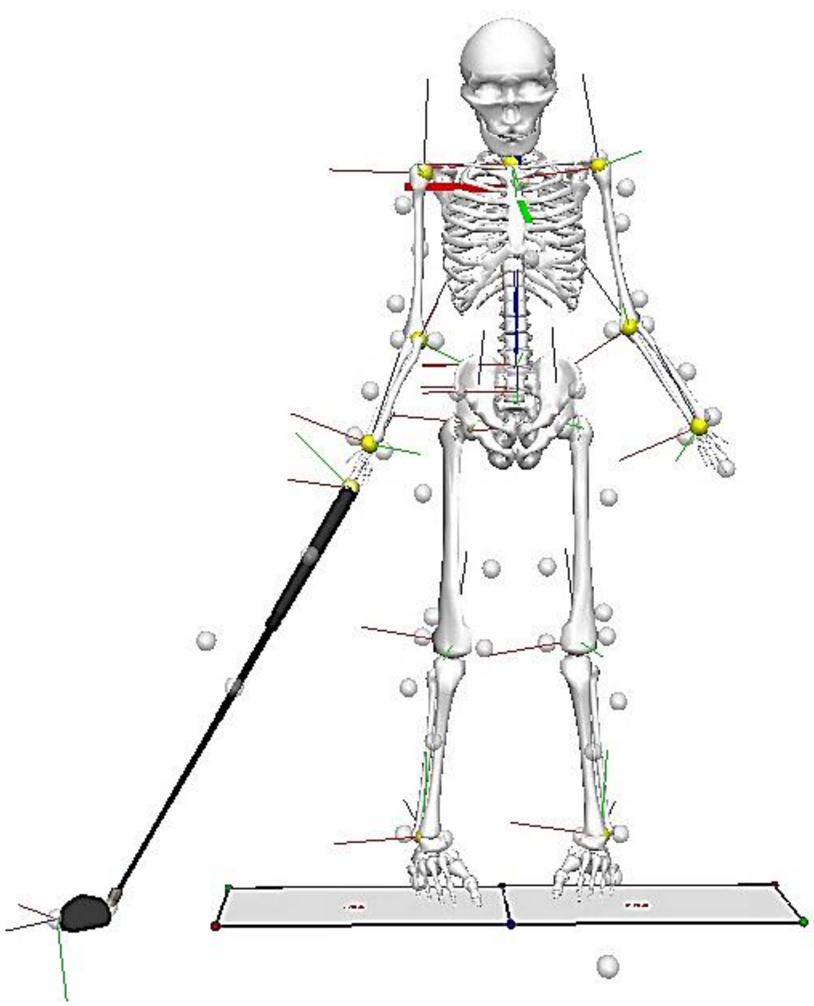


Figure 4.8. Golfer model showing initial segments that were defined using the golfer marker set.

The method used to define a segment LCS in Visual 3D is illustrated for the right shank in Appendix D. The local co-ordinate system is based on a right hand Cartesian coordinate system. The initial stage of creating the LCS is defining the frontal plane, which is created by the markers placed at proximal and distal segment endpoints. Subsequently, the segment endpoints are defined based on the markers that were used. The origin of the LCS was positioned at a mid-point between the proximal endpoint markers. By default in Visual 3D, the z-axis (blue) was defined by the vector from the distal segment end point to the proximal segment end point. The y-axis (green) is defined as the vector which is perpendicular to the frontal plane and z-axis. Finally, the x-axis (red) was based on the right hand rule. In this thesis, the z-axis was directed from distal to proximal, the y-axis was anterior to posterior and the x-axis medial to lateral for the majority of LCS defined by the markers in (Table 4.7). The only exception was the foot and clubhead segments. The variation between segment constructions was due to the difference in defining segment end points (Table 4.7).

In addition, the thigh and pelvis required additional calculations to form the segments. For the thigh, the distal segment end point was between the lateral and medial epicondyle of the knee and proximal end point was the hip static joint centre (SJC). Right and left hip SJC were estimated based on the following equation and ASIS distances (Bell et al., 1989):

Right hip SJC = (0.36*ASIS_distance, -0.19*ASIS_distance, -0.3*ASIS_distance)
Left hip SJC = (-0.36*ASIS_distance, -0.19*ASIS_distance, -0.3*ASIS_distance)
The ASIS distance was calculated in Visual 3D as the distance between RASIS and LASIS markers, therefore it was important to achieve correct positioning of these markers. The estimates of static hip joint centre positions was adapted from the work of Bell et al. (1989) who reported predicting hip joint centres in adults to within 2.6 cm of actual joint centre locations.

The pelvis segment was initially defined using the ASIS and PSIS marker positions. The origin of the pelvis LCS was defined as the mid-point between the ASIS markers. The x-axis was defined from the origin to the right ASIS, z-axis was vertical and y-axis was anterior-posterior (Figure 4.9). However, Visual 3D warn that using this segment definition will result in a pelvis segment that is tilted approximately 20º forward from the horizontal and advocate a segment with zero tilt should be created (i.e. x-axis parallel with the floor) (C-Motion, 2011). This is achieved by creating iliac crest landmarks to define the proximal joint end points and static hip joint centres to define distal joint end points. The static hip joint centres were offset in the z-direction of the laboratory co-ordinate system by 0.5*ASIS_distance to create iliac crest landmarks. Defining the pelvis in this way would result in a z-axis which is directed vertically upward and the pelvis has no anterior tilt in the static trial where the subject is standing in the anatomical position.

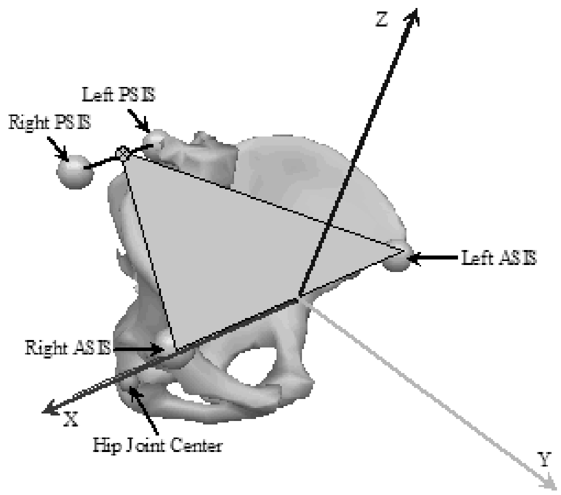


Figure 4.9. Pelvis segment created with Visual 3D based on ASIS and PSIS markers (C-Motion, 2011)

Each segment was considered to be a geometric shape based on the Hanavan model of the human body (Hanavan, 1964). Thereby, the mass, centre of mass and moment of inertia of each segment were defined. The segment mass was determined from the total golfer body mass and Dempster's anthropometric data (Robertson et al., 2004). All other segment properties were computed based on the mathematical model of Hanavan (1964) and could be used in the calculation of whole body COG. Those segments which were custom built in later chapters (e.g. lumbar, thorax and upper thorax) were classified as kinematic only segments and did not affect COG calculations.

Table 4.7. Visual3D golfer model segment definitions

Segment Name	Tracking Markers	Origin	Proximal Endpoint	Distal Endpoint
Head	RFHD, LFHD, RBHD, LBHD	Mid-point between RFHD and LFHD	RFHD - LFHD	RBHD - LBHD
Left Forearm	LFA, LLELB, LRAD, LULN	Mid-point between LLELB and LMELB	LLELB - LMELB	LRAD - LULN
Right Forearm	RFA, RLELB, RRAD, RULN	Mid-point between RLELB and RMELB	RLELB - RMELB	LRAD - LULN
Left Shank	LSK1, LSK2, LSK3, LSK4	Mid-point between LLK and LMK	LLK - LMK	LLA – LMA
Right Shank	RSK1, RSK2, RSK3, RSK4	Mid-point between RLK and RMK	RLK – RMK	RLA - RMA
Left Upper Arm	LSHO, LUP1, LUP2	Left static shoulder joint centre	Left static shoulder joint centre. Negative offset from LAC by measured shoulder width.	LLELB - LMELB
Right Upper Arm	RSHO, RUP1, RUP2	Rights static shoulder joint centre	Right static shoulder joint centre. Negative offset from RAC by measured shoulder width.	RLELB - RMELB
Left Thigh	LTH1, LTH2, LTH3	Left static hip joint centre	Left static hip joint centre defined using equation by Bell et al., (1989)	LLK - LMK
Right Thigh	RTH1, RTH2, RTH3	Right static hip joint centre	Right static hip joint centre defined using equation by Bell et al., (1989)	RLK - RMK
Pelvis (without tilt)	RASIS, LASIS, RPSIS, LPSIS	Mid-point between RASIS and LASIS	RT_ILLIAC - LT_ILLIAC	Right static hip joint centre to left static hip joint centre
Trunk (Thorax & Abdomen)	CLAV, STRN, C7, T10, RBAK	Mid-point of iliac crest	RT_ILLIAC - LT_ILLIAC	RAC - LAC
Right Hand	RRAD, RULN, RHA	Mid-point of RRAD and RULN	RRAD – RULN	RHA and radius of 0.05 m
Left Hand	LRAD, LULN, LHA	Mid-point of LRAD and LULN	LRAD - LULN	LHA and radius of 0.05 m
Right Foot	RLA, RMA, RTOE, RHEEL	Mid-point of RLA and RMA	RLA - RMA	RTOE and radius of 0.05 m
Left Foot	LLA, LMA, LTOE, LHEEL	Mid-point of LLA and LMA	LLA - LMA	LTOE and radius of 0.05 m
Golf Club Shaft	OBJ1, OBJ2, RHA	RHA	RHA and radius of 0.02 m	OBJ3 and radius of 0.005 m
Golf Clubhead	OBJ2, OBJ3, OBJ1	OBJ2	OBJ3 and radius of 0.05 m	OBJ2 and radius of 0.05 m

4.3.2.1 Functional Joint Centres

An additional feature of Visual 3D is the ability to determine functional joint centres (FJC) as opposed to SJC which rely on predictive methods. The limitations of determining joint centres with predictive methods (e.g. SJC) are the errors associated with estimating joint centre co-ordinates through palpation techniques and errors due to the regression equations used. Functional joint centres allow the determination of subject-specific joint centres based on marker displacement data and can overcome the limitations associated with the predictive methods. The algorithm used to determine functional joint centres requires movement of one segment relative to another segment and then finds a position that is stationary relative to the two segments (C-Motion, 2011). The algorithm used by Visual 3D is based on Schwartz and Rozumalski (2005) method for estimating joint parameters. For the hip and shoulder joints, with three degrees of freedom (3 DOF) a movement trial is required where the joint moves about all three axes of rotation individually (i.e. flexion-extension, abduction-adduction and circumduction).

In this thesis, to determine shoulder FJC the golfers stood in the anatomical position and were asked to perform shoulder flexion-extension, abduction-adduction and shoulder circumduction movements. For the hip FJC golfers were asked to perform right thigh flexion, abduction and circumduction movements. Previous studies have examined the effect of the number of cycles of movements, velocities and range of movement (Begon et al. 2007). Based on these recommendations and those in the Visual 3D documentation, the golfers were asked to perform five cycles of the movements, at a moderate speed and to limit movement to approximately 20º in each direction. A detailed description of the process can be found in Schwartz and Rozumalski (2005). Calculated FJC were then used to determine segments relative to these subject specific anatomically determined locations (Figure 4.10).

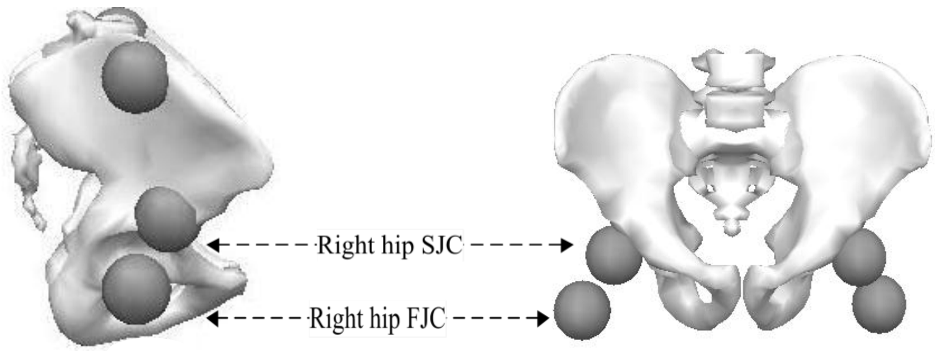


Figure 4.10. Example locations of functional (FJC) and static (SJC) joint centres for the right hip. Example difference in x, y and z positions for a single golfer are 0.03 m, 0.02 m and 0.04 m respectively

4.3.3 Golfer Model Segment Tracking

To determine the motion of the golfer throughout the golf swing, the position and orientation of all segments needs to be calculated. Visual 3D provides two methods for computing the position and orientation of segments which are the six degree of freedom method (Spoor & Veldpaus, 1980) or the inverse kinematic method (Lu & O'Connor, 1999). The six degree of freedom method, or segmental optimisation method, as termed by Lu and O’Connor (1999) is so called because each segment is considered to have six variables that describe its position and orientation (three translational and three rotational). The six degree of freedom method assumes that all segments move independently whereby two segments in close proximity, (i.e. proximal end of one segment and distal end of another segment) are assumed to be linked but not constrained. This method also assumes that the position and orientation of the segment is determined by the set of tracking markers attached to the segment and accounts for skin movement artefact. The position and orientation of segments are based on the transformation matrix between static and dynamic trials and the degree of marker deformation between dynamic and static trials is accounted for using a least squares method adapted from work by Spoor and Veldpaus (1980). The segmental residual calculated describes the goodness of fit between static and dynamic segment positions and orientations. As aforementioned, this method treats joints separately without joint constraints which could lead to apparent joint dislocations. Therefore, the inverse kinematics method or alternatively known as the global optimisation method, accounts for joint constraints by stating which segments are connected by a joint and applying realistic joint properties to minimise soft tissue error. This method may overcome errors in apparent joint dislocations or changes in segment length (Lu & O'Connor, 1999).

The six degree of freedom method was used in this thesis. This method was used as it allowed more than three tracking markers (up to 8 markers) to be chosen to track each segment which allowed Visual 3D to calculate segment position and orientation if more than one marker was occluded which happened readily with regards to the trunk.

4.3.3.1 Golfer Model Segment Residuals

The six degree of freedom method accounts for soft tissue artefact using static pose. The segment residuals give a measure of the soft tissue artefact correction required. For example, if markers were attached to a perfectly rigid body the segment residual would be close to zero. Table 4.8 displays the mean ± SD of the segment residuals for three golfers throughout the golf swing.

Table 4.8. Mean ± SD for segment residuals during the golf swing for three golfers and 15 trials

Segment	Residual (mm)	
Left shank	0.3 ± 0.0	
Head	0.5 ± 0.1	Very Low
Pelvis	3.0 ± 1.0	
Thorax	9.0 ± 4.0	
Left thigh	10.0 ± 3.0	Low
Left upper arm	10.0 ± 4.0	
Left hand	20.0 ± 5.0	
Left forearm	20.0 ± 5.0	Moderate
Shoulder	20.0 ± 7.0	
Golf shaft	70.0 ± 1.0	High

The low to very low residuals (< 10 mm) for the head, shank, pelvis, thorax, thigh and left upper arm suggest that the marker positions are tracking the segment well. For the shoulder, left forearm, and left hand the residuals are higher and perhaps suggest that these markers are not tracking the segment as effectively. Nevertheless, the residual values are still relatively low < 20 mm for these segments. The largest residuals were recorded for the markers defining the golf shaft. This result is not surprising given the golf shaft is not a completely rigid segment and will experience significant bending during the golf swing (Penner, 2003).

4.3.4 Filtering

Filtering of data becomes more important when determining derivatives of displacement data such as velocities and accelerations because of errors introduced during the interpolation process. Care should be taken not to over smooth data so that key instances are not missed such as values at impact, therefore it is important to examine frequency spectra.

Frequency spectra were produced for the raw marker positions exported from Vicon for a selection of golfers during the data collection in subsequent chapters using custom written Matlab (The Mathworks, Natick, MA) scripts. The frequency spectra of markers attached to those segments that reported poor residuals are presented in Appendix E. The frequency spectra were visually inspected and the portion where the curve began to plateau was deemed a suitable cut-off frequency for the filter (Figure 4.11). Based on visual inspection of the frequency spectra, for both body and club marker positions (Figure 4.11), it was decided that a low pass filter at cut-off frequencies of 10 Hz and 20 Hz would be applied to body and club marker positions respectively. The most common filter applied in golf biomechanical studies is a zero-lag Butterworth fourth order low pass filter with cut-off frequencies between 10 and 20 Hz (Coleman & Rankin, 2005a; Wheat et al., 2007; Betzler, 2010). Coleman and Rankin (2005) similarly chose to use different cut-off frequencies for body markers and club markers of 10 Hz and 20 Hz respectively.

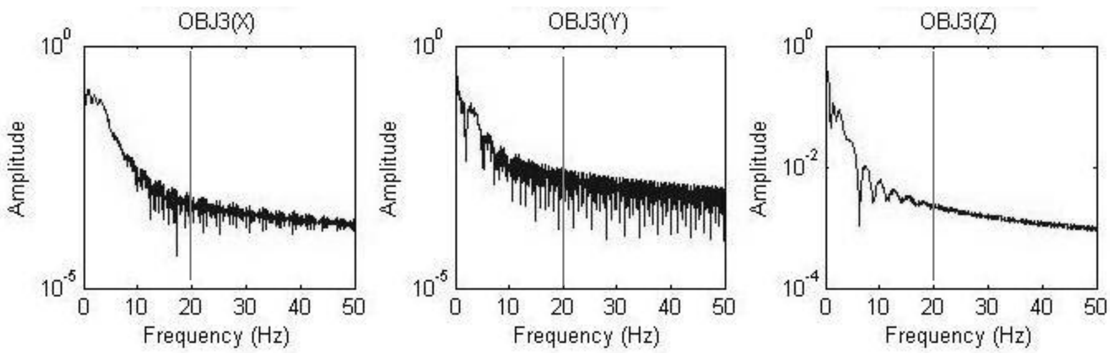


Figure 4.11. Frequency spectrum for selected club marker positions

Similarly, frequency spectra were produced for GRF data from both force plates as it has been recommended that force data should be filtered. Based on visual inspection of the frequency spectra a low-pass filter at cut-off frequencies of 25 Hz was applied to all GRF data.

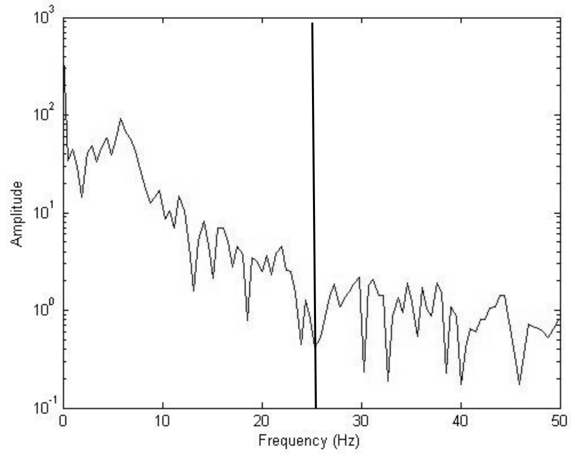


Figure 4.12. Frequency spectra for vertical GRF data during the golf swing.

4.3.5 Three- Dimensional Joint Angle Definitions

After filtering the raw positional data, 3D joint angles were calculated using Visual 3D. A reference segment (proximal) and segment (distal) were selected based on the desired angle. The joint angle was then calculated as the transformation between the two chosen segment co-ordinate systems, which could either be the GCS or LCS. For example, the right knee angle was calculated as the rotation of the right shank (distal) relative to the right thigh (proximal) segment.

The angle can also be represented in a number of ways the widely used Cardan angles were used here where the joint angle depends on the order of the rotation matrix.

The following equation is used to calculate joint angles:

$R_{joint} = R_{distal} * R_{proximal'}$

The resulting rotation matrices for R_{joint} with a ZYX rotation order were as follows (C-Motion, 2011):

$$[R_{joint}] = [R_x][R_y][R_z]$$

$$[Rx][Ry][Rz] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{bmatrix} \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \begin{bmatrix} cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[Rx][Ry][Rz] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{bmatrix} \begin{bmatrix} cos\theta_y \cos\theta_z & cos\theta_y \sin\theta_z & -\sin\theta_y \\ -\sin\theta_z & \cos\theta_z & 0 \\ \sin\theta_y \; cos\theta_z & \sin\theta_y \; \sin\theta_z & \cos\theta_y \end{bmatrix}$$

$$R_{joint} = \begin{bmatrix} cos\theta_y \; cos\theta_z & \cos\theta_y \sin\theta_z & -\sin\theta_y \\ -sin\theta_z \; cos\theta_x + \sin\theta_x \sin\theta_y \; \cos\theta_z & \cos\theta_x \; \cos\theta_z + \sin\theta_x \sin\theta_y \sin\theta_z & \sin\theta_x \cos\theta_y \\ \sin\theta_x \; \sin\theta_z + \cos\theta_x \sin\theta_y \cos\theta_z & -\sin\theta_x \cos\theta_z + \cos\theta_x \sin\theta_y \sin\theta_z & \cos\theta_x \cos\theta_y \end{bmatrix}$$

$$\text{R} = \begin{vmatrix} R_{00} & R_{01} & R_{02} \\ R_{10} & R_{11} & R_{12} \\ R_{20} & R_{21} & R_{22} \end{vmatrix}$$

$$\theta y \; (abduction) = \text{asin}(\text{R}_{02})$$

$$\theta x \; (flexion) = asin\left(\frac{R_{12}}{cos_{\theta y}}\right)$$

$$\theta z \; (rotation) = \text{asin}\left(\frac{R_{01}}{cos\theta y}\right)$$

The default setting within Visual3D for calculating joint angles using Cardan angle rotation orders is XYZ. Further detail regarding the calculation of required joint angles will be presented in proceeding chapters, including the choice of Cardan rotation order.

4.3.6 Swing Events and Temporal Alignment

Biomechanical data was analysed from takeaway (TA) and the end of follow through (FT) or mid-follow through (MidFT), with top of the backswing (TB) and impact (IMP) also identified. The clubhead linear velocity was used as the basis to define swing events as it allowed easily identifiable stages across golfers. The phases of the golf swing were defined using the following threshold functions in Visual 3D: TA when the x-component of velocity of the clubhead heel marker (i.e. horizontal velocity in the target direction) first exceeded 0.2 $m.s^{-1}$; TB when the x-component of velocity of the clubhead heel marker changed from positive to negative; IMP as the time point immediately preceding the frame where ball positional data changed; MidFT when the club shaft (defined as a vector between OBJ1 and OBJ2) was parallel to the GCS x-axis and FT when the x-component of velocity of the clubhead heel marker changed from negative to positive.

Temporal differences in gait cycles have been reported and therefore temporal alignment techniques are applied in order to make point-by-point comparisons of time-series data (Helwig et al., 2011). The same problem can be assumed during the golf swing, as the swing stages, TB and IMP can occur at different instances in the swing between golfers and within golfers. Therefore, a piecewise linear length normalisation (PLLN) approach was employed to temporally align golfer data when required as this approach could identify temporal and intensity differences between sub-phases (Helwig et al., 2011). The golf swing was divided into three sub-phases TA to TB, TB to IMP and IMP to MidFT or IMP to FT, as these points were easily identified in each golfer. Temporal alignment of golf swing data was performed using a custom written Matlab function (The Mathworks, Natick, MA) which used the piecewise linear length normalisation technique (Appendix F).

4.4 Summary

The objective of this Chapter was to present the data collection and analysis processes that would allow the research questions three and four to be addressed. The general data collection and analysis methods used throughout this thesis were detailed and will be referred to through the processing chapters. The high speed video settings and reliability of the TrackMan launch monitor were also presented. The TrackMan and Vicon motion analysis methods showed good agreement for measuring club head linear velocity and ball velocity at impact. The software Visual 3D was used to process motion analysis and force plate data. A seventeen segment 6DOF basic golfer model was developed and the six degrees of freedom method was used to estimate the pose and orientation of golfer segments throughout the golf swing. The most suitable filtering for raw marker positional data and analogue data were determined and applied to the collected golf swing trials. The swing events TA, TB, IMP, MidFT and FT were defined and used to temporally align data using piecewise linear length normalisation.

The proceeding methods chapters will discuss the specific data collection and analysis methods used to quantify the key technical parameter posture and body rotation.

Chapter 5 Methods for Defining Posture

5.1 Introduction

Posture was identified by the golf coaches in the qualitative study as one of the key technical parameters of a successful elite golf swing (§2.5.4). However, when the coaches perceptions were compared to the golf biomechanical literature, it was found that posture during the golf swing was not well defined (§3.5).

Posture has been described in terms of the position of the body relative to the vertical, which shall be referred to as postural kinematics and includes postural balance i.e. the dynamics of postural kinematics to prevent falling (Winter, 1995). Postural kinematics typically refers to measurement of trunk kinematics and in clinical gait analysis, it has been recommended that the term trunk should be used to represent the lumbar and thorax segments (Leardini et al., 2009). Therefore, the clinical definition of trunk will be used in this thesis.

As presented in the literature review (§3.5.1), there have been contrasting results with regards to the importance of the trunk angle on measures of performance and how the trunk angle changes throughout the swing (McTeigue et al., 1994; Chu et al., 2010). The contrasting results could be due to the differences in methodologies used, including different segments of the trunk being analysed. In golf biomechanical literature, postural kinematics have often been reported as 2D trunk angle obtained from motion analysis systems (Zheng et al., 2008a; Zheng et al., 2008b; Chu et al., 2010) and electromagnetic systems (McTeigue et al., 1994; Lindsay & Horton, 2002). The 2D trunk angles are calculated by creating a vector that defines the trunk segment and then projecting the vector onto the GCS sagittal plane (Bradshaw et al., 2009; Chu et al., 2010). For example, Bradshaw et al. (2009) calculated 2D trunk flexion as a vector created between the right proximal humerus and the right iliac crest relative to the vertical global axis.

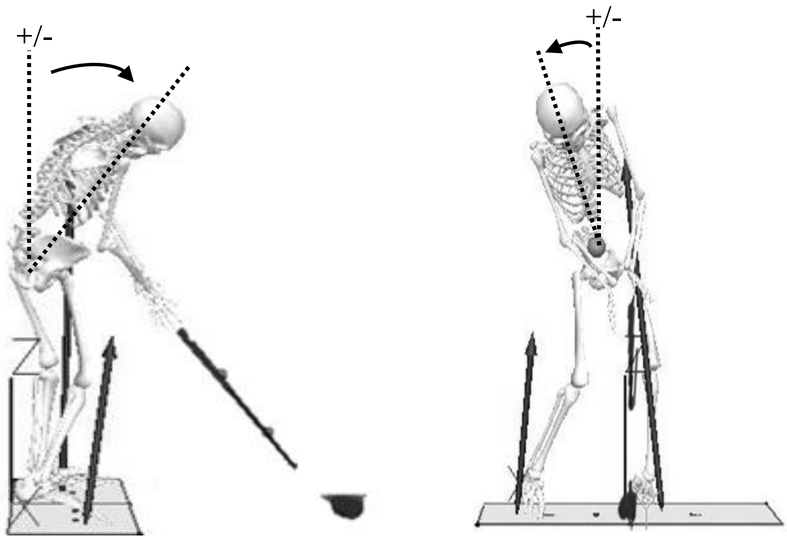


Figure 5.1. The definition of 2D trunk angles relative to the vertical axis for flexion (-ve angles) and lateral bend angles. The figure also shows a single trunk segment.

The 2D projection method for calculating postural kinematics is susceptible to perspective errors, hence it is important to investigate 3D measurement of postural kinematics to provide a more accurate representation of movement (Wheat et al., 2007; Horan et al., 2010; Joyce et al., 2010). However, in this case, sequence dependency of 3D angles needs to be considered as different rotation sequences can yield varying results (Bonnefoy-Mazure et al., 2010).

In addition, modelling the trunk as either a single segment or multiple segments can produce varying results regarding trunk movement. Many studies, including those conducted in golf, have modelled the trunk as a single rigid segment (Figure 5.1) (Zheng et al., 2008a; Bradshaw et al., 2009). However, clinical research has shown that modelling the trunk as separate segments for example thorax and lumbar, can result in different kinematics and ranges of motion compared to a single segment trunk for various movements such as gait and step-ups (Leardini et al., 2009). In particular, Leardini et al. (2009) commented that lumbar motion is not accounted for if only the entire trunk was modelled as a single segment. Joyce et al. (2010) stated that a multi-segment model (i.e. thorax and shoulder) of the trunk should be implemented when examining motion during the golf swing, in particular when measuring X-factor. However, this conclusion was reached from observations on a single golfer and the lumbar segment was not reported. Furthermore, some coaches also referred to head position and knee angles when discussing postural kinematics which should also be accounted for when investigating posture during the golf swing. Therefore, a more detailed examination of the methods used to measure postural kinematics in golf is presented here.

Perturbations to a normal erect posture, such as bending the trunk or raising the arms, will result in changes to the control mechanisms of balance (Winter, 1995), which was also alluded to by golf coaches. The two main biomechanical measures of postural balance are centre of pressure (COP) and centre of gravity (COG). As aforementioned, changes to postural kinematics can change the control mechanisms of balance and much research has focused on determining how such perturbations alter the balance of the body. Therefore, the study of both postural kinematics and postural balance could be applied to the golf swing in order to reveal mechanisms for maintaining a balanced body position throughout the golf swing. The measurement of COP has readily been documented in the golf literature through utilising a force plate positioned under each foot of the golfer (Wallace et al., 1994; Barrentine et al., 1994; Ball and Best, 2007a; Ball and Best, 2007b). The study of COP has identified different weight transfer patterns between golfers; however, this has not been compared to a golfer's postural kinematics or COG. A golfer's COG has been calculated through combining motion analysis data with anthropometric data originating from regression equations (Burden et al., 1998) which is the widely accepted method for estimating COG.

Therefore, the purpose of this chapter was to define the posture measurements used to define the methods and analysis used to describe postural kinematics and postural balance throughout the golf swing. This would be achieved through several objectives. The first objective was to define the measures of postural kinematic parameters which included knee angles and head position. The second objective was to evaluate the suitability of current trunk models for measuring trunk angles relative to the vertical and to determine whether 3D analysis of trunk angles was necessary. The third objective was to define golf specific measures of COP and COG. These definitions are then used in subsequent chapters of this thesis to investigate body posture biomechanics.

5.2 Postural Kinematics

5.2.1 Knee Angle

Three-dimensional knee flexion/extension, abduction/adduction and axial rotation angles were computed between the thigh and shank segments using the XYZ Cardan rotation order. This rotation order is commonly used to report 3D knee angles (Lees et al., 2010). The knee joint angle conventions are displayed in Table 5.1.

Table 5.1. Left and right knee angle conventions

	Flexion	Extension	Abduction	Adduction	Inward Rotation	Outward Rotation
Left Knee Angle	-ve	+ve	+ve	-ve	-ve	+ve
Right Knee Angle	-ve	+ve	-ve	+ve	+ve	-ve

5.2.2 Head Position

Head position was defined as the position of the head centre of gravity (head COG) in the GCS (Figure 4.2). The head COG movement was then measured in the global x-y plane throughout the swing (Figure 4.2), which is similar to previous studies that have examined head position in cricket batsmen (Taliep et al., 2007). Positive translation was reported for movement in the lateral direction to the right (x), anterior direction (y) and upward direction (z). All head COG movements were expressed as the percentage distance between the front and back foot , in accordance with COP measurements defined in §5.3.1.

5.2.3 Two- and Three- Dimensional Trunk Angles

In golf biomechanics research, two-dimensional (2D) trunk angles have been calculated from projecting the vector, created between marker positions (e.g. T2 and mid PSIS landmark) onto the sagittal plane (y – z) or frontal plane (x – z) of the GCS. Conversely, the three-dimensional (3D) trunk angles refer to the angles relative to the GCS. The 2D and 3D trunk angles were compared during the golf swing in order to determine which method adequately represents a golfer's trunk movement. The results from this study could then be used in subsequent studies investigating the relationship between posture and golf swing performance.

5.2.3.1 Two-dimensional Trunk Angles

Two-dimensional trunk angles were defined as the angle between a vector created by the T2 marker and the mid PSIS landmark projected onto the GCS frontal and sagittal plane (Figure 5.1). In addition, the trunk was divided into two segments to define the lumbar and thorax regions. The 2D lumbar and thorax angles were calculated as the vectors created between T2 - T10 (thorax) and T10 - Mid PSIS (lumbar) projected onto the GCS frontal and sagittal planes, to calculate flexion and lateral bend angles respectively. Some example values for a single golfer stood in an upright and golf posture at set-up is shown in Table 5.2.

Table 5.2. Two dimensional trunk, thorax and lumbar angles during upright and golf posture with a driver for a single golfer. Negative angles represent trunk flexion and lateral bend in the target direction.

	Upright Posture		Golf Set-up Posture	
Segment	Flexion/Extension	Lateral Bend	Flexion/Extension	Lateral Bend
Trunk	0.8	-0.8	-35.4	7.7
Thorax	-6.0	0.4	-47.5	15.8
Lumbar	8.5	0.6	-26.0	6.0

5.2.3.2 Three-dimensional Trunk Angles

Before 3D trunk kinematics could be considered for future analysis of postural kinematics it was necessary to conduct a short study to compare trunk models used to measure 3D trunk kinematics in order to determine with a multi segment trunk best represented the movement throughout the golf swing. Therefore, the purpose of the study was to determine the most appropriate methods for analysing 3D trunk kinematics during the golf swing. It was hypothesised that a multi-segment trunk model would produce different patterns in trunk kinematics throughout the golf swing compared to a single segment trunk model. Each model was considered based on the overall depiction of motion during the golf swing. In addition, the choice of Cardan rotation order was considered.

5.3.3.2.1 Methods

Eighteen right handed low handicap male golfers (handicap range = +3 to 4; age = 25 ± 8 years; height = 180.5 ± 7 cm; weight = 79.4 ± 13.1 kg) were chosen for analysis, based on a priori power analysis detailed in the statistical analysis section. The golfers were either members of the Loughborough University golf team or PGA professional golfers from local clubs and all gave their informed consent prior to testing (§4.2.6).

The golfers were prepared for motion analysis data collection by placing retro-reflective markers on the golfer in accordance with the marker set presented in §4.2.5.3. Three-dimensional marker trajectories were collected using the Vicon Nexus Motion Analysis System sampling at 250 Hz. Frontal plane high speed video was collected at 250 Hz. Each golfer performed several warm up swings at their own discretion before the testing began in the laboratory as setup in §4.2.1. Initially, a static trial was collected followed by ten shots with their own driver, with an adequate rest period given between shots. Following each shot, golfers performed a subjective assessment of shot quality, using

10-point scale (1 - 10) where the highest ratings were considered representative of their best shot.

Five drives were selected for analysis based on the golfer's subjective rating of shot quality and those trials with minimal marker drop-out. All raw positional data was filtered according to the techniques defined in §4.3.4. The Visual3D software was used for modelling by following the conventions presented in §4.3.2. The trunk was defined by six models (Trunk, Thorax 1, 2 & 3, Lumbar 1 & 2) which are defined in Table 5.3. Some model definitions were taken from previous literature whilst others were based on recommendations from the Visual3D software.

There were several iterative stages to the data analysis process. Firstly, mean maximum residuals were calculated for each model to provide an indication of marker movement due to soft tissue movement and the non-rigidity of the segment. Secondly, using only the trunk model, angles were computed for all six Cardan rotation orders. The Cardan rotation orders were visually compared and the most appropriate rotation order was selected based on the knowledge from previous biomechanical studies. Using this Cardan rotation order, the 3D angles for each model were measured and compared. A more detailed statistical analysis of the models at discrete stages of the swing was used to determine if there were differences between models. Finally, the chosen model were compared against 2D trunk angles and evaluated based on visual inspection and confirmed with statistics if required. All data was temporally aligned and swing events identified in accordance with §4.3.6 using Matlab (The Mathworks, Natick, MA).

A repeated measures ANOVA with two factors (i.e. model type and angle) was used to determine the effect of the trunk model on calculated trunk kinematics at discrete stages throughout the swing. The significance was set at $p < 0.05$. Using the online power analysis program, G*Power 3.1.5 (University of Kiel, Germany, Faul et al., 2007) a priori power analysis for a repeated measures design indicated that 12 to 24 participants were required to have 80% power for detecting a small (0.2) to large (0.8) effect size, as defined by Cohen's conventions, with 0.05 statistical significance (Brace et al., 2006). Data was statistically analysed using SPSS 17.0 (SPSS, Inc., Chicago, IL).

Table 5.3. The six models considered for three-dimensional analysis including relevant literature reference, tracking markers, segment co-ordinate system definitions and maximum residual (mm) for the golf swing (mean ± SD across 18 golfers).

Model	Name	Reference	Tracking markers	Origin	Proximal	Distal	X-axis	Y-axis	Z-axis	Max. Residual (mm)
1	Trunk	-	RT_ILLIAC,LT_ILLIAC, RAC, LAC, CLAV, STRN, T10, T2, T8	Mid-point of illiac crests	Right illiac crest to left iliac crest landmarks	RAC to LAC	Origin to the right	Anterior - Posterior	Distal to proximal Z+	30.0 ± 1.0
2	Thorax1	Leardini et al. (2011)	T2, CLAV, T8,STRN	Mid-point between CLAV and T2	Landmark between T2 and CLAV	Landmark between T8 and STRN	Origin to the right	Anterior - Posterior	Distal to proximal Z+	10.0 ±
3	Thorax2	Wu et al. (2005)	CLAV, C7, STRN, T8	Mid-point between C7 and CLAV	Landmark between CLAV and C7	Landmark between T8 and STRN	Origin to the right	Anterior - Posterior	Distal to proximal Z+	10.0 ±
4	Thorax3	Visual3D	C7, CLAV, STRN, T2,T8,T10	Mid-point of illiac crests	Landmark midway between left and right iliac crests	RAC to LAC	Origin to the right	Anterior - Posterior	Distal to proximal Z+	10.0 ±
5	Lumbar1	Visual3D	L4,L5, LPSIS, RPSIS	Projection of T10 onto plane created by mid illiac – left acromion and T10 landmarks/markers	Landmark T10_PROJ	Landmark midway between LPSIS and RPSIS	Origin to the right	Anterior - Posterior	Distal to proximal Z+	10.0 ±
6	Lumbar2	Visual3D	L4, L5, LPSIS, RPSIS	Mid illiac crests	Landmark midway between left and right iliac crests	RAC to LAC	Origin to the right	Anterior - Posterior	Distal to proximal Z+	10.0 ±

* origin = mid-point of proximal markers (§4.3.2)

5.3.3.2.2 Results

Average Segment Residuals

The maximum segment residual during the golf swing, averaged across the 18 golfers was between 10 mm and 30 mm m across the six models (Table 5.3). The trunk model may have higher segment residuals due to the increased number of markers tracking this segment. Nevertheless, there appeared to be no substantial differences in the amount of soft tissue movement and also non rigidity of the thorax or lumbar segments estimated by the segment residuals.

Cardan Rotation Order

The 3D angles for all six Cardan rotation orders, measured relative to the GCS, are presented as time-histories for the trunk model (Figure 5.2). To aid in the choice of Cardan rotation order, the high speed video was visually compared to 3D trunk angles for all golfers. All rotation orders were judged based on their representation of a golfer's motion in all planes of movement. The time-histories of XZY and YZX did not represent the movement during the golf swing in all planes. The degree of lateral bend and flexion using these Cardan rotation orders was deemed excessive for the golf swing (Figure 5.2). In addition, the rotation orders XYZ and YXZ appeared to mask changes in the flexion angle during the golf swing. More specifically, using the rotation orders XYZ and YXZ the golfer appeared to become more flexed following IMP where the HSV showed that the golfer became more upright following IMP. The Cardan rotation orders ZXY and ZYX appeared to follow similar patterns throughout the golf swing and either rotation order was deemed suitable to represent 3D trunk movement during the golf swing. The trunk flexion, lateral bend and axial rotation angles reported by Joyce et al. (2010) follow similar patterns to those reported here using the ZYX rotation order in this study. Therefore, the Cardan rotation order ZYX was chosen for analysing 3D trunk kinematics during the golf swing. This rotation order has previously been used for studies investigating rotational movement and coupled lateral flexion from different postural positions (i.e. different degrees of flexion) (Edmondston et al., 2007).

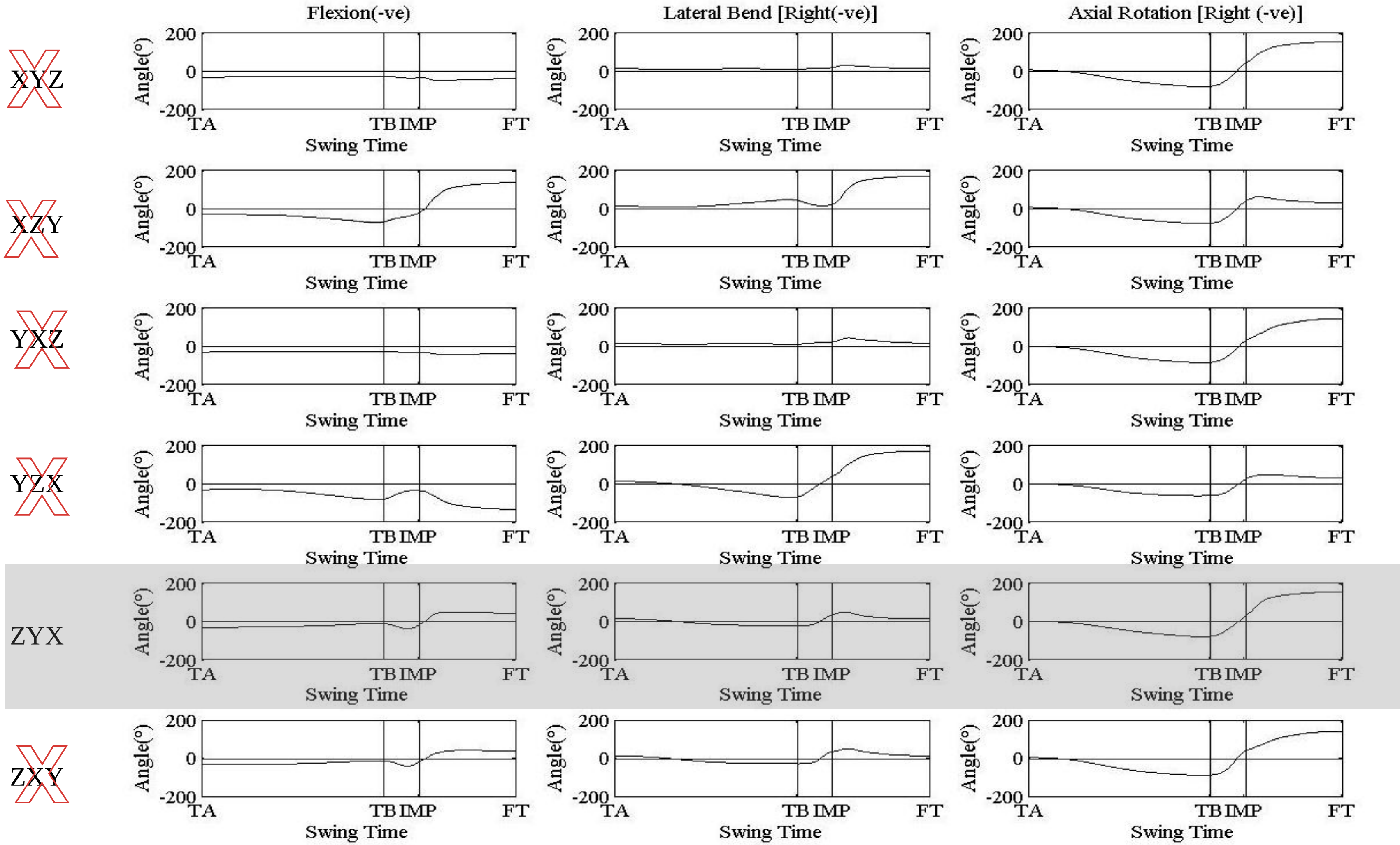


Figure 5.2. Time-histories of trunk motion (flexion/extension, lateral bend and rotation) in the GCS during the golf swing the six Cardan rotation orders (XYZ, XZY, YXZ, YZX, ZYX, ZXY) for a representative golfer across five trials. TA is takeaway, TB is top of the backswing, IMP is impact and FT is follow-through. The chosen rotation order is highlighted in grey and the disregarded Cardan rotation orders are struck out.

Trunk Models

Using the Cardan rotation order ZYX the time-histories of trunk kinematics were compared between the six trunk models (i.e. Lumbar 1 - 2 vs. Trunk, Thorax 1 - 3 vs. Trunk) (Figure 5.3). When inspecting time-histories across golfers, similar patterns were observed between models (Figure 5.3). Both lumbar models appeared to follow similar patterns for all angles. This observation is not surprising given both models were tracking the lumbar region of the trunk. However, there are large differences between the lumbar models and the trunk model. All three thorax models displayed similar patterns throughout the golf swing. Furthermore, only slight differences were seen between the thorax and trunk models.

The repeated measures ANOVA determined several statistical differences between models in all three angles at TA, TB and IMP. At TA, following greenhouse-geisser corrections, there was a significant difference between models ($F_{2,39} = 15.12$, $p < 0.05$) with a medium effect size of 0.47. The post hoc Bonferroni corrected tests revealed that several pairwise comparisons were significantly different (i.e. $p < 0.05$) at TA and are identified in Table 5.4. There was also a significant difference between models at TB, $F_{2,41} = 47.8$, $p < 0.05$) with a moderately large effect size, 0.76. The post hoc tests identified statistical differences between more of the models, most notably between the lumbar models and all other trunk models Table 5.4. Finally, at IMP, statistical differences were noted between models ($F_{2,50} = 211$, $p < 0.05$) and a large effect size 0.92. There were evidently more statistical differences between models at IMP than the other swing stages (Table 5.4).

The visual and statistical differences between the lumbar and trunk models and between the thorax and trunk models suggest that a two segment model of the trunk (i.e. thorax and lumbar) can provide additional information regarding postural kinematics during the golf swing compared to single trunk segment. There were no significant differences reported between the two lumbar models and therefore the Lumbar2 was selected for future analysis. There were a few statistical differences between the three thorax models. Thorax1 and Thorax3 did not show any statistical differences at any stage during the swing; however, both displayed significant differences to Thorax2. This highlights that even models representing the same segment can produce varying results and it is necessary for studies to state how segments were defined in order for comparisons to be made across studies. For the purpose of this study, the Thorax3 model was selected for future analysis as the additional markers offer redundancy should markers become obstructed during data collection.

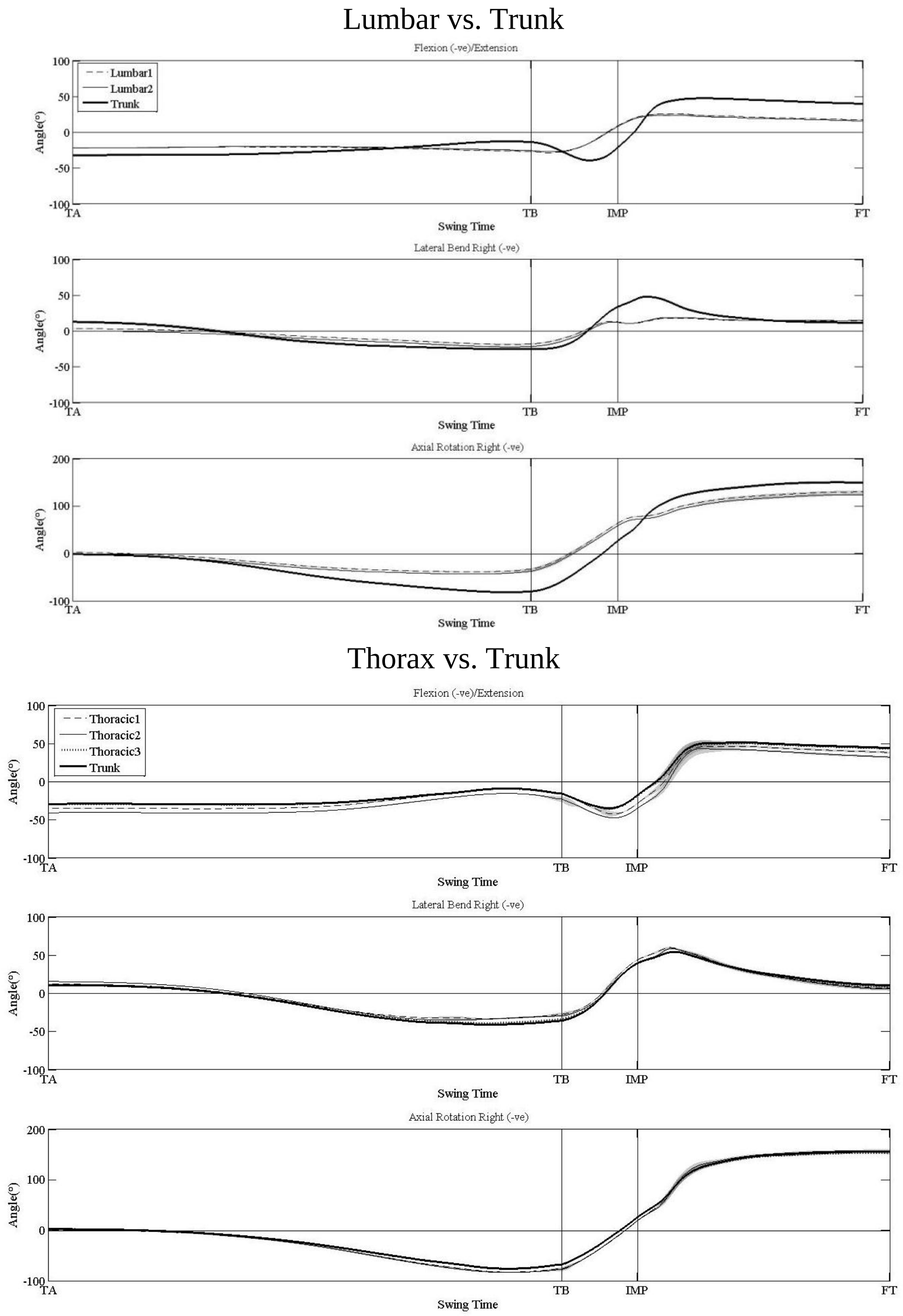


Figure 5.3. Time-histories of flexion, lateral bend and axial rotation for lumbar vs. trunk models and thorax vs. trunk models. The curves represent mean ± SD (shaded area) for a representative golfer.

Table 5.4. Mean, standard error (std. error), 95% confidence intervals (lower (L.CI) and upper (U.CI)) of flexion (X, -ve = initial flexion), lateral bend (Y, -ve= initial right) and axial rotation (Z, -ve = initial right) at TA, TB and IMP. The mean and standard error were calculated for 18 golfers.

		TA (°)					TB (°)					IMP (°)				
Model	Angle	Mean	Std. Error	L.CI	U.CI	Sig. Diff.	Mean	Std. Error	L.CI	U.CI	Sig. Diff.	Mean	Std. Error	L.CI	U.CI	Sig. Diff
a. Lumbar1	X	-21.0	1.6	-24.4	-17.5	f	-19.5	1.7	-23.1	-15.8	c, d,	4.6	2.2	-0.2	9.3	c, d,
	Y	-2.9	1.3	-5.6	-0.3		-19.7	1.3	-22.5	-16.9	e, f	9.4	1.3	6.7	12.1	e
	Z	-0.5	1.3	-3.4	2.3		-40.2	2.6	-45.7	-34.7		39.6	4.0	31.2	48.0	
b. Lumbar2	X	-21.4	1.6	-24.8	-17.9	f	-20.3	1.6	-23.8	-16.8	c, d,	4.3	2.2	-0.4	8.9	c, d,
	Y	0.0	0.8	-1.7	1.7		-16.9	1.1	-19.1	-14.7	e, f	11.7	1.1	9.4	13.9	e, f
	Z	0.6	1.2	-1.8	3.0		-38.7	1.9	-42.8	-34.7		41.7	3.2	34.9	48.6	
c. Thorax1	X	-30.4	1.4	-33.3	-27.4	d, f	0.2	2.1	-4.3	4.6	a, b,	-28.1	1.2	-30.7	-25.5	a, b,
	Y	11.2	0.9	9.3	13.2		-30.4	1.4	-33.3	-27.4	d	32.6	1.7	29.0	36.3	d, f
	Z	3.0	0.9	1.0	4.9		-88.3	2.2	-92.9	-83.6		12.8	2.5	7.6	18.1	
d. Thorax2	X	-35.2	1.2	-37.8	-32.6	c, e, f	-4.8	2.0	-9.1	-0.6	a, b	-33.1	1.2	-35.7	-30.6	a, b,
	Y	11.9	0.9	10.1	13.7		-28.7	1.4	-31.6	-25.7		31.9	1.7	28.2	35.6	c, e,
	Z	3.0	1.0	1.0	5.1		-87.8	2.1	-92.4	-83.3		14.0	2.5	8.7	19.2	f
e. Thorax3	X	-29.1	1.4	-32.1	-26.1	d, f	-1.5	2.4	-6.6	3.6	a, b	-24.5	1.5	-27.6	-21.4	a, b,
	Y	10.5	0.8	8.7	12.3		-34.1	1.5	-37.1	-31.0		28.9	1.6	25.5	32.4	d, f
	Z	4.0	0.8	2.2	5.8		-84.5	2.4	-89.6	-79.5		18.5	2.1	13.9	23.0	
f. Trunk	X	-31.3	1.3	-34.1	-28.6	a, b, c,	2.5	2.3	-2.3	7.4	a, b	-25.4	1.3	-28.1	-22.7	b, c,
	Y	14.3	1.0	12.1	16.5	d, e	-32.1	1.6	-35.4	-28.7		32.2	1.6	28.9	35.5	d, e
	Z	12.4	0.9	10.5	14.2		-90.4	1.6	-93.8	-86.9		28.8	2.2	24.0	33.5	

N.B [a,b,c,d,e,f] Denotes statistically significant difference ($p < 0.05$) to Lumbar1, Lumbar2, Thorax1, Thorax2, Thorax3 and Trunk respectively.

Two- vs. Three-Dimensional Angles

Finally, the 2D lumbar, thorax and trunk angles (flexion and lateral bend) were visually compared against 3D angles measured using the Lumbar2, Thorax3 and Trunk models respectively. From Figure 5.4 the 2D and 3D lumbar flexion and lateral bend angles followed relatively similar patterns. However, when comparing 2D and 3D thorax and trunk angles there were marked differences in the magnitudes and trends for both flexion and lateral bend angles throughout the swing (Figure 5.4). The 2D angles throughout the swing may help to explain some coaches comments about the fixed flexion throughout the swing (§2.5.4) as there is not much change in the 2D angle.

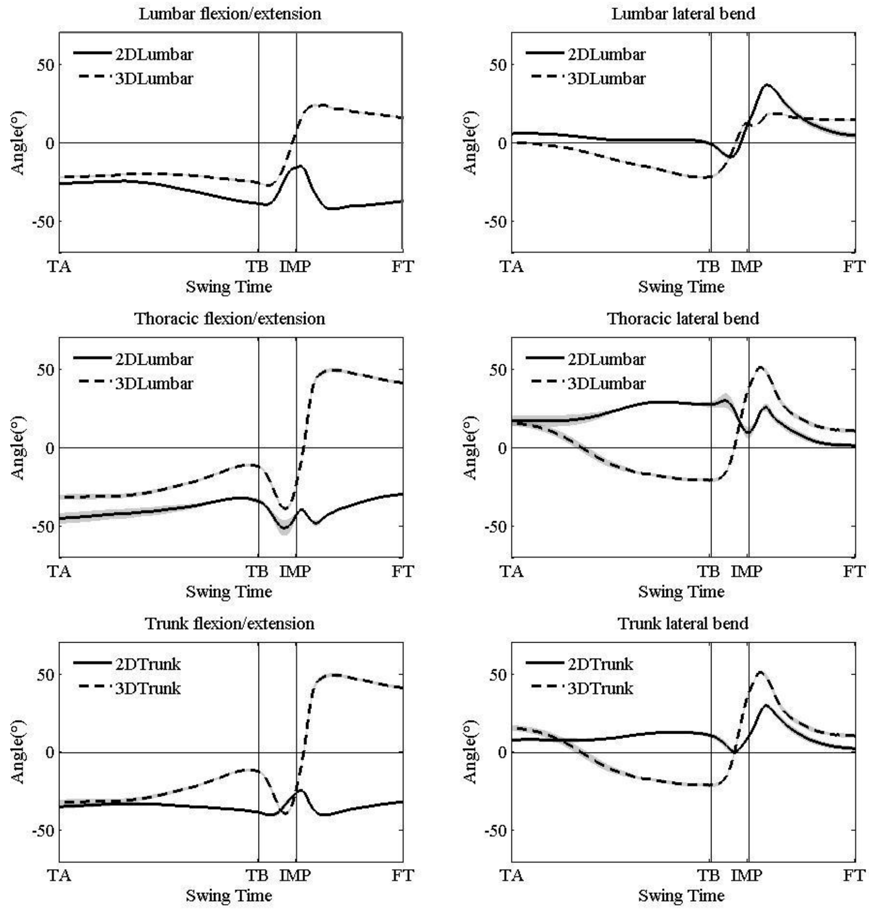


Figure 5.4. Mean and standard deviation (shaded area) for lumbar, thorax and trunk segments calculated as 2D (blue) and 3D (green) angles for a single golfer using a driver.

5.2.3.3 Discussion

The purpose of this study was to determine the most appropriate methods for analysing and reporting trunk kinematics during the golf swing. The ZYX (axial rotation – lateral bend – flexion) Cardan rotation order was selected as it represented the complex motion of the golfer and showed good agreement to patterns seen in previous data of 3D trunk kinematics (Joyce et al., 2010).

The time-histories of the 3D kinematics for the different trunk models, it revealed different patterns during the golf swing, supporting the hypothesis and the use of a two segment model to analyse the trunk during the golf swing. There were noticeable and significant differences in kinematics between the lumbar, trunk and thorax models for all 18 golfers examined. This was also revealed in the study by Joyce et al. (2010); however they only used a single golfer during their analysis. In addition, it appeared that treating the trunk segment as a single segment could mask lumbar motion during the golf swing, which has also be noted during clinical studies (Leardini et al., 2009). Furthermore, models representing the same trunk segment (e.g. thorax) could produce significantly different angles at swing events. Therefore, as Leardini et al. (2009) recommended, it is important that definitions of segment models, such as markers involved and LCS definitions are understood in order to make comparisons between studies.

Finally, the comparison of 2D projection angles and 3D angles revealed some considerable differences for thorax and trunk flexion and lateral bend angles. Crawford et al. (1996) suggested using projection angles to choose the most appropriate rotation orders for 3D angles. However, this suggestion was made for simple planar movements and is, shown here not to be appropriate for the golf swing which has movement about all three axes (i.e. rotation, lateral bend and flexion). The 2D and 3D lumbar angles showed relatively good agreement, which may be due to the smaller rotation of the lumbar segment compared to the trunk and thorax. For example, at TB the lumbar segment was rotated approximately -38.7º ± 1.9º compared to -90.4º ± 1.6º of trunk rotation. Previous studies have reported reduced lumbar axial rotation in the end of flexion and extension ranges of motion compared to a neutral posture (i.e. upright) due to the increased stiffness of passive spinal structures (Burnett et al., 2008). This result highlights the coaches' idea that posture can affect the subsequent degree of rotation. In addition, the 2D and 3D trunk and thorax angles show poor agreement which could be due to the coupled movement of lateral bend which is not accounted for in 2D angles. This emphasises the need for 3D angles of postural kinematics during the golf swing, as this information is missed if only 2D angles are considered.

The recommendations from this section (i.e. 3D representation of trunk kinematics using a two segment model (Lumbar2 – Thorax3) can now be used for more in-depth analysis of postural kinematics during the golf swing and the effect on golf swing performance (presented in Chapter 6).

5.3 Postural balance

This section describes the data analysis methods used to define measures of postural balance which include centre of pressure (COP) and centre of gravity (COG) measurements.

5.3.1 Centre of Pressure

To define COP position, the force structure FS3_1 (as defined in §4.2.4) which included both force plates, was used to measure the overall displacement of the COP in the GCS (§4.2.1, Figure 4.2). The COP was defined along the x-axis (i.e. medial - lateral COP $_{M-L}$) and y-axis (anterior - posterior COP $_{A-P}$) of the GCS. To normalise the COP measurements between golfers, the COP $_{M-L}$ was expressed as a percentage of the medial - lateral distance between the mid-points of the feet at set-up. The mid-point of each foot was defined as the mid-point between TOE and HEEL markers in the x and y directions.

This method for defining COP $_{M-L}$ is in accordance with previous studies that have extensively investigated COP during the golf swing (Ball & Best, 2007a; Ball & Best, 2007b) (x 100

Equation 1).

$$\%COP_{M-L} = \frac{COP_{\ M-L} - Mid\ back\ foot_{\ M-L}}{Mid\ front\ foot_{\ M-L} - Mid\ back\ foot_{\ M-L}} \text{ x } 100$$

Equation 1. Normalisation of COP $_{M-L}$ (medial - lateral direction) between feet

The COP $_{A-P}$ was normalised as a percentage of the anterior - posterior distance between the furthest toe marker position and furthest heel marker position between the front and back foot at set-up.

$$\%COP_{A-P} = \frac{COP_{A-P} - Heel\,marker_{A-P}}{Toe\,marker_{A-P} - Heel\,marker_{A-P}} \times 100$$

Equation 2. Normalisation of COP_{A-P} (anterior – posterior direction) between feet

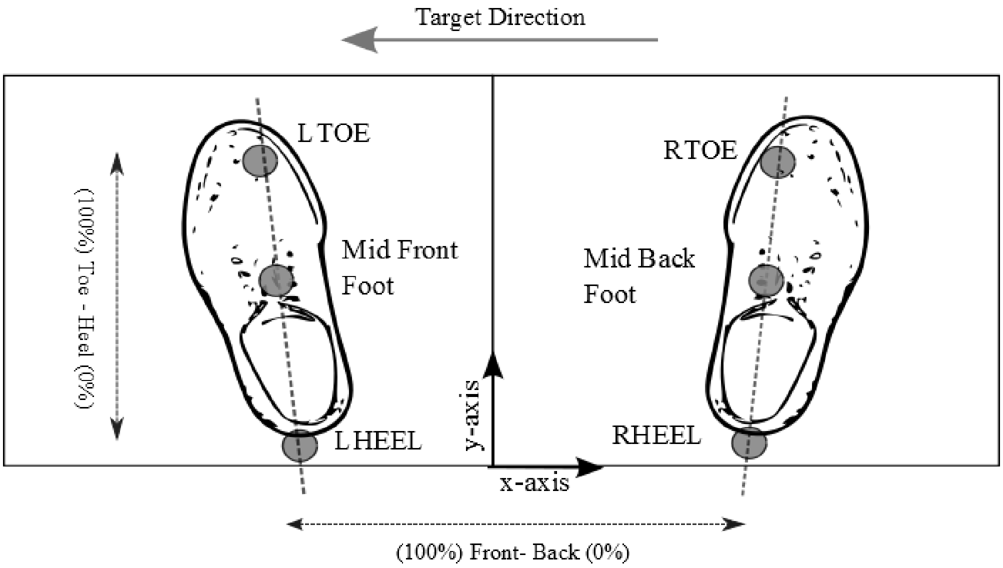


Figure 5.5. Illustration of the normalisation procedure used for COP and COG measurements between front and back foot for all golfers. For COP_{A-P} and COG_{A-P} 0% represented COP/COG entirely on the heels and 100% entirely on toes. For $\%COP_{M-L}$ and $\%COG_{M-L}$, 0% represented COP/COG on the back foot and 100% on the front foot.

5.3.2 Centre of Gravity

The whole body COG position was estimated as the weighted sum of the individual segments centre of gravity positions (based on their percentage of body mass) in accordance with Dempster's regression equations (Robertson et al., 2004) and the Hanavan model of the human body (Hanavan, 1964). The golf club was also included in this COG determination. This is based on previous studies on COG in cricket batsmen which included the bat in COG calculations (Taliep et al., 2007). For modelling purposes, the golf clubhead weight was approximated as 0.2 kg and the shaft (including grip) as 0.15 kg which are within ranges stated for average clubhead and shaft weights in previous studies (Harper et al., 2005; Betzler, 2010). The COG locations of the shaft and clubhead were estimated based on their dimensions. Initially, the 3D position of the whole body centre of gravity was measured in the GCS. However, in order to compare COG and COP throughout the golf swing, the COG was also normalised between golfers using the same equations as COP. Therefore, the measurements %COG $_{M-L}$ and %COG $_{A-P}$ were used to compare against %COP $_{M-L}$ and %COP $_{A-P}$ throughout the golf swing. Another method for calculating COG displacement involves the double integration of ground reaction forces. Gait studies that compared COG displacements using full body kinematic analysis and force plate data have shown good agreement between methods (Gard et al., 2004; Gutierrez-Farewik et al., 2006).

It was possible to determine the validity of the full body kinematic model for computing COG through comparing the COP and COG projections during a static trial (Winter, 1995). The average difference between COG and COP during quiet standing, for two golfers is presented in Table 5.3. There was a greater difference between COG and COP in the anterior-posterior direction. This offset could be explained due to the golfer resting the golf club in front of them in their right hand off the force plate during the quiet standing trial which may have caused a slight anterior shift in the COG position. Therefore, due to the small differences in COG and COP it was deemed acceptable to use the full body kinematic analysis approach for estimating whole body COG.

Table 5.5. The difference between COG and COP (mm) during quiet standing in medial-lateral and anterior-posterior direction for the full body golfer kinematic model.

Golfer ID	COG – COP (mm)	
	Medial-lateral (X)	Anterior-posterior (Y)
01	2	14
02	6	16

5.4 Summary

This chapter has presented the analysis methods used to measure postural kinematics and postural balance throughout the golf swing. This has included knee angles, head position, three dimensional trunk angles (i.e. thorax and lumbar), COP and COG throughout the swing. The limitations with previous analysis methods for measuring trunk angles were identified and addressed with this Chapter. A single trunk segment was found to mask changes in lumbar segment motion throughout the swing and therefore a two segment trunk would be used to investigate changes in posture between golfers. Furthermore, previous 2D posture analysis would tend to underestimate changes in posture throughout the swing. Therefore, 3D thorax and lumbar angles are recommended to report posture parameters throughout the swing.

The closeness of COP and COG measures during quiet standing confirms the validity of the analysis methods. The COP analysis methods were consistent with those previously reported (Ball & Best, 2007a; Ball & Best, 2012).

These methods for defining posture are used in the following chapter to identify the biomechanical features of posture throughout the golf swing.

Chapter 6 Identification of Biomechanical Features of Posture throughout the Golf Swing

6.1 Introduction

A golfer's posture was identified by golf coaches in Chapter 2 as a key technical parameter during the golf swing. The term posture encompassed the two sub-categories postural kinematics and postural balance. When comparing the coaches' perceptions of posture to the current golf biomechanical literature there were several gaps in knowledge which required further research. Firstly, there was a need to determine methodologies for measuring and analysing both postural kinematics and postural balance which were addressed in Chapter 5. Following the development of methodologies to define 3D postural kinematics and postural balance it was necessary to investigate posture parameters throughout the swing, as was deemed important by the golf coaches. Although TA, TB and IMP were identified as key events, it was important for coaches to understand the whole movement pattern during the golf swing (§2.5.2). The relationship between postural kinematics and postural balance also needed to be explored in order to gain a better understanding of the interaction between parameters in these sub-categories (§3.5.4). Finally, it was of interest to explore the relationship between posture and performance given coaches identified it as a key technical parameter of a successful golf swing.

Typically, biomechanical parameters are expressed as temporal data curves throughout a movement. The data curves are formed from a series of measures taken at equally spaced time intervals and are therefore considered to be highly correlated measures. The most commonly used methods for analysing data curves are to identify key events during the movement (e.g. maximum and minimum) and extracting the relevant values at those events for further analysis. For example, previous golf biomechanical studies of posture have identified mean values at swing events (e.g. TA, TB and IMP) and used statistical techniques to investigate differences between conditions, golfers or identify relationships with measures of performance (Bradshaw et al., 2009; Chu et al., 2010). However, there are limitations with this approach as a large portion of the data is neglected, which could lead to important information related to the biomechanical parameters being overlooked (Donà et al., 2009). The key events are often subjectively selected by the researcher, which may lead to inaccurate conclusions being drawn from the data and may not adequately represent the overall pattern in data. In addition, there is no account of which subjectively chosen key event is the most important. Finally, the key event data is often combined for group-based analysis which may conceal differences between individual subjects (Brown et al., 2011).

The limitation of analysing data at key events has been recognised by several biomechanical studies and as a result continuous data analysis techniques have been used. In particular, biomechanical studies of movement co-ordination and variability have sought to use continuous data analysis techniques to compare, for example, angle-angle plots of adjoining segments under various experimental conditions. Often angle–angle plots are qualitatively compared to identify differences between the data curves; however it is more challenging to quantitatively compare the data curves. Several continuous data analysis techniques have been used to examine differences between data curves including discrete and continuous relative phase, vector coding, cross-correlations, normalised root mean squared differences, one-dimensional statistical parametric mapping and curve clustering (Wheat & Glazier, 2006; Sangalli et al., 2008; Pataky, 2012; Vanrenterghem et al., 2012). Wheat and Glazier (2006) provided a comprehensive explanation of the strengths and limitations for the first five continuous data analysis techniques which are summarised in Table 6.1. The first three methods appear to have many limitations for analysis of biomechanical data as there may not be definitive peak values in the data and often some form of time normalisation of the data is required between trials or subjects. Hence, more recent biomechanical studies have used cross-correlations and normalised root mean squared differences instead. For example, Terry et al. (2011) used cross-correlations to identify two balance strategies in participants, by comparing COG and COP displacement data curves during a balance task. The authors suggested that, with further research, the protocol could be used as a clinical screening tool for falls prevention (Terry et al., 2011). Cross-correlations and normalised root mean squared, however, were unable to identify differences in data curves at specific portions of the movement and only a single measure of the variance between data curves was given.

The analysis method called one-dimensional statistical parametric mapping has only recently been used as a continuous analysis technique in the biomechanics literature (Pataky, 2012; Vanrenterghem et al., 2012; Pataky et al., 2013). Vanrenterghem et al. (2012) identified the speed-dependency of knee loading throughout the entire stance phase of running using one-dimensional statistical parameter mapping. Whilst this technique was effective at testing the effect of an intervention on kinematics, it did not provide a clear depiction of the biomechanical features[1] which vary the most between data curves. Lastly, the curve clustering techniques aim to group curves into homogenous sub-groups based on their overall shape (Sangalli et al., 2008). This method relies on clustering methods such as k-means to group curves. However, using k-means clustering may not be adequate as the number of clusters in which to group data curves needs to be predefined (Sangalli et al., 2008).

An alternative data analysis technique which could be used in analysis of data curves is principal component analysis (PCA) which is also summarised in Table 6.1. Principal component analysis overcomes several limitations of the other continuous data analysis techniques. However, care must be taken when biomechanically interpreting the results as PCs are movement specific and dependent on the length of movement used in the analysis.

Principal component analysis is a multivariate statistical technique whereby a highly correlated set of data is reduced to a new set of uncorrelated variables called principal components. The purpose of PCA is to extract the most important information from data curves, to reduce the size of a data set by only considering the most important information and to allow further analysis to be performed. The principal components account for the variance in the original data set and are ranked in order of importance (i.e. the first PC will account for the largest variation between data curves). The results of the PCA can then be used to identify hidden or simplified patterns in data curves at specific portions of the movement.

Principal component analysis has already been shown to be a useful tool for identifying unique technique features in elite race walkers and weight lifters (Wrigley et al., 2006; Donà et al., 2009) and for identifying features of gait associated with knee osteoarthritis (Deluzio & Astephen, 2007). A recent study has also used PCA to examine GRF between beginner and collegiate level golfers (Lynn et al., 2012). The results of the PCA reported differences in GRF patterns between the diverse group of golfers at specific portions of the swing which would be expected given the extreme difference in golfing abilities. The study by Lynn et al. (2012), however, did not compare measures of golfer kinematics and kinetics or measures of performance following their PCA. A

[1] The term biomechanical features refer to distinguishable biomechanical aspects of the technical parameter

more meaningful study would be to use PCA to compare golfers with similar overall ability (i.e. elite/highly skilled golfers) and to characterise features of their individual technical parameters. This approach has been successfully applied to elite race walkers for identifying unique technique features in knee angles and knee moments in a homogenous group of ability athletes (Donà et al., 2009).

The results of the PCA gave instant visual representation of the main differences between athletes and identified where in the gait cycle these differences occurred. Brown et al. (2011) suggested that future golf biomechanical studies should consider individual rather than group analysis when examining the kinematics of a group of low handicap female golfers.

Therefore, the purpose of this chapter was to address Research Question 4 (§1.3) by exploring the use of PCA to identify the postural biomechanical differences (both kinematics and balance) throughout the drive, in a group of highly skilled golfers. This purpose would be achieved by addressing four objectives. The first objective was to develop methods for analysing whole data curves rather than at discrete events and to demonstrate the benefits of such analysis. The second objective was to examine the suitability of PCA for identifying similarities and differences between individual golfer's techniques. The third objective was to identify relationships between posture parameters by examining several hypotheses which were generated based on the coaches' perceptions and previous biomechanical literature. These hypotheses were:

i. COP and COG movement would be strongly related in A-P and M-L directions.
ii. Lumbar and thorax flexion angles would be related to lumbar and thorax lateral bend throughout the swing.
iii. Golfers range/rate of change in lumbar or thorax flexion would be strongly related to $COP_{A\text{-}P}$ movement
iv. Head COG in A-P and M-L directions would be closely related to thorax flexion and lateral bend angles respectively.
v. Right and left knee flexion angles would be closely related.

Table 6.1. Summary of continuous data analysis techniques used to compare data curves as detailed in Wheat and Glazier (2006)

Method	Description	Strengths	Limitations
Discrete relative phase	Temporal difference between peak points on data curves	- No manipulation of data required	- Data must be sinusoidal and one-to-one - Requires definitive peak values
Continuous relative phase	Temporal difference between data curves at each time point throughout a movement	- Temporal and spatial differences identified	- Requires data to be interpolated - Results vary based on normalisation procedures
Vector coding	Data curves reproduced on a grid and transform the curve into digital points. A chain of digital points are created which can be cross-correlated with other chains to differences	- No normalisation required - Easier interpretation	- Converts data to nominal scale may lose important information - Requires equally spaced points - Does not identify temporal differences
Cross-correlations	Measures similarity between data curves by applying a time-lag to a single data curve.	- No normalisation required (if linear data) - Temporal and pattern differences identified	- One measure for whole data curve - Assumes a linear relationship between data curves
Normalised root mean squared difference	Root mean square calculated of resultant distance between data and mean curves at each time point. Root mean square values are averaged across the trial and normalised	- Magnitude and pattern differences identified	- One measure for whole data curve
One dimensional statistical parametric mapping (SPM)	Topological analysis of curves	- Statistical hypothesis testing on multiple trajectories - Results in a biomechanical context - Examine interventions on kinematics or kinetics	- No clear description of features of curves

Table 6.2. Summary of continuous data analysis techniques continued.

Method	Description	Strengths	Limitations
Curve clustering	Cluster homogenous curves based on shape into sub-groups	- Easily identify outliers	- Choice of number of clusters - Outliers may cause ineffective clustering
Principal component analysis	Measures the directions in which data curves vary using orthogonal transformations	- Multiple measures for whole data curve - Allows normalisations procedures to be performed - Temporal and magnitude differences identified - Rank importance of each variation measure - Allows inter- and intra- variability measures - Visual and functional interpretation of results	- Sometimes difficult to biomechanically interpret data

The fourth objective was to relate the key posture parameters to performance where possible. A series of four hypotheses were also produced to help guide this analysis:

i. Greater rate of change in lumbar or thorax lateral bend would relate to increased clubhead linear velocity.
ii. Greater range in %COP $_{M-L}$ direction would result in increased clubhead linear velocity.
iii. Greater lumbar and thorax lateral bend angles in the downswing would increase vertical launch angles
iv. Lumbar and thorax flexion angles would be closely related to vertical and horizontal launch angles.

The results of this Chapter could then be compared to the coaches' perceptions and existing literature to either reinforce existing coaching and biomechanical knowledge or provide new insights into technique.

6.2 Methods

This section briefly describes the data collection methods which are presented in further detail in Chapter 4. The data analysis techniques are defined and further detail is provided on the implementation of PCA on the posture parameters.

6.2.1 Participants

Nineteen right handed low handicap male golfers (handicap range +3 to 4; age = 26 ± 7 years; height = 179.5 ± 7.3 cm; weight = 79.4 ± 13.1 kg) were recruited for the study. The golfers were either members of the Loughborough University golf team or PGA professional golfers from local clubs and all gave voluntary informed consent prior to testing (§4.2.6).

6.2.2 Data Collection

The golfers were prepared for motion analysis data collection by placing retro-reflective markers on the golfer in accordance with the marker set presented in §4.2.5.3. The golfers performed ten full shots with their own driver following the instructions as detailed in §4.2.6. Three-dimensional marker trajectories were collected using the Vicon Nexus Motion Analysis System sampling at 250 Hz. The system was calibrated according to §4.2.5.1. Two Kistler force plates synchronised with the motion analysis system collected ground reaction force data at 1000 Hz (§4.2.4). The TrackMan launch monitor was used to capture measures of performance (Appendix C) and was set-up as detailed in §4.2.1.

6.2.3 Data Analysis

Following data collection, the raw positional data was visually inspected and filtered using the techniques in §4.3.4. Five trials for the driver were selected for analysis based on the golfer's subjective rating of shot quality and those trials with minimal marker-drop out. Visual3D software was used to define the golfer model by following the procedures in §4.3.2 and also to calculate the posture parameters which are discussed in further detail in Chapter 5. Twelve time varying posture parameters were analysed: thorax angles (flexion and lateral bend), lumbar angles (flexion and lateral bend), %COG $_{M\text{-}L}$ (medial – lateral), %COG $_{A\text{-}P}$ (anterior – posterior), %COP $_{M\text{-}L}$ (medial – lateral), %COP $_{A\text{-}P}$ (anterior – posterior), left and right knee flexion angles and %Head COG $_{M\text{-}L}$ (medial – lateral), %Head COG $_{A\text{-}P}$ (anterior – posterior). Swing events (TA, TB, IMP and MidFT) were identified for the individual trials of each golfer as detailed in §4.3.6. The data was then temporally aligned and normalised between TA to TB, TB to IMP and IMP to MidFT across the five trials, for each individual golfer, based on the methods presented in §4.3.6 and using the Matlab function in Appendix F. The position MidFT was chosen as this was the first position defined by coaches following IMP (§2.5.2) and it was deemed necessary to analyse the swing past IMP to provide a representation of the whole swing. Temporally aligned data has been documented as a reasonable preliminary stage to PCA and is left to the discretion of the researcher as to whether this stage is required (Ryan et al., 2006).

6.2.3.1 Statistical Analysis

The first stage of analysis involved PCA which would provide an exploration of the biomechanical features in the posture parameters through identifying where the majority of variance occurred within the data curves. The PCA was conducted in Matlab using the inbuilt Matlab function 'pca' and based on the methods of O'Connor and Bottum (2009). For each golfer, an n x p data matrix was formed where n was the number of trials and p the number of variables, which corresponded to each normalised time point throughout the swing. All golfer's matrices were then vertically concatenated to form a single data matrix, $\boldsymbol{X}_{95 \times 501}$. Therefore, for each posture measurement, a 95 x 501 data matrix[2], $\boldsymbol{X}_{95 \times 501}$, was formed which was used as the input data for the PCA Matlab function.

The PCA was performed on one posture measurement at a time which converted the data into new uncorrelated variables called principal components (PC). The first stage of PCA analysis involved computing the covariance matrix, $\boldsymbol{S}_{95 \times 501}$, from the original data matrix, $\boldsymbol{X}_{95 \times 501}$. An eigenvalue analysis was then performed on the covariance matrix to produce $\boldsymbol{U}_{501 \times 95}$ eigenvector and $\boldsymbol{L}_{1 \times 95}$ eigenvalue matrices. The eigenvector matrix, $\boldsymbol{U}$, (defined as coefficients in Matlab pca function) represented the weighting factors for each principal component. The weighting factors were used to identify the portions of the swing that accounted for the greatest variability in the data curve. The eigenvalues matrix, $\boldsymbol{L}$, (defined as latent in Matlab pca function) represented the contribution of each PC to the overall variation in the data curves. A unique capability of PCA is that if the majority of variance is explained in the first few PCs then the remaining components can be disregarded (Deluzio & Astephen, 2007). Therefore, all PCs were considered until at least 90% of the variance in the original data had been cumulatively explained which is consistent with previous studies (Deluzio & Astephen, 2007; Lynn et al., 2012). The PCs were organised in decreasing order of the amount of variance they explained from the original data set and each component represented specific features of a data curve. Finally, the z-scores (i.e standardised scores) for the entire $\boldsymbol{X}_{95 \times 501}$ data matrix were computed using the equation:

$$\text{z-scores} = \frac{(x - \mu)}{\sigma}$$

whereby x represented the original data, μ represented the mean of the golfers individual time points and σ represented the standard deviation of golfers individual time points. The z-scores were computed as it normalises the data which when multiplied by the weighting factors matrix and summed, resulted in a PC score for each principal component, golfer and trial, which could then be used to compare across golfers. A large positive or negative PC score represented golfers whose curves were further away from the mean curve in the portions of the swing that were most highly weighted. The quality of how well the retained PCs could reconstruct the original data was also explored and deemed adequate for reconstructing original data (Appendix G).

[2] For the data matrix, 95 represents 19 golfers x 5 trials and 501 is the number of interpolated data points per swing.

Qualitative biomechanical interpretation of the PCA results was achieved by examining the weighting factor curves (Figure 6.1), for each principal component, throughout the swing and by observing the mean data curves plus and minus a multiple of this PC (Figure 6.2). In Figure 6.1, the weighting factor curves for PC1 and PC2 display different patterns related to different biomechanical features in the original data. In this example, PC1 weighting factors were all positive throughout the swing which suggests that the greatest variation in the original data was due to a consistent offset (Figure 6.1). PC2 weighting factors ranged from negative to positive from TA to after TB and positive to negative after TB to MidFT. This suggests that the original data varied due to rate/range of change in motion in these portions of the swing (Figure 6.1). In addition, there was a sudden change in direction of weighting factor values in the downswing which could be related to timing differences (Figure 6.1). Greater weighting factor values represented the portions of the swing where the greatest variation between data curves occurred. The interpretations above were also compared to the mean curves of posture parameters to confirm the biomechanical interpretation.

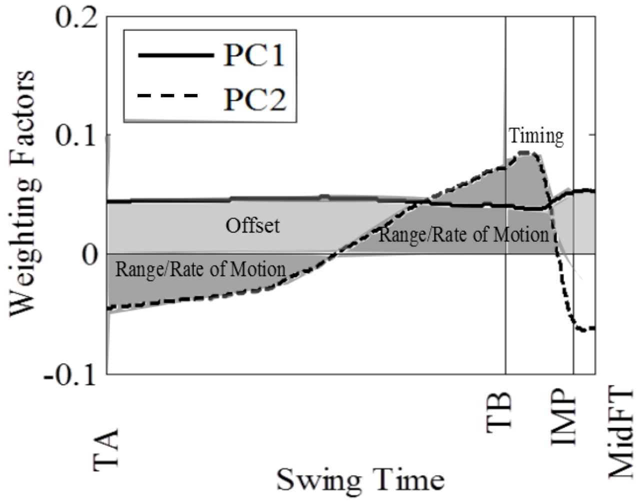


Figure 6.1. Example of weighting factors for two principal components illustrating the terms offset, range/rate of motion and timing related to portions of the weighting factor curves.

The mean curves plus or minus a multiple of the PC were also used to help identify differences between golfers' PC scores (Figure 6.2). The multiple was calculated by multiplying the weighting factors by the eigenvalue (latent) matrix. The multiple was then added to or subtracted from the mean data curve. The curves of added or subtracted multiples were increased by a factor of 50 for PCs explaining lower variance in order to enable easier visualisation of their effect. The added and subtracted multiples were used to guide interpretation of positive and negative golfer PC scores. Using Figure 6.2 as an example, golfers with a positive PC score would have original data closer to the Mean+ curve. This method was applied to each posture parameter in order to provide qualitative biomechanical interpretation of the PCs.

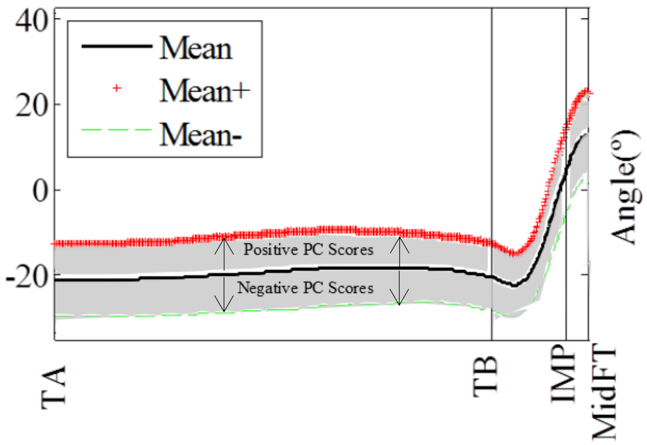


Figure 6.2. Mean curve plus and minus multiple of a PC. Golfers with positive PC scores have data closer to the Mean+ curve and golfers with negative PC scores have data closer to the Mean- curve.

Once the qualitative biomechanical interpretation of the PCA results had been achieved, scatterplots of PC scores were produced which provided a visual representation of the similarities, differences and trends in PC scores between golfers (Figure 6.3). The nineteen golfers were assigned a unique shape and colour marker and the same marker was used to represent that golfer's five swing trials. The dotted lines represent the PC scores for the multiples added to or subtracted from mean data in Figure 6.2. For example, Golfer 5 has positive PC1 score close to the dotted line, therefore their original data, in terms of the offset would be close to the Mean+ line in Figure 6.2.

Further exploratory statistical analysis was conducted on PC scores to determine if there were relationships between posture parameters and with measures of performance. Initially, the posture parameters were checked for normality using the Shapiro-Wilk test of normality. Normality could not be assumed for all posture parameters ($p < 0.05$); therefore, a two-tailed Spearman's correlation was conducted on the relationships hypothesised in the introduction. The TrackMan measured parameters were standardised by using the z-scores equation in order to investigate the relationship with posture parameters.

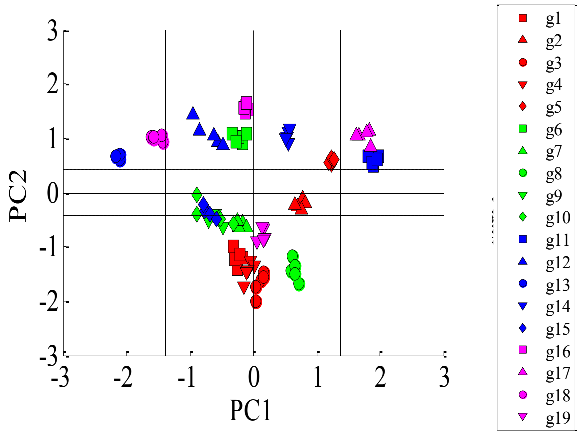


Figure 6.3. Scatterplot of principal component scores of PC1 and PC2 for all 19 golfers.

6.3 Results

This section will present the results that address the four main objectives of this Chapter. Firstly, the overall PCA results and the biomechanical interpretation of PCs over the whole swing are presented. The PCA results are then compared with the data at discrete swing events to determine the benefits of PCA over discrete analysis. Secondly, three scatterplots of posture parameters PC scores are selected and compared to the original data for four golfers which showed differences and similarities between golfers. Thirdly, correlations between posture parameters are investigated by testing the hypotheses outlined in the Introduction. Finally, correlations between measures of performance and posture parameters are presented by testing the hypotheses also outlined in the Introduction.

6.3.1 Principal Component Analysis

The number of PCs required to explain at least 90% of the variance for each posture parameter are summarised in Table 6.3. The majority of posture parameters were typically explained by two to three PCs which suggested that there were some core underlying biomechanical features which explained the variability throughout the golf swing between golfers. However, for COP measurements four to five PCs were required to explain the variability in these postural balance parameters.

The PCA results of posture parameters could be biomechanically interpreted using the weighting factors and mean curves (plus or minus PC multiples) as explained using Figure 6.1 and Figure 6.2 respectively. The weighting factors and mean curves (plus or minus PC multiples) for lumbar flexion are shown in Figure 6.4. Lumbar flexion PC1 explained the offset in lumbar flexion throughout the swing. PC2 lumbar flexion represented the range of lumbar flexion from TA to after TB and the rate of change from after TB to MidFT. To make the PCA data accessible to a coach, the biomechanical interpretation of PCs could be translated into coaching terminology as shown in the example in Table 6.4.

The three terms offset, range/rate of motion and timing were frequently used when qualitatively describing the biomechanical interpretation of PCA results as defined in Figure 6.1. Often PC1 related to offsets between data curves, PC2 related to differences in the rate/range of motion and PC3 related to both rate/range of motion and timings. However, this was not clear for all posture parameters. For example, PC1 of $\%COP_{M\text{-}L}$ related to offset, rate/range of motion and timing differences between curves at different portions of the swing (Figure G.10). The associated weighting factors and mean curves for the remaining posture parameters are shown Appendix G. To aid qualitative interpretation of PCs for each posture parameter, a chart of graded colour bars, associated to the three terms offset; rate/range of motion and timing was produced (Figure 6.5). The graded colour bars represent the weighting factor values from -0.1 to 0.2 which are shown in the weighting factor curves of each posture parameter (Figure 6.4 & Appendix G). High weighting factor values (i.e. ≥ 0.2) were represented by red, blue and purple, for offset, rate/range of motion and timing respectively. Low weighting factor values (i.e. ≤ -0.1) were represented by yellow, green and pink colours for offset, rate/range of motion and timing respectively. Many of the PCs accounted for variance throughout the whole swing (TA to MidFT) but the weighting factors also revealed that the downswing and early backswing were also important parts of the swing where a large proportion of the variation between data curves occurred.

Table 6.3. Principal components and total variance explained for each posture parameters.

Posture Parameter	Number of PCs	PC (%) PC1	PC2	PC3	PC4	PC5	Total Variance Explained (%)
Postural Kinematics							
Thorax (Flexion)	3	73.0	16.8	4.6			94.4
Thorax (Lateral Bend)	3	55.1	23.2	11.8			90.1
Lumbar (Flexion)	2	83.3	8.3				91.6
Lumbar (Lateral Bend)	3	72.2	10.4	9.4			92.0
Right Knee Flexion	3	58.1	27.4	7.8			93.3
Left Knee Flexion	3	67.4	19.6	7.0			94.0
%Head COG $_{M-L}$	2	79.0	12.3				91.3
%Head COG $_{A-P}$	2	79.3	15.3				94.6
Postural Balance							
%COG $_{M-L}$	2	82.6	9.8				92.4
%COG $_{A-P}$	2	73.4	20.7				94.1
%COP $_{M-L}$	5	34.9	24.1	18.7	7.2	5.7	90.6
%COP $_{A-P}$	4	37.0	20.0	18.2	15.9		91.1

6.3.2 Discrete Analysis

The values of posture parameters at the swing events TA, TB and IMP are shown in Table G.1, Table G.2 and Table G.3 in Appendix G. The group mean lumbar flexion values at TA (-21.3 ± 6.7º) and TB (-20.4 ± 6.7º) suggest that golfers have consistent lumbar flexion during the backswing. At IMP, golfers had increased lumbar extension (4.8 ± 9.3º). The mean lumbar flexion curves (plus or minus multiples of PC1 scores) shown in Figure 6.4 support the consistent pattern observed in discrete values. Nevertheless, the PCA results provided more information regarding the difference in the magnitude of lumbar flexion between golfers during the backswing which was not captured from group mean values. In addition, PC2 for lumbar flexion revealed variation in the rate of change in lumbar flexion during the downswing which was not possible with discrete analysis.

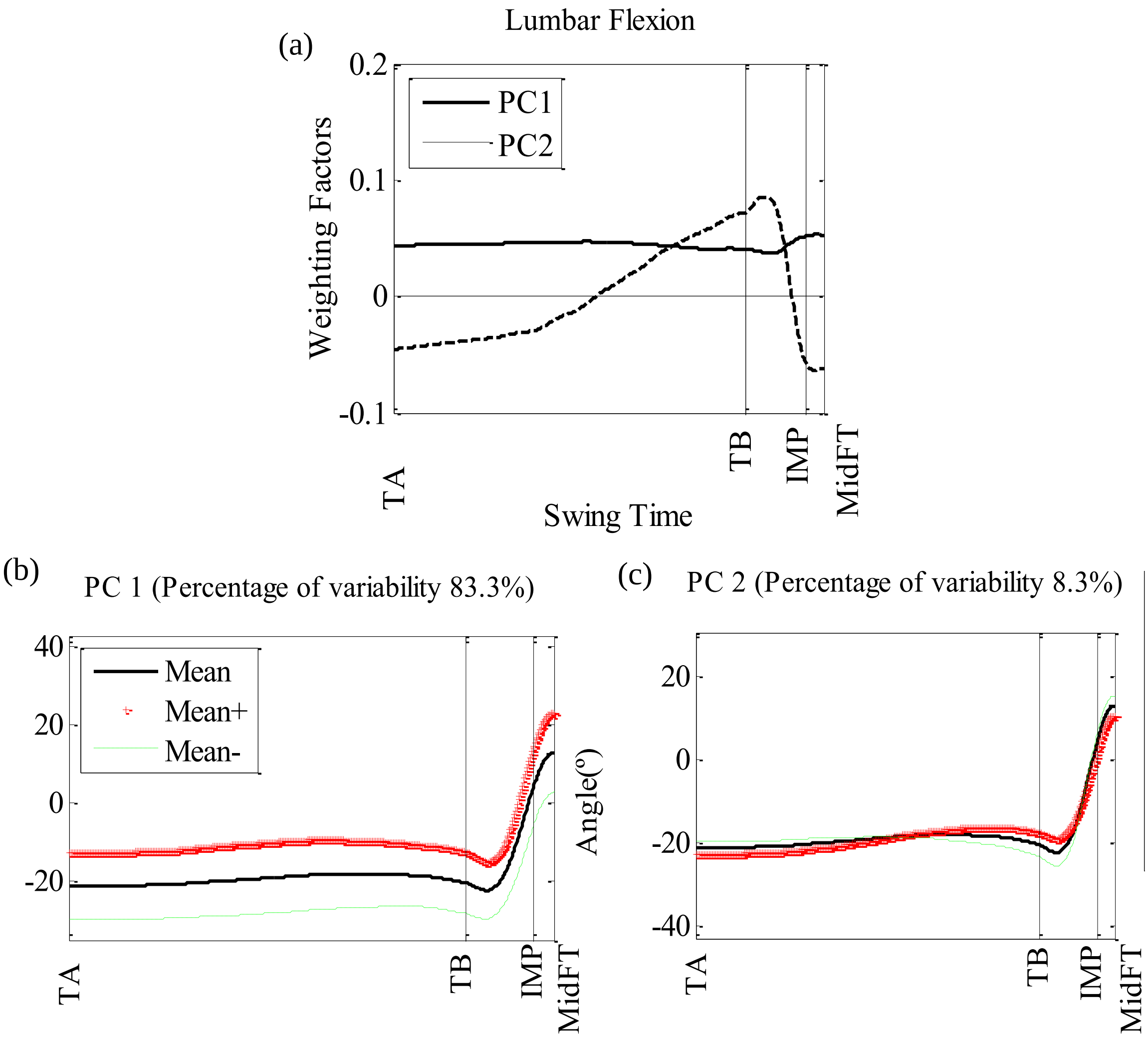


Figure 6.4. Lumbar flexion PCA results (a) The weighting factors for the first two principal components, PC1 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean lumbar flexion curve (black line) with a multiple of PC1 added (red) and subtracted (green) from mean curve (c) Mean lumbar flexion curve (black line) with a multiple of PC2 added (red) and subtracted (green) from mean curve.

Table 6.4. Principal components translated into coaching terminology

Posture Parameter	PC Score	Sign	Coach Translation
Lumbar Flexion	PC1	Positive	Golfer maintains less lumbar flexion throughout the swing
		Negative	Golfer maintains more lumbar flexion throughout the swing
	PC2	Positive	Lumbar flexion reduces during the backswing and golfer is more upright through impact
		Negative	Lumbar flexion increases during the backswing and golfer is more flexed through impact

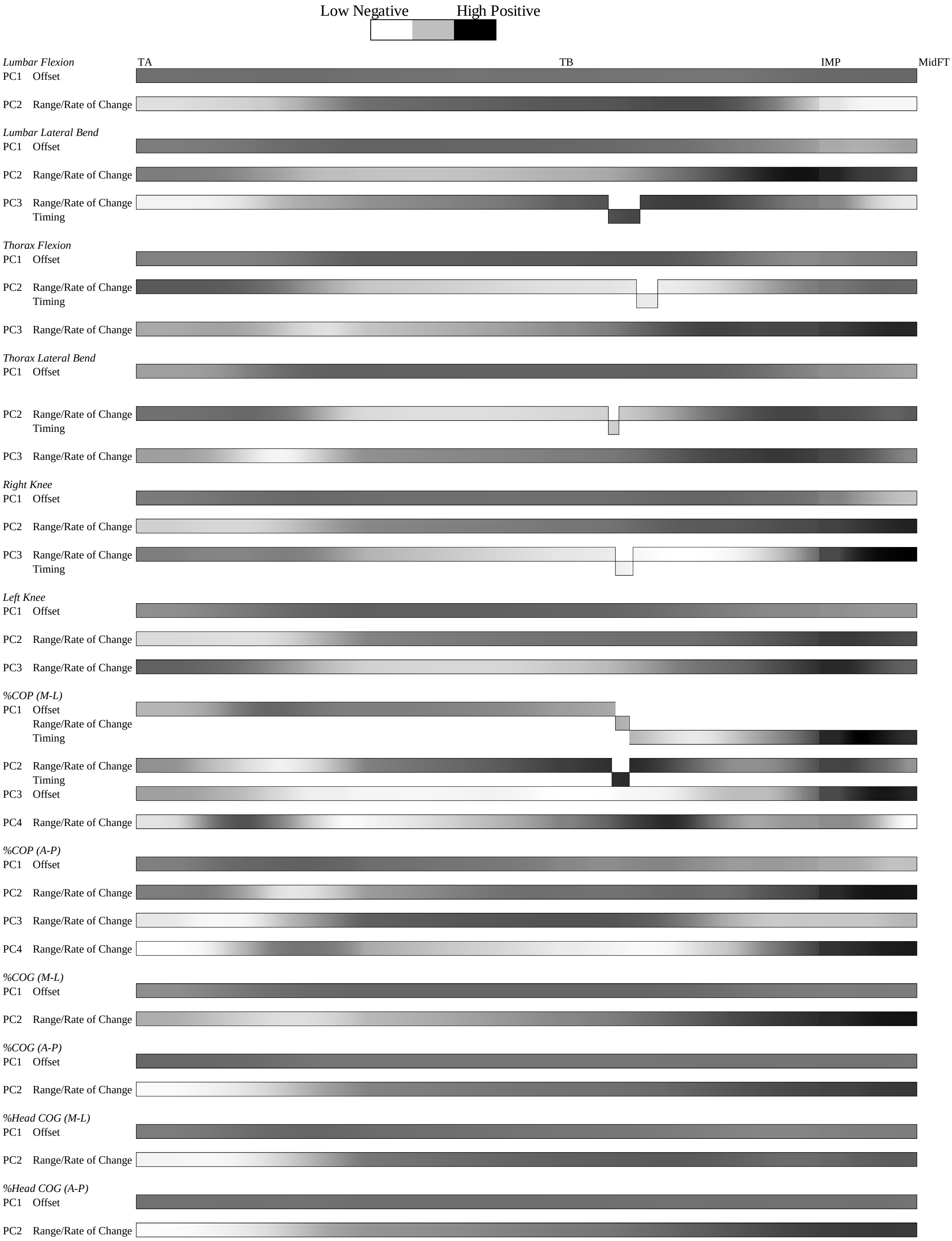


Figure 6.5. Biomechanical interpretation of the principal components of postural kinematic parameters throughout the swing. The graded colour coding is shown in the legend.

The discrete values of group mean right knee flexion angles at the swing events TA (-25.3º ± 5.3), TB (-23.9º ± 7.2) and IMP (-20.1º ± 10.5) would suggest that right knee flexion remained relatively consistent throughout the swing (Table G.2). From observing the mean curves from PCA, right knee flexion angles varied considerably in the backswing and downswing and did not remain consistent throughout the swing (Figure G.6). Positive PC1 scores were associated with greater knee extension (~ 5º) in the backswing and slight knee flexion during the downswing. Negative PC1 scores were associated with greater knee flexion in the backswing and increased knee flexion from TB to mid-downswing before rapid extension through IMP. By IMP relatively similar right knee angles were approached for high and low PC1 scores. Similarly, the PC2 component of right knee flexion revealed that some golfers would go through a greater range of right knee flexion from TA to MidFT than others. Therefore, the PCA had revealed patterns of movement in the right knee during the downswing which were not observable with discrete analysis.

6.3.3 Difference in Posture Parameters between Golfers

When comparing the PC scores to the golfers' original data, it was evident that the PC scores could identify observable differences, similarities and trends in the golfers' posture parameters.

For example, golf coaches believed that thorax flexion should remain relatively constant throughout the swing. The PCA results revealed that thorax flexion changed throughout the swing and PC1 scores suggested that the degree of thorax flexion varied between golfers. Golfers 9 and 15 (highlighted by the blue circles on Figure 6.6b) have similar positive PC1 scores whereas Golfers 13 and 10 (highlighted by the green circles on Figure 6.6b) have similar negative PC1 scores. On examining the original data, thorax flexion is similar within the pairs of golfers (Figure 6.6a) but there is a clear relatively stable offset between the two pairs of golfers, which is consistent with PC1 for thorax flexion, explaining varying offset (Figure 6.5).

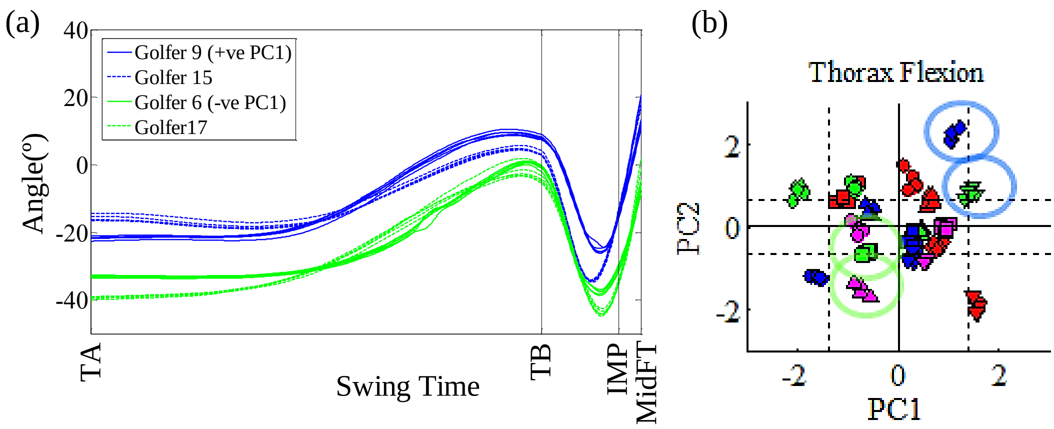


Figure 6.6. (a) Thorax flexion for two golfers with positive PC1 scores (Golfer 9 & 15, blue circles) and two golfers with negative PC1 scores (Golfer 6 & 17, green circles) as shown on (b) Scatterplots of PC scores for thorax flexion.

The PCA results for lumbar flexion also highlight the ability of PCA to differentiate between golfers with similar PC1 scores but different PC2 scores. PC1 explained the offset in lumbar flexion and PC2 explained the variation due to range/rate of change in lumbar flexion. The scatterplots of PC1 and PC2 scores showed that, many of the golfers had PC1 scores close to zero and the golfers' PC2 scores mainly varied (Figure 6.7b). The original lumbar flexion data was plotted for four golfers with similar PC1 scores and opposing PC2 scores (i.e. Golfers 3 and 4 had positive PC2 scores and Golfers 6 and 16 had negative PC2 scores) (Figure 6.7a). The golfers varied in the range of lumbar flexion during the backswing and showed greater variation in the rate of change in lumbar flexion during the downswing. The golfers with negative PC2 scores have a higher rate of change in lumbar flexion through IMP than those with positive PC1 scores.

Finally, differences were observed in the golfers' %COP $_{M\text{-}L}$ PC scores despite %COP measures requiring a greater number of PCs to explain 90% or more of the variance. The %COP $_{M\text{-}L}$ PC1 was biomechanically defined as the offset in %COP $_{M\text{-}L}$ in the backswing and the range/rate of change in the downswing. When observing the data for four golfers, two with positive PC1 scores (Golfers 10 and 13) and two with negative PC1 scores (Golfers 9 and 1), those golfers with negative PC1 scores positioned the majority of their COP on the back foot in the mid-backswing compared to golfers with positive PC1 scores.

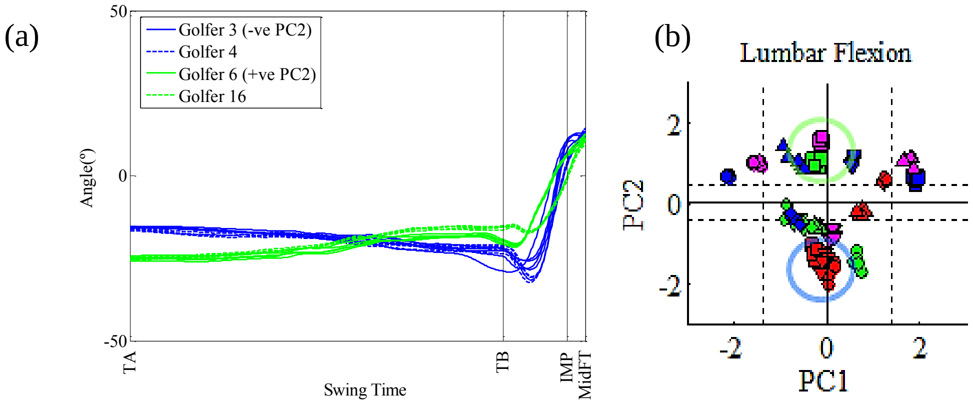


Figure 6.7. (a) Lumbar flexion for two golfers with negative PC2 scores (Golfer 3 & 4, blue circles) and two golfers with negative PC1 scores (Golfer 6 & 16, green circles) as shown on (b) Scatterplots of PC scores for lumbar flexion.

These golfers also transferred their COP closer to the front foot in the early downswing before moving to the back foot in the late downswing. Conversely, golfers with positive PC1 scores continued to translate their COP closer to the front foot through IMP. Therefore, by solely considering PC1 scores two %COP $_{M-L}$ styles emerged for these four golfers; these have been referred to previously as front-foot and reverse foot players (§3.5.3).

Scatterplots of PC scores, for each posture parameter, provided a visual representation of the spread in golfers' scores (Figure 6.9 & Figure 6.10).

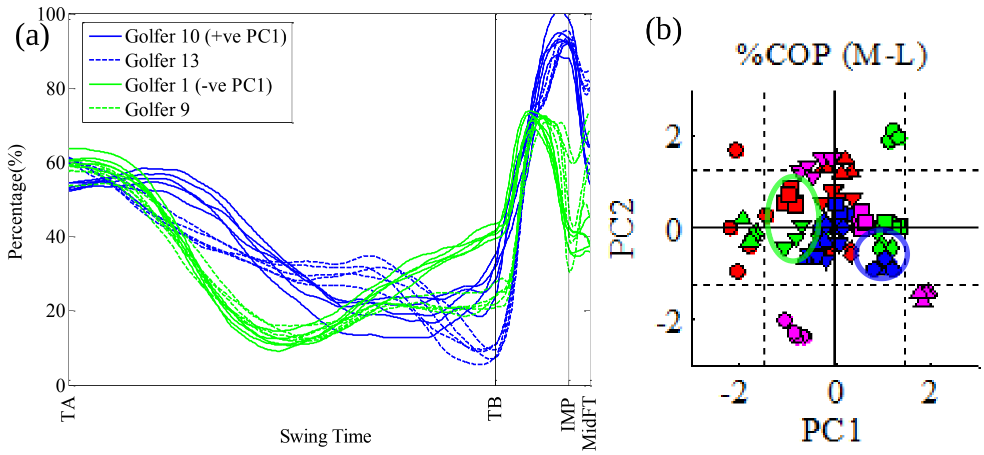


Figure 6.8. (a) %COP $_{M-L}$ for golfers with positive PC1 scores (Golfer 10 & 13) and golfers with negative PC1 scores (Golfer 1 & 9) as displayed on (b) Scatterplots of PC scores for %COP $_{M-L}$.

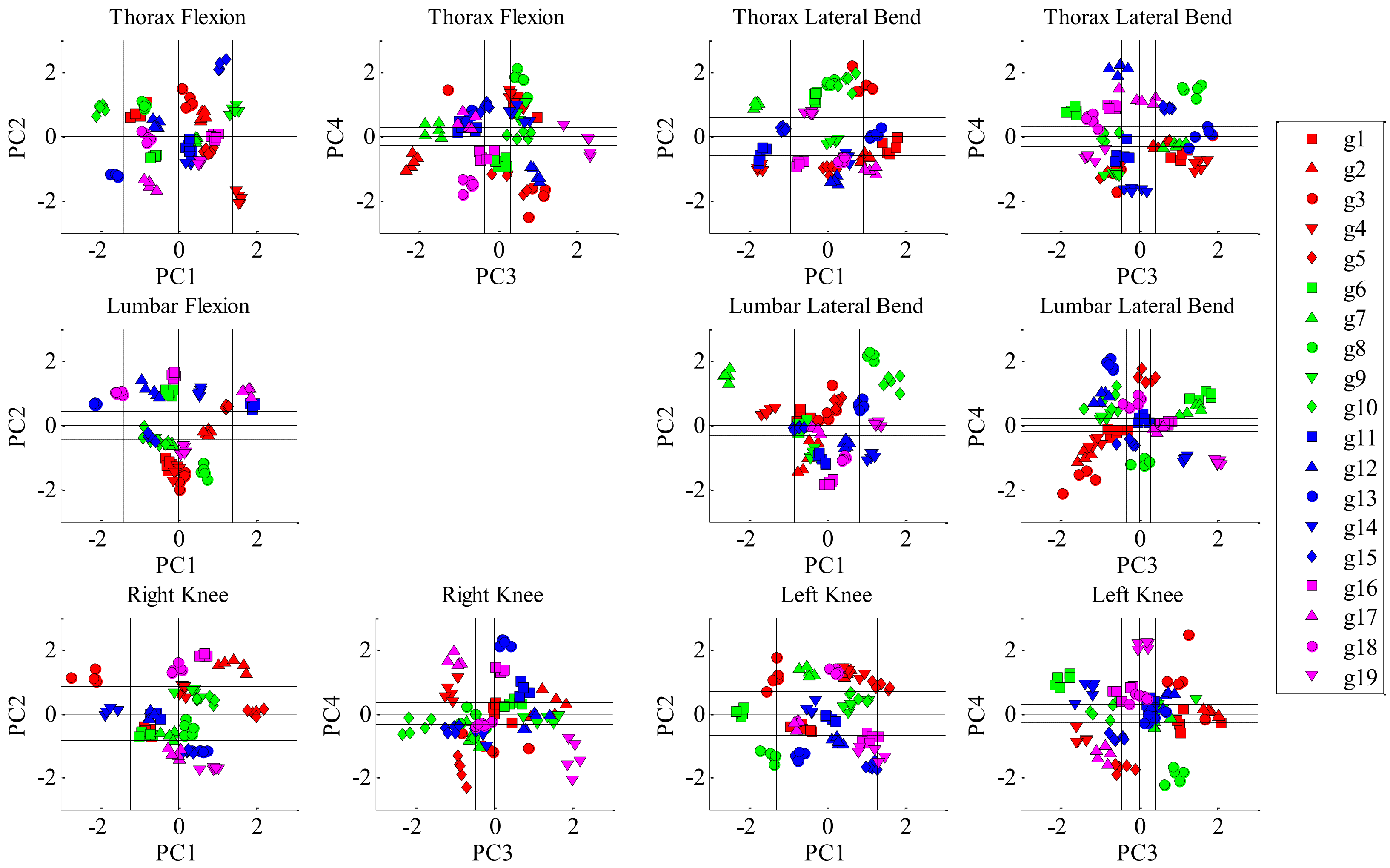


Figure 6.9. Scatterplots of PC scores for the postural parameters thorax flexion and lateral bend, lumbar flexion and lateral bend, right and left knee flexion. The equation Standardised PC score = (PC Score – Mean Score)/Standard deviation of scores was used.

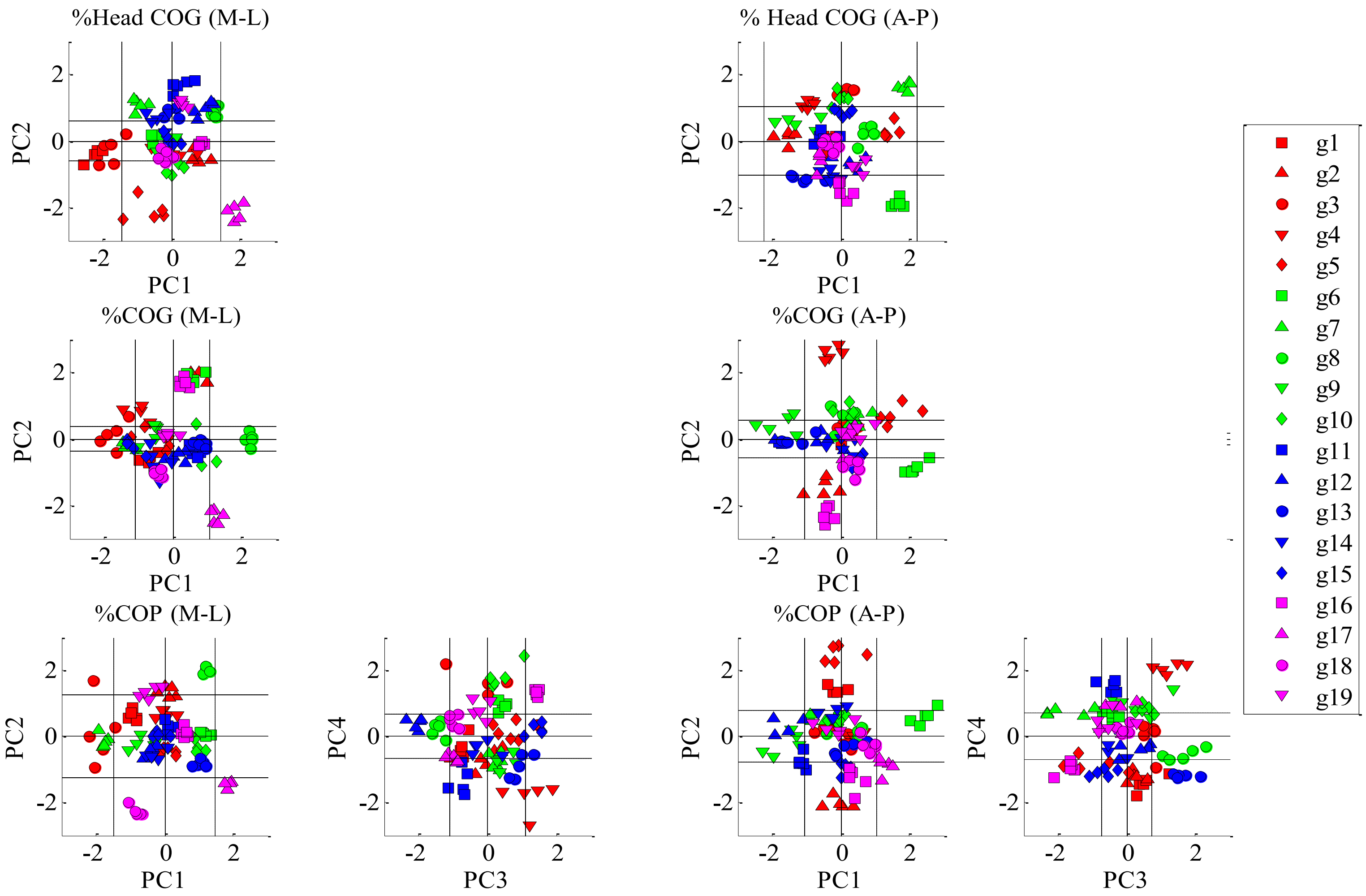


Figure 6.10. Scatterplots of PC scores for the postural parameters; %Head COG $_{M-L}$, %Head COG $_{A-P}$, %COG $_{M-L}$, %COG $_{A-P}$, %COP $_{M-L}$ and %Head COG $_{A-P}$. The equation Standardised PC score = (PC Score – Mean Score)/Standard deviation of scores was used.

6.3.4 Relationship between Postural Parameters

The third objective was to identify relationships between posture parameters by testing several hypotheses. The Spearman correlations for the five tested hypotheses are presented in Table 6.5.

Table 6.5. Spearman's correlation coefficients (r) of relationships between PC scores of posture parameters for hypothesis testing.

Hypotheses	Posture Parameter	PC Score Correlations	Correlation Coefficient (r)
i.	$\%COG_{M\text{-}L}$ - $\%COP_{M\text{-}L}$	PC1 - PC1	0.85*
	$\%COG_{A\text{-}P}$ - $\%COP_{A\text{-}P}$	PC1 – PC1	0.49*
ii.	Lumbar Flexion – Lumbar Lateral Bend	PC1 – PC1	-0.02
		PC2 – PC2	-0.61*
	Thorax Flexion – Thorax Lateral Bend	PC1 – PC1	-0.57*
		PC2 – PC2	0.42*
iii.	Lumbar Flexion - $\%COP_{A\text{-}P}$	PC1 – PC1	0.01
		PC2 – PC2	0.19
		PC1 – PC2	-0.05
		PC2 – PC1	0.19
	Thorax Flexion - $\%COP_{A\text{-}P}$	PC1 – PC1	-0.16
		PC2 – PC2	-0.07
		PC1 – PC2	-0.25*
		PC2 – PC1	-0.29*
iv.	%Head $COG_{A\text{-}P}$ – Thorax Flexion	PC1 – PC1	-0.07
		PC2 – PC2	0.46*
	%Head $COG_{M\text{-}L}$ – Thorax Lateral Bend	PC1 – PC1	-0.08
		PC2 – PC2	0.23
v.	Right Knee – Left Knee	PC1 – PC1	0.67*
		PC2 – PC2	0.61*
		PC3 – PC3	0.48*

* Statistical significance, $p < 0.05$

The first hypotheses stated that the offset in %COP and %COG in A-P and M-L directions would be closely related. There was a strong positive correlation between %COG and %COP PC1 scores in the M-L direction ($r = 0.85$, $p < 0.05$) (Figure 6.11a). Golfer 7 and Golfer 17 were chosen to explore this relationship as they had opposing PC1 scores for %COG and %COP (Figure 6.11a). Both golfers positioned their COG towards the back foot in the backswing with Golfer 7 COG closer to the back foot that Golfer 17 (Figure 6.11c). In the downswing, both COG positions moved towards the front foot and at IMP Golfer 7's COG was positioned almost evenly between the feet, whereas Golfer 17's COG was closer to the front foot. The COG movement was coupled with Golfer 7 shifting their COP to the back foot early in the backswing to the back foot and to a greater extent than Golfer 17. In the downswing, Golfer 7 appears to reverse their COP path from front to back foot whereas Golfer 17 continues to translate their COP closer to the front foot through IMP. In addition, the golfers appear to be clustered above and below the line of best fit. Golfers above the line of best fit tended to have positive $\%COP_{M\text{-}L}$ PC1 scores and those below had negative $\%COP_{M\text{-}L}$ PC1 scores.

The $\%COP_{A\text{-}P}$ and $\%COG_{A\text{-}P}$ PC1 scores were also moderately correlated ($r = 0.50$, $p < 0.05$). PC1 explained 73.4% of the variance in $\%COG_{A\text{-}P}$ and was related to the offset in COG position between the heel and toes. The COG was positioned closer to the toes throughout the swing and there was a shift of COG towards the heel in the downswing, however, this change was relatively small (~ 5%) (Figure G.9). Only a small percentage of $\%COP_{A\text{-}P}$ was explained by PC1 (i.e. 34.9% (Table 6.3)) and therefore not all variation between data curves was adequately explained by PC1.

For the second hypothesis, a negative relationship was found between thorax lateral bend and thorax flexion PC1 scores ($r = -0.56$, $p < 0.05$). In biomechanical terms, golfers with less thorax flexion in the backswing (i.e. +ve thorax flexion PC1 scores) displayed greater thorax lateral bend angles in the backswing (i.e. –ve thorax lateral bend PC1 scores) (Figure G.3 and Figure G.4). In addition, there was a negative relationship between lumbar lateral bend and lumbar flexion PC2 scores ($r = -0.61$, $p < 0.05$). Hence, golfers with a greater range of lumbar flexion in the backswing and rapid lumbar extension earlier in the downswing typically showed rapid lumbar lateral bend in the downswing (Figure 6.4 and Figure G.5).

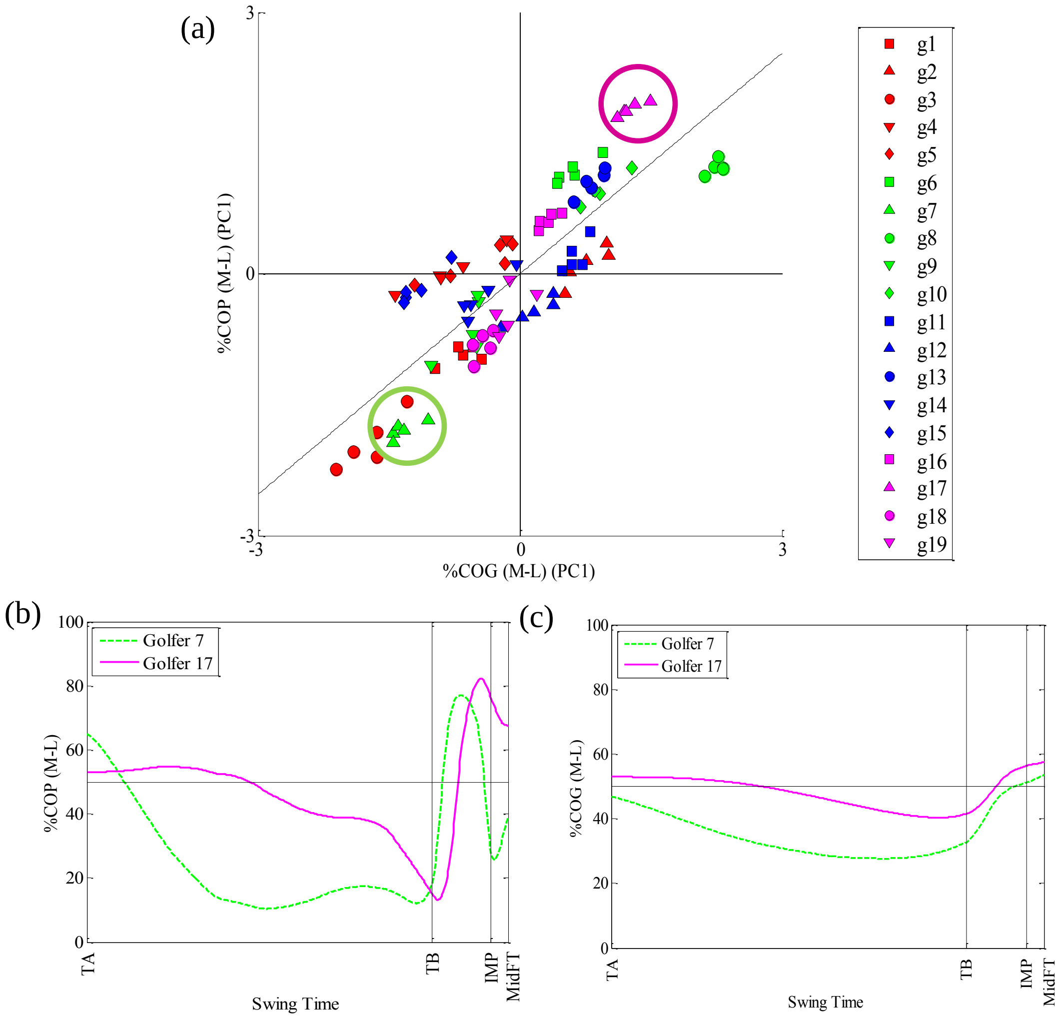


Figure 6.11. Relationship between %COP $_{M-L}$ and %COG $_{M-L}$ PC1 scores (a) Scatterplot of %COG $_{M-L}$ and %COP $_{M-L}$ PC1 scores. (b) Mean %COP $_{M-L}$ for golfer 7 (green) and golfer 17 (pink) with extreme PC1 scores and (c) Mean %COG $_{M-L}$ for golfer 7 (green) and golfer 17 (pink) with extreme PC1 scores.

The third hypothesis correlated lumbar and thorax flexion angles to %COP $_{A-P}$ measures. There was no statistical significant relationships between lumbar flexion (PC1 scores) and %COP $_{A-P}$ (PC1 scores). In addition, when scatterplots of the comparisons were examined there appeared to be no patterns in the data (Figure 6.12a).

Thorax flexion PC2 scores showed a weak negative relationship with %COP $_{A-P}$ PC1 scores ($r = -0.29$, $p < 0.05$) (Figure 6.12b). This relationship suggests that as the range/rate of thorax flexion increases through the swing, the golfer's %COP $_{A-P}$ would be positioned closer to the heels in the backswing and move rapidly towards the toes in the downswing, however this is obviously not the only contributing factor to %COP $_{A-P}$ position.

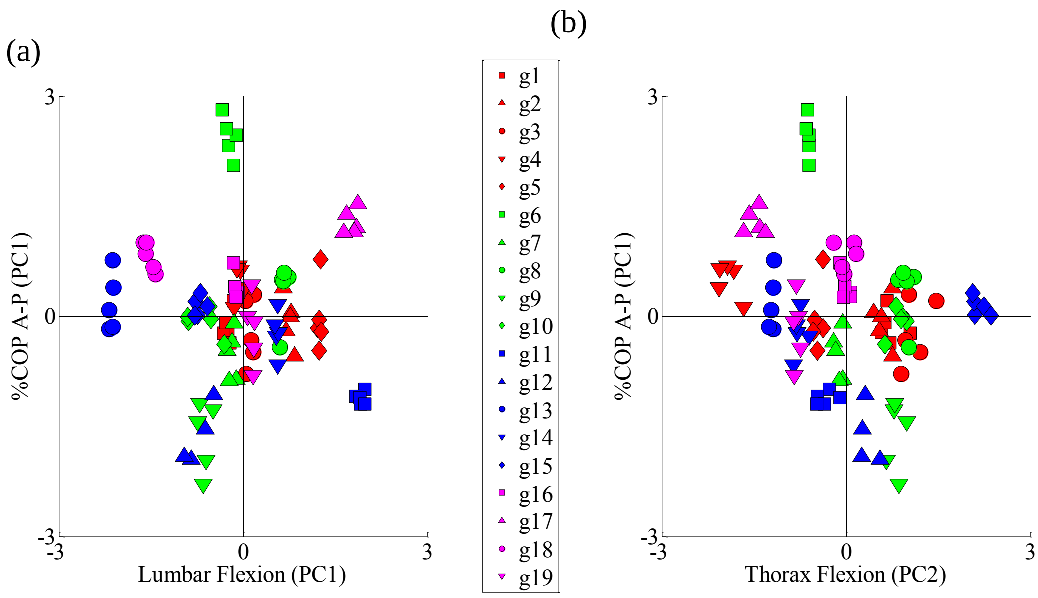


Figure 6.12. Scatterplots of (a) Lumbar flexion (PC1) & %COP $_{A\text{-}P}$ PC1 scores ($r = 0.01$, $p > 0.05$) and (b) Thorax flexion PC2 & %COP $_{A\text{-}P}$ PC1 scores ($r = -0.29$, $p < 0.05$).

The fourth hypothesis tested the relationship between Head COG and thorax movement. The %Head COG $_{A\text{-}P}$ PC2 scores were related to thorax flexion PC2 scores ($r = 0.46$, $p < 0.05$). The %Head COG $_{M\text{-}L}$ were not statistically related to thorax lateral bend respectively.

The fifth hypothesis tested the relationship between right and left knee angles. This hypothesis was supported by the strong correlation values reported between the PC1, PC2 and PC3 scores for right and left knee flexion (Table 6.5). The offset of right and left knee flexion angles (PC1 scores) were strongly correlated (Figure 6.13a) suggesting that golfers with greater right knee flexion would also have greater left knee flexion during swing (Figure G.6b and Figure G.7b). Similarly, based on the correlations between PC2 scores, the range/rate of knee flexion throughout the swing would be similar for right and left knee (Figure 6.13b). Finally, the timing of left and right knee extensions were significantly related ($r = 0.48$, $p < 0.05$).

6.3.5 Relationship to Measures of Performance

The descriptive data for each golfer are summarised in Table 6.6 together with their mean and standard deviation for the measures of performance obtained using TrackMan. The remaining calculated TrackMan data is presented in Appendix G as radial plots. The golfers' average clubhead velocity (45.8 $m.s^{-1} \pm 2.1$) and ball velocity (66.4 $m.s^{-1} \pm 4.2$) were consistent with those values reported in previous literature for golfers with similar low handicaps (Betzler et al., 2012; Joyce et al., 2013).

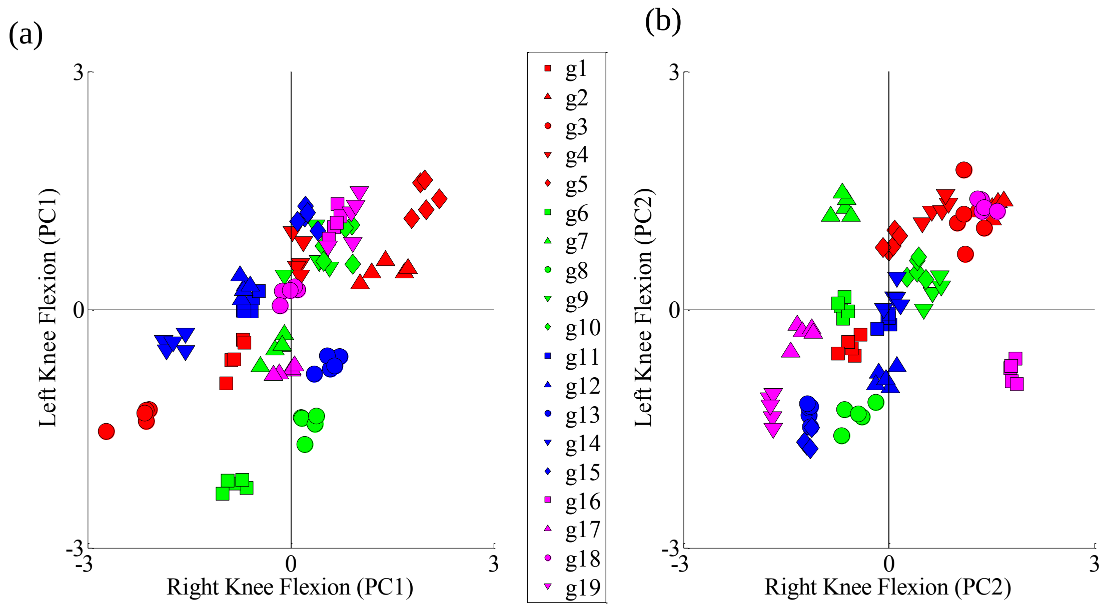


Figure 6.13. Right and left knee flexion PC scores scatterplots (a) PC1 scores and (b) PC2 scores.

Attack angle (0.0 º ± 2.9) and club path (1.9º ± 3.7) were marginally different to previously reported values of 1.5 º ± 2.5 and -0.5º ± 3.0 respectively (Betzler et al., 2012). Mean vertical swing plane at IMP (45.6 º ± 4.7) was lower than the average values of 54.5 º ± 3 (Coleman & Anderson, 2007) although this was the average vertical swing plane from TB to IMP.

The correlation results between posture parameters and measures of performance are shown in Table 6.7. A moderately strong correlation was found between the rate/range of change in lumbar lateral bend (i.e. PC2) and clubhead linear velocity ($r = 0.50$, $p < 0.05$). The rate/range of change in thorax lateral bend (i.e. PC2) and clubhead linear velocity also showed a moderately strong correlation ($r = 0.59$, $p < 0.05$). The scatterplot of standardised clubhead linear velocity and thorax lateral bend PC2 scores shows the emergence of two groups of golfers (although this was not formally tested) (Figure 6.14). Golfers contained in group two had greater clubhead linear velocities than golfers in group one. Coupled with this, golfers in group two displayed greater range of thorax lateral bend from TA to TB and a rapid increase in lateral bending in the downswing.

Table 6.6. Descriptive data and TrackMan measures of performance [3] (mean (SD) for five trials) for nineteen highly skilled male golfers.

					Measures of Performance															
Golfer ID	H'cap	Age (yrs)	Height (cm)	Weight (kg)	Clubhead Velocity @ IMP ($m.s^{-1}$)		Ball Velocity ($m.s^{-1}$)		Attack Angle @ IMP (º)		Vertical Swing Plane @ IMP (º)		Horizontal Swing Plane @ IMP (º)		Club Path @ IMP (º)		Horizontal Launch Angle @ IMP (º)		Vertical Launch Angle @ IMP (º)	
1	1	19	173.0	62.8	45.3	(0.5)	68.1	(0.8)	2.6	(0.5)	43.1	(1.9)	1.9	(1.1)	-1.0	(1.5)	0	(2.4)	12.7	(1.6)
2	2	21	184.0	76.9	44.1	(0.1)	64.9	(0.5)	0.3	(0.6)	51.1	(0.9)	0.8	(0.4)	0.6	(0.4)	-1.1	(1.2)	8.3	(1.1)
3	1	23	191.0	79.9	48.1	(1.1)	72.1	(1.3)	3.6	(1.0)	46.4	(0.6)	2.1	(1.2)	-1.2	(0.8)	-1.6	(2.3)	10.6	(1.8)
4	1	21	172.7	60.9	45.3	(0.3)	62.7	(2.3)	-1.9	(2.1)	45.6	(1.1)	-6.9	(1.4)	-5.1	(0.7)	1.6	(3.4)	12.4	(1.5)
5	4	19	187.9	70.9	43.9	(0.6)	64.0	(0.6)	-6.7	(1.3)	50.1	(1.5)	-8.4	(0.9)	-2.8	(0.8)	-2.0	(1.4)	10.7	(0.8)
6	1	23	190.3	84.4	48.8	(0.3)	70.7	(1.1)	1.7	(1.5)	48.4	(2.6)	9.2	(1.5)	7.7	(0.5)	1.9	(1.4)	7.9	(1.0)
7	0	21	189.3	82.1	49.7	(0.5)	71.4	(1.3)	-2.3	(0.8)	46.5	(0.8)	2.5	(1.0)	4.7	(1.1)	0.9	(0.4)	12.2	(1.7)
8	0	22	184.7	75.8	48.4	(0.6)	67.5	(3.3)	-0.2	(1.3)	39.9	(1.1)	5.5	(0.6)	5.8	(1.2)	4.1	(2.3)	15.3	(3.2)
9	4	24	169.3	66.8	44.8	(0.6)	66.3	(0.7)	1.6	(1.2)	43.6	(1.4)	5.9	(1.8)	4.2	(0.9)	3.8	(1.8)	9.4	(2.7)
10	0	21	176.0	68.3	45.5	(0.5)	64.2	(1.5)	-2.0	(2.2)	45.4	(0.8)	-7.8	(2.5)	-5.9	(1.2)	-0.5	(3.2)	11.8	(1.7)
11	1	23	184.8	79.7	44.0	(5.8)	61.7	(9.7)	-0.4	(1.0)	48.1	(2.2)	3.4	(1.2)	3.7	(1.0)	-1.1	(1.6)	15.0	(1.7)
12	0	34	181.8	88.9	46.1	(0.8)	67.7	(1.3)	-1.6	(1.1)	44.8	(1.6)	0.1	(1.4)	1.7	(1.4)	-2.0	(2.2)	8.0	(2.7)
13	0	47	174.8	120.9	45.3	(0.7)	66.5	(0.9)	-0.3	(1.0)	40.7	(1.4)	2.9	(0.8)	3.4	(1.3)	2.9	(3.3)	14.1	(2.5)
14	0	30	177.5	82.1	46.9	(0.4)	68.2	(0.9)	5.2	(1.8)	48.6	(2.2)	8.9	(1.3)	4.4	(0.7)	0.2	(1.1)	12.9	(1.6)
15	0	33	171.0	75.5	45.6	(0.3)	68.7	(0.5)	2.7	(1.7)	38.5	(1.3)	8.2	(1.7)	4.8	(1.1)	2.0	(2.2)	10.4	(2.8)
16	0	33	179.4	82.3	43.7	(0.4)	65.0	(0.9)	3.6	(0.7)	42.1	(1.6)	9.2	(0.9)	5.2	(1.2)	1.2	(2.4)	11.9	(1.9)
17	0	33	176.2	87.8	44.9	(1.1)	64.3	(2.0)	0.3	(0.3)	42.8	(2.6)	2.6	(0.7)	2.2	(0.7)	-2.1	(1.1)	13.8	(1.8)
18	0	28	181.1	92.2	41.8	(0.3)	54.5	(1.3)	-4.1	(1.0)	58.6	(1.6)	-1	(1.7)	1.5	(1.4)	-1.1	(0.6)	18.0	(0.8)
19	2	18	167.0	65.1	48.6	(0.4)	72.0	(0.5)	-1.4	(0.7)	41.9	(0.9)	-0.2	(1.2)	1.3	(1.0)	1.2	(1.0)	11.9	(1.0)
Mean (SD)		26 ± 7	179.5 ± 7.3	79.1 ± 13.5	45.8	(2.1)	66.4	(4.2)	0.0	(2.9)	45.6	(4.7)	2.0	(5.4)	1.9	(3.7)	0.4	(2.0)	12.0	(2.6)
Range		18 - 47	167 - 191	60.9 - 120.9	41.8 - 49.7		54.5 – 72.1		-6.7 – 5.2		38.5 – 58.6		-8.4 – 9.2		-5.9 – 7.7		-2.1 – 4.1		7.9 - 18	

[3] Definition of TrackMan variables can be found in Appendix C

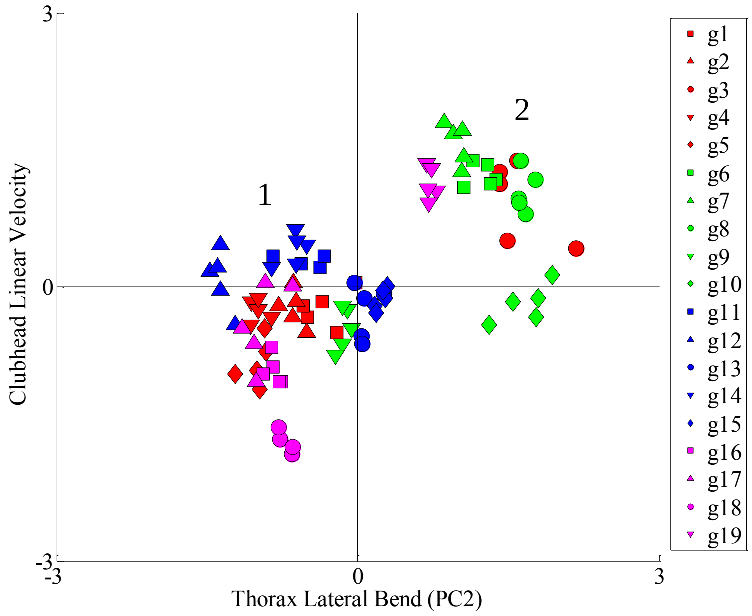


Figure 6.14. Scatterplot of clubhead linear velocity as a function of thorax lateral bend PC2 score showing the emergence of two sub-groupings in golfers' data

Secondly, there was no statistically significant relationship between %COP $_{M\text{-}L}$ PC1 scores and clubhead linear velocity (Figure 6.15a). Furthermore, there was no emerging pattern or groupings of golfers from the scatterplot of %COG $_{M\text{-}L}$ PC1 scores and clubhead linear velocity. Although, an interesting note is that Golfer 6 and Golfer 19 had relatively similar mean clubhead linear velocity, 48.8 m.s^{-1} and 48.6 m.s^{-1} respectively and largely different PC1 scores resulting in variation between %COP $_{M\text{-}L}$ paths (Figure 6.15a & b).

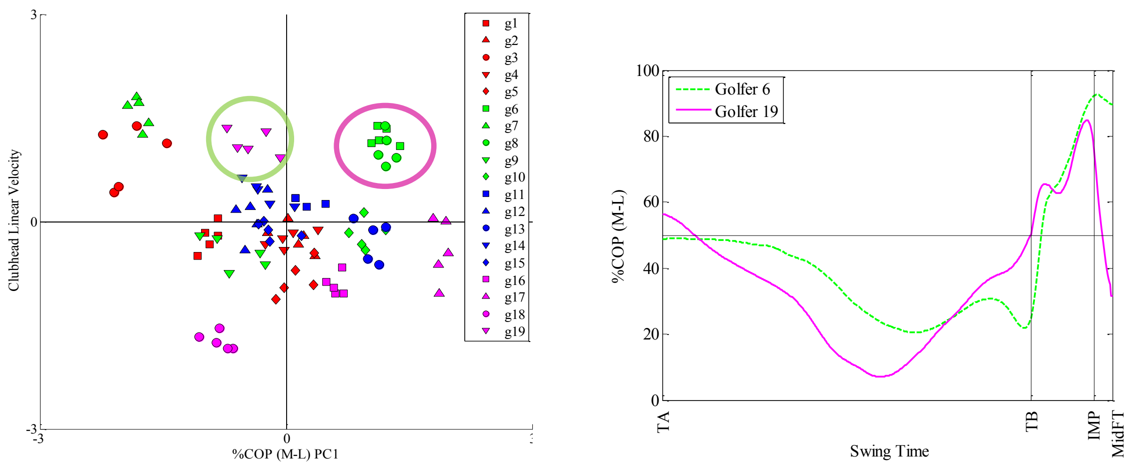


Figure 6.15. (a) Scatterplot of %COP M-L PC1 scores and clubhead linear velocity and (b) Mean %COP $_{M\text{-}L}$ for two golfers (Golfer 6 & 19) with similar mean clubhead linear velocity (48.8 m.s^{-1} & 48.6 m.s^{-1} respectively).

Table 6.7. Spearman's correlation coefficients (r) for relationships between PC scores of posture parameters and measures of performance for hypothesis testing.

Hypotheses	Posture Parameter	PC Score	Correlation Coefficient (r)
i.	Lumbar Lateral bend - Clubhead Linear Velocity	PC2	0.35*
	Thorax Lateral Bend - Clubhead Linear Velocity	PC2	0.59*
ii.	%COP $_{M\text{-}L}$ – Clubhead Linear Velocity	PC1	-0.11
iii.	Lumbar Flexion – Vertical Launch Angle	PC1	0.05
	Lumbar Flexion – Horizontal Launch Angle	PC1	-0.26
	Thorax Flexion - Vertical Launch Angle	PC1	-0.32*
	Thorax Flexion - Horizontal Launch Angle	PC1	0.12
iv.	Lumbar Lateral Bend – Vertical Launch Angle	PC1	0.08
	Thorax Lateral Bend – Vertical Launch Angle	PC1	0.14

* Statistical significance, $p < 0.05$

The third hypothesis stated that the magnitude of lumbar flexion and thorax flexion would affect vertical and horizontal launch angles. There were no clear relationships between these parameters and no patterns were observed from scatterplots of both sets of data (Figure 6.17). Similarly, there was also no clear relationship between lumbar and thorax lateral bend and vertical launch angle. There also seemed to be much greater spread of data points for each individual golfer, especially for vertical and horizontal launch.

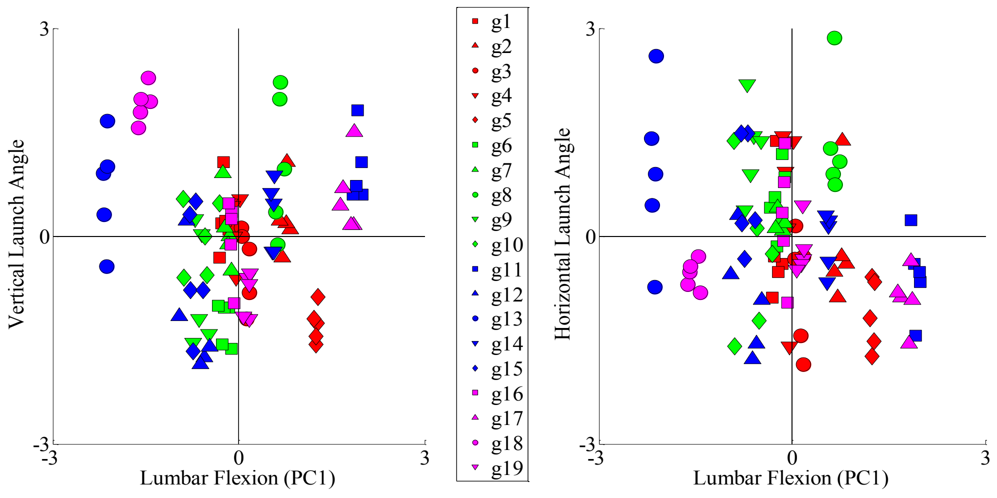


Figure 6.16. Scatterplots of lumbar flexion PC1 scores and vertical/horizontal launch angle

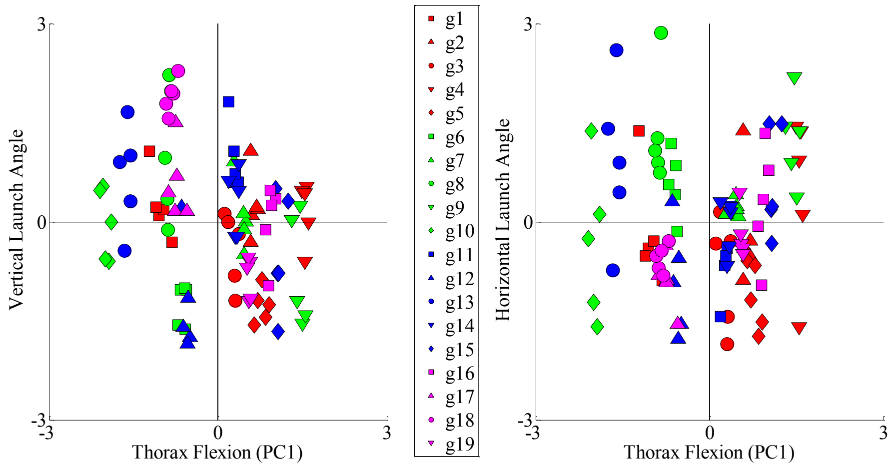


Figure 6.17. Scatterplots of thorax flexion PC1 scores and vertical/horizontal launch angles.

Finally, a correlation matrix was produced between posture parameters and measures of performance to ascertain if there were any further relationships that required investigation (Figure 6.18). Some relationships which returned moderately strong correlations and may require further investigation include (i) lumbar flexion (PC2) & %Head COG $_{A-P}$ (PC2) ($r = -0.70$, $p < 0.05$) and (ii) %COP $_{M-L}$ (PC1) & %Head COG $_{M-L}$ (PC1) ($r = 0.85$, $p < 0.05$).

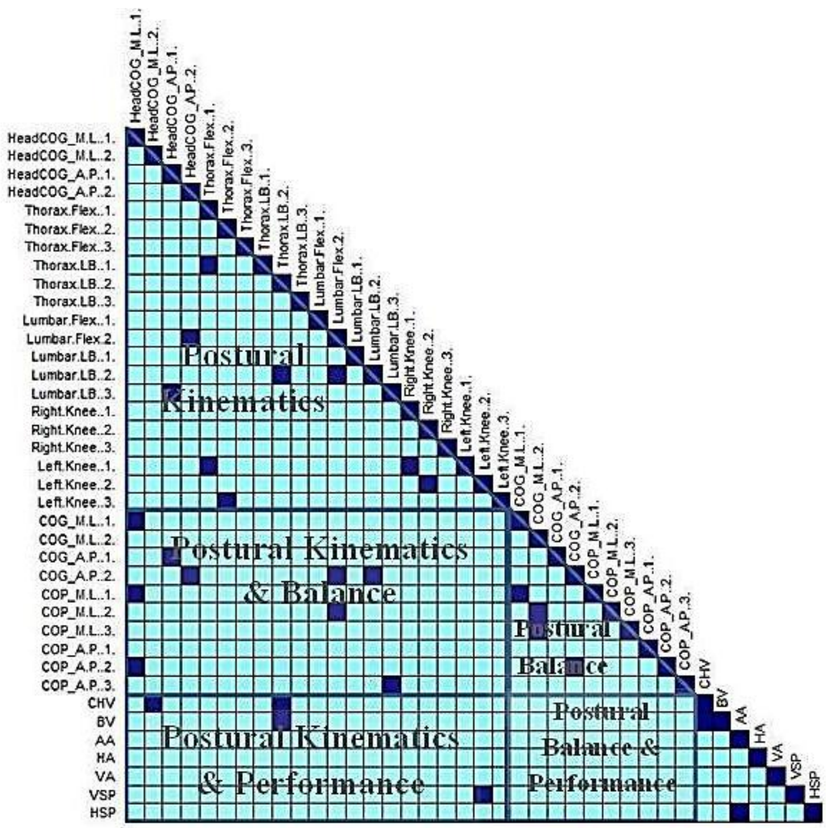


Figure 6.18. Correlation matrix of significant relationships (i.e. $p < 0.05$) and r values greater than or less than 0.5 and -0.5 respectively (i.e. $-0.5 \geq r \geq 0.5$) between posture parameters and measures of performance shown in dark blue.

6.4 Discussion

The purpose of this chapter was to address Research Question 4 (§1.3) by exploring the use of PCA to identify the postural biomechanical differences (both kinematic and balance) throughout the drive, in a group of highly skilled golfers. Principal component analysis identified the greatest variance between posture parameters which were biomechanically interpreted using the terms offset, rate/range of motion and timing. The PCs identified variation in data curves throughout the swing, including in the backswing and during the downswing as well as providing additional information to discrete analysis. Golfers with similar or different posture parameters were readily identified using PC scores and further analysis of PC scores identified significant relationships between some posture parameters and with some measures of performance.

6.4.1 Principal Component Analysis

The first objective was to develop methods for analysing whole data curves rather than at discrete events and to demonstrate the benefits of such analysis. The PCA revealed two to three PCs, were required to explain the variance in many of the posture parameters (Table 6.3). For the postural kinematic parameters (e.g. lumbar flexion) a large proportion of the variance was explained within the first and second PCs. Therefore, this suggests there were some core underlying differences between golfers postural kinematics. However, the golfers' COP parameters required a greater number of PCs to explain over 90% of the variance between data curves. The low percentage of variance explained by each PC score for COP measures suggests there were more complex variations in COP patterns between data curves. For kinematic data there were subtle variations between golfers but with the same overall trend in data. For kinetic data, there were distinct differences in COP patterns between golfers (Figure 6.8) which may explain the increased number of PCs required to explain 90% of the variance. An alternative explanation was offered in a study by O'Connor and Bottum (2009) that reported a total of seven PCs were required to explain the variation in the sagittal knee moment data curves whilst five PCs were required to explain variance in frontal and transverse knee moments during a cutting movement task. The authors concluded that a greater number of PCs were required to explain the variance for these kinetic measures due to the greater within-subject variation from trial-to-trial based on comparison of PC scores for individual trials (O'Connor & Bottum, 2009). Although within-subject variation was not formally investigated the scatterplots of PC scores can give an indication of the variation between golfers' trials. Nevertheless, Ball and Best (2012) reported inconsistent COP patterns for their most skilled golfer between swings. Furthermore, Lynn et al. (2012) are the only study to have used PCA techniques for the analysis of GRF data curves and they reported that five principal components were required to explain 90% of the variance in GRF data curves in collegiate and beginner golfers. This finding suggests that even using different groups of ability golfers would result in similar PCA outputs, however, it does not explain the increased number of PCs required for kinetic measures. Therefore, COP PCA results could have been affected by the inconsistencies in individual golfers' COP patterns but this requires confirmation with further analysis.

The PCs for posture parameter data could be biomechanically interpreted using three terms which were offset of position or angle, rate of change or range in position/angle and timing of change in position/angle. Often PC1 related to the offset in position or angle and PC2 to the rate/range of change in position/angle and timing of change in position/angle. Previous studies have also noted that the variation explained by each PC could be associated to these three common terms (Wrigley et al., 2006; O'Connor & Bottum, 2009). The PCs accounted for variance throughout the whole swing (TA to MidFT) but the weighting factors also revealed that from TA and through early backswing and downswing were important parts of the swing where most variation between data curves occurred (Figure 6.1). PCA results can be affected by the section of the swing analysed and it is sometimes used as a statistical method for determining the most important phases of a movement for future analysis. Takeaway to MidFT was chosen to account for the golf swing as a whole movement and were key stages identified by golf coaches in §2.5.2. Previous studies have chosen to focus on the downswing, including an arbitrary percentage either side of TB and IMP and not the backswing, without any justification for only analysing this part of the swing (Horan et al., 2010; Horan et al., 2011; Horan and Kavanagh, 2012). Brown et al. (2011) commented that the backswing played an important role in the outcome of the swing, therefore the PCA results in this study were related to measures of performance to examine the importance of golfer kinematics and kinetics between TA to MidFT.

The discrete mean values at TA, TB and IMP for lumbar flexion and knee flexion angles showed good agreement with PCA results (§6.3.2). However, PCA results revealed more information about the range/rate of change in postural kinematics such as lumbar flexion throughout the swing. In addition, the PCA identified potentially important information regarding knee angle changes between TB and IMP, which was not, captured using discrete values alone. The limitations of discrete analysis and potential benefits of PCA have been noted by previous studies (Donoghue et al., 2008; O'Connor & Bottum, 2009) O'Connor and Bottum (2009) reported that although discrete analysis detected differences in knee flexion between genders it did not identify potentially clinical important differences in frontal plane knee mechanics that were identified from PCA. The PCA results also could reveal links between joint moments and kinematics that were not readily identified using discrete analysis (O'Connor & Bottum, 2009).

6.4.2 Difference in Posture Parameters between Golfers

The second objective was to examine the suitability of PCA to identify similarities and differences in posture parameters between golfers. The scatterplots of principal component scores provided good visual representation of the differences and similarities in golfers' PC scores which related to differences in biomechanical features for several posture parameters. A strength of PCA is the ability to analyse differences between athletes techniques and also within athletes, as shown for elite race walkers (Donà et al., 2009). Whilst this study has shown the usefulness of PCA for identifying differences between golfers throughout the swing it has not examined differences within golfers. Hence, a future study could use PCA to explore variability within a golfer's swing.

The PC1 score scatterplots were able to identify differences in the offset of thorax flexion from TA to MidFT between golfers (Figure 6.6). Thorax flexion appeared to change from mid-backswing through to IMP and did not remain constant. In accordance with the PC1 scores, golfers varied in the offset of thorax flexion which began from TA. In addition, PC score scatterplots were able to separate golfers with similar lumbar flexion PC1 scores but vastly different PC2 scores which related to differences in the range/rate of change in lumbar flexion through the backswing and especially in the downswing (Figure 6.7). Golf coaches in the perception study advocated that golfers should maintain a consistent spine axis to facilitate axial rotation (§2.5.4).

The PCA results revealed the emergence of different $\%COP_{M\text{-}L}$ styles in golfers based on PC1 scores (Figure 6.8) which closely resembled the front and reverse foot styles reported in the studies by Ball and Best (2007a, 2007b) (§3.5.3). Nevertheless, as PC1 for %COP $_{M-L}$ only explained 34.9% of the variance, not all variance between data curves was captured and more PCs were required to fully distinguish between golfers %COP $_{M-L}$ patterns. As aforementioned, Lynn et al. (2012) identified differences in GRF patterns between two groups of different ability golfers. For this cohort of golfers, PC1 of vertical ground reaction forces explained the variance due to the magnitude of vertical ground reaction forces in the backswing and timing of peak force on both front and back foot. Although, not directly comparable to the results of this study there were similarities in the PC1 weighting factors for vertical GRF data under front and back foot and the PC1 weighting factors for %COP $_{M-L}$ in this study which were both biomechanically interpreted as differences in the offset of these parameters. A further benefit of PCA is the ability to examine the relationship between PCA results and other technical parameters or with measures of performance which has not been readily pursued in the current golf literature.

6.4.3 Relationship between Postural Parameters

The third objective was to identify relationships between posture parameters which were explored using correlation analysis for several hypotheses. The %COP $_{M-L}$ and %COG $_{M-L}$ PC1 scores were strongly correlated (Table 6.5). The interrelationship of COP and COG measures is widely accepted from balance studies (Winter, 1995; Santos et al., 2010) and sporting movements (Welch et al., 1995), however no study has observed both measures during the golf swing. Welch et al. (1995) reported that the interaction of the COP and COG in medial-lateral direction served to move the baseball hitter in linear direction towards the ball. Baseball hitters with equal alignment of COP and COG positions (i.e. COG positioned evenly between the feet) emphasised the rotational component of the baseball movement, whereas hitters with an offset in COP and COG towards the front foot would have a greater linear component. The authors concluded that regardless of COG and COP patterns, there were commonalities in segment rotations (e.g. pelvis rotation). Only one previous golf biomechanical study has reported a golfer's COG position when using a driver and the reported pattern in $_{M-L}$ movement of the COG in this study is similar to that described by Burden et al. (1998). In addition, Burden et al. (1998) noted differences between individual golfers which were also evident in this study with the scatter of PC1 scores across golfers (Figure 6.10).

Moderately, strong correlations were also reported between %COG $_{A-P}$ and %COP $_{A-P}$. As, there have been no previous studies of %COP $_{A-P}$ and %COG $_{A-P}$ during the golf swing; the patterns here cannot be compared to past literature. Therefore, the results of this study provide a description of the relationship between these parameters in this cohort of ability golfers.

There was a negative relationship found between thorax lateral bend and flexion in the golf swing (Table 6.5). The close relationship between movements of the thorax has been documented in clinical studies and could influence thorax axial rotation (Edmondston et al., 2007). Axial rotation was shown to decrease when the movement began in a flexed thorax position, however thorax lateral bend increased (Edmondston et al., 2007). The results of Edmondston et al. (2007) are in contrast to the correlation results in this study whereby golfers' with more thorax flexion exhibited less thorax lateral bend throughout the swing, however, axial rotation values were not investigated. Therefore, Chapter 8 will examine the influence of thorax flexion and lateral bend on axial rotation during the golf swing. When comparing thorax and lumbar flexion to %COP $_{A-P}$ there were weak relationships between thorax flexion and %COP $_{A-P,}$ which suggests that more parameters were required to explain differences in %COP $_{A-P}$ patterns than lumbar and thorax flexion alone and may not fully support the coaches beliefs that establishing posture was related to COP patterns.

The range/rate of change in %Head COG $_{A-P}$ was moderately correlated with the range and rate of change in thorax flexion which varied between golfers (Table 6.5). The studies on head position in the golf swing have been limited. Horan and Kavanagh (2012) discussed the notion that skilled golfers were not required to control head motion based on lower coupling values between the thorax and head segments and suggested that coaches should allow varying degrees of head motion between golfers whilst making them aware of general patterns. The %Head COG $_{M-L}$ direction was not clearly linked to thorax lateral bend, but %Head COG $_{M-L}$ moved laterally throughout the swing. One study has commented that the head should move laterally in the direction of ball flight and not remain still, as suggested by some coaches in this study, because it would constrain lateral movement of the golfer's body (Sanders & Owens, 1992) (§3.5.1).

Right and left knee angles were closely linked for all PCs (Figure 6.13). There was a gradual increase in left knee flexion in the backswing and knee extension in the downswing whereas right knee flexion displayed a gradual increase in knee extension and slight flexion and extension in the downswing. The rate/range of this knee motion was also correlated. Lower limb kinematics, have received little attention in the current golf biomechanical literature (§3.5.2) which some golf coaches also acknowledged. The most detailed description of knee motion was by Egret et al. (2003) who reported greater left knee flexion at TB than right knee flexion. Whilst this finding is shown in the PCA results for knee flexion the PCA results are able to show a much clear depiction of knee motion and can show that each golfer displays varying degrees of right and left knee flexion throughout the backswing and downswing.

6.4.4 Relationship with Measures of Performance

PC1 for lumbar lateral bend and thorax lateral bend accounted for the offset of lateral bend to the right from TA to mid-downswing. The PC2 weighting factors accounted for rate of change and magnitude in lumbar and thorax lateral bend angle through the downswing. There was a moderately strong relationship between thorax lateral bend and clubhead linear velocity and two sub-groups emerged in the golfers' data. Golfers contained in the group with an increased rate of change in thorax lateral bend also showed higher clubhead linear velocities. Past literature has suggested that trunk lateral bending was an important variable at TB explaining approximately 25% of ball velocity (Chu et al., 2010). In addition, the portion of the swing between acceleration to impact was identified as a critical phase for generating an upward club path (i.e. positive attack angle) although the authors did not directly measure club parameters (Chu et al., 2010). Although not directly comparable, due to the differences in methodologies, this study suggests that lumbar lateral bend was a distinguishable feature between golfers in terms of the magnitude during the backswing and rate of change during the downswing. Therefore, the results of this study do not confirm coaches' ideals for golfers to maintain a stable spine axis.

Individual movement patterns in $\%COP_{M\text{-}L}$ were not correlated to clubhead linear despite a previous study strongly linking the range of $\%COP_{M\text{-}L}$ measurements to clubhead linear velocity (§3.5.3) (Ball & Best, 2012). In addition, inconsistent COP patterns in the most skilled golfer were coupled with consistent measures of clubhead linear velocity. Due to the increased number of PCs required to explain variance in $\%COP_{M\text{-}L}$ data curves it may require regression type analysis to account for additional variation and the affect this has on clubhead linear velocity.

Finally, there appeared to be a greater spread in launch angle data (vertical and horizontal angles) when examining the scatterplots of relationships to lumbar and thorax lateral bend and flexion. There were no relationships found between launch angles and the postural parameters, as had been hypothesised and also no groupings of golfers' data occurred. Correlations between vertical and horizontal launch angles were used as these measures accounted for both the clubhead orientation (e.g. attack angle) and clubhead path (e.g. horizontal swing plane and face angle). However, variation in the calculated club parameters such as face angle or dynamic loft, for example, may have affected the correlation results.

6.4.5 Limitations

There were limitations and areas for future work identified during this chapter. The PCA was able to identify the main variances between data curves and between golfers. It may also prove useful to perform a discriminatory analysis to determine whether a combination of PC scores could further distinguish between golfers' techniques. Discriminatory analysis was able to identify the PCs that most effectively separated the groups of subjects during gait analysis (Deluzio & Astephen, 2007) . The swing was analysed from TA to MidFT as it was important for coaches to analyse the entire swing and previous studies had acknowledged the importance of the backswing and downswing. However, PCA results are susceptible to different outcomes if larger or small portions of a movement are analysed. Therefore, in order to compare PCA results between studies it is important to consider the length of time over which movement is analysed. Nevertheless, PCA was more effective that discrete analysis at identifying technique differences between individual golfers throughout the swing which could help to guide any future discrete based analysis. In addition, there may be concern that using a different population of subjects would result in alternative PCA results. As this is one of the first studies to report PCA results of kinematic and kinetic parameters for a group of low handicap golfers, there are no studies to directly compare with. However, the only study in golf was able to show comparable PCA results, such as the number of PCs required to explain 90% variance, for GRF parameters in two distinct groups of golfers. This suggests that if this study was repeated using a different cohort of golfers the PCA results should remain relatively consistent, however this would require further analysis. Lastly, the PC scores have been used in this study to solely explore relationships between posture parameters and measures of performance. The PCA techniques do not allow causative reasons to be deduced from the results.

6.4.6 Coaching Knowledge

The results of this chapter can support current coaching ideas and also provide new information regarding posture during the golf swing. Table 6.8 summarises the coaches' perceptions regarding posture from Chapter 2 and compares it to the results from Chapter 6.

6.5 Summary

This chapter has used the continuous data analysis technique, principal component analysis, to identify postural biomechanical differences throughout the drive in a group of highly skilled golfers.

The PCA was able identify two to three core biomechanical differences in postural kinematics. PCA also identified more complex variations in COP data curves throughout the swing; hence more PCs were required to explain ≥ 90% of the variance. The PCA revealed that variations in data curves occurred throughout the swing, including backswing (TA – TB) and downswing (TB – IMP). Individual differences in golfers posture parameters were readily identified and there was potential to quantitatively examine within golfer differences using PCA.

Correlations between PC scores revealed a close relationship between COG and COP movement patterns which revealed distinct differences in golfers COP and COG styles throughout the golf swing. Thorax flexion and thorax lateral bend were also correlated and golfers with more thorax flexion were found to have less thorax lateral bend throughout the swing. This finding could have implications for body rotation during the swing and therefore warranted further investigation which would be addressed in Chapter 8. The movement patterns in right and left knee flexion and head COG were described and variations between golfers was shown which has not been done in the previous literature.

The rate/range of thorax lateral bend particularly in the downswing was closely related to clubhead linear velocity and there was an emergence of a sub-grouping in the scatterplot of golfers' PC scores. Golfers with a greater rate of change in thorax lateral bend also tended to have increased clubhead linear velocity. There was no pattern in %COP $_{M\text{-}L}$ and clubhead linear velocity correlations and golfers with distinctly different PC scores and therefore different COP patterns had similar clubhead linear velocities, suggesting that COP style alone could not explain the differences in this measure of performance. Horizontal and vertical launch angles appeared to show greater a spread within golfers than clubhead linear velocity which may have caused difficulty to determine any relationships with posture parameters.

The results were compared to coaches' perceptions and provided new information regarding posture throughout the swing as well as supporting the coaches current perceptions of posture. In addition, it was demonstrated how PCA results might be translated into coaching terminology to be used in biomechanical feedback.

The techniques defined here would be applied to body rotation parameters in Chapter 8.

Table 6.8. Summary of coaches' perceptions of posture and the comparable biomechanical results from Chapter 6

Coaches' Perceptions	Biomechanical Results
Constant degree of spine flexion particularly between TA and TB. Consistent posture creates a centred strike.	- Lumbar flexion relatively constant throughout the backswing for all golfers - Lumbar extension increased in the downswing for all golfers but at different rates - Thorax flexion changes considerably throughout the swing - Negative relationship between thorax flexion and lateral bend. - No clear relationship between lumbar and thorax flexion and launch angles
Slight lateral movement of spine	- Golfers' largely differed in the degree of lumbar and thorax lateral bend throughout the swing - Rate of lumbar and thorax lateral bend in the downswing was a distinguishing feature between golfers - Greater range and rate of change in lumbar and thorax lateral bend correlated to increased clubhead linear velocity
Small degree of knee flexion	- Right knee flexion shows slight extension in the backswing, before flexing and extending in the downswing. Golfers' varied in the magnitude and range of right knee flexion throughout the swing. - Left knee considerable flexion during the backswing and rapid extension in the downswing. - Right and left knee movements were moderately correlated.
Head position remains central	- Head position moved laterally - Head position in the anterior-posterior direction was linked to thorax flexion
Thorax flexion created a balanced body position	- No clear relationship between COP in the anterior-posterior direction and thorax flexion observed.
Balanced body position	- COP styles varied between golfers - Relationship between COG and COP also varied between golfers

Chapter 7 Methods for Defining Body Rotation

7.1 Introduction

Body rotation was identified as a key technical parameter of the golf swing by coaches (§2.5.5). Within golf biomechanical studies, the most widely measured body rotation parameters related to golf performance outcomes are pelvis and thorax rotations and, in particular, the resulting difference in axial rotation between these segments, otherwise known as X-factor (Burden et al., 1998; Myers et al., 2008; Horan et al., 2010).

Several authors have reported X-factor to be a key performance parameter contributing to golf swing performance outcomes typically quantified by ball velocity (Myers et al., 2008; Chu et al., 2010) and/or clubhead linear velocity at impact (Cheetham et al., 2000). In particular, Myers et al. (2008) noted that X-factor at the top of the backswing and maximum X-factor showed moderate positive correlations with ball velocity and suggested that maximising the golfer's X-factor at the top of the backswing could increase ball velocity. Despite the emphasis placed on X-factor as a key parameter influencing performance, there appears to be no universally adopted measurement method for X-factor.

A number of methods have been used to measure X-factor in the golf swing, based on the measurement of pelvis and thorax rotation angles from marker positional data. These methods include simply using the marker positions (e.g. acromion and anterior superior iliac spine (ASIS) markers) to define thorax and pelvis segment vectors (Burden et al., 1998). The resulting vectors are then projected onto the horizontal plane of the GCS to measure 2D rotational angles and the resulting X-factor as the angle between the projected vectors. In reality, the golfer's thorax rotates about an inclined spine (McTeigue et al., 1994; Chu et al., 2010) and projecting the thorax vector onto the GCS horizontal plane could lead to 'perspective errors' in joint angle measurements which could affect X-factor calculations. In addition to the potential introduction of perspective errors into the data, the 2D vector projection method for calculating X-factor does not account for the six degrees of freedom of the golf swing motion (Horan et al., 2010). Hence, it is important to investigate the three-dimensional (3D) measurement of X-factor which would account for additional movement during the golf swing and provide a more accurate representation of the movement (Wheat et al., 2007; Horan et al., 2010; Joyce et al., 2010). However, in this case, sequence dependency of angle rotations needs to be considered as different rotation sequences can yield varying results (Bonnefoy-Mazure et al., 2010, Joyce et al., 2010). In addition, 3D angle conventions consider translation and rotational motion separately. Therefore, a separate measure of segment translation is required in order to account for this motion during the golf swing, which golf coaches also identified as important when discussing body rotation.

Several authors have warned that the complex motions at the shoulder (scapular protraction/retraction) could influence the vector created by the acromion markers and as a result, the upper thorax rotation angles and subsequent X-factor value (Wheat et al., 2007; Myers et al., 2008).

Hence, the purpose of this chapter was to compare the current methods used to calculate the body rotation parameter X-factor in order to determine which is the most appropriate for investigating the link between X-factor and measures of performance. The results are used in subsequent chapters examining body rotation and the relationship with other key technical parameters, such as posture, throughout the swing. The first objective was to compare 2D methods against 3D methods (i.e. 2D marker positions against 3D marker positions, 2D functional joint centres against 3D functional joint centres) and the second objective was to compare the different segment definitions of 2D method of calculating X-factor (i.e. 2D marker positions versus 2D static and 2D functional joint centre methods). This will indicate whether the more complex processes of calculating the 3D X-factor and of using static or functional joint centres are necessary to more accurately determine X-factor in the golf swing.

7.2 Methods

7.2.1 Participants

Whole body kinematics were recorded for thirteen right-handed male golfers (age 28 ± 9 years, mass 80.3 ± 10.2 kg, height 180 ± 9 m, handicap 14 ± 9) and four right-handed female golfers (age 44 ± 15 years, mass 66.2 ± 5.6 kg, height 169.5 ± 3.9 m, handicap 13 ± 13) of varying abilities. The overall age range was 19 – 55 years and the overall range of handicaps was 1 – 29. All subjects gave their informed consent and ethical clearance was obtained from Loughborough University Ethical Advisory Committee.

7.2.2 Data Collection

The experimental set-up and marker set detailed in §4.2.1 and §4.2.5.3 respectively were used. Each golfer performed several warm up swings at their own discretion before the testing began. Initially, a static trial was collected followed by ten shots with their driver, with an adequate rest period between shots. Following each shot, golfers gave a subjective assessment of shot quality using a 10-point scale (1-10) where the highest ratings were considered representative of their best shot.

Three-dimensional marker trajectories were collected using a thirteen camera Vicon Nexus Motion Analysis System sampling at 250 Hz. The TrackMan launch monitor was used as a measure of club and ball performance outcomes for each shot. Frontal plane high speed video was collected at 250 Hz.

7.2.3 Data Analysis

Five trials for both the driver were selected for analysis based on the quality of data and a high subjective rating. The average subjective rating for the trials selected for data analysis was 8 ± 1. Marker positional data were processed as detailed in §4.3.1. Maximum clubhead linear velocity was calculated using the hosel marker and confirmed using the TrackMan launch monitor.

Five methods were used to calculate X-factor (Table 7.1). Methods one and two were called 2D and 3D marker positions (2DMP & 3DMP) respectively and defined segments purely based on marker positions. Method three was called 2D static joint centres (2DSJC), which, involved determining static thorax and hip joint centres. Static thorax joint centres were determined relative to the thorax by offsetting the acromion markers in relation to a shoulder marker placed in line with the head of the humerus on the most lateral part of the shoulder, and the mid-point of the shoulder width (Anglin & Wyss, 2000). Static hip joint centres were determined based on regression equations used by Bell et al., (1989). Methods four and five were called 2D and 3D functional joint centres (2DFJC & 3DFJC) respectively involved determination of FJC within the segment definition. The functional joint centre (FJC) methods required the determination of shoulder and hip joint centres using dynamic calibration techniques. An algorithm employed by the Visual3D software was used to estimate shoulder and hip joint centres using the movement trials described earlier (Schwartz & Rozumalski, 2005). This approach is proposed to be one of the most accurate for determining the centre of rotation of ball and socket joints (Ehrig et al., 2006). Notably, all methods were based on the same trials and 3D marker positional data, but differed in the points used to define the pelvis and shoulder segments and / or on whether X-factor was evaluated from the 3D segment angles or from 2D projections of the segments onto the GCS horizontal plane (3D, 2D) (Table 7.1).

For 2D X-factor calculations, the relevant shoulder and pelvis vectors were projected onto the GCS horizontal plane and subsequent X-factor was defined as the angle between the two projected vectors. When these vectors were closely aligned X-factor was close to 0º and as their separation increased the magnitude of the X-factor increased. Positive X-factor values equate to the shoulders being rotated in a more clockwise position than the pelvis when viewed in the horizontal plane.

Three-dimensional X-factor was defined as the axial rotation angle between the shoulder and pelvis segments. The Cardan rotation order ZYX was selected for the calculation of three-dimensional X-factor. This rotation order was deemed the most appropriate following examination of postural kinematic methods (§5.2.3.2) and given that the largest shoulder and pelvis rotations during the golf swing occur about the vertical axis of these segments (Lees et al., 2010; Vena et al., 2011a).

X-factor at TB, IMP and maximum X-factor (MAX) during the downswing were computed and compared between each of the following pairs of methods; (i) 2D MP vs. 2D SJC, (ii) 2D MP vs. 2D FJC, (iii) 3D MP vs. 3D FJC, (iv) 2D MP vs. 3D MP and (v) 2D FJC vs. 3D FJC. In addition, the timing of maximum X-factor relative to top of the backswing was calculated.

7.2.4 Statistical Analysis

Data was statistically analysed using Matlab. Pearson correlation coefficients were computed between each X-factor method comparisons (i.e. 2D MP vs. 2D SJC and 2D MP vs. 3D MP) at TB, IMP and MAX. Bland-Altman analyses were used to calculate the mean difference (bias) and 95% confidence intervals (CI) between methods in each pair (Bland & Altman, 1986).

Table 7.1. Definition of the five X-factor analysis methods, including segment definitions.

Method	Upper Thorax Definition	Pelvis Definition	X-factor Definition
2DMP	Vector between RAC and LAC	Vector between RASIS and LASIS markers	Vectors projected onto GCS horizontal plane. X-factor is the angle between the projected vectors
2DSJC	Vector created between left and right static shoulder joint centres	Vector created between left and right static hip joint centres	Vectors projected onto the GCS horizontal plane and X-factor angle between the projected vectors
2DFJC	Vector created between left and right functional shoulder joint centres	Vector created between left and right functional hip joint centres	Vectors projected onto the GCS horizontal plane and X-factor angle between projected vectors
3DMP	Segment created using LAC, RAC and mid-point between mid-acromion and T10. Origin was defined as mid-point between mid-acromion and T10, x-axis from origin to the right, y-axis was anterior-posterior and z-axis was distal to proximal.	As defined in Table 4.7.	Axial rotation angle between shoulder/upper thorax and pelvis segments.
3DFJC	Segment created using functional shoulder joint centres. Origin was defined as mid-point between mid-shoulder FJC's and T10, x-axis defined from origin towards right shoulder FJC, z-axis from shoulder origin to mid shoulder SJC, y-axis cross product of x and z-axis.	As defined in Table 4.7. Static hip joint centres were replaced with functional hip joint centres.	Axial rotation angle between shoulder/upper thorax and pelvis segments.

Pearson correlation coefficients were also computed between maximum clubhead velocity and X-factor at TB, IMP and MAX for each method. Correlation coefficients were determined based on the mean of the repeated trials for each golfer. Difference in timing of maximum X-factor relative to TB for each of the method comparisons were assessed using paired samples t-tests for the individual golfers. The level of significance was $p < 0.05$.

7.3 Results

7.3.1 Descriptive Analysis

The descriptive data recorded for the seventeen golfers is given in Table 7.2. The overall age range was 19 – 55 years and the overall handicap range was 1 – 29.

Table 7.2. Descriptive data for the seventeen golfers.

Golfer No.	Gender	H'cap	Age	Height (cm)	Weight (kg)	Driver CHV($m.s^{-1}$)
1	Male	28	23	193.0	99.5	31.7
2	Male	15	25	183.1	72.1	43.6
3	Male	6	53	165.4	89.5	35.6
4	Male	10	31	179.0	82.4	42.2
5	Female	7	55	163.2	71.1	33.1
6	Male	20	25	173.0	78.4	39.5
7	Male	13	22	186.5	96.1	45.1
8	Male	1	26	175.0	69.5	41.8
9	Male	15	29	183.6	80.8	39.1
10	Male	19	35	179.0	81.7	41.4
11	Female	25	24	173.1	56.9	33.0
12	Male	4	22	181.7	70.3	43.2
13	Male	28	23	181.6	73.3	43.5
14	Male	2	22	173.0	73.7	45.0
15	Male	28	26	167.0	62.7	36.5
16	Female	29	55	172.5	69.6	24.4
17	Female	3	41	169.9	68.2	34.1

[*] CHV = maximum clubhead linear velocity (Vicon) ($m.s^{-1}$); H'cap = handicap

7.3.2 Clubhead Linear Velocity

The average maximum driver clubhead linear velocity was 38.4 ± 5.8 ms^{-1} from Vicon data and 40.8 ± 6.2 ms^{-1} when using TrackMan. Driver clubhead linear velocity from Vicon data was strongly correlated with X-factor calculated using 2DMP methods (r = 0.72 - 0.81, $p < 0.05$) and 3DMP (r = 0.72 - 0.79, $p < 0.05$) at all three swing instances (Table 7.3). However, maximum clubhead linear velocity was less strongly correlated with X-factor calculated using 2DFJC methods (r = 0.51 - 0.58, $p < 0.05$) and 3DFJC methods (r = 0.48 - 0.71, $p < 0.05$) (Table 7.3).

Table 7.3. Pearson correlation coefficients (r) between maximum clubhead linear velocity and X-factor at top of the backswing (TB), impact (IMP) and maximum values (MAX) with a driver.

Method	TB	IMP	MAX
2DSJC	0.74	0.75	0.81
2D MP	0.72	0.76	0.81
3D MP	0.72	0.74	0.79
2D FJC	0.51	0.66	0.58
3D FJC	0.52	0.71	0.60

[*] All significant at $p < 0.05$ level

7.3.3 Two Dimensional Methods

2D static joint centres showed a strong correlation with 2D marker positions at all instances ($0.99 < r < 1.00$, $p < 0.05$) with little scatter in the data and minimal bias when using a driver (Figure 7.1a). When comparing 2D functional joint centres against 2DMP the correlation remained quite strong at all instances ($0.73 < r < 0.83$, $p < 0.05$) and minimal bias. However, there was more scatter in the data giving wider confidence intervals (Figure 7.2a and Figure 7.2b).

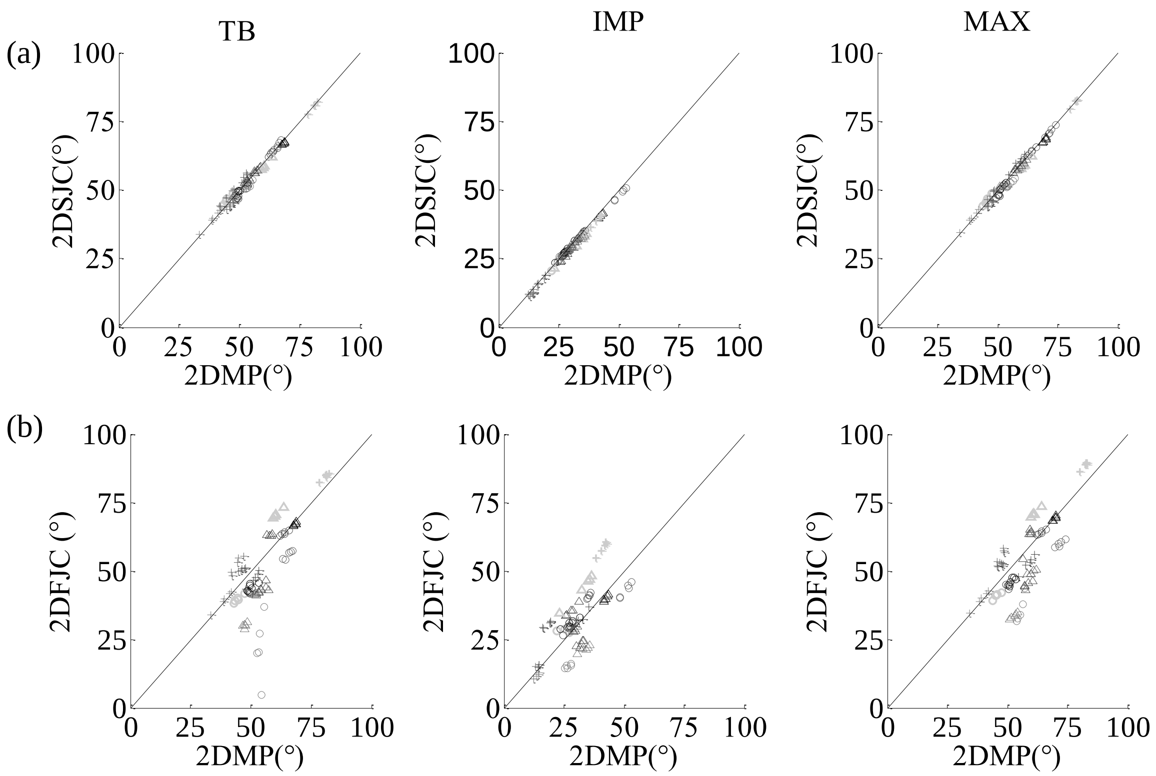


Figure 7.1. Correlation plots for X-factor measured using 2DMP and (a) 2DSJC and (b) 2DFJC with the line of equality, at TB, IMP and MAX for the driver.

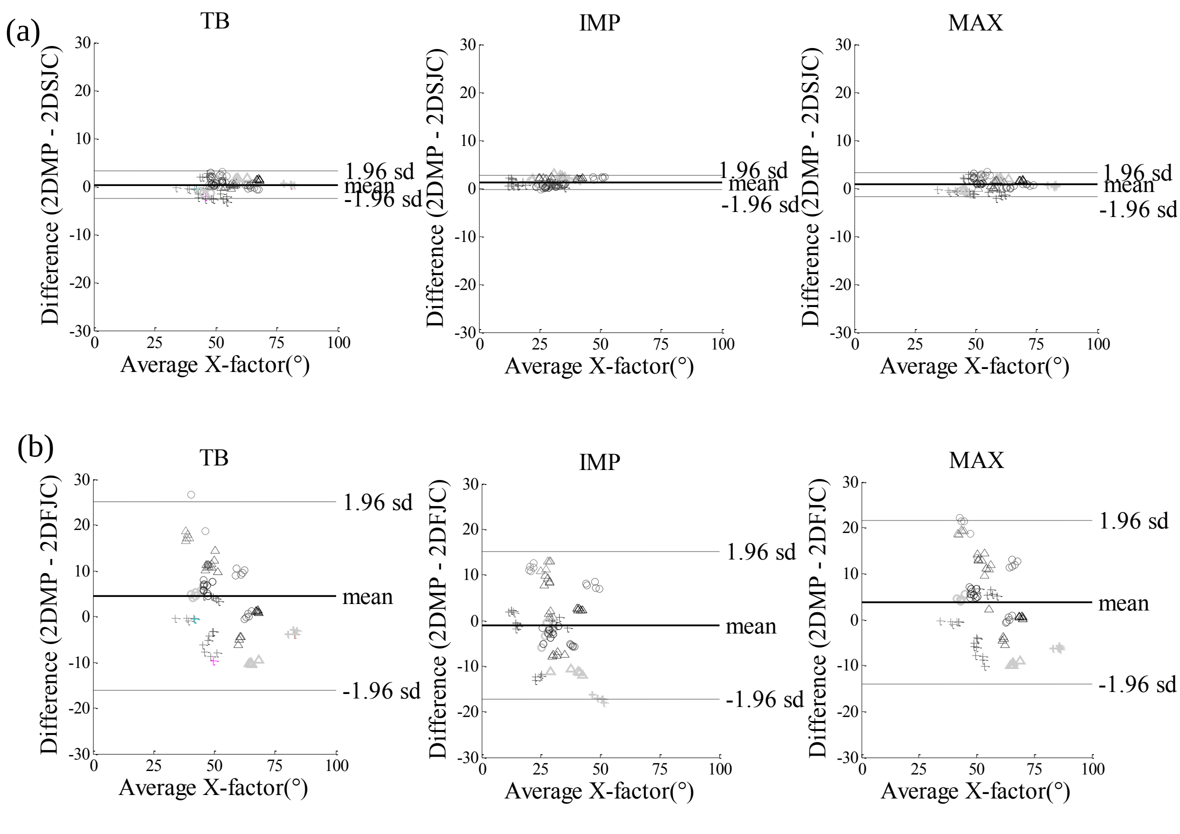


Figure 7.2. Bland-Altman plots of X-factor difference at TB, IMP and MAX (a) 2DMP – 2DSJC and (b) 2DMP – 2DFJC for the driver.

7.3.4 Comparison of Two Dimensional versus Three Dimensional Methods

There were strong correlations at all three instances between 2DFJC and 3D X-factor when measured using MP methods ($0.78 < r < 0.97$, $p < 0.001$) and FJC methods ($0.91 < r < 1.00$, $p < 0.05$) for the driver (Figure 7.3). The Bland-Altman plots (Figure 7.4) and data presented in Table 7.4 suggest evidence of a bias (offset) between 2D and 3D methods, with 2D methods consistently giving larger X-factor values particularly at TB and MAX values. Despite the strong correlations between 2D and 3DFJC there were notable differences in the actual values of X-factor.

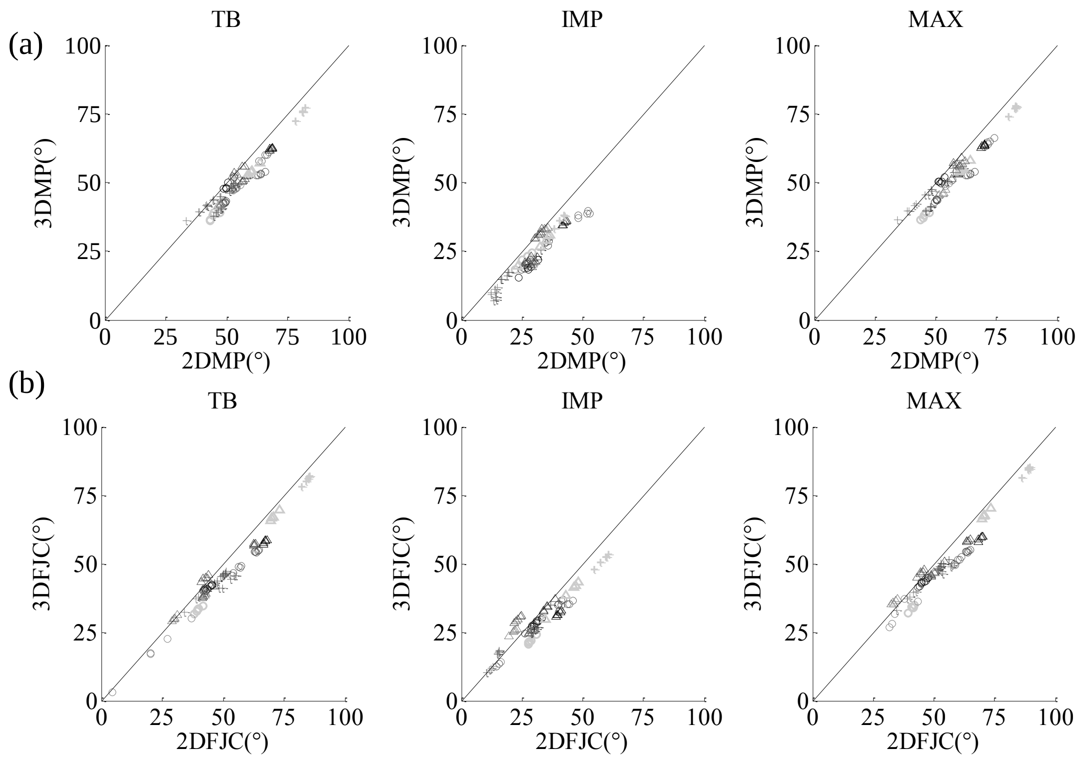


Figure 7.3. Correlation plots for X-factor measured using 2DMP and (a) 3DMP and (b) 3DFJC with a driver at TB, IMP and MAX.

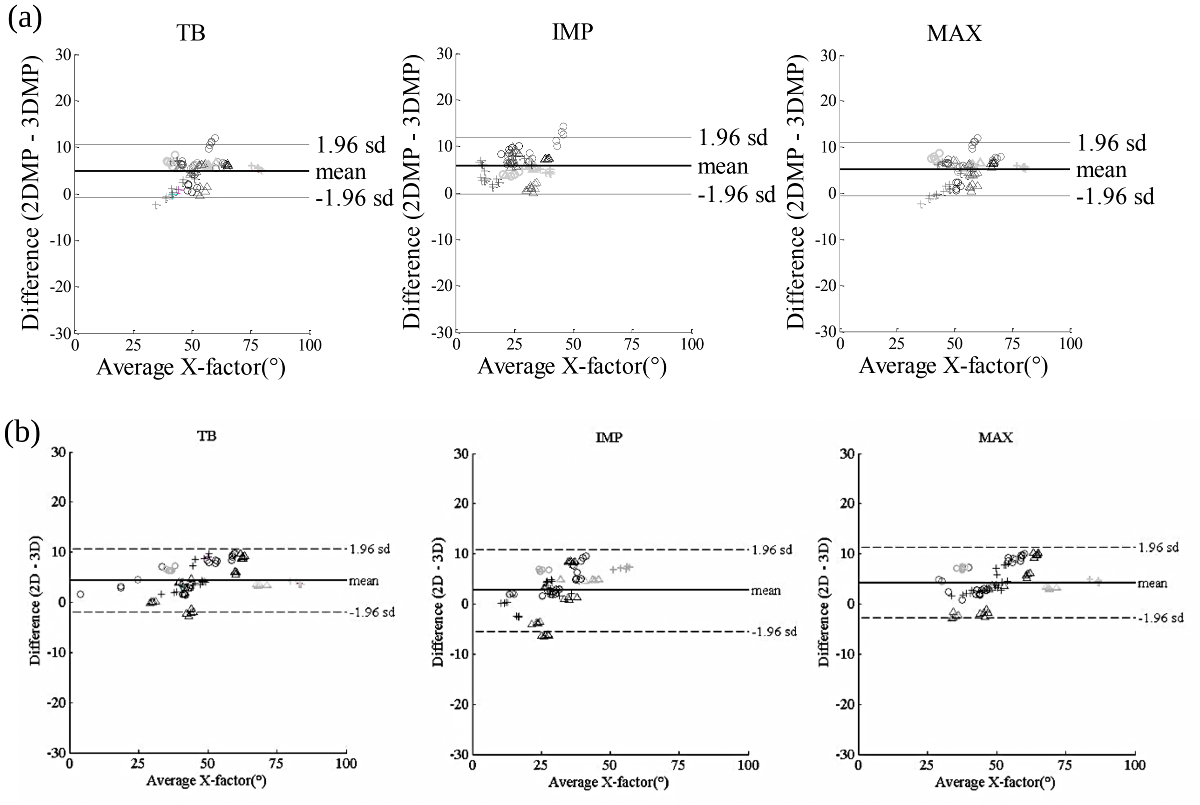


Figure 7.4. Bland-Altman plots of X-factor difference (a) 2DMP – 3DMP and (b) 2DFJC – 3DFJC for a driver at TB, IMP and MAX.

7.3.5 Timings of Max X-factor relative to TB

In addition, there appeared to be a difference in the timing of the MAX X-factor values relative to TB between 2DMP and 3DMP and 2DFJC and 3DFJC methods for the majority of golfers which will be discussed in a later section. Twelve of the 17 golfers showed a significant difference in timing of MAX X-factor between 2DMP vs 3DMP methods ($p < 0.05$). Eleven of the seventeen golfers showed significant differences in timings between 2DFJC vs. 3DFJC ($p < 0.05$). Of those golfers who showed a significant difference between timings, eight of those golfers displayed a tendency for maximum 2D X-factor to occur before maximum 3D X-factor relative to TB when comparing 2DMP and 3DMP methods and seven golfers when comparing 2DFJC and 3DFJC methods.

Table 7.4. Pearson correlation coefficient (r) and Bland-Altman mean ± standard deviation of mean difference between methods and lower/upper confidence intervals (CI) (all r have p <0.001) for a driver at TB, IMP and MAX.

Method	TB				IMP				MAX			
	r	Mean ± SD (°)	Upper CI (°)	Lower CI (°)	r	Mean± SD (°)	Upper CI (°)	Lower CI(°)	r	Mean± SD (°)	Upper CI (°)	Lower CI (°)
(i) 2D MP vs. 2D SJC	0.99	0.3 ± 1.5	2.6	-3.2	1.00	1.3 ± 0.8	2.8	-0.3	0.99	0.8 ± 1.3	3.3	-1.7
(ii) 2D MP vs. 2D FJC	0.78	4.2 ± 9.6	22.9	-14.6	0.73	-0.9 ± 8.3	15.4	-17.2	0.83	3.8 ± 9.1	21.7	-14
(iii) 3D MP vs. 3D FJC	0.79	2.8 ± 8.7	19.9	-14.3	0.78	0.7 ± 7.5	14	-15.4	0.78	2.2 ± 8.1	18.3	-13.8
(iv) 2D MP vs. 3D MP	0.96	5.9 ± 2.9	11.5	0.2	0.78	2.5 ± 3.5	9.4	-4.4	0.97	5.9 ± 2.8	11.3	0.5
(v) 2D FJC vs. 3D FJC	0.98	4.5 ± 3.2	10.8	-1.8	1.00	2.7 ± 4.1	10.9	-5.5	0.97	4.3 ± 3.6	11.3	-2.6

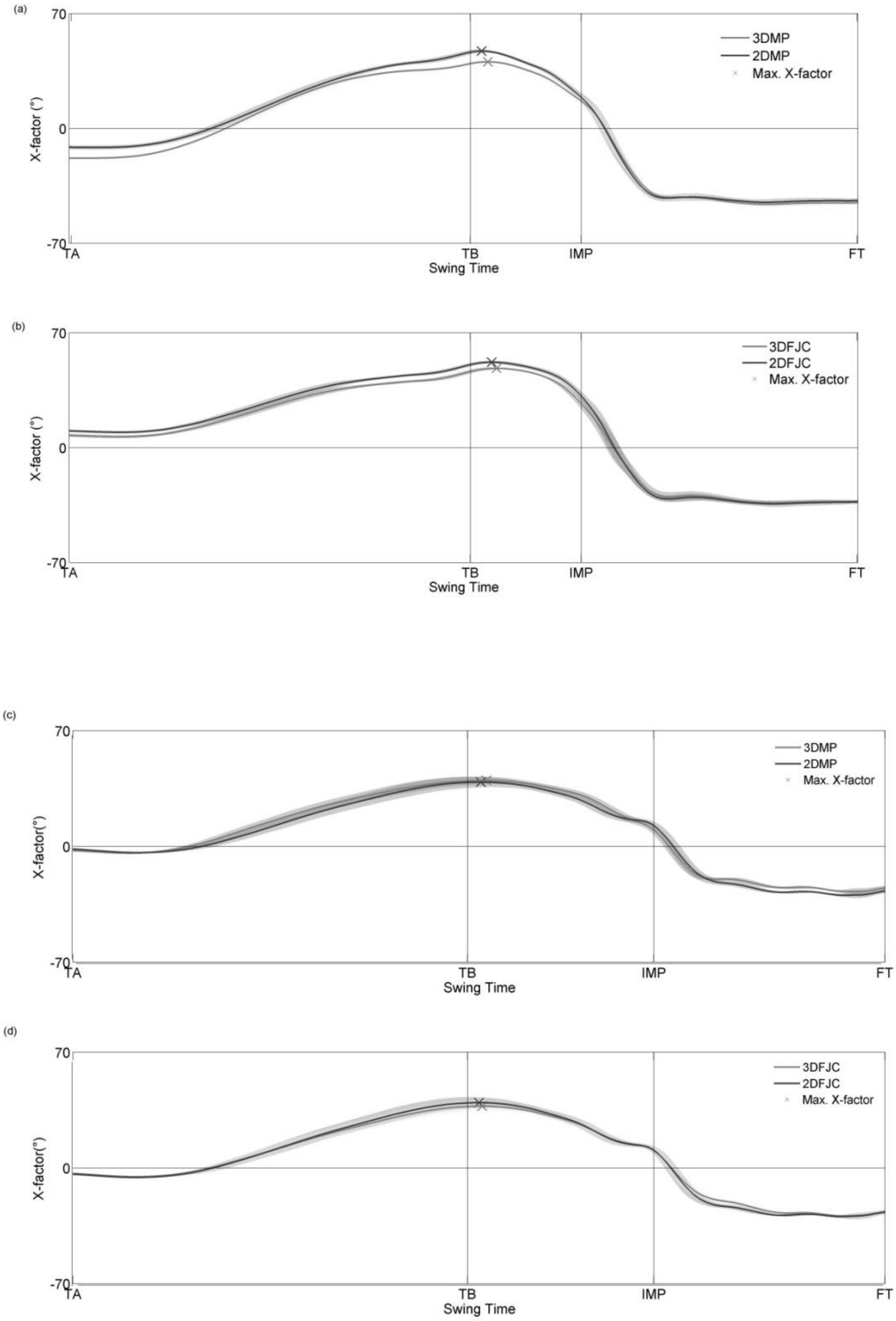


Figure 7.5 Mean ± SD of all five trials for a single golfer for 2D and 3D X-factor throughout the swing calculated using MP and FJC methods for two representative golfers: (a) - (b) female, handicap = 3, age = 41 showing poor agreement in timing of maximum X-factor between methods; and (c) - (d) female, handicap 29, age = 55 showing good agreement in timing of maximum X-factor between methods. The solid lines represent TB and IMP and one unit on x-axis represents the downswing time 0.232 ± 0.004 s for golfer in (a) - (b) and 0.483 ± 0.005 s for golfer in (c) - (d).

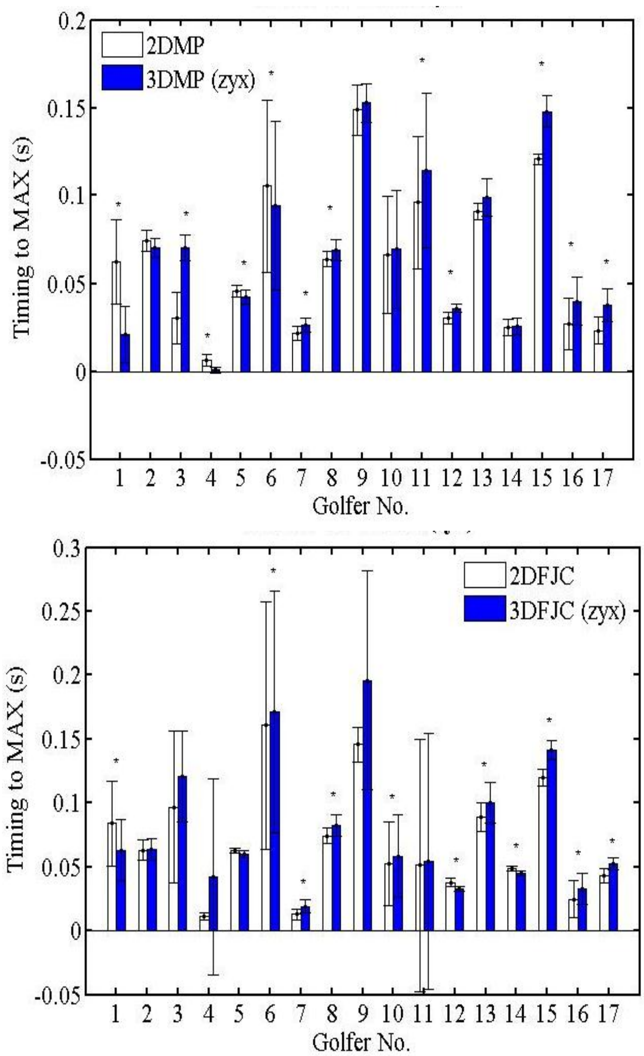


Figure 7.6. Mean ± SD of timing of MAX X-factor relative to TB for seventeen golfers. * represents those differences which were statistically significant at $p < 0.05$

7.4 Discussion

The purpose of this chapter was to compare the current methods used to calculate body rotation parameters and X-factor in order to determine which is the most appropriate for investigating the link between X-factor and performance outcomes. The results are used in subsequent chapters examining body rotation and the relationship with other key technical parameters, such as posture, throughout the swing.

7.4.1 Two Dimensional versus Three Dimensional Methods

The first objective was to compare 2D and 3D methods and the results indicated that these were highly correlated for both marker positions and functional joint centres at all three swing instances investigated. However, there was a systematic offset in the X-factor values between the 2D and 3D methods at TB and MAX with the 3D methods giving lower values compared to 2D methods. 3D X-factor evaluation has recently been reported in the literature and suggested to better account for the complex 3D movement of the golf swing with the shoulders and pelvis being laterally bent, axially rotated and flexed throughout the swing (Joyce et al., 2010, Horan et al., 2010). The offset in X-factor values between 2D and 3D methods in this study can be explained by the perspective error associated with the measurement of 2D angles for a movement that is not restricted to the measurement plane. Investigating golf swing plane perspective errors, Harper (2006) reported a sinusoidal trend in the measurement error between rotated angles (0º to 180º) projected onto the global co-ordinate system and those projected onto an inclined plane (30º, 45º and 60º), with the magnitude of error increasing proportionally to the angle of incline. In this study, the observed X-factor offset suggests that there is sufficient lateral bending and flexion-extension occurring during the swing to introduce perspective error effects at the key instances. Notably, the direction and magnitude of perspective error will depend on the degree of lateral bending and flexion-extension a golfer exhibits; for the subject group used in this study 3D X-factor values were on average 4° - 10° less than 2D values. Furthermore, the upper and lower confidence intervals suggest that methods could have been dependent on the golfer. For example, golfers with different thorax flexion or lateral bend angles may result in different offset values between 2D and 3D methods. Therefore, it would be interesting to apply PCA to this cohort of golfers to examine their posture parameters in order to confirm these differences. Nevertheless, it further supports the use of 3D analysis of body rotation parameters.

The perspective error may have also led to observed differences in the timing of maximum X-factor relative to the top of the backswing between the 2D and 3D methods for twelve of the seventeen golfers examined. From those golfers, there was a tendency for 2D MAX X-factor values to occur closer to TB compared to 3D MAX X-factor (i.e. smaller timing for 2D methods). This suggests that the methods used to calculate X-factor values may also affect the timings of key instances during the swing; this may be important when investigating their influence on performance outcomes measures, i.e. distance and accuracy. For example, Tinmark et al. (2010) found that the timing of pelvis, torso and hand segment velocities showed a proximal-to-distal sequencing which was suggested to affect shot accuracy. However, further investigation is required to fully understand and confirm this observation.

7.4.2 Segment Definitions

Extremely good agreement was reported between the 2D marker positions and 2D static joint centres for the driver. This result is not surprising given that static hip joint centres were calculated based on an algorithm whereby the ASIS markers are offset as a percentage of inter-ASIS distance (Bell et al., 1989) and shoulder joint centres are determined by offsetting acromion markers (Anglin & Wyss, 2000). Therefore, marker positions and static joint centres could be used interchangeably to define shoulder and pelvis segment when calculating 2D X-factor.

However, when 2D / 3D marker positions and functional joint centres are compared there is substantial scatter in the data at all instances. Several studies have warned about the use of acromion markers to define the shoulder segment due to scapula movement (Elliott et al., 2002, Joyce et al., 2010), therefore, using functional joint centres may alleviate these limitations and theoretically should be more accurate than marker positions or static joint centres. The functional joint centres determined in this study were based upon recommendations made in previous studies detailing the types of movements, marker positions and number of movement cycles to be used to determine the most accurate joint centre for both hip (Begon et al., 2007) and shoulder (Rettig et al., 2009). Although several studies have examined the determination of accurate functional joint centres, few studies have explored the implementation and reconstruction of the obtained functional joint centres during movement (Rettig et al., 2009; Roosen et al., 2009). Static joint centres and marker positions approximate joint centre positions are based on regression equations which may smooth individual differences in joint locations and would produce less scatter in joint positions. Alternatively, the functional joint centre positions may be susceptible to error due to noise which has not been quantified and functional joint centres is still an on-going area of research. Therefore, further investigation is required into the application of functional joint centres during the golf swing.

7.4.3 Clubhead Linear Velocity

X-factor has been identified as a key performance parameter in the golf swing as it positively correlates with clubhead linear velocity and ball velocity at impact (Cheetham et al., 2000, Myers et al., 2008). In this study, maximum clubhead linear velocity correlated strongly with X-factor calculated using both 2D and 3D marker positions. The strong correlation observed between 2DMP X-factor values and clubhead linear velocity has been reported previously (Myers et al., 2008; Meister et al., 2011). With 3DMP X-factor values also correlating strongly, this supports the notion that X-factor is important for generating greater clubhead linear velocity. The correlation between maximum driver clubhead linear velocity and functional joint centres methods was weaker and may reflect the greater spread of calculated 3DFJC X-factor values across golfers. This again suggests that further investigation into the use of functional joint centres for golf swing analysis is needed.

7.4.4 Limitations

It may be argued that the non-homogenity of the group could have influenced the results and that a more appropriate approach would have been to sub-divide the golfers into more homogeneous groups. However, this would have reduced the X-factor range within each group, and made the correlation approach more challenging. The subject group intentionally included golfers with a wide range of ages (19 - 55 years), handicaps (1 - 29) and gender (13M - 4F) with the aim of obtaining a wide range of X-factor values (35º - 70º), as necessary to address the study objective of comparing methods for calculating X-factor through a correlational analysis. In addition, the Bland-Altman approach is concerned with quantifying variation in between-method differences for individual subjects which was in keeping with the objective of this study. Furthermore, the resulting scatter plots indicated a similar overall trend throughout the group, supporting the single group approach. These results support the findings of Horan et al . (2010) who found no significant differences in X-factor variables between male and female golfers. Sub-grouping would provide an interesting extension to this study; however, it appears the selected single group approach has provided a robust means of addressing the stated objectives.

7.5 Summary

This chapter has determined the most appropriate method for calculating body rotation parameters, in particular X-factor. The 2D and 3D methods for X-factor measurement gave strongly correlated values but there was an offset at the swing events TB and MAX. The 2D methods gave consistently larger X-factor values than 3D methods, however this observation could have been dependent on the golfer. The timings of maximum X-factor could also be affected by the 2D or 3D methods.

The SJC and MP segment definitions were strongly correlated but FJC resulted in greater variation. Even though FJC are theoretically more accurate than SJC or MP for use in defining segments, the accuracy of FJC calculations are still not clear.

It appears that for an in-depth analysis of the golf swing to include measures of timings and magnitudes then the 3D X-factor measurement is required. Therefore, the 3D measures of body rotation and 3D X-factor will be used in the proceeding chapter which aims to identify differences in body rotation parameters between golfers.

Chapter 8 Identification of Body Rotation Features throughout the Golf Swing with Links to Posture and Measures of Performance

8.1 Introduction

Body rotation was identified by golf coaches (§2.5.5) and in the biomechanical literature (§3.6) as a key technical parameter during the golf swing. Due to the emphasis placed on axial rotation in the golf swing, it was necessary to determine the most appropriate methods of quantifying biomechanical body rotation parameters which included pelvis and trunk (i.e. lumbar, thorax and upper thorax) axial rotations and the resulting X-factor. This was addressed in Chapter 7. In brief, following investigation of several data collection and analysis techniques informed from previous literature, it was deemed necessary to use 3D methods for calculating body rotation parameters during the golf swing due to a number of problems with 2D analysis methods as summarised below.

Three-dimensional analysis of body rotation was required to eliminate the perspective errors introduced when using 2D measurements of body rotation, due to thorax rotation occurring about an inclined spine during the swing. In addition, 3D analysis could account for the 6DOF of each body segment. Horan and Kavanagh (2012) examined the 3D relationship between head, thorax and pelvis rotational motion during the downswing. The authors concluded that analysis of upper body kinematics should not be limited to axial rotation as strong coupling was reported within thorax segment directions, in particular, between lateral bend and axial rotation velocities (Horan and Kavanagh, 2012).

The coupled motion of thorax axial rotation and lateral bend angles has also been reported in clinical studies (Edmondston et al., 2007). Furthermore, Edmonston et al. (2007) found that the range of thorax axial rotation significantly decreased (approximately 20% reduction) and coupled lateral bend increased (approximately 115% increase) when movement began in a flexed thorax position. It was suggested that the ligaments of the thorax spine produced tension when in a flexed position and increased lateral bend is required to gain further axial rotation. In contrast, the PCA results of Chapter 6 identified a negative relationship between thorax lateral bend and thorax flexion whereby golfers with more thorax flexion displayed less thorax lateral bend especially in the backswing (§6.4.3). This finding may have implications for axial rotation during the swing Therefore, the studies by Horan and Kavanagh (2012), Edmondston et al. (2007) and the results from Chapter 6 highlight the need to investigate a golfer's body rotation in conjunction with a golfer's posture. Coaches also made links between a golfer's posture and body rotation, for example one coach stated that (§2.5.4):

> *The guys that are more efficient [and] powerful are the guys that maintain a good centre and rotate around it...not necessarily making massive rotations. We've seen some guys have shorter rotations [hips and shoulders] but they are staying stable...it's about maintaining those postures...to reduce injury and to allow the club to get back to the golf ball more consistently.*

The study by Horan and Kavanagh (2012) provides a good basis for investigating the relationship between posture and body rotation; however, the coupling in thorax lateral bend and axial rotation, identified using cross-correlations, was only done for the downswing and not throughout the whole swing. Indeed, the authors only examined the downswing and given the importance placed on posture parameters during the backswing and downswing in Chapter 6, it would be important to examine body rotation from takeaway to mid-follow through.

Body rotation parameters at discrete events such as TB or maximum have been widely linked to measures of performance such as clubhead linear velocity and ball velocity (§3.6). However, no study has examined the relationship between body rotation and measures of performance throughout the swing. Furthermore, previous studies have often analysed differences in body rotation parameters between groups of golfers of different abilities and it is not known the extent to which body rotation varies between golfers of similar abilities. Hence, PCA analysis combined with additional statistical analysis could firstly identify individual differences in body rotation parameters and subsequently whether there were discrete sub-groupings of golfers within main group of homogenous ability golfers.

Therefore, the purpose of this chapter was to further address Research Question 4 (§1.3) by applying PCA methods to body rotation parameters for a group of highly skilled golfers. This purpose would be achieved by addressing five objectives. The first objective was to use the PCA methods developed in Chapter 6 to identify biomechanical differences in body rotation parameters throughout the drive in the group of highly skilled golfers. The second objective was to identify similarities and differences between golfers' body rotation parameters. The third objective was to investigate the relationship between body rotation parameters by examining the following hypotheses:

i. Pelvis and lumbar axial rotation would be positively correlated
ii. Lumbar and thorax axial rotation would be positively correlated
iii. Thorax and upper thorax axial rotation would be positively correlated
iv. Upper thorax axial rotation and X-factor would be positively correlated

The fourth objective was to investigate the relationship between posture and body rotation parameters by examining several hypotheses which were generated based on coaches' perceptions and previous biomechanical literature:

v. Thorax flexion would be negatively correlated with upper thorax axial rotation and X-factor
vi. Thorax lateral bend would be positively correlated with upper thorax axial rotation and X-factor.
vii. %Head COG $_{A-P}$ and $_{M-L}$ would be correlated with thorax axial rotation
viii. Magnitude of X-factor would be correlated with the range of %COP $_{M-L}$

The fifth objective was to investigate the relationship between body rotation parameters and measures of performance by again examining a number of hypotheses which were generated based on coaches' perceptions in §2.5.5 and previous biomechanical literature (§3.6):

i. X-factor would positively correlate with clubhead linear velocity and ball velocity
ii. Rate/range of X-factor would be positively correlated with clubhead linear velocity
iii. Upper thorax axial rotation would positively correlate with clubhead linear velocity and ball velocity.
iv. Thorax lateral bend would positively correlation with clubhead linear velocity

The results of this chapter are compared to the coaches' perceptions and existing literature to either reinforce existing coaching and biomechanical knowledge or to provide new insights into technique.

8.2 Methods

8.2.1 Participants

Nineteen right handed low handicap male golfers (handicap range +3 to 4; age = 26 ± 7 years; height = 179.5 ± 7.3 cm; weight = 79.4 ± 13.1 kg) were recruited for the study. The golfers were either members of Loughborough University golf team or PGA professional golfers and gave their informed consent prior to testing (§4.2.6).

8.2.2 Data Collection

The golfers were prepared for motion analysis data collection by placing retro-reflective markers on the golfer in accordance with the marker set presented in §4.2.5.3. Three-dimensional marker trajectories were collected using the Vicon Nexus Motion Analysis System sampling at 250 Hz. The system was calibrated according to §4.2.5.1. Two Kistler force plates synchronised with the motion analysis system collected ground reaction force data at 1000 Hz (§4.2.4). The TrackMan launch monitor was used to capture measures of performance (Appendix C) and was set-up as detailed in §4.2.1. The golfers were given the instructions as detailed in §4.2.6 before data collection. The golfer's used their own driver and performed at least ten swings during the testing session.

8.2.3 Data Analysis

Following data collection, the raw positional data was visually inspected and filtered using the techniques in §4.3.4. Five trials for the driver were selected for analysis based on the golfer's subjective rating of shot quality and marker visibility throughout the swing. Visual 3D software was used to define the golfer model by following the procedures in §4.3.2. Visual 3D was also used to calculate the body rotation parameters which were identified in Chapter 7. A number of time varying body rotation parameters were selected for analysis: thorax axial rotation, lumbar axial rotation, upper thorax rotation (used to represent the coaches' idea of shoulder rotation) and 3D X-factor (defined as the angle between upper thorax and pelvis). Both thorax and upper thorax axial rotation will be examined in this chapter, as the upper thorax segment was defined in Chapter 7 to reflect the coaches term 'Shoulder rotation' and was defined slightly differently to the thorax segment used in Chapter 5. The swing events (TA, TB, IMP and MidFT) were identified for the individual trials of each golfer as detailed in §4.3.6.

The data was then temporally aligned and normalised from TA to TB, TB to IMP and IMP to MidFT across the five trials, for each individual golfer, based on the methods presented in §4.3.6 and using the Matlab function in Appendix F. Temporally aligned data has been documented as a reasonable stage to PCA and it is left to the discretion of the researcher as to whether this stage is required (Ryan et al., 2006).

8.2.4 Statistical Analysis

The first stage of analysis involved a PCA of body rotation parameters in accordance with the methods used in Chapter 6. The PCA resulted in the variance explained by each PC and the associated weighting factors. The PC scores for each body rotation parameter for the five trials of each of the nineteen golfers were also computed. Biomechanical interpretation of the results were achieved using the methods defined in §6.2.3.1.

Following qualitative biomechanical interpretation of the PCA results, further exploratory statistical analysis was conducted on the PC scores to identify relationships between body rotation parameters and with posture parameters using a one-tailed Spearman correlations. To investigate whether the relationship between body rotation parameters could be grouped into a few discrete categories, cluster analysis was performed on the PC scores whose scatterplots showed an emergence of sub-groupings in the golfers' data.

If sub-groupings in golfer PC scores emerged, the k-means approach to cluster analysis was peformed. The purpose of cluster analysis was to divide observations into a pre-defined number of clusters, whereby each observation was assigned to a cluster with the closest mean to that observation value. The k-means method of cluster analysis required an input for *k* which represents the number of mutually exclusive clusters into which the data was grouped. To ascertain the correct numbers of clusters to use, the number of clusters (i.e. *k*) were incremented from one to eight. For each increment value of *k*, the Matlab functions 'kmeans' and 'silhouette' were used to obtain a qualitative representation of the clustering performed. The mean silhouette values for each value of *k* provided a measure of how tightly the data was grouped in each cluster. Subsequently, a larger mean silhouette value indicated a better quality cluster (Appendix H). This stage of cluster analysis allowed the most appropriate number of clusters to be determined.

The k-means clustering algorithm performed an iterative process whereby it first selected *k* random observations from the data set, referred to as the centroids. All other observations were then assigned to one of the k centroids based on their proximity to the centroid. The proximity of observations to the centroid were determined by drawing a line between the centroids and perpendicular lines drawn halfway between the centroid connecting lines. The distance of each observation to the perpendicular lines was calculated using the squared Euclidian distance calculation and consequently each observation was assigned to that centroid. Following this, the centroid of each cluster was determined by taking the mean of all observations contained within that cluster and the process of calculating the distance from each centroid was repeated. This iterative process was repeated until the sum of the distances from each observation to the cluster centroid could not be decreased.

Finally, the hypotheses of relationships between body rotation and measures of performance, as obtained from TrackMan, were tested using a Spearman correlation with p set at < 0.05.

8.3 Results

This section will present the results that address the five objectives of this chapter. Firstly, the overall PCA results and biomechanical interpretation of PCs are presented. Secondly, the scatterplots of body rotation parameters are presented and compared to original data to represent the difference between golfers' body rotation parameters. Thirdly, correlation results are presented for body rotation parameters and for the hypotheses testing of posture and body rotation parameters as outlined in the introduction. Finally, the relationships between body rotation and measures of performance are presented. The emergence of groupings in golfers PC scores were identified using cluster analysis techniques.

8.3.1 Principal Component Analysis for Body Rotation

The body rotation parameters required three to four principal components to explain 90% or more of the variance between data curves (Table 8.1). The biomechanical interpretation of PC's was achieved using three terms; offset, rate/range of change and timing of this rate/range of change as described in §6.3.1. The biomechanical interpretation of PCA results is presented as a chart of graded colour bars associated to the three terms The length of the bar represented the swing time (TA - MidFT) and colours are graded based on the values of the weighting factors for each PC (Figure 8.1). The mean curves (with multiples added or subtracted) are presented in Appendix H which were used to help biomechanically interpret PCA scores.

Table 8.1. Number of principal components and total variance explained for each body rotation parameter.

		PC (%)				
Body Rotation Parameter	No. of PCs	PC1	PC2	PC3	PC4	Total Variance Explained
Upper Thorax (Rotation)	3	55.7	26.0	9.5		91.2
Thorax (Rotation)	4	55.4	22.3	10.9	6.2	94.8
Lumbar (Rotation)	3	55.7	25.9	8.5		90.1
Pelvis (Rotation)	3	61.0	21.5	8.2		90.8
X-factor	3	70.5	18.9	6.9		96.4

8.3.2 Difference in Body Rotation Parameters between Golfers

The golfers' body rotation parameters were described by their standardised PC scores scatterplots which allowed differences between golfers' to be readily identified. For example, the original X-factor data for golfers with similar PC1 scores but different PC2 scores were compared (Figure 8.2). PC1 for X-factor explained the offset from mid-backswing to mid-downswing (Figure H.5). The PC2 largely explained the variance in the rate/range of X-factor from TA to TB and the timing of the change in X-factor near TB. Golfers 8 and 16 (positive PC2 scores) displayed a greater range of X-factor in the backswing and the maximum X-factor occurred before or close to TB.

Conversely, Golfers 1 and 2 displayed a smaller range of X-factor in the backswing and maximum X-factor occurred after TB. The scatterplots of PC scores of the remaining body rotation parameters provided a visual representation of the spread in golfers scores (Figure 8.3).

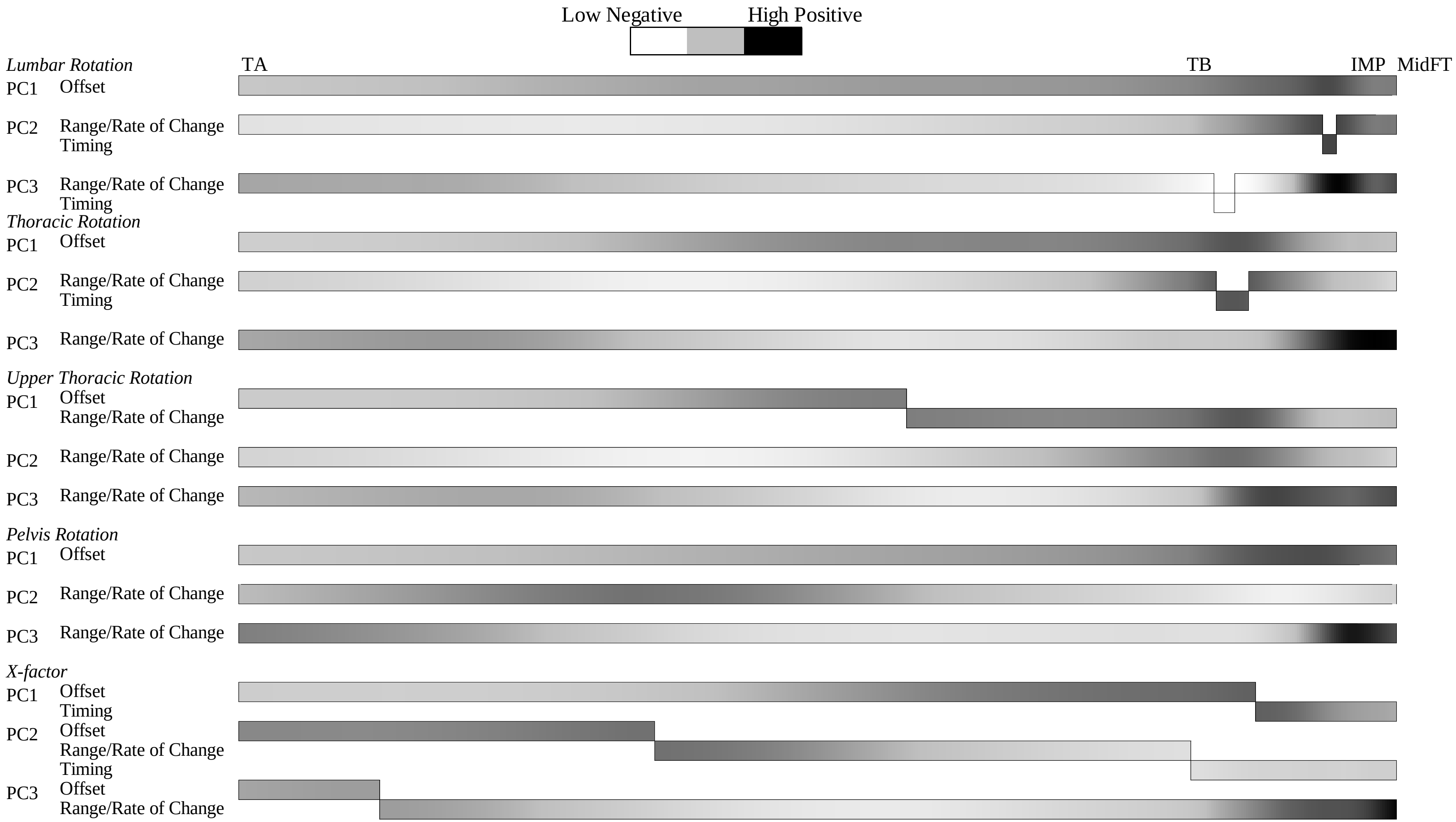


Figure 8.1. Biomechanical interpretation of the principal components of body rotation parameters throughout the swing. The colour coding is shown in the legend

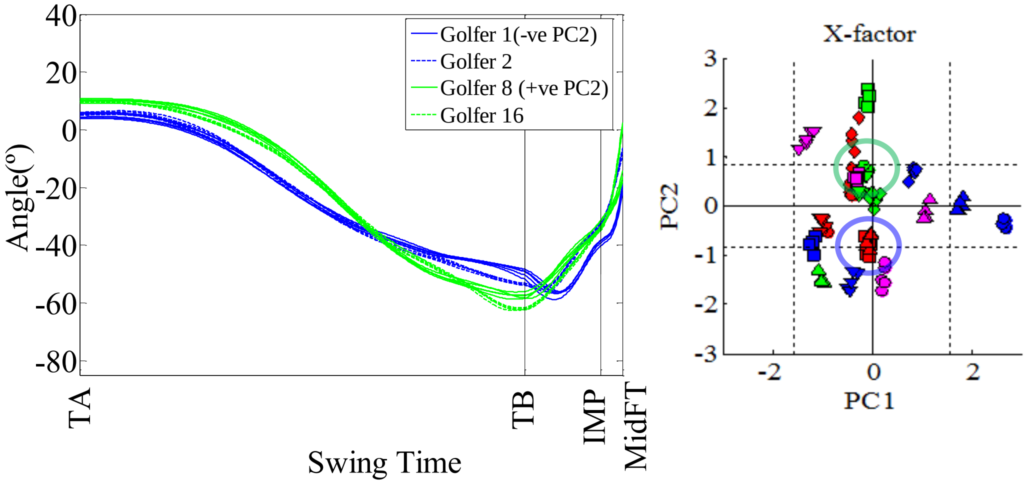


Figure 8.2. (a) X-factor for two golfers with negative PC2 scores (Golfer 1 & 2, blue circle) and two golfers with positive PC2 scores (Golfer 8 & 16, green circle) as shown on (b) Scatterplots of PC scores for X-factor.

8.3.3 Relationship between Body Rotation Parameters

The third objective was to identify relationships between body rotation parameters by testing several hypotheses. The Spearman correlations for the five test hypotheses are presented in Table 8.2.

Table 8.2. Spearman's correlation coefficients (r) of relationships between body rotation parameter PC scores hypothesis testing

Hypotheses	Body Rotation Parameter	PC Score	Correlation Coefficient (r)
i.	Pelvis axial rotation - Lumbar axial rotation	PC1 – PC1	0.74*
		PC2 – PC2	-0.85*
		PC3 – PC3	0.77*
ii.	Lumbar axial rotation – Thorax axial rotation	PC1 – PC1	0.49*
		PC2 – PC2	0.45*
iii.	Thorax axial rotation – Upper thorax axial rotation	PC1 – PC1	0.79*
		PC2 – PC2	0.95*
		PC3 – PC3	0.83*
iv.	Upper thorax axial rotation – X-factor	PC1 – PC1	0.75*
		PC2 – PC2	-0.72*
		PC3 – PC3	0.49*
v.	Pelvis axial rotation – X-factor	PC1 – PC1	-0.37*

* Statistical significance, $p < 0.05$

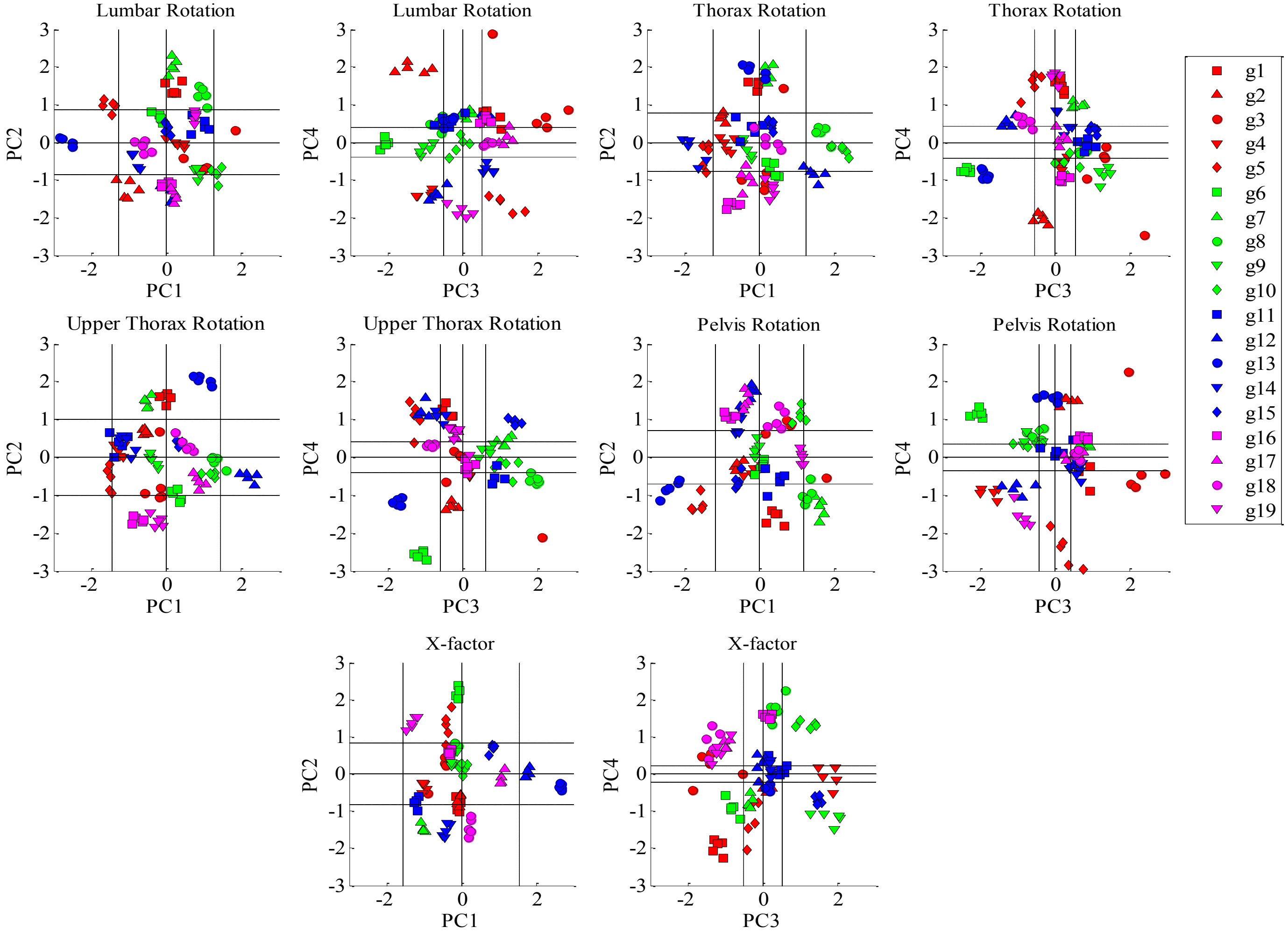


Figure 8.3. Scatterplots of standardised PC scores (one to four) for body rotation parameters. The equation Standardised PC score = (PC Score – Mean Score)/Standard deviation of scores was used.

The first hypotheses was supported by correlations between pelvis and lumbar axial rotation PC1 scores ($r = 0.74$, $p < 0.05$) (Figure 8.4a) and PC3 scores ($r = 0.77$, $p < 0.05$) but displayed an opposite relationship for pelvis and lumbar axial rotation PC2 scores ($r = -0.85$, $p < 0.05$) (Figure 8.4b). The positive relationship between pelvis and lumbar axial rotation PC1 scores suggested that those golfers with larger magnitudes of pelvis axial rotation also tended to have larger magnitudes of lumbar axial rotation throughout the swing. The relationship between PC2 scores suggests that a greater range in pelvis rotation throughout the swing was linked to a gradual increase lumbar rotation in the backswing and a lesser rate of change in lumbar rotation during the downswing.

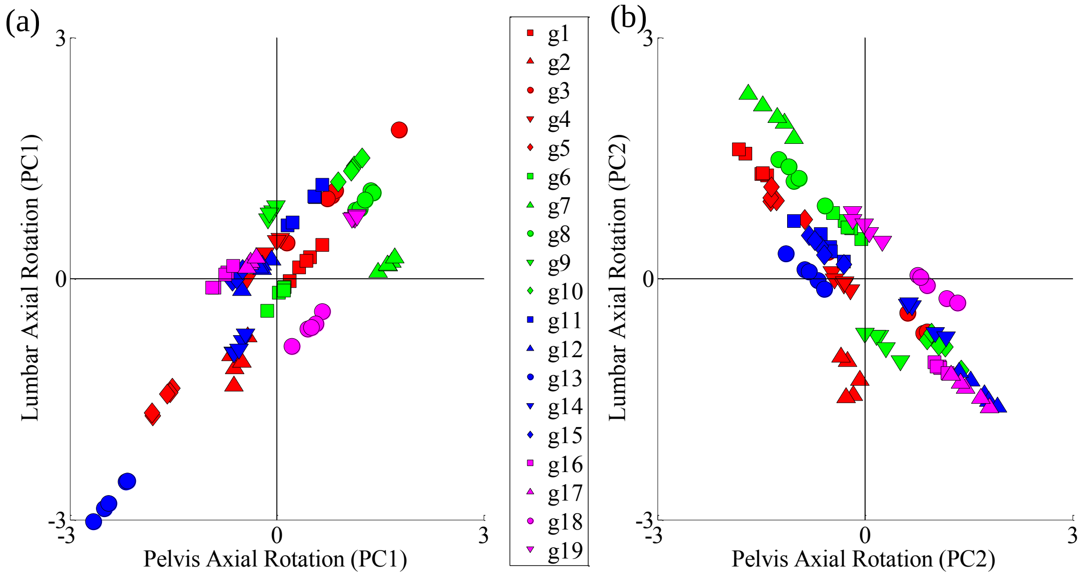


Figure 8.4. Pelvis and lumbar axial rotation PC scores scatterplots for (a) PC1 scores and (b) PC2 scores.

The second and third hypotheses were also supported by the Spearman's correlation results (Table 8.2). Lumbar and thorax axial rotation were positively correlated for PC1 and PC2 scores, however these were not completely linear relationships as shown in the scatterplot for PC2 scores (Figure 8.5a). Thorax axial rotation and upper thorax axial rotation PC2 scores were strongly positively correlated ($r = 0.95$, $p < 0.05$) which suggests that the range and rate of change in thorax and upper thorax axial rotation were very closely related (Figure 8.5b).

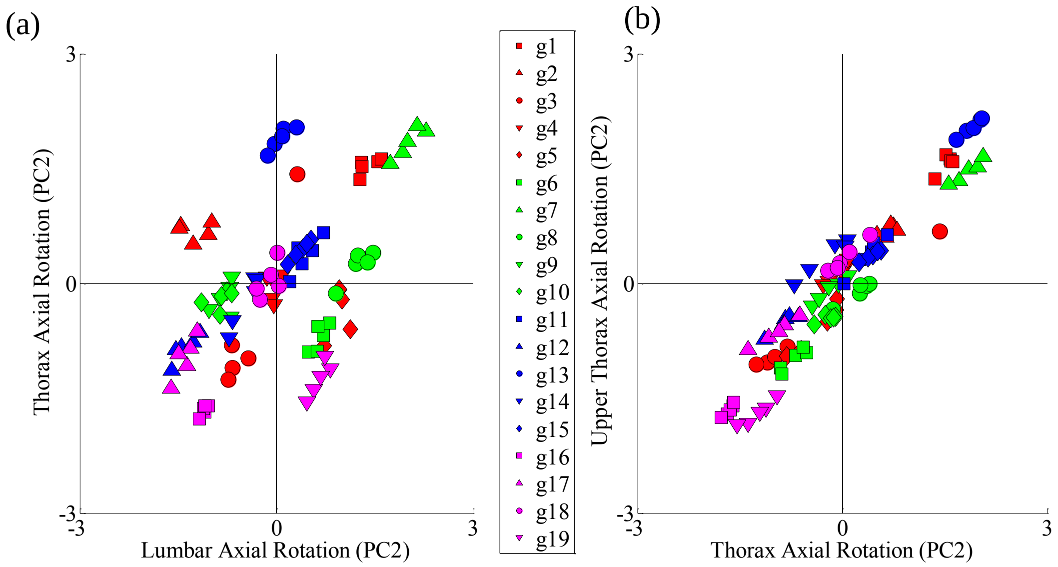


Figure 8.5. (a) Scatterplots of thorax axial rotation and lumbar axial rotation PC2 scores and (b) Upper thorax axial rotation and thorax axial rotation PC2 scores.

Spearmean correlations of upper thorax axial rotation and X-factor PC1 scores were positively correlated, although the scatterplots do not show a clear linear relationship. The PC2 scores were negatively correlated ($r = -0.72$, $p < 0.05$) and could be interpreted as a greater range of upper thorax axial rotation was related to a greater range of X-factor particularly from mid-backswing to TB (Figure 8.1 & Figure 8.6).

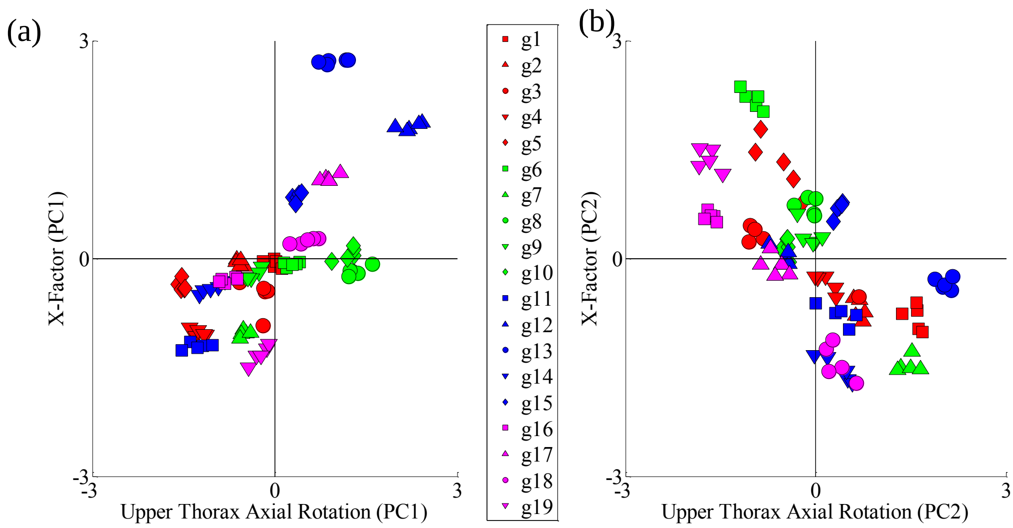


Figure 8.6. (a) Scatterplots of upper thorax axial rotation and X-factor PC1 scores and (b) Upper thorax axial rotation and X-factor PC2 scores.

8.3.4 Relationship to Posture Parameters

The fourth objective was to identify relationships between posture parameters and body rotation parameters by examining several hypotheses. The Spearman correlations for the four tested hypotheses are presented in Table 8.3. The first hypothesis, that thorax flexion would be negatively correlated with upper thorax axial rotation, was supported by the correlation analysis ($r = -0.68$, $p < 0.05$). Furthermore, two sub-groupings of golfers emerged which were confirmed using k-means cluster analysis (Figure 8.7). Golfers in cluster one had negative upper thorax PC1 scores and positive thorax flexion PC1 scores. Therefore, golfers in cluster one exhibited greater thorax flexion and reduced upper thorax axial rotation. Cluster two identified golfers with positive upper thorax axial rotation PC1 scores and negative thorax flexion PC1 scores. The golfers in cluster two could be characterised as having reduced thorax flexion and greater upper thorax axial rotation.

Table 8.3. Spearman's correlation coefficients (r) of relationships between posture parameter and body rotation parameter PC scores hypothesis testing

Hypotheses	Body Rotation Parameter	PC Score	Correlation Coefficient (r)
i.	Thorax flexion – Upper thorax axial rotation	PC1 – PC1	-0.68*
	Thorax flexion – X-factor	PC1 – PC1	0.49*
ii.	Thorax lateral bend – Upper thorax axial rotation	PC1 – PC1	0.37*
	Thorax lateral bend – X-factor	PC1 – PC1	0.55*
iii.	%Head COG $_{M-L}$ – Thorax axial rotation	PC1 – PC1	0.17
		PC2 – PC2	0.16
	%Head COG $_{A-P}$ – Thorax axial rotation	PC1 – PC1	0.44*
		PC2 – PC2	0.34*
iv.	%COP $_{M-L}$ – X-factor	PC1 – PC1	0.31*
		PC1 – PC2	0.37*
		PC2 – PC1	-0.46*

* Statistical significance, $p < 0.05$

Thorax flexion PC1 scores were less strongly (and positively) related to X-factor PC1 scores.

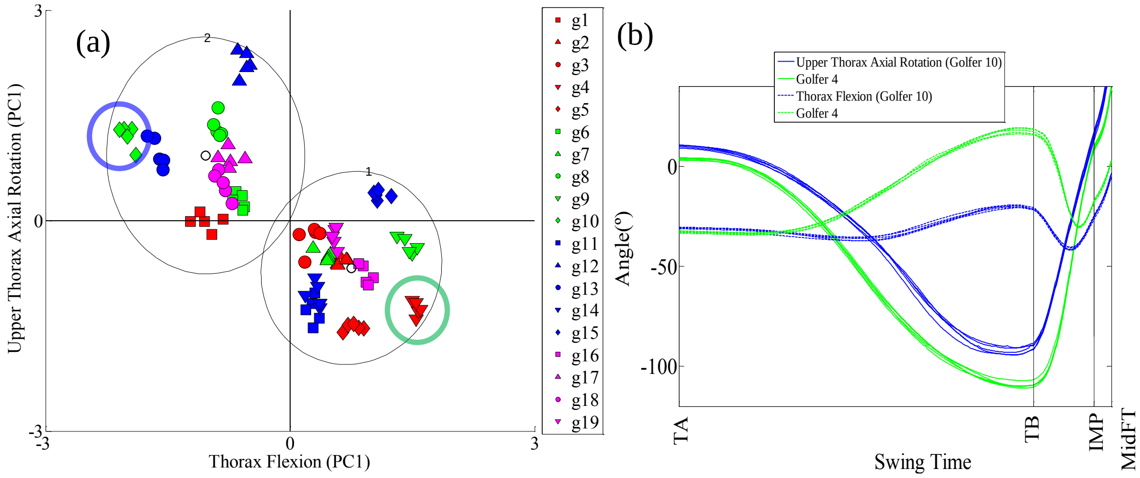


Figure 8.7. (a) Scatterplot of upper thorax axial rotation and thorax flexion PC1 scores with two k-means clusters (1 & 2) and (b) Thorax flexion and upper thorax axial rotation data for a golfer in cluster two (Golfer 10, blue) and cluster one (Golfer 4, green).

Thorax lateral bend and X-factor were weakly correlated and scatterplots did not distinguish any obvious sub-groupings of golfers. Thorax lateral bend and X-factor PC1 scores displayed moderately strong correlations ($r = 0.55$, $p < 0.05$) and again there were no distinct sub-groupings in golfers.

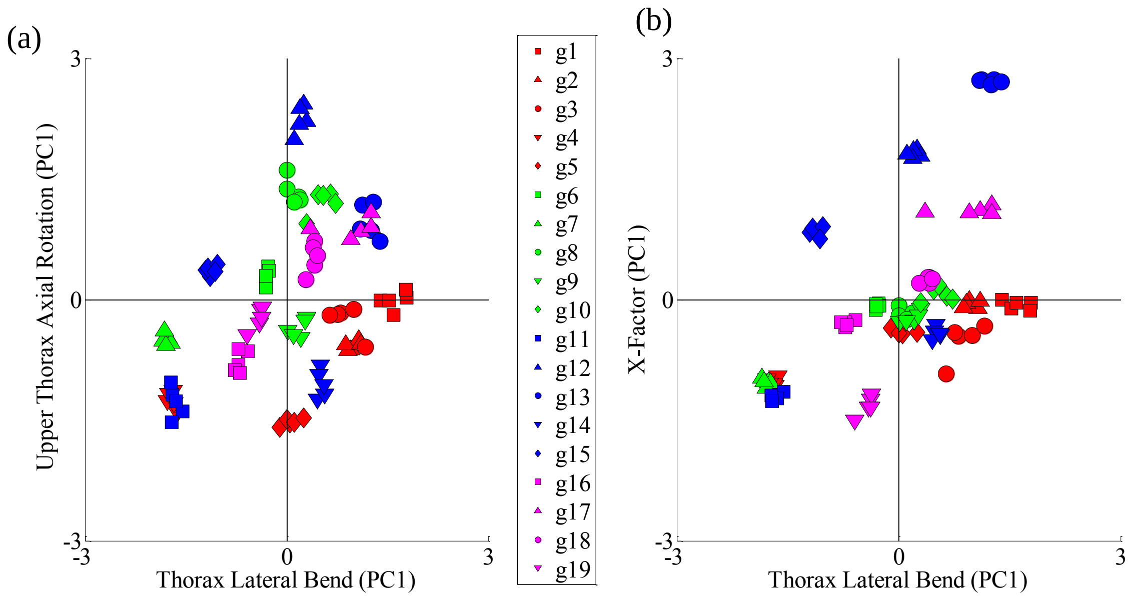


Figure 8.8. (a) Scatterplots of thorax lateral bend and upper thorax axial rotation PC1 scores and (b) Thorax lateral bend and X-factor PC1 scores.

The only significant positive correlations between %Head COG position and thorax axial rotation was for %Head COG $_{A-P}$ and thorax axial rotation PC1 ($r = 0.44$, $p < 0.05$) and PC2 ($r = 0.37$, $p < 0.05$) scores. However, when examining the scatterplots there were no clear sub-groupings of golfers in these PC scores, therefore it is difficult to comment on this relationship with correlation results alone.

The final hypothesis for posture and body rotation relationships stated that the magnitude of X-factor would be correlated with the range/rate of %COP $_{M-L}$. Whilst the correlations were statistically significant they were only moderately correlated (i.e. $r \leq 0.5$).

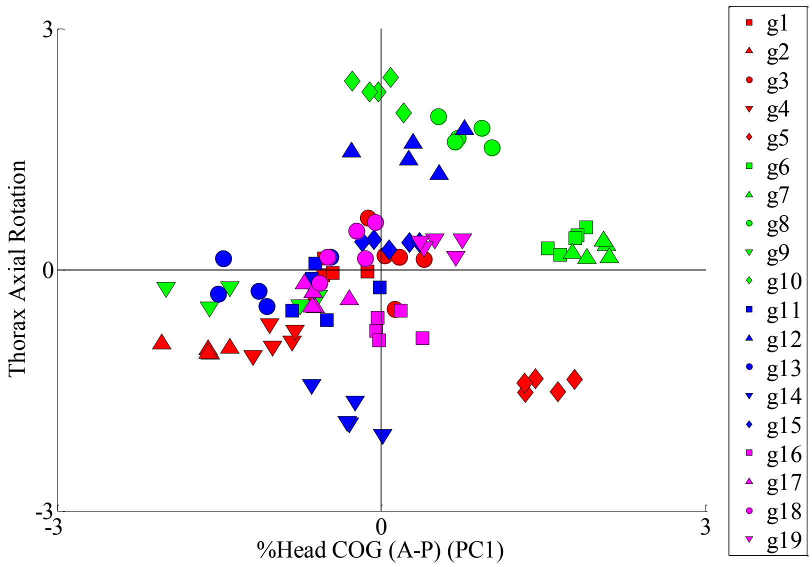


Figure 8.9. Scatterplots of %Head COG $_{A-P}$ and upper thorax axial rotation PC1 scores

8.3.5 Relationship of Body Rotation Parameters and Measures of Performance

The final objective required correlation of body rotation parameters to measures of performance to test a series of hypotheses (Table 8.4).

Table 8.4. Spearman's correlation coefficients (r) for the relationships between body rotation parameter PC scores and measures of performance hypothesis testing

Hypotheses	Body Rotation Parameter	PC Score	Correlation Coefficient (r)
i.	X-factor – Clubhead linear velocity	PC1	-0.33*
	X-factor – Ball velocity	PC1	-0.20*
ii.	X-factor – Clubhead linear velocity	PC2	0.11
ii.	Upper thorax axial – Clubhead linear velocity	PC1	0.11
		PC2	-0.06

From the hypotheses tested, only three significant relationships were found between body rotation and measures of performance however, the correlation coefficients between parameters were relatively weak (i.e. $r \leq 0.5$). The scatterplot of X-factor PC1 score and clubhead linear velocity confirm the weak trend between offset in X-factor increases, clubhead linear velocity also increases. Golfers 7 and 19 recorded the greatest clubhead linear velocities (49.7 $m.s^{-1}$ and 48.6 $m.s^{-1}$ respectively) and had similar X-factor PC1 scores, however they varied greatly in PC2 scores (Figure 8.3) and X-factor curves varied between golfers.

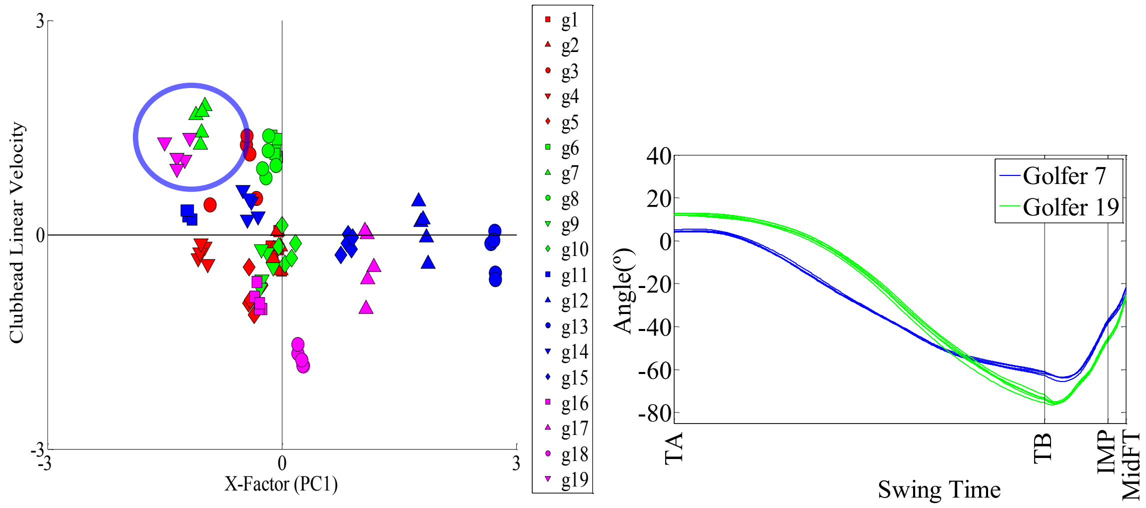


Figure 8.10. (a) Scatterplot of X-factor PC1 scores and clubhead linear velocity and (b) X-factor curves for Golfers 7 and 19 with high clubhead linear velocity, similar PC1 scores and different PC2 scores.

The correlation matrix in Figure 8.11 was produced to ascertain if there were any further relationships that required investigation. Many of the relationships had been covered by the hypotheses that were tested.

8.4 Discussion

The purpose of this Chapter was to address Research Question 4 (§1.3) by exploring the use of PCA to identify biomechanical differences in body rotation parameters throughout the drive, in a group of highly skilled golfers. Principal component analysis identified the greatest variation between body rotation parameters and biomechanical interpretation of PC results could be explained using the terms offset, rate/range of motion and timing. The variance between data curves was found throughout the swing, including in the backswing and downswing. Golfers with similar and different body rotation could be readily identified using PC scores. The correlations between PC scores did reveal some relationships between body rotation parameters and posture parameters. However, correlations with measures of performance were not strongly correlated and suggested that more than one PC is required to explain the variance in measures of performance.

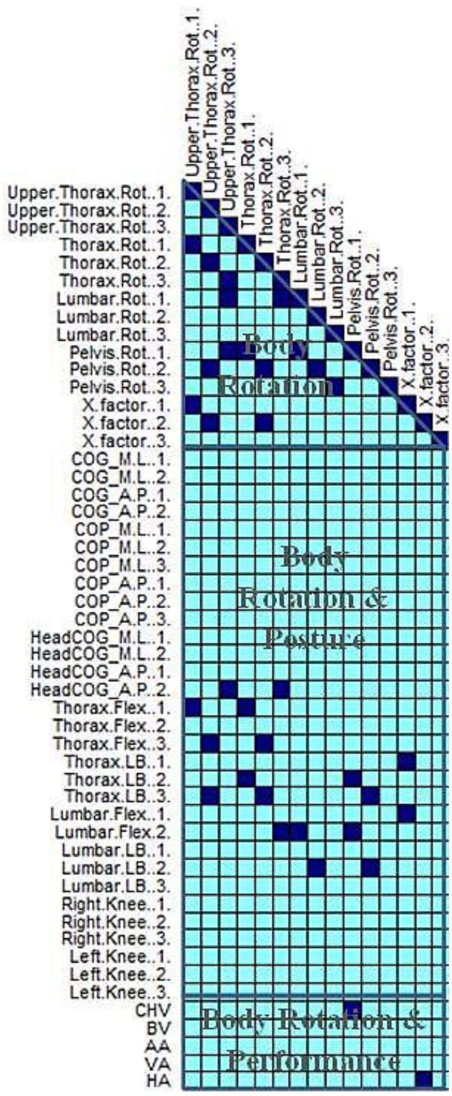


Figure 8.11. Correlation matrix of significant relationships (i.e. $p < 0.05$) and r values greater than or less than 0.5 and - 0.5 respectively (i.e. $- 0.5 \geq r \geq 0.5$) between posture, body rotation parameters and measures of performance shown in dark blue.

8.4.1 Principal Component Analysis

The first objective was to identify biomechanical features in body rotation parameters. Principal component analysis revealed three to four PCs were needed to explain at least 90% of the variance in body rotation parameters (Table 8.1).

The few PCs suggests that there were core trends in body rotation parameters which could distinguish between golfers' techniques, as was found for postural kinematics in Chapter 6. The PCs were biomechanically interpreted using three terms; offset, range of motion/rate and timing as described in §6.2.3.1. Also, the PCs identified variances in body rotation throughout the swing from TA to MidFT. In general, PC1 described the offset between data curves from TA to MidFT, PC2 described the rate/range of motion in the backswing and downswing and PC3 described the rate/range of motion and timing of motion particularly in the downswing. The mean curves of body rotation parameters, followed similar patterns to those seen in previous literature with clockwise upper thorax and thorax axial rotation angles were larger than lumbar and pelvis axial rotation during the backswing (Burden et al., 1998; Horan et al., 2010; Horan et al., 2011) (Appendix H). There was also greater anti-clockwise pelvis axial rotation at IMP compared to lumbar, thorax and upper thorax axial rotation, which suggests that the pelvis leads the rotation. The results of this multi segment trunk analysis could have implications for X-factor calculations; X-factor is sensitive to the trunk segment used and the lumbar segment would result in lower X-factor values as was shown by Joyce et al. (2010). Therefore, it was important to specify the segments used in X-factor calculations, in this study it was the upper thorax and pelvis segments.

8.4.2 Difference in Body Rotation Parameters between Golfers

The second objective was to examine the difference in body rotation biomechanical features between golfers. The scatterplots of PC scores for body rotation parameters indicated a range of techniques and generally there was a lack of clear sub-groupings of golfers in the scatterplots (Figure 8.3). For some scatterplots, such as X-factor PC1 vs. PC2 scores, there was evidence that many golfers were tightly clustered around low PC1 scores with only a few apparent outliers displaying high PC1 scores (Figure 8.2). Future studies may look to explore these outliers in more detail. The wider spread was found in PC2 scores which explained the rate/range of X-factor in the backswing and the timing of maximum X-factor close to or after TB. Previous studies have shown that highly skilled (handicap ≤ 0) and low skilled golfers (handicap ≥ 15) significantly increase X-factor in the early downswing (compared to TB) but that the highly skilled golfers created a greater difference between X-factor at TB and maximum X-factor, resulting in a larger X-factor stretch (Cheetham & Martin, 2001). The PCA results in this study suggest that the timing of maximum X-factor varied across a group of similar ability golfers and those with positive PC2 scores may have maximum X-factor occurring too close to TB, thereby limiting their X-factor stretch.

8.4.3 Relationship between Body Rotation Parameters

The third objective of this study was to investigate the relationship between body rotation parameters. The adjacent segments were closely related and r-values ranged from $-0.37 \leq r \leq 0.95$ with $p < 0.05$. The strong correlations ($r \geq 0.7$) were expected due to the segments being physically linked in the golfer and in the golfer model used in this study. The strongest correlations were between upper thorax and thorax axial rotation which is not surprising given both segments used similar marker sets. Lumbar and thorax correlations had the lowest correlation coefficients between PC1 and PC2 scores. These correlations were not as strong as those reported between pelvis and thorax axial rotation velocity profiles in Horan and Kavanagh (2012). These authors examined the coupling (defined as association between linked segments) between thorax and pelvis velocity profiles using cross-correlations and reported strong relationships ($r = 0.98$, $p < 0.05$) between thorax and pelvis velocity during the downswing (Horan & Kavanagh, 2012). The differences between studies could be due to the different portions of the swing analysed as the downswing was analysed in Horan and Kavanagh (2012) compared to the full swing in this study.

X-factor PC1 scores and upper thorax axial rotation PC1 scores showed strong correlation ($r = 0.75$, $p < 0.05$) (Figure 8.6c) compared to X-factor and pelvis PC1 scores ($r = -0.37$, $p < 0.05$). This correlation is not surprising given that the degree of upper thorax axial rotation is greater than the pelvis axial rotation and hence will have a stronger contribution to X-factor also noted by Meister et al. (2011).

8.4.4 Relationship between Body Rotation and Posture Parameters

The fourth objective was to identify relationships between body rotation and posture parameters from Chapter 6. There were several moderately strong relationships found between body rotation and posture parameters (Table 8.3). An interesting negative relationship ($r = -0.68$, $p < 0.05$) was found between upper thorax rotation PC1 scores and thorax flexion PC1 scores along with two sub-groupings of golfers identified using k-means cluster analysis (Figure 8.7a). Cluster one identified golfers with positive thorax rotation PC1 scores and negative PC1 thorax flexion scores. Cluster two grouped golfers with positive thorax flexion PC1 scores and negative upper thorax PC1 scores.

The golfers in cluster one could be characterised as having increased thorax flexion but less upper thorax axial rotation throughout the swing and golfers in cluster two had reduced thorax flexion throughout the swing, especially towards TB, and produced greater upper thorax axial rotation in the backswing as was shown in Figure 8.7b. This finding is in agreement with the clinical study of Edmondston et al. (2007) who reported that their subjects exhibited less thorax axial rotation in a more flexed position compared to when the movement began in a neutral posture. A recent study by Joyce et al. (2013) also alluded to the possibility of reduced lower trunk flexion at TB leading to increased trunk axial rotation at TB. The results of this study reinforce that the degree of upper thorax axial rotation is related to the degree of thorax flexion a golfer exhibits and differences can be seen in group of homogenous ability golfers, thus a golfer's posture needs to be considered when reporting rotation parameters. This echoes one of the coaches' comments regarding the importance of setting a good posture and links to body rotation (§2.5.4).

%Head COG $_{M\text{-}L}$ were not significantly correlated to thorax axial rotation but %Head COG $_{A\text{-}P}$ was moderately correlated to thorax axial rotation for PC1 and PC2 scores. One golf coach stated that limiting the shift in head movement would allow a golfer to rotate better during the swing (§2.5.4). There was no evidence in the PCA results to suggest that medial-lateral head movement was related to thorax axial rotation during the swing.

8.4.5 Relationship of Body Rotation Parameters and Measures of Performance

The fifth objective was to explore the relationships between body rotation parameters and measures of performance. In particular, it was hypothesised that body rotation would be closely related to the measures of clubhead linear velocity and ball velocity as has been found in previous biomechanical literature (§3.2). Only three significant correlations were reported from the hypothesis testing but these displayed weak correlations (i.e. $r \leq 0.4$) (Table 8.4). From examination of the scatterplot between X-factor PC1 scores and clubhead linear velocity there was a suggestion that greater X-factor throughout the swing would lead to increased clubhead linear velocity, however the weak correlations suggests there was more than X-factor offset that influenced clubhead linear velocity (Figure 8.10). Brown et al. (2012) also suggested that body rotation parameters alone, in particular, X-factor, could not explain differences in clubhead linear head velocity in a group low handicap female golfers.

The weak correlations could be due to the inter relationship between body rotation PCs and with other technical parameters, such as posture. To examine the influence of multiple parameters and PCs on measures of performance, multiple regressions could be used; however, it was not used in this study due to the small sample size. For example, to include up to five technical parameters (i.e. independent variables) in a multiple regression on clubhead linear velocity (i.e. dependent variable) with a power of 0.8 (i.e. probability of obtaining a statistically significant result, if one exists), $p < 0.05$ and correlation coefficient above 0.05, approximately 250 subjects would be required.

8.4.6 Limitations

There were limitations and areas of future work identified during this chapter. The PCA was able to identify the main variances in body rotation data curves between golfers'. The hypothesis testing identified a number of moderate-strong correlations between body rotation parameters, between posture parameters and measures of performance; however there were no clear relationships between body rotation parameters and measures of performance. This may be a sign that the complex interrelationship between body rotation parameters and measures of performance were not captured using simple correlation analysis and would require other statistical techniques such as multiple regressions. Therefore, the limiting factor in this study was the number of subjects which was too small for multiple analysis to be performed.

8.4.7 Coaching Knowledge

The results of this chapter can support current coaching ideas and also provide new information regarding body rotation during the golf swing. Table 8.5 summarises the coaches' perceptions regarding body rotation from Chapter 2 and compares it to the results from Chapter 8.

8.5 Summary

This chapter has also used the continuous data analysis technique, principal component analysis, to identify body rotation differences throughout the drive in a group of highly skilled golfers. Furthermore, the PCA results have been used to investigate relationships between body rotation parameters, posture parameters and measures of performance.

The PCA identified three to four core biomechanical differences in body rotation parameters for pelvis, lumbar, thorax and upper thorax axial rotation and X-factor. PC1 for all body rotation parameters largely explained the offset in axial rotation between the data curves. In addition, the timing of thorax and upper thorax anti-clockwise rotation in the downswing was captured in PC1. PC2 typically explained the variation in data curves due to the range in axial rotation from TA to TB. Finally, PC3 accounted for he rate of change in anti-clockwise rotation during the downswing.

Individual golfer differences in each body rotation parameter were identified using scatterplots of PC scores. There was a spread in the golfers' PC scores across the PCs for each body rotation parameter which suggests there were observed difference in techniques for this group of highly skilled golfers. The scatterplots provided easy visualisation of this spread in golfers' techniques and there appeared to be no clear sub-groupings of golfers based on a single body rotation parameter.

Correlations between body rotation parameter PC scores revealed that there were generally strong relationships between body rotation parameters, most probably due to the segments being linked in golfer and the golfer model.

Postural kinematics, in particular thorax flexion did appear to influence axial rotation. Thorax flexion PC1 scores and upper thorax axial rotation PC1 were strongly correlated and the observed sub-groupings of golfers showed that increased thorax flexion was related to reduced axial rotation. This could have implications for golf coaches during their coaching of the rotational component of the golf swing.

The measures of performance were poorly correlated with body rotation parameters perhaps to the complex interaction of other key technical parameters.

The PCA results allowed individual golfer differences in body rotation parameters to be identified which satisfied Research Question 4 (§1.3). The relationships and sub-groupings found between some of body rotation and posture parameters has provided new information and supported the current coaching knowledge which could inevitably be used in biomechanical feedback of key technical parameters for coaches.

Table 8.5. Summary of coaches' perceptions of posture and the comparable biomechanical results from Chapter 8

Coaches' Perceptions	Biomechanical Results
Posture and body rotation closely linked	- Greater thorax flexion in the backswing was related to less upper thorax axial rotation in the backswing - Sub-groupings of golfers based on their degree of thorax flexion and upper thorax axial rotation - Head movement in medial-lateral direction not related to thorax axial rotation - Moderate relationship between X-factor and medial-lateral COP movement
Difference between trunk and pelvis rotation in the backswing and the rate at which the difference is decreased in the downswing	- Golfers' largely differed in the degree of lumbar, thorax, upper thorax and X-factor axial rotation throughout the swing - Timing of maximum X-factor was a distinguishing feature between golfers - Rate of change in X-factor also important in downswing - Pelvis was more rotated towards the target than thorax and upper thorax.
Body rotation linked to powerful swings	- Individual body rotation parameters did not explain differences in clubhead linear velocity or ball velocity - Complex interaction between body rotation parameters and posture parameters required to explain clubhead linear velocity
Body rotation produces simple and repeatable swings	- Core trends in body rotation parameters between golfers and variation was due to subtle differences

Chapter 9 Preliminary Biomechanical Report for Golf Coaches

9.1 Introduction

Expert golf coaches have previously advocated the use of technology in their coaching in order to further their coaching ability (Schempp et al. 2007). These expert coaches understand that precise quantitative feedback may be more beneficial for elite performers who require accurate information to detect errors and strengths in an already proficient technique (Smith and Loschner 2002). The quantitative feedback provided by biomechanical analysis can be used as an instructional aid in coaching or as a resource for gaining new information. As Lees (2002) reported, there are multiple stages involved in effectively utilising biomechanical analysis for improving an individual sporting performance. Firstly, the key technical parameters need to be identified and secondly, appropriate data collection and analysis methods need to be established to measure the key technical parameters. Following this, the data must be interpreted, in order to identify deficiencies or strengths in the technique and inevitably feedback to the coach to help determine effective coaching practices. Thus far, the studies in this thesis have identified the key technical parameters of a successful golf swing using golf coaches' perceptions and comparison to the current literature (Chapter 2 & Chapter 3). Data collection and analysis techniques have been refined in order to quantify several of these key technical parameters during the golf swing (Chapter 5 & Chapter 7). In addition, further work has been done to identify individual golfer differences and to understand the relationships between key technical parameters further (Chapter 6 & Chapter 8). Therefore, there was a need to communicate the biomechanical data to golf coaches, which has been identified as a challenging stage in biomechanical analysis (Buttifield et al., 2009). Buttifield et al. (2009) suggested that biomechanical feedback should allow for measures of long term effectiveness, account for movement variability, address an athletes learning style and account for the frequency of in-depth biomechaincal analysis. In addition, one coach from the qualitative study (Chapter 2) spoke about the limitation with current biomechanical reporting in golf with reporting data at discrete key events rather than throughout the swing:

> *The problem with a lot of the [biomechanical analysis] systems [are] they generally track what it is like at the start or the end of the movement. I don't quite like the idea of that, I like the journey that the body will go on, it is equally*

important. A lot of systems seem to be there is the top [of the backswing] there is impact but how has that happened...is more important.

The purpose of this chapter is to generate a report to present the biomechanical data identified within this thesis to golf coaches. The key objectives were: to include biomechanical data of the key technical parameters of the golf swing at discrete swing events and throughout the swing; to include measures of a golfers variability (e.g. multiple swing trials); have the capabilities for the report be produced on the day and have the capability to compare across conditions (e.g. clubs or testing sessions). This chapter details the methods used to create a preliminary golfer report as well as providing recommendations for future development.

9.2 Methods

Following the general data collection and analysis methods in Chapter 4 a biomechanical report was generated using the reporting tool in Visual 3D (C-motion, USA). The Visual 3D reporting tool was used because much of the data processing and analysis was performed using this software and the report template offered good degree of flexibility when presenting the golfer's data.

The Visual 3D reporting tool allowed the data processing, analysis and report generation to be conducted in one action using the pipeline commands. This software feature could be useful if the biomechanical feedback needed to be delivered immediately proceeding the data collection. The report template contained a series of pages which included the desired kinematic or kinetic parameters which would be presented to the coach. For example, the page could include temporal curves of pelvis axial rotation throughout the swing or a table of values at key swing events. Visual 3D can store data from multiple golfers within a database which can be imported into report templates. The database capability could then allow benchmark data to be included within reports. Finally, Visual 3D could distinguish between conditions (e.g. clubs, testing sessions) by setting up 'tags'. The tags were key words or phrases that described the data trials and could be selected so that data analysis or reporting was performed on the selected tags only. Images could also be added to the report pages.

Based on the list of key objectives presented in §9.1 the biomechanical report for golf coaches was designed to include measurements of; swing timing, set-up parameters, impact parameters, posture parameters (2D and 3D), knee angles, centre of gravity and centre of pressure displacements, total force, body rotation (i.e. pelvis, trunk and X-factor), sequential movement of body segments (i.e. axial rotation velocity and X-factor velocity), depiction of shaft motion and arm and wrist angles. These parameters were identified by golf coaches during the qualitative study (Chapter 2).

A custom pipeline was written using the Visual 3D scripting language to analyse the data and generate a biomechanical report for coaches' (Appendix I). A flow diagram of the pipeline process is presented in Figure 9.1. It was envisaged that a database of golfers could be generated in order for mean and standard deviations across a group of similar golfers to be incorporated into the report to provide benchmarking data. Therefore, group mean and standard deviaitons were included in the report and created from data of over 30 low handicap golfers from whom biomechanical swing data had been collected during this project. This involved creating a specific Visual 3D database of golfers whereby the mean and standard deviations could be calculated and could be easily updated when more golfers were tested.

9.3 Results

An example of a biomechanical report for a single golfer and multiple trials using a driver is provided in the following pages. The information contained in the report could then be used by coaches to support future coaching sessions or provide a benchmark for future biomechanical analysis. The mean and standard deviations at key swing events are presented in tables for both the individual golfer and the mean values from golfers contained in the database (i.e. GRP Mean). The key technical parameters are also presented as temporal data curves and normalised from TA to FT. In all temporal data curves, the green vertical line represents the mean TB position across trials and the purple vertical line represents the mean IMP position. The shaded area on the curves represents the standard deviation across the number of trials analysed. The red paths of the club are the marker paths for OBJ1 (attached at the grip) and OBJ2 (attached at the hosel). Once data had been collected and gap filing achieved using Vicon Nexus, the report could be generated instantly following execution of the pipeline.

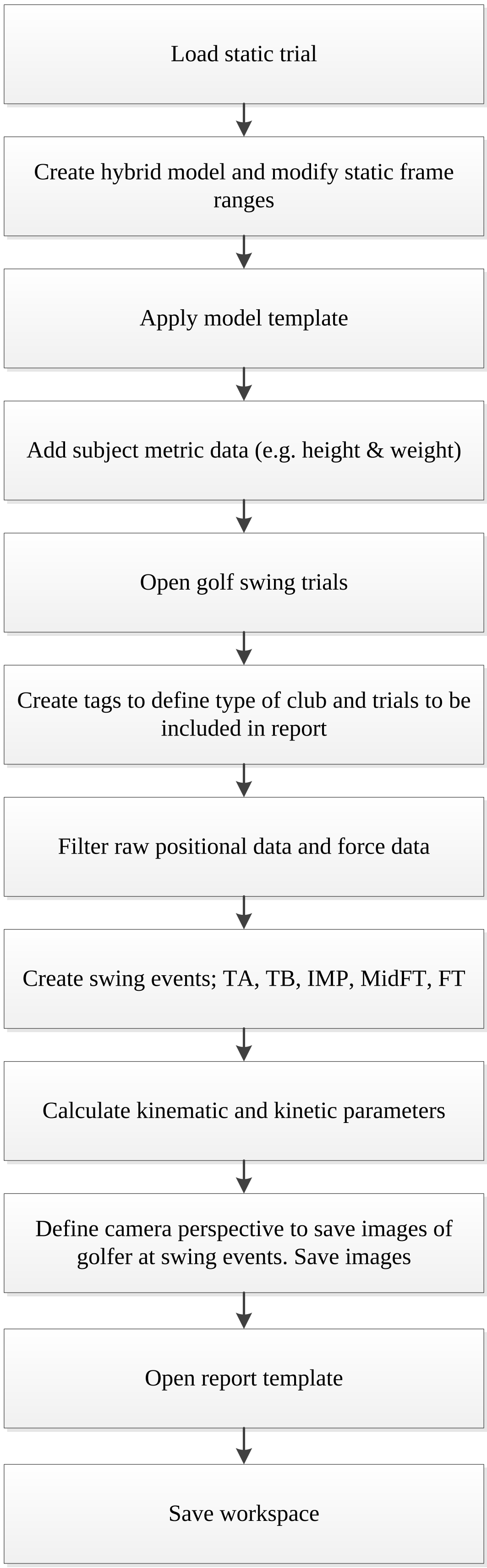


Figure 9.1. Flow diagram of custom written Visual3D pipeline process to produce a golf biomechanical report.

Subject Information

Golfer Biomechancial Analysis

Name : ____________, ____________ ___Subject ID : ______________

Height : _______ m   Weight : _______ Kg   Sex : _______

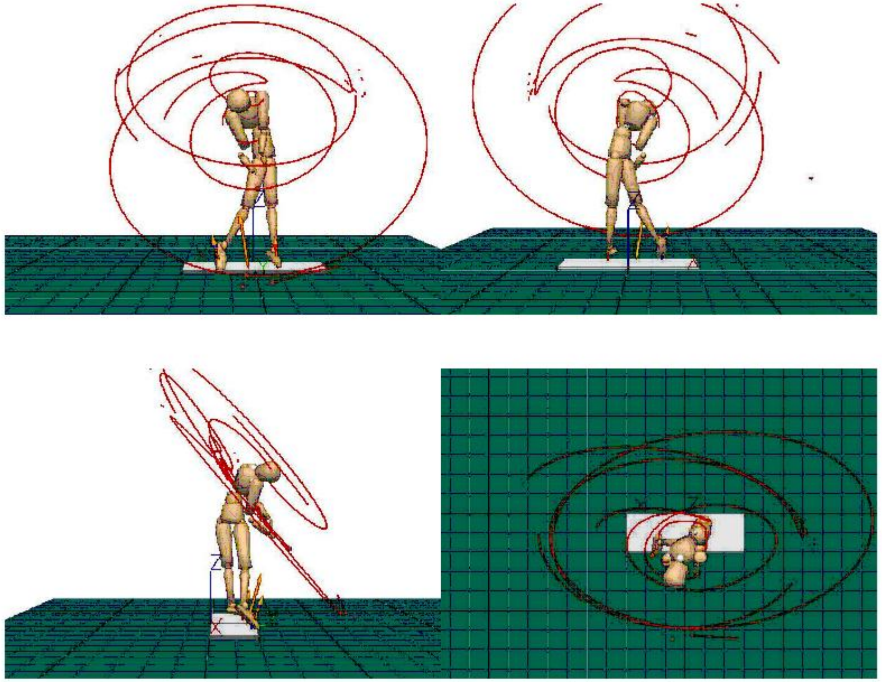
Date of Birth (mm/dd/yyyy) : ____/____/________

Test Date (mm/dd/yyyy) : ____/____/________

Diagnosis:

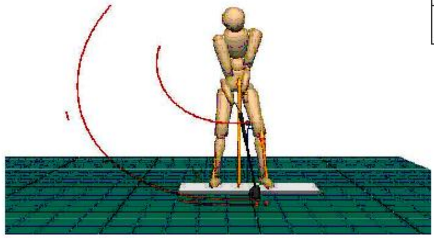
Test Conditions:

Swing Time

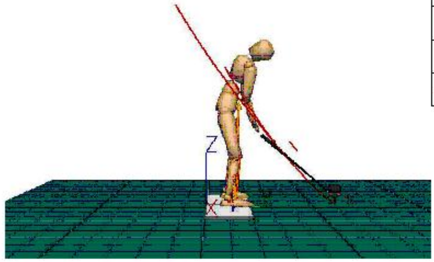


	Swing Timing (s)			
	Mean	SD	GRP Mean	GRP SD
Swing Time	1.3	0.0	1.1	0.2
Backswing	1.0	0.0	0.9	0.2
Downswing	0.3	0.0	0.3	0.0

Set-Up

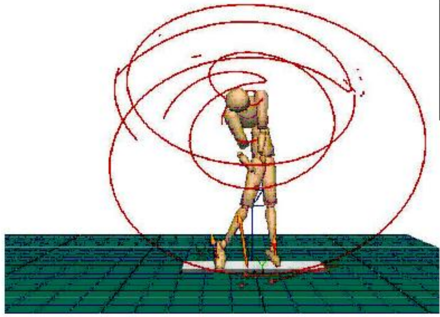


	Postural Balance			
	Mean	SD	GRP Mean	GRP SD
Stance Width (cm)	43	1	51	5
Ball position (cm)	-4	1		
%COP (M-L)	50	3	56	5
%COP (A-P)	60	2	60	7

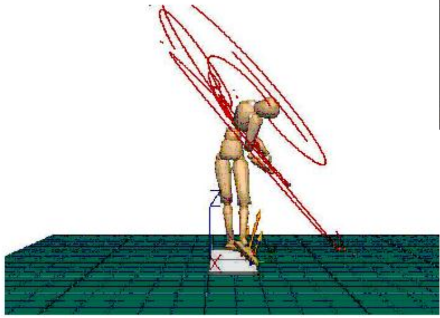


	Postural Kinematics			
	Mean	SD	GRP Mean	GRP SD
3D Trunk Flexion (°)	-30	1		
3D Trunk Lateral Bend (°)	-11	0		
Right Knee Flexion (°)	-23	0	-25	3.3
Left Knee Flexion (°)	-27	0	-24	3
2D Trunk Flexion (°)	31	0	35	3
2D Trunk Lateral Bend (°)	-2	2	-5	3

Impact

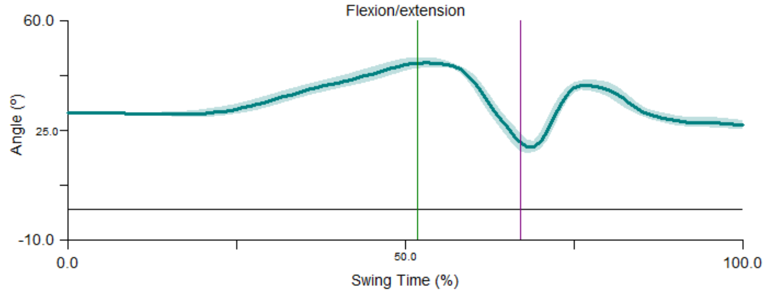


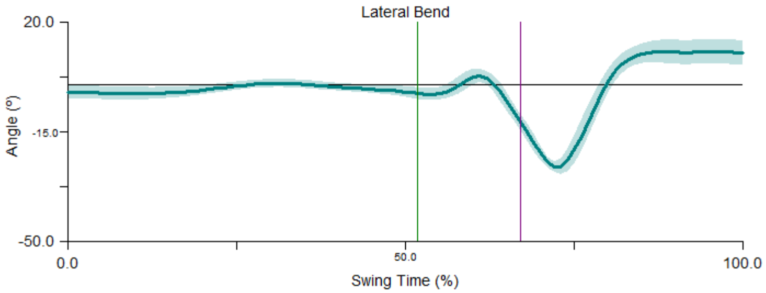
	Postural Balance			
	Mean	SD	GRP Mean	GRP SD
Stance Width (cm)				
Ball position (cm)				
%COP (M-L)	63	6	65	26
%COP (A-P)	79	1	70	11



	Postural Kinematics			
	Mean	SD	GRP Mean	GRP SD
3D Trunk Flexion (°)	-18	0		
3D Trunk Lateral Bend (°)	-32	3		
Right Knee Flexion (°)	-14	1	-20	4
Left Knee Flexion (°)	-3	1	-13	3
2D Trunk Flexion (°)	21	2	27	6
2D Trunk Lateral Bend (°)	-12	0	-11	0

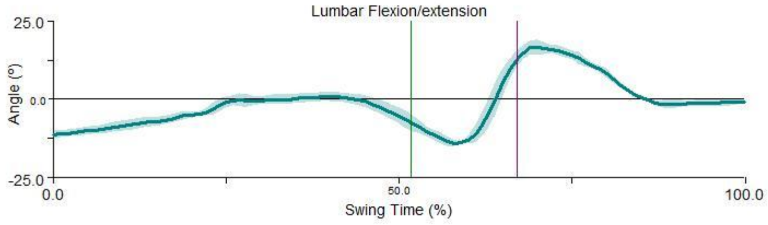
2D Trunk Angle

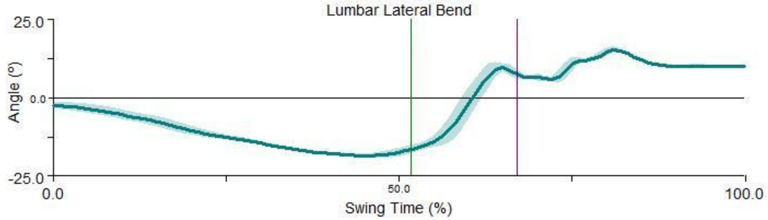


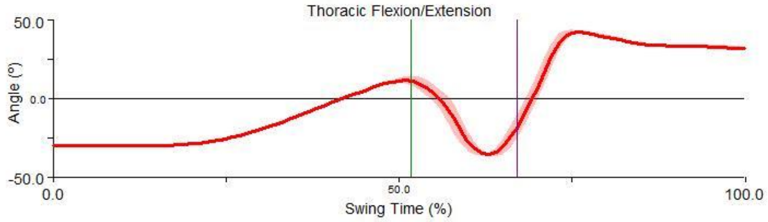


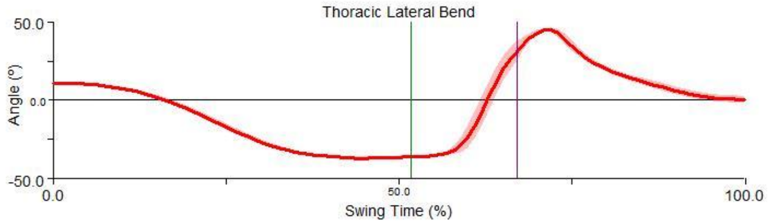
	Mean (Flexio	SD	GRP Mean	GRP SD	Mean (Later	SD	GRP Mean	GRP SD
TB (°)	46.5	1.7	43.1	4.6	-2.8	1.7	-4.4	5.6
IMP (°)	21.1	1.7	27.5	5.9	-11.9	0.5	-11.1	5.2

3D Lumbar and Thoracic Angles

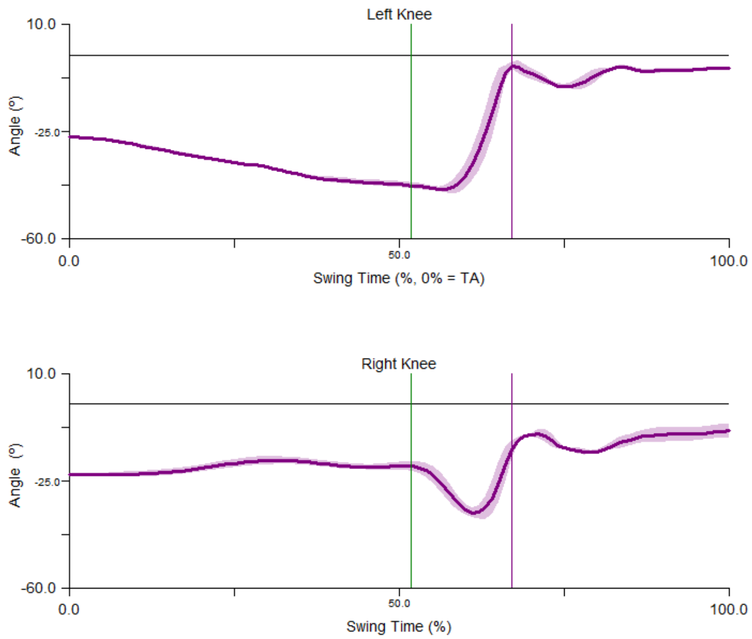






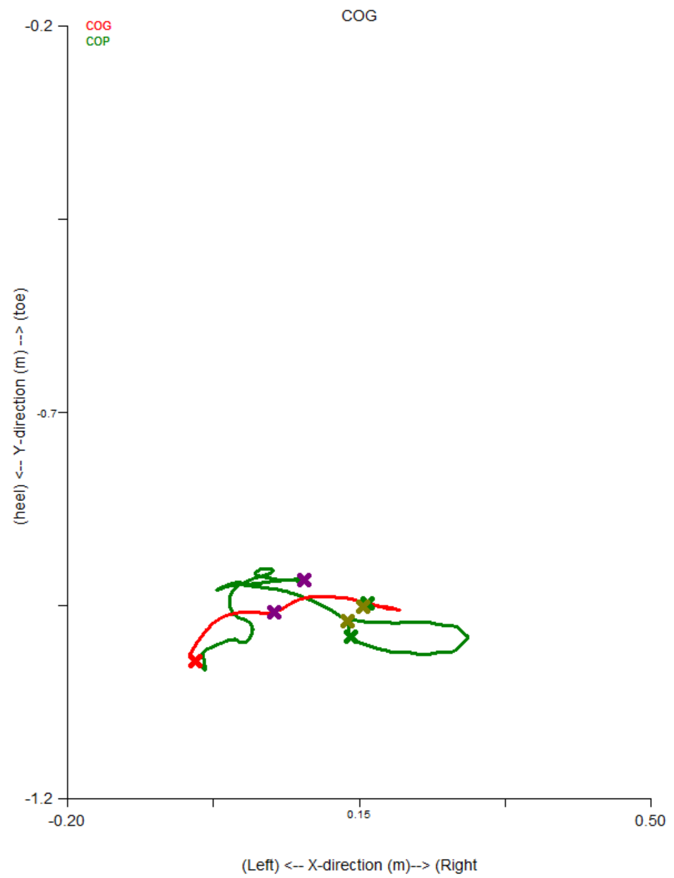


Knee Flexion Angle

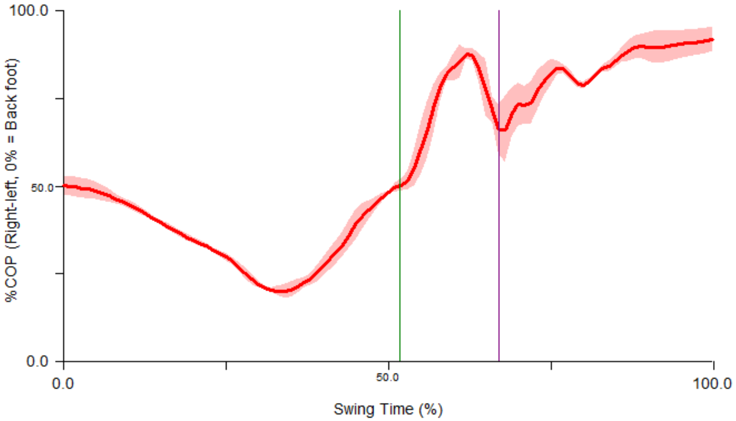


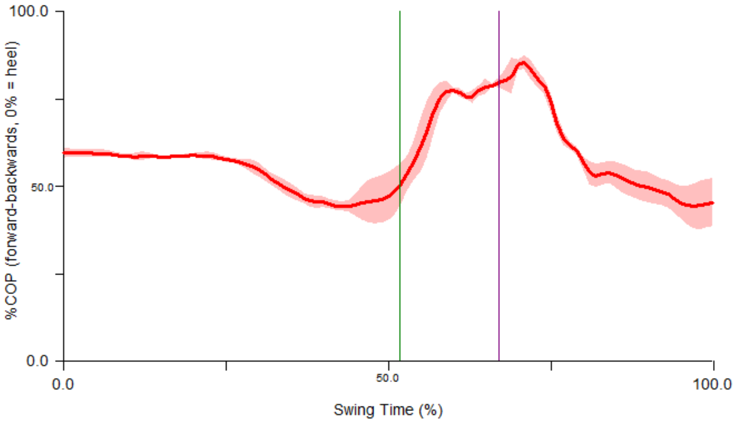
	Mean (Left)	SD	GRP Mean	GRP SD	Mean (Right	SD	GRP Mean	GRP SD
TB (°)	-42.5	1.1	-42.0	8.1	-20.3	1.8	-15.9	7.0
IMP (°)	-2.7	0.7	-12.8	9.3	-13.7	1.0	-19.7	10.3

Centre of gravity vs. Centre of Pressure

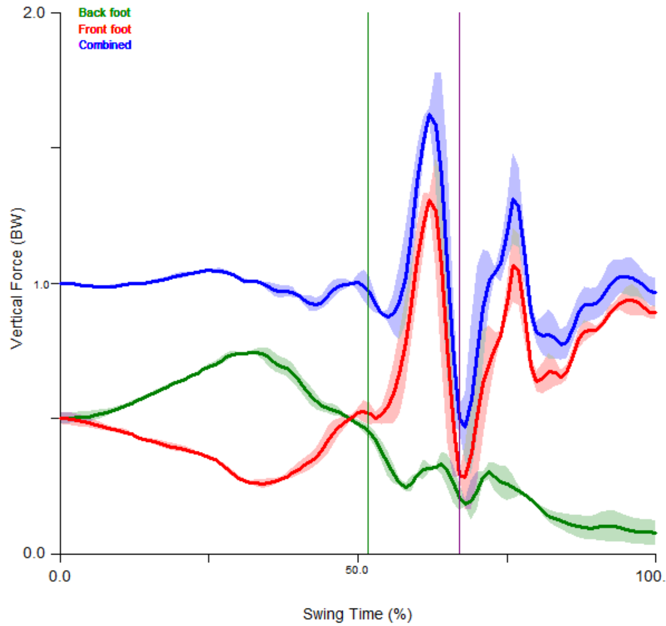


Centre of pressure





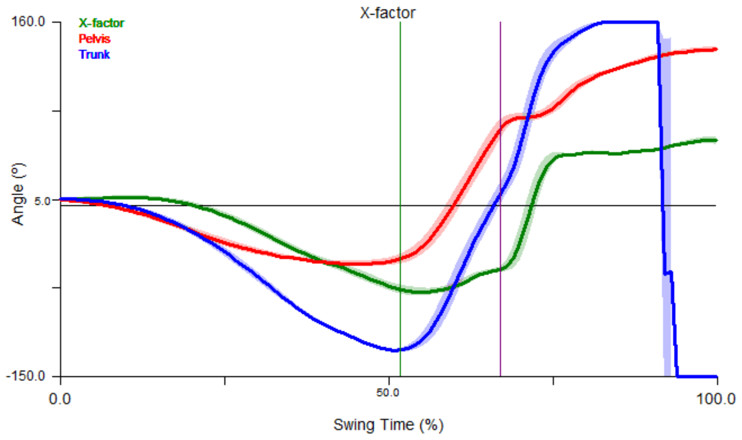
Total Force



	Front Foot (Total force N)				
	Mean	SD	%BW	GRP Mean	GRP SD
TA (N)	279	12.4	50	54	
TB	285	21.0	51	29	
IMP	134	17.8	24	61	

	Back Foot (Total force N)				
	Mean	SD	%BW	GRP Mean	GRP SD
TA (N)	279	11.3	50	46	
TB	254	3.1	45	57	
IMP	110	9.9	20	21	

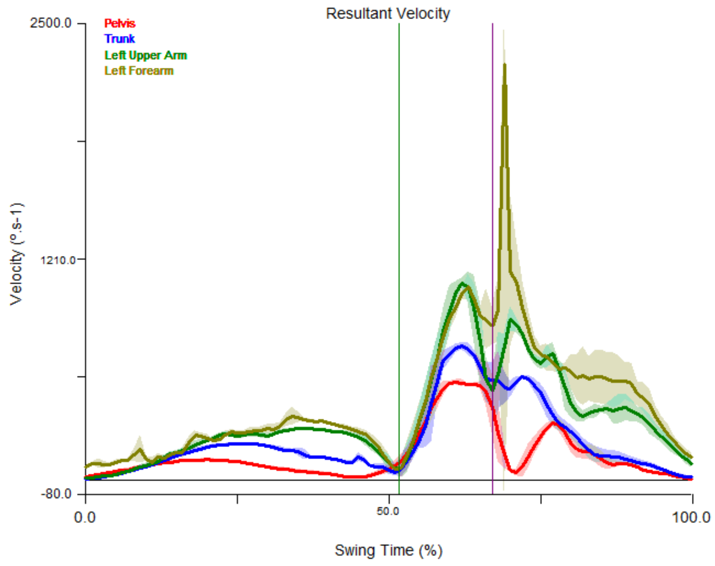
Body Rotation



	X-factor (°)			
	Mean	SD	GRP Mean	GRP SD
Set-up	4.5	1.7	8.5	5.0
TB	-73.7	3.5	-53.0	11.6
IMP	-56.9	2.5	-32.3	8.1

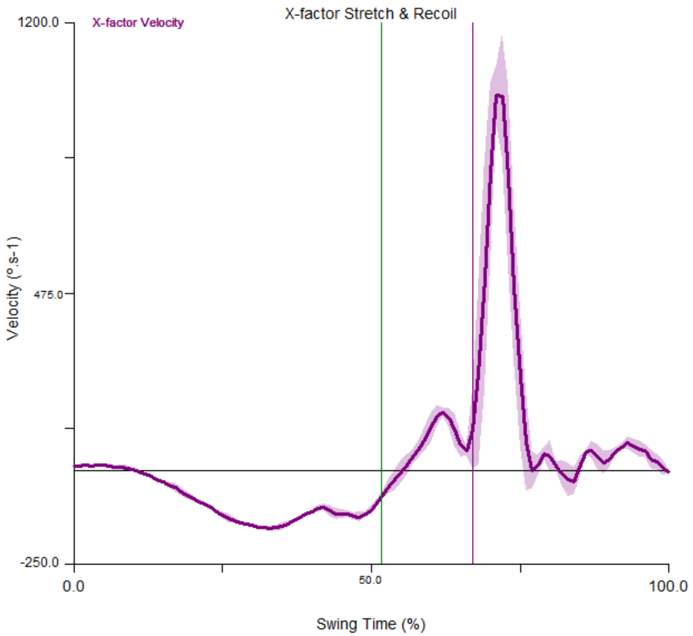
	Pelvis (°)					Trunk (°)			
	Mean	SD	GRP Mean	GRP SD		Mean	SD	GRP Mean	GRP SD
Set-up	4.8	1.9	1.6	3.9	Set-up	5.7	0.4	4.6	3.3
TB	-47.6	3.1	-42.4	7.5	TB	-127.2	1.0	-98.6	11.9
IMP	67.2	2.9	45.5	12.4	IMP	10.0	0.8	11.3	9.1

Sequential Movement



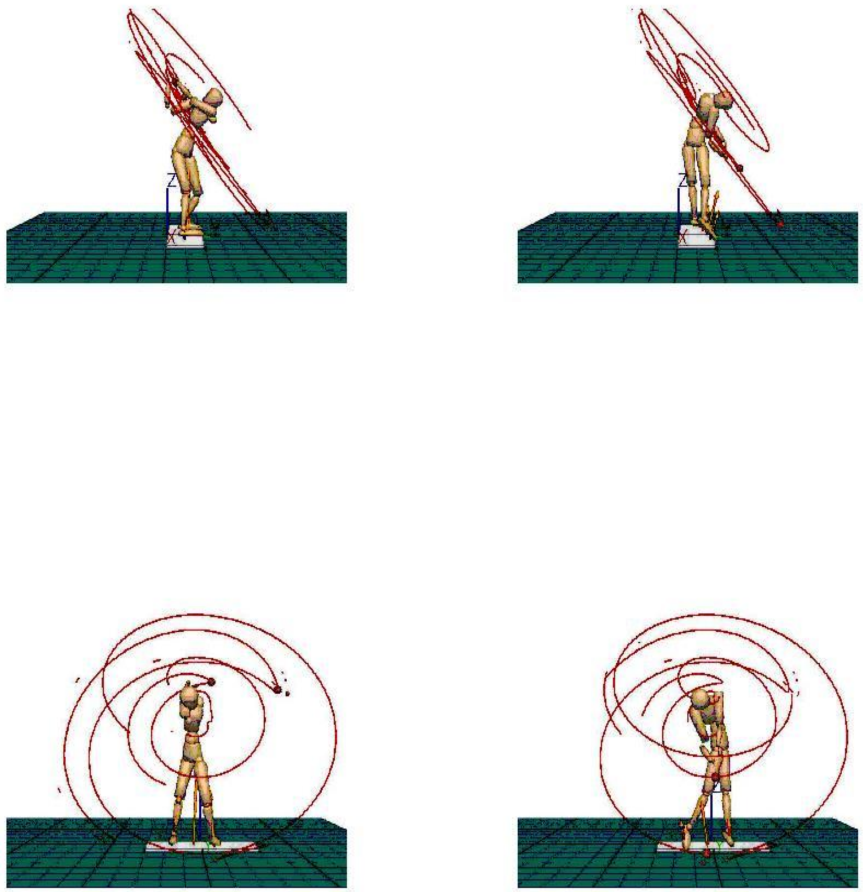
	Time (s)	
Pelvis to Trunk	0.03	if -ve trunk max. velocity before pelvis
Trunk to Left Upper Arm	0.08	if -ve lupa max. velocity before trunk
Left Upper Arm to Left forearm	-0.05	if -ve lfa max. velocity before lupa

X-factor Velocity

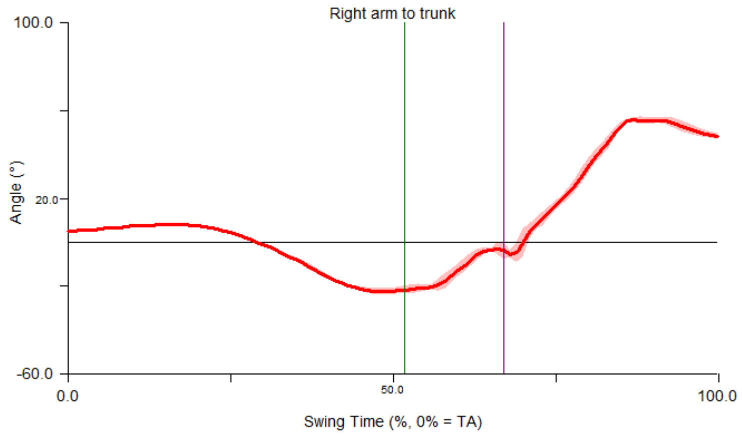


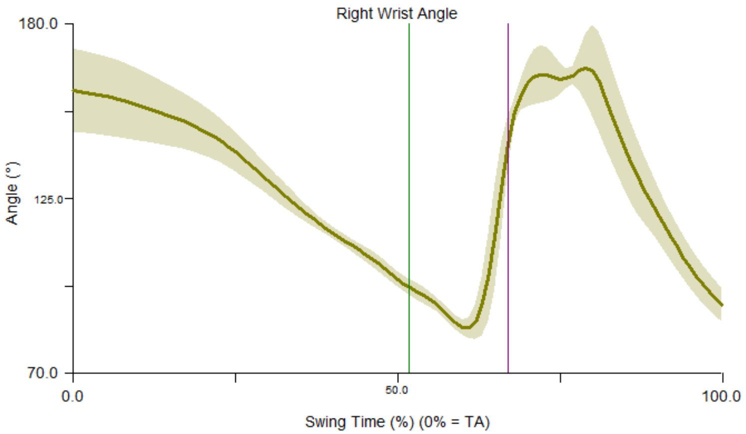
	Mean	SD	GRP Mean	GRP SD
X-factor TB (°)	-73.7	3.5	-53.0	11.6
X-factor Max (°)	-76.3	3.4	-54.6	11.8
X-factor Stretch	2.6	0.2	1.6	

Shaft Motion



Arm Kinematics





9.4 Discussion

The purpose of this Chapter was to generate a report to present biomechanical data to golf coaches. The first objective was to include biomechanical data of the key technical parameters at discrete swing events and throughout the swing. This was achieved by presenting the data in tabular format and as data curves. A second objective was to include measures of a golfers variability as had been recommended by (Buttifield et al., 2009). The variability between golfer's swings was represented by the standard deviation values in the tables and as shaded regions on the temporal data curves. Thirdly, the report was required to include comparison across conditions such as clubs or testing sessions. This functionality was developed into the report by setting up 'tags' to identify different conditions, such as clubs, so that the relevant trials could be presented in the final report. In addition, benchmark data of the mean and standard deviation of the group of golfers was provided at key swing events in order to detect the variability between an individual golfer and group of similar ability golfers.

The report has been given to a few coaches following a testing session with a golfer. The coach has been guided through the report by a biomechanist who explained the data and highlighted any noteworthy findings. The biomechanical data is also accompanied by TrackMan data which provides measures of performance for the swings presented. For some coaches who were comfortable with biomechanical data, the data curves and values were readily interpreted. However, for other coaches a greater explanation of the biomechanical data was required. Therefore, this suggests further developments need to be made to communicate the data more effectively.

For future biomechanical reports it would be beneficial to incorporate results from principal component analysis as these outputs can provide clear indication of differences in technique between golfers and within golfer trials. However, further work would be required to develop data visualisation techniques to communicate PCA results with coaches in an easy interpretable manner.

The report in its current form has several limitations despite addressing the main objectives of this chapter. The report is currently 15 pages long which may include information not relevant to all golfers. Online presentation of the report could improve the communication of important features to coaches as relevant pages can be highlighted and directly navigated to.

9.5 Summary

This chapter has presented the development and design of an example biomechanical report produced using Visual 3D and based on the findings of this thesis. The report included many of the key technical parameters identified by golf coaches during the qualitative study. The report presented both discrete values and temporal data curves of key technical parameters throughout the golf swing. For future biomechanical reports it would be beneficial to incorporate results from principal component analysis, as these outputs can provide clear identification of differences in techniques between golfers and within golfer's trials. Whilst some of the features of effective biomechanical feedback have been addressed in the golf biomechaincal reports there is still further work required to refine the report.

Chapter 10 Conclusion - Implications, Limitations and Future Directions

10.1 Introduction

The purpose of this thesis was to (i) identify the key technical parameters of a successful golf swing, (ii) to compare coaches perceptions to the current golf biomechanical literature, (iii) to define suitable methodologies for measuring key technical parameters and (iv) to biomechanically underpin the key technical parameters and further identify differences in golfers' technique related to performance. This chapter assesses the outcome of these through the research questions, as well as identifying the novelty and implications of this research, the main limitations of the work and suggestions for future research.

10.2 Research Questions

The research questions posed in the general introduction (Chapter 1) will be addressed and summarised based on the outcomes of each chapter.

Q1. What are the key technical parameters that golf coaches' perceive to be important for a successful golf swing?

Although golf coaches used various terminologies to describe the key technical parameters, there were five parameters perceived to be key to a successful golf swing. The five key technical parameters were 'club motion', 'posture', 'body rotation', 'sequencing of body movements' and 'arm and wrist motion'. There were six descriptors of performance often used in combination with the key technical parameters, which were 'simple', 'consistent', 'repeatable', 'accurate', 'powerful' and 'controlled'. The key technical parameters were often interlinked and contained sub-categories. Coaches also stated that they would analyse the swing at stages but were keen to analyse the movement as a whole.

Q2. How do golf coaches' perceptions of the key technical parameters of the golf swing compare to current golf biomechanical literature?

Several of the coaches' perceptions had received attention in the current biomechanical literature. However, limitations existed in previous data collection and analysis methodologies.

Posture was also described in terms of postural kinematics and postural balance in the literature. Often postural kinematics were reported as 2D angles for a single trunk segment which was similar to the description of spine angle offered by golf coaches. However, 3D studies of trunk kinematics questioned the suitability and accuracy of 2D trunk angles for describing the anatomical movements. Other related parameters to postural kinematics, such as head and knee kinematics, have received little to no attention in the golf literature. Furthermore, the relationship between postural kinematics and postural balance had not been investigated.

Much of the golf biomechanical literature was focused on biomechanical parameters related to clubhead linear velocity or ball velocity. The most widely investigated parameters in the literature were thorax and pelvis axial rotation, X-factor and proximal-to-distal sequencing of body segments. Whilst coaches identified body rotation and sequential sequencing as key technical parameters, a greater number of coaches made reference to a golfer's posture.

Therefore, based on the prevalence of posture being identified by coaches and the lack of biomechanical literature it was necessary to conduct further analysis in this area. In addition, the close association with body rotation was also considered (Chapter 3).

Q3. Are existing biomechanical data collection and analysis methods appropriate for measuring key technical parameters of the golf swing?

There were limitations with current biomechanical data collection and analysis methods. Often golfers' posture was reported as 2D angles for a single trunk segment which did not account for the six degrees of freedom of the golf swing. The single trunk segment also masked differences between the lumbar and thorax regions of the trunk. Hence, a 3D analysis and a two segment trunk were developed and applied in subsequent studies. The COP and COG measures were widely reported in the literature and adapted for the golf swing. The COP in medial-lateral direction was computed based on a previous study by Ball and Best (2009). However, as COP in the anterior-posterior direction had not been reported in golf studies it was defined as the position between the toe and heel. The whole body COG position included the golf club which was achieved by modelling the golf club based on mean club shaft and club head weights and dimensions. Furthermore, COG was measured relative to the front and back foot of the golfer in anterior-posterior and medial lateral directions which could be used in future studies (Chapter 5).

Body rotation, in particular X-factor, has typically been reported as 2D projected angles. These angles are susceptible to perspective errors. Therefore, a 3D X-factor measurement method was developed using upper thorax and pelvis segments.

Q4. How can we biomechanically analyse the key technical parameters of individual golfers to support future work in understanding the relationship with performance?

Principal component analysis was chosen as the most suitable continuous data analysis technique which could identify underlying biomechanical differences in posture parameters (Chapter 6) and body rotation (Chapter 8). The PCA weighting factors showed where in the swing these differences occurred and together with mean curves could be used to biomechanically interpret the differences between data curves. The most common terms used to biomechanically interpret the principal components were offset, rate/range of motion and timing for the rate/range of motion. For kinematic parameters often two to four principal components were required to explain over 90% of the variance and for kinetic parameters (i.e. COP) four - five parameters were required to explain the variance. The variation between data curves occurred throughout the swing, from TA to MidFT, including the backswing and downswing.

Scatterplots of PC scores provided clear representation of the differences between individual golfers which were confirmed by comparing golfers with similar or different PC scores to the original data. The PC scores could then also be used to investigate relationships between technical parameters.

In Chapter 6, the differences in golfers' $\%COP_{M\text{-}L}$ styles were strongly correlated to $\%COG_{M\text{-}L}$ movement which could be used to distinguish between golfers' techniques. The magnitude of thorax flexion and lateral bend were strongly correlated which could have implications for body rotation. Right and left knee flexion magnitudes and rate of motion were also correlated throughout the swing, although there were different patterns in knee flexion between them. The rate/range of thorax lateral bend, particularly in the downswing was closely related to clubhead linear velocity and a sub-grouping appeared in the data. There were no clear relationships between horizontal and vertical launch angles perhaps due to the scatter in these measures of performance within golfers.

In Chapter 8, strong relationships were found between body rotations PCs which were most likely due to the segments being linked in the golfer and golfer model. Postural kinematics did appear to correlate with body rotation. There was evidence to suggest that golfers with more thorax flexion would have less upper thorax axial rotation. However, the relationships between body rotation and measure of performance were poorly related which suggests that the complex interrelationship of technical parameters may better explain differences in performance.

10.3 Novelty of Research and Implications

This research has provided novel approaches to golf biomechanical research and has provided contributions to golf biomechanical literature and golf coaching knowledge.

Firstly, golf coaches' perceptions of the key technical parameters of the golf swing had not been documented using a scientific approach in the previous golf literature. Using the qualitative coaching-biomechanics interface approach, this thesis was able to systematically capture golf coaches' perceptions of the key technical parameters which were directly related to a successful golf swing (Chapter 2). By comparing the coaches' perceptions the gaps, differences and similarities to current golf biomechanical literature were identified and provided justification for the subsequent biomechanical studies contained in this thesis.

Whilst the literature review served to identify gaps and similarities between coaches' perceptions and current golf biomechanical literature, it also highlighted potential limitations with previous data collection and analysis techniques, notably those used to measure posture and body rotation. Therefore, this thesis addressed the limitations of previous studies examining posture and body rotation in the golf swing. Of note, was the demonstration of the benefits of defining a two segment trunk model, to include lumbar and thorax segments, for significantly improving the computation of posture parameters. Furthermore, 2D measurement of X-factor was found to be susceptible to perspective errors and therefore 3D measurement of X-factor was developed. The methodology chapters (Chapter 5 & Chapter 7) provided recommendations for future biomechanical studies which measured posture or body rotation parameters.

Although, PCA had been used in previous biomechanical studies to identify differences in running and weight lifting techniques, it had not been readily applied to the golf swing. Only one other study had used PCA to investigate biomechanical parameters throughout the golf swing; however this was between two vastly different ability groups and considered only the ground reaction forces. Therefore, applying PCA to key technical parameters during the golf swing, in a group of similar ability golfers was a relatively unique approach of this thesis and provided results which can be used to inform golf coaching.

The results from the PCA analysis served to reinforce existing coaching knowledge which had not been clearly supported in the current golf literature. For example, a golfer's posture was related to their body rotation during the swing. Therefore, coaches should be aware that body rotation is closely associated to a golfer's posture when coaching. The combination of the qualitative coaches study and PCA also provided new insights into unexplored parameters, such as head movement, knee angles and the relationship between postural balance and postural kinematics during the golf swing.

This approach was also used to develop biomechanical reports to provide relevant and comprehensive feedback for golf coaches on a golfer's techniques. To the author's knowledge, these are the most advanced and coach-led reports available from golf biomechanics testing.

Overall, the approaches adopted in this thesis sought to better integrate golf coaching knowledge and biomechanical analysis. Whilst this has partly been achieved there are limitations and areas for future research which should be acknowledged.

10.4 Limitations

In Chapter 2, a total of 16 golf coaches were included in the qualitative study, which was more than previous studies in this area had used. Whilst it was assumed that theoretical saturation had been reached from this sample of coaches, it is not known whether coaches from different countries shared similar or contrasting views, as all coaches in this country had been through the PGA coaches training program.

The analysis of golfer kinematic required the use of the Vicon motion analysis system. The attachment of retro-reflective markers is susceptible to skin movement artefact which may not represent underlying skeletal motions. The residual measures calculated in Visual 3D can offer an estimate of the amount of movement and for the majority of segments these values were less than 0.03 m. The ideal solution to compute skeletal motion is to use bone mounted markers however, due to ethical issues this would not be feasible. Furthermore, the testing was conducted in an indoor laboratory which may not replicate real on course or range conditions.

In Chapter 6 and Chapter 8, PCA was used effectively to distinguish differences between golfers' posture and body rotation parameters throughout the swing. The correlations and cluster analysis began to show the emergence of commonalities between groups of golfers, however due to the small sample size it was not possible to observe further commonalties across principal component scores.

10.5 Future Directions

Over the course of this thesis there have been several areas identified for future research directions. Examining the sources of coaches' perceptions of the key technical parameters could provide interesting connections between coaches. Furthermore, it would be of interest to include coaches from other countries with a strong golfing history (e.g. USA, Spain) with which to compare the key technical parameters identified in this study.

The coaches identified several more key technical parameters such as sequential movement of body segments, arm and wrist kinematics and club motion which could not be addressed in this thesis. Therefore, by first defining appropriate methodologies and subsequent principal component analysis, these parameters could also be biomechanically analysed.

There are clear limitations with collecting biomechanical data indoors as it may not adequately represent real on course or range conditions. Therefore, future studies could look to collect biomechanical data outdoors using motion analysis systems adapted to be used in bright light conditions. Such systems have recently become available making this a timely opportunity.

A concern for coaches was the repeatability of within golfer's technique variability. The principal component analysis has provided a useful method for quantifying within golfer variation (i.e. between trials) and provided visual interpretation. However, it was beyond the scope of this thesis to within golfer variability using PCA. Therefore, future studies could evaluate the effectiveness of PCA in examining within golfer variability.

The results of PCA, correlation and cluster analysis were useful exploratory stages to further understanding of golfer kinematics, kinetic, measures of performance and the relationship between them. A further powerful stage would be to identify commonalities in PC scores across multiple technical parameters. This may be able to identify groupings in golfers' techniques according to a number of biomechanical features seen in their data. Also, by including PCA results of the additional technical parameters it could result in a robust model of a golfer's swing. The ability to group golfers based on biomechanical features of their technique could then be used to tailor the benchmark data provided in the biomechanical reports in order to provide more targeted advice/feedback to the golfer relative to those exhibiting similarity in technique.

Finally, it would be of interest to examine the biomechanical differences in the key technical parameters when using different clubs.

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Appendix A Observation Guideline

Observation of Golf Coach

Subject Number	
Date	

Aims & Objectives: Observe golf coach delivering a technical coaching session, identify types of feedback golf coaches use and how it is presented to the golfer, determine technical aspects of golf swing

Name	
Gender	Male Female
DOB	
Coaching Qualification if so level	Yes No Level:
Venue	
Level of Golfer Being Coached in session	

Structure of Session
Beginning, aims & objectives, content, where, resources, input from golfer, end

Set-up
No. Of shots, different shots performed

Coach Behaviour
Position of coach and golfer

Technical Identification
Aspect of swing focused on, aspect of technique focused on

Golfer behaviour & interaction
Golfer input during feedback, player coach interaction

Technology Used
What is used, how is it used, where is it positioned, how often is it used during session, explanation accompanying the technology

Appendix B Interview Guideline

Subject Number	
Date	

1. Introductory Explanation

I would like to begin by thanking you for agreeing to participate in this interview study. As part of my PhD project we are talking to all levels of golf coaches about their thoughts on the important or key technical aspects of a successful golf shot, both in terms of a drive and iron shots.

I will be using a tape recorder and video camera to get complete and accurate information and to provide a more efficient interview process. The tape recorder will also be used to reproduce a typed transcript for later reference. The information received will remain completely confidential. If selected quotes from the interview are used to illustrate important ideas these will remain strictly anonymous.

Your participation in this study is entirely voluntary and you are free to decline to answer any questions or stop the interview at any time. There are no right or wrong answers to the questions that I will be asking. We wish to learn from your experience and your expertise what technical aspects are regarded as important or key to a successful golf shot. When answering the questions please reply with regards to the highest skilled golfer than you have or do coach i.e. the lowest handicap golfer. We want you to take your time and think as deeply as you can.

2. Specific Questions

Name			
DOB		**Gender**	
Handicap			
Coaching qualification, if so level	Yes ☐ No ☐ Level:		
Courses attended			
No. years coaching			
Level of golfer coached most often			
Highest level golfer coached			
No. Hours coaching a week			
Club association			

Structure of Technical Coaching Session

Q1. Describe a typical coaching session

Set-plans, Beginning, Golfers actions/instructions, Location, Resources, Golfer input, Feedback methods.

- How do you begin your technical coaching session?
- Is there a structure to your technical coaching session?
- How many times do you get the golfer to swing during your session before any points are raised?
- Where would your technical coaching take place?
- What resources do you use during your coaching session?
- Do you follow the same structure for each session?
- Is there any input from the golfer at any stage?
- How do you feedback to the golfer, what methods do you use, e.g. demonstration, verbal feedback?

Notes:

Q1. What in your opinion are the key or vital technical characteristics of a top level golf swing (driver and iron)?

Driver and Irons, Swing outcome, Technical models, Fundamentals, Stages of the golf swing, Key words

- What do you mean/Clarify by that technical characteristic?
- Why is that 'technical coaching point' so important in your opinion?
- What should that 'technical coaching point' be?
- If you have an incorrect 'technical coaching point' what are the consequences to performance?

- What determines a successful golf swing performance in your opinion?
- What outcome would satisfy your description of a successful golf swing?
- What stage of the golf swing do you look to determine a successful golf swing?
- Do you look at the golf swing as a whole or do you break it down into stages?
- If so, what are these stages?
- What, if any, do you believe are the fundamentals to a golf swing?
- What are the buzz words or key words you most often use when coaching?

Notes :

Theory of Technical Analysis

Q. What has guided your technical analysis of the golf swing/shot?

Mechanisms, Classic coaching theories, Coaching principal source, Development/Future ideas,

- What do you base your coaching principals on?
- Are you open to new theories?
- Why do you believe that your coaching principals are right?
- Has your theory of what is a successful swing changed over recent years and if so why?

- Are there any classic coaching theories which the coach uses?
- Are there any theories that are not valued by the coach, if so why are they not?
- What is your understanding of the underlying mechanisms of the key technical aspects raised?
- Have the coaching qualifications been significant?
- If so what aspect? If not why not?
- Where does the coach gain his resources for coaching?
- What sources of information do you find most useful?
- Where does the coach see future knowledge will come from?

Notes :

Checklist:

Books		
Magazines		
TV		
Scientific Journals		
Coaching Manuals		
Observing other coaches		
Classic Coaching Theories		
Coaching courses		

Interview Feedback

Are there any important factors that we failed to discuss?

Did you feel I lead or influenced your responses in any way?

Did the recording equipment inhibit or affect you in any way?

Have you any comments or suggestions about the interview itself?

Are there any ways in which we could improve the interview structure?

Thank you for helping with this interview

Appendix C TrackMan Technology and Definitions

A single TrackMan radar continuously emits radio waves towards an object, and a change in wave frequency is experienced when they are reflected back from a moving object (i.e. the golf ball). Based on a series of equations, the change in the frequency of the wave can be used to give accurate measurements of an object's velocity relative to the radar source. In addition, based on monopulse principals, the TrackMan system uses multiple receivers to determine the angular position of the object (i.e. golf ball). In accordance with the monopulse principal, the receivers are set at a specific distance (D) and angle away from each other. The incidient angle or direction of the reflected wave (α) can then determined from the extra path the wave must travel between each receiver, which results in a phase difference between the two receivers ($\Delta\Phi$)(Figure C.1).

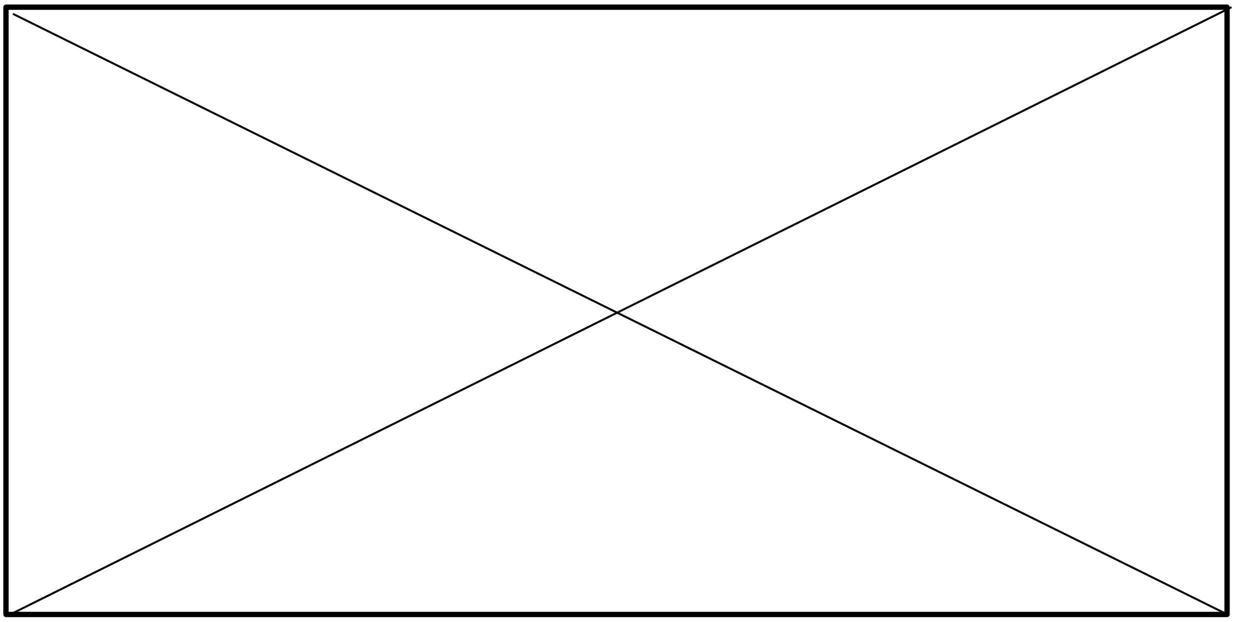


Figure C.1. Depiction of the phase-monopulse principal. C = speed of light, F_{TX} = original wave frequency, $F_{RX1/2}$ = shifted wave frequency, $f_{d1/2}$ = doppler frequency (Trackman, 2003)

Due to this advanced radar technology, TrackMan Launch claims to have the world's highest accuracy for measuring ball spin (± 15 - 20 rpm) and in turn will provide higher accuracy for calculating the trajectory of the ball. In addition, TrackMan calculates clubhead linear velocity from the centre of the club face, immediately before impact and claims to record clubhead linear velocity with an accuracy of ± 0.44 ms^{-1} (TrackMan, 2008). Nevertheless, even across the club face there is ~ 14% difference in clubhead linear velocity (Figure C.2). This difference in clubhead linear velocity can be explained by both the increased rotation of the clubhead through impact (i.e increasing rotational velocity) and the increased radii of the toe of the club compared to the heel of the club relative to the centre of rotation (i.e the hands).

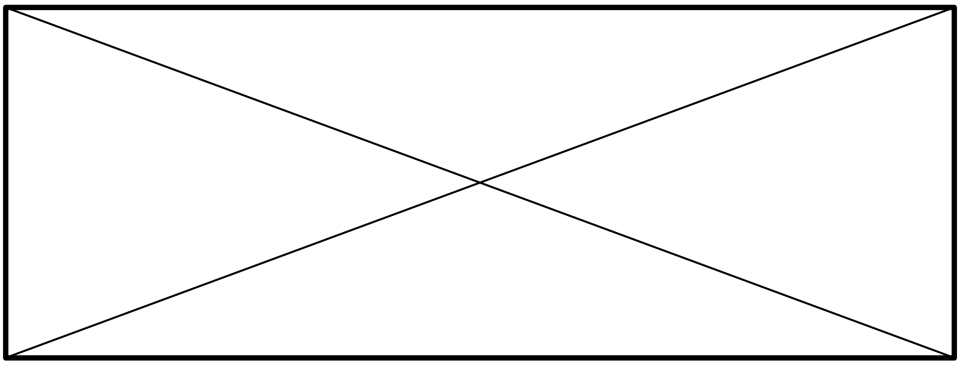


Figure C.2 Difference in clubhead velocity across the clubhead face (1) is centre of the clubface, (2) toe of club face and (3) heel of club face (TrackMan, 2008).

Validating such a system against a 3D motion analysis system would be advisable to ensure values obtained for clubhead linear velocity and ball velocity are reasonable (Betzler et al., 2006). Betzler et al. (2006) reported significant differences between mean peak clubhead velocities (42.3 m/s and 47.6 m/s) and ball velocities (63 m/s and 65m/s) when measured using a 3D motion capture system and launch monitor respectively. Nevertheless, the results from the different data collection methods yielded high correlations which the author suggested were due to differences in data acquisition.

Table C.1. TrackMan definitions, accuracy values and correlations for measured and calculated parameters

Variable	Definition	Accuracy	Correlation	Type
Clubhead Speed	Measured just before impact	±1.5 mph	Ball speed, carry and total	Measured
Ball Speed	Measured just after impact	±0.1mph	Club speed, ball type, club COR, dynamic loft, impact location	Measured
Smash factor	Ball speed divided by club speed, the ability to transfer power from club to ball	±0.01	-	Measured
Attack Angle	The vertical direction of the clubhead' s center of gravity movement, relative to flat ground level, at the point of maximum compression of the golf ball	±1.0º	Vertical launch angle, spin rate	Measured
Vertical Swing Plane	The angle of the swing plane of the clubhead seen from the ground and up	±0.3º		Measured
Horizontal Swing Plane	The swing plane of the clubhead, seen from above. Orientation left/right measured in relation to the target line	±0.3º	Club path, horizontal launch angle	Measured
Club Path	The horizontal direction of the clubhead's center of gravity, relatice to the target line, at the point in time of maximum compression of the golf ball	±1.0º	Horizontal swing plane, spin axis, horizontal launch angle	Measured
Spin rate	The launch spin measured just after impact	±15 rpm	Dynamic loft, attack angle	Measured
Horizontal Launch Angle	The launch angle measured after impact in relation to target line. +ve angles to the right		Club path, face angle	Measured
Vertical Launch Angle	The launch angle measured just after impact in relation to horizontal		Dynamic loft, attack angle	Measured
Dynamic Loft	The vertical clubface orientation at impact point on the clubface, relative to flat ground level, at the time point of maximum compression of the golf ball	±0.8º	Attack angle, vertical launch angle, spin rate	Calculated
Face Angle	The horizontal clubface orientation at the impact point on the club face relative to the target line, at the point in time of maximum compression of the golf ball.	±0.6º	Horizontal swing plane, horizontal launch angle, spin axis, club path	Calculated
Spin axis	The spin axis is the axis around which the ball is spinning. The tilting of the axis dictates in the ball will draw or fade. Positive when ball is going right.	±1º	Club path, face angle	Calculated
Total Distance	Carry plus calculated bounce and roll		Carry, landing angle and ground conditions	Calculated
Total Side	Total left or right distance calculated in relation to the target line		Horizontal launch angle, spin axis and ground conditions	Calculated

Appendix D Visual 3D Segment Definition

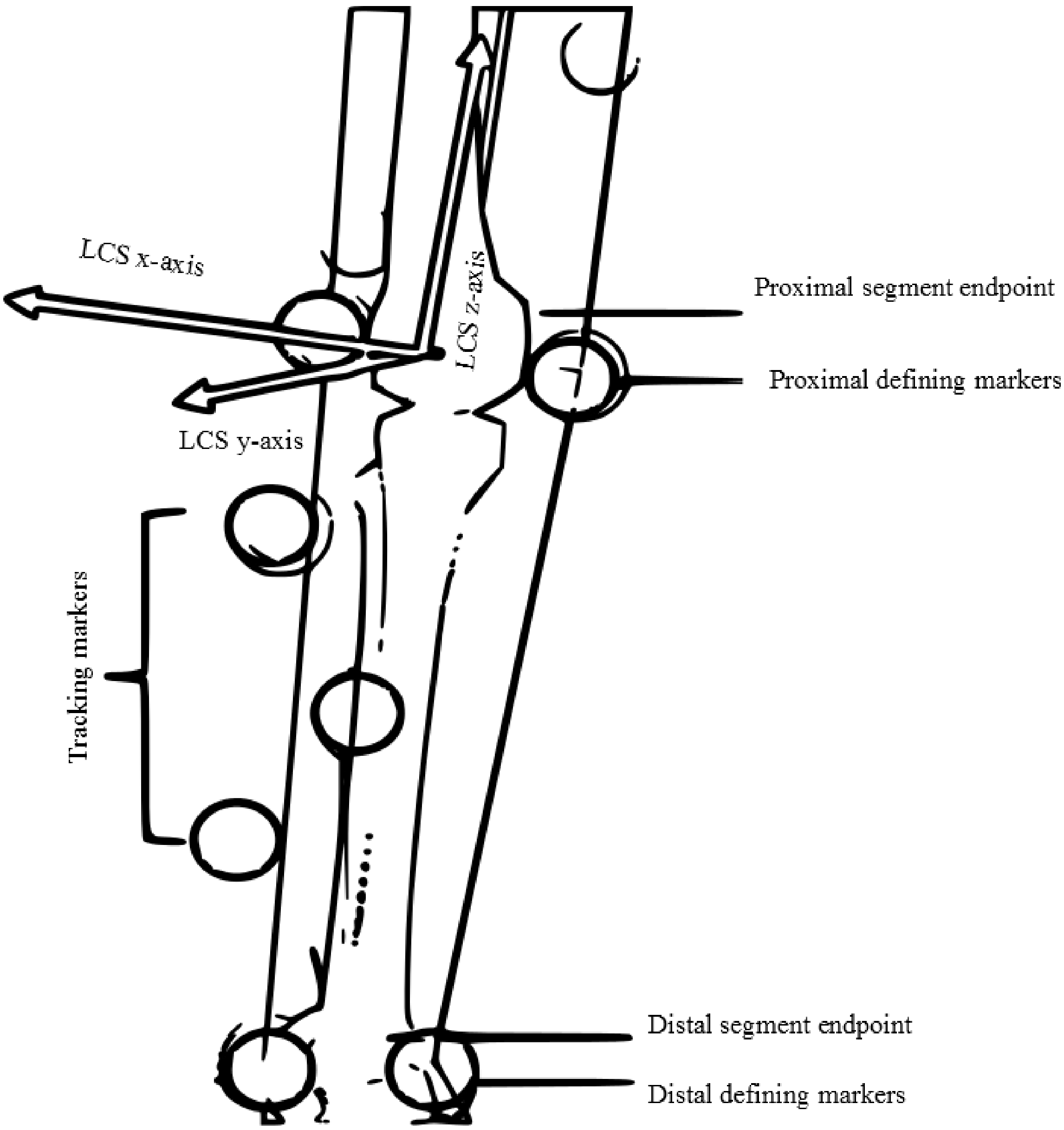


Figure D.1. Diagrammatic representation of segment LCS definitions. The figure above is for the right shank segment

Appendix E Frequency Spectra

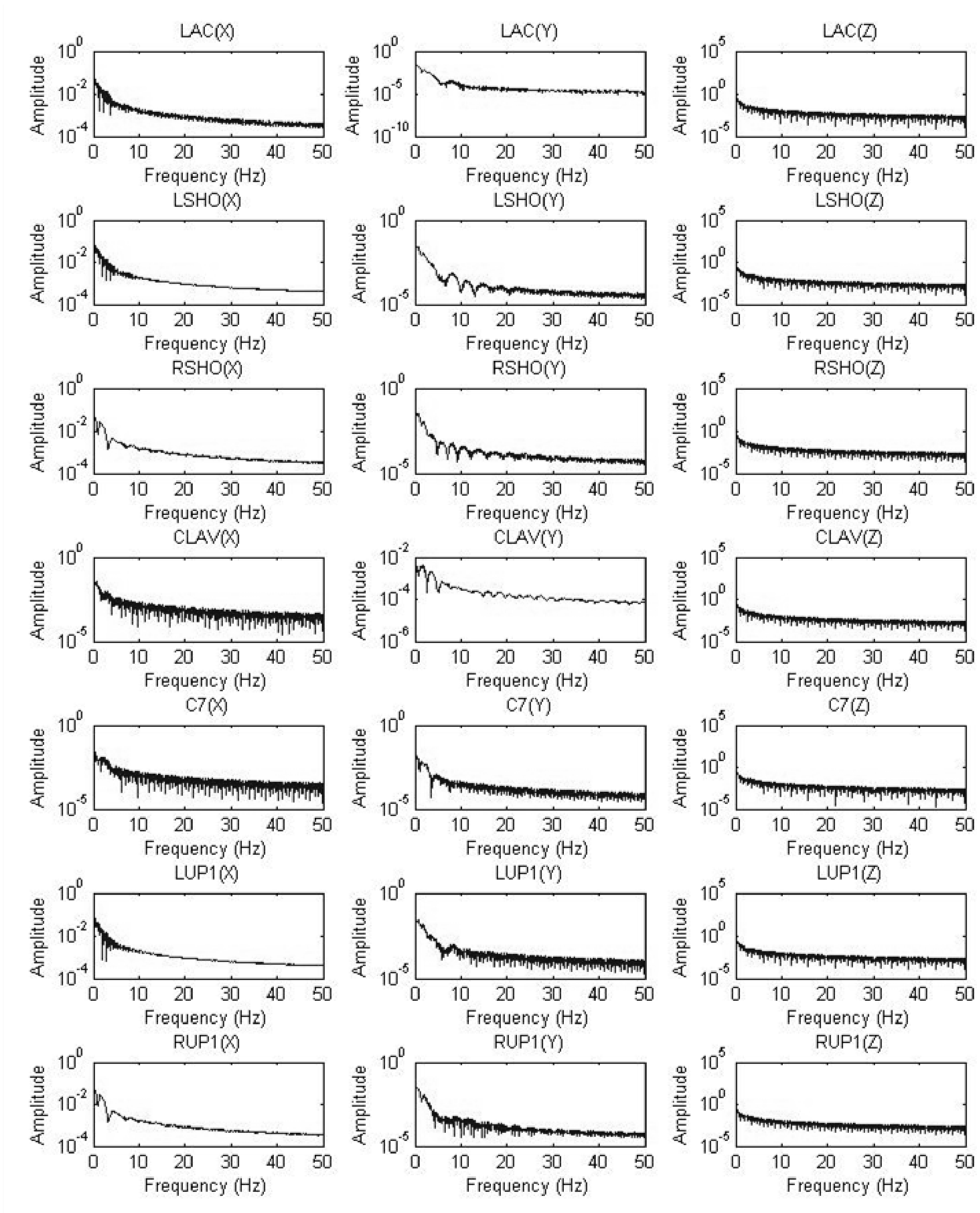


Figure E.1. Frequency spectra for select markers LAC, LSHO, RSHO, CLAV, C7, LUP1 and RUP1.

Appendix F Temporal Alignment Matlab Function

```
%%%Interpolate data between specific points of interest%%%%
%%new_data will be interpolated data%%
%%%data is the original un-interpolated data%%
%%%pts is the number of points you want to interpolate between i.e. 1-101%%%%
%%%per is the row number you are forcing the data to%% i.e. for the golf swing row 48 will be TB based on average position of TB%%%%
%%%stages is the actual row numbers of data%%%%%

function [new_data]=timewarp(data,per,pts,stages)

X=(0:1:(stages(2)-stages(1)))*(per(2)/(stages(2)-stages(1)));
X(stages(2):stages(3))=(0:1:(stages(3)-stages(2)))*((per(3)-per(2))/(stages(3)-stages(2)))+per(2);
X(stages(3):stages(4))=(0:1:(stages(4)-stages(3)))*((per(4)-per(3))/(stages(4)-stages(3)))+per(3);

tnorm=(((0:1:pts-1)/(pts-1))*100).';

new_data=interp1(X,data(stages(1):stages(4),:),tnorm);
```

Appendix G Chapter 7 Results

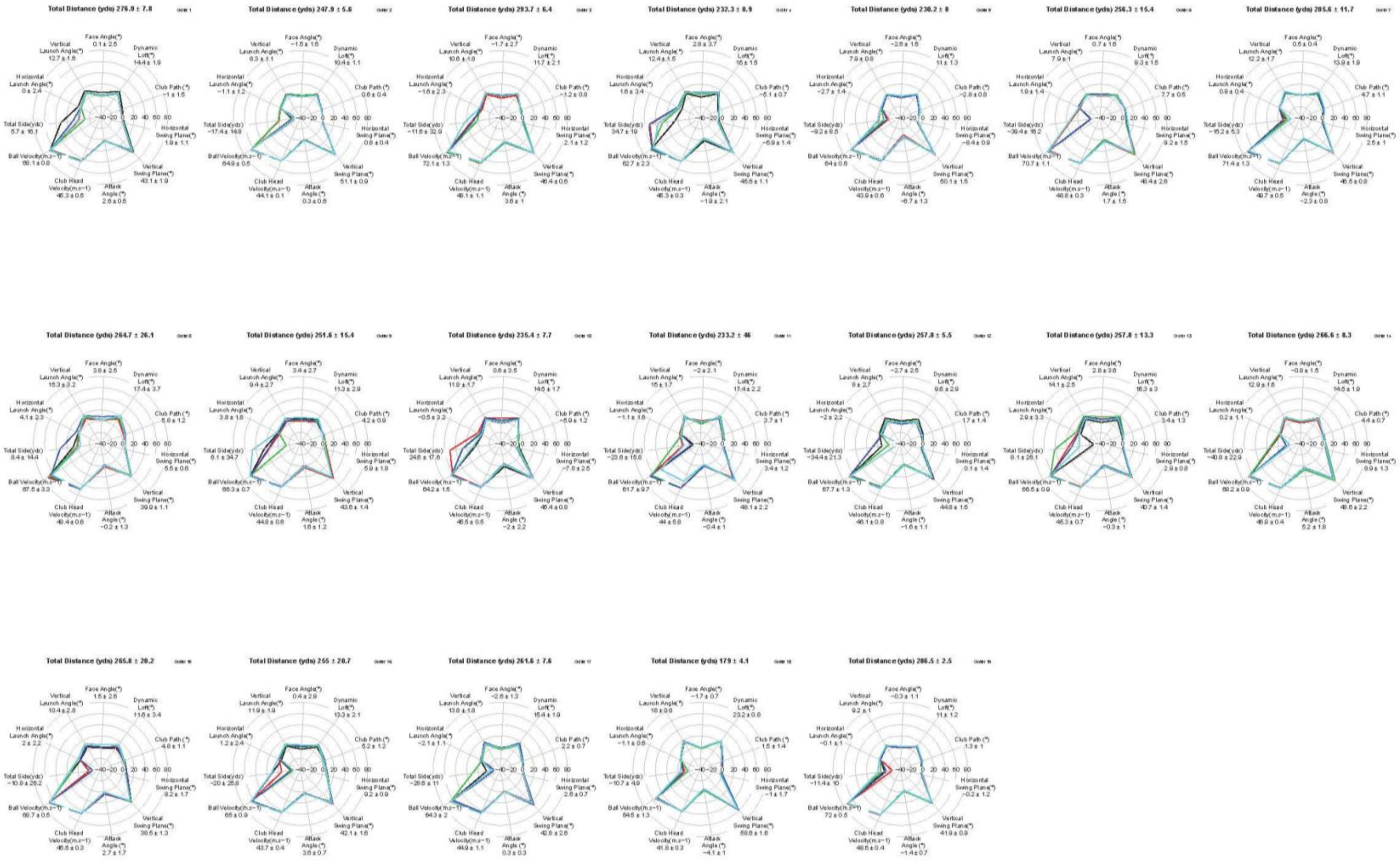


Figure G.1. TrackMan results for all golfers for five trials as radial plots. Mean±SD for each parameter are also presented

Table G.1. Mean and SD of posture kinematic values at the swing events TA, TB and IMP for nineteen golfers.

Golfer ID	Posture Parameter																							
	Posture Kinematics																							
	Thorax (Flexion) (º)						Thorax (Lateral Bend) (º)						Lumbar (Flexion) (º)						Lumbar (Lateral Bend) (º)					
	TA		TB		IMP		TA		TB		IMP		TA		TB		IMP		TA		TB		IMP	
1	-31.9	1.5	-13.6	0.9	-21.1	0.7	12.5	0.9	-23.8	0.8	32.9	0.6	-21.9	0.7	-25.5	0.4	8.1	0.6	-0.1	0.4	-21.8	0.9	11.6	0.2
2	-24.3	1.0	0.7	0.8	-27.3	0.8	9.2	0.4	-28.3	0.7	31.7	0.7	-15.3	0.5	-16.9	0.6	-5.7	1.8	2.3	0.9	-19.2	0.7	6.3	1.9
3	-21.7	0.5	-1.0	5.2	-19.2	1.0	14.6	0.4	-32.5	1.1	45.0	1.8	-15.5	0.2	-24.0	2.9	10.0	1.3	2.3	1.0	-18.6	2.3	7.3	0.6
4	-32.8	0.5	17.3	1.3	-17.7	0.5	8.8	0.4	-37.7	0.5	29.8	0.6	-16.1	0.4	-22.1	1.0	3.9	0.6	-0.8	0.3	-24.8	1.0	12.3	0.6
5	-28.6	0.4	9.1	1.3	-22.6	1.3	9.9	0.6	-30.8	0.9	27.6	0.6	-15.6	0.5	-10.3	0.4	16.0	1.6	-0.2	0.4	-15.6	0.6	17.8	0.7
6	-33.0	0.3	-1.0	0.6	-30.2	0.9	13.4	0.4	-40.8	0.2	23.9	0.6	-25.0	0.6	-20.0	0.6	6.2	0.3	-4.8	0.6	-16.0	0.3	14.4	0.8
7	-25.7	0.6	3.9	1.1	-27.4	0.9	14.3	0.2	-46.5	0.1	37.5	1.2	-20.4	0.6	-23.9	0.5	3.6	0.6	-7.9	0.2	-24.7	0.7	19.6	0.6
8	-29.4	0.3	-15.9	1.2	-18.3	0.6	10.5	0.2	-34.0	0.8	38.9	0.6	-13.5	0.6	-22.3	0.8	15.9	0.6	5.3	0.3	-9.7	0.4	16.8	0.6
9	-21.7	0.6	8.0	0.6	-14.9	0.5	11.2	0.2	-32.4	0.5	27.3	0.6	-25.3	1.2	-24.8	0.4	4.4	0.6	-1.0	0.4	-18.7	0.5	11.2	0.4
10	-31.3	1.0	-21.3	0.4	-25.5	0.7	16.1	0.9	-37.0	0.6	32.3	1.1	-26.4	2.4	-28.1	1.2	0.4	0.8	6.3	0.8	-13.9	0.9	14.8	0.3
11	-29.9	0.8	1.7	0.9	-26.4	0.7	9.9	0.6	-41.9	0.5	22.6	1.5	-12.6	0.3	-8.7	0.5	22.6	0.5	-1.6	0.1	-17.2	0.5	7.5	0.7
12	-29.0	0.4	-5.7	1.2	-24.3	0.4	2.5	0.7	-33.3	0.3	20.4	0.9	-26.4	2.1	-19.5	0.5	-4.7	0.9	1.0	0.7	-16.8	0.4	12.6	0.3
13	-40.2	0.1	-15.9	1.0	-34.3	0.6	12.7	0.9	-25.8	0.3	31.6	0.4	-34.5	0.2	-31.3	0.5	-15.5	0.7	4.5	0.3	-13.0	0.1	17.3	0.7
14	-31.3	0.7	3.7	0.8	-24.5	1.2	13.9	0.4	-26.4	0.6	22.6	0.5	-19.1	0.3	-14.0	0.7	6.7	1.1	1.2	0.5	-8.1	0.4	4.6	0.5
15	-15.8	0.9	3.2	0.6	-13.5	0.6	10.5	0.3	-41.0	0.5	29.6	0.4	-28.5	1.0	-26.7	0.2	4.4	0.4	-1.7	0.4	-20.5	0.4	9.9	0.4
16	-25.9	0.4	9.8	0.5	-25.4	0.8	5.7	0.2	-37.7	0.2	18.6	0.4	-25.3	0.4	-15.7	0.5	-0.6	0.5	-3.0	0.4	-14.3	0.3	5.2	0.3
17	-39.3	0.4	-3.6	2.1	-34.6	0.6	5.5	0.4	-28.5	2.7	27.3	0.9	-11.2	0.9	-6.9	0.6	10.5	0.6	-1.5	0.3	-15.4	0.4	11.6	0.4
18	-31.2	0.5	-6.0	1.0	-33.8	0.9	8.4	0.3	-34.1	0.4	21.3	0.4	-31.7	0.7	-24.5	0.5	-8.5	0.6	-0.7	0.4	-15.5	0.6	9.1	0.4
19	-30.6	0.2	11.5	0.6	-15.0	0.6	13.6	0.3	-39.4	0.4	29.4	0.8	-21.0	0.4	-23.1	0.4	13.6	0.5	-0.4	0.2	-5.9	0.7	8.1	0.3
Mean ± SD	-29.1	5.8	-0.8	10.4	-24.0	6.5	10.7	3.5	-34.3	6.2	29.0	6.8	-21.3	6.7	-20.4	6.7	4.8	9.3	0.0	3.4	-16.3	5.0	11.5	4.4

Table G.2. Mean and SD of posture kinematic values at the swing events TA, TB and IMP for nineteen golfers.

Golfer ID	Posture Parameter																							
	Posture Kinematics																							
	Right Knee Flexion (º)						Left Knee Flexion (º)						%Head COG $_{(M-L)}$						%Head COG $_{(A-P)}$					
	TA		TB		IMP		TA		TB		IMP		TA		TB		IMP		TA		TB		IMP	
1	-26.2	0.9	-30.4	0.8	-27.6	0.5	-21.8	1.5	-47.9	1.0	-13.8	1.8	30.3	1.5	18.2	2.0	17.0	2.4	170.9	1.3	166.1	3.1	170.8	2.9
2	-22.6	1.2	-12.7	1.2	2.9	2.7	-20.8	0.6	-35.5	1.0	4.8	0.4	48.2	1.4	35.8	1.4	25.4	1.9	149.0	3.0	155.2	2.8	148.4	2.2
3	-39.2	1.2	-30.6	2.7	-11.5	4.3	-29.7	0.6	-48.2	2.7	2.8	3.3	35.1	1.6	18.6	4.3	24.4	4.3	163.3	2.2	178.5	2.2	189.1	4.2
4	-31.0	1.3	-19.3	0.9	-19.2	1.6	-32.3	1.2	-28.7	1.5	-10.3	0.6	43.8	2.5	31.9	3.1	26.4	1.6	140.6	1.5	164.3	2.6	162.7	1.8
5	-18.8	0.7	-7.9	1.5	-23.1	1.3	-22.0	1.6	-23.9	1.2	-9.8	0.5	43.1	4.1	18.3	3.3	23.0	3.5	185.5	1.5	184.4	3.1	190.5	3.1
6	-23.3	0.9	-31.4	1.0	-24.1	1.6	-33.8	0.7	-58.4	0.7	-22.8	0.8	38.9	2.1	31.2	1.5	27.9	2.0	194.0	1.3	183.2	2.0	166.5	2.5
7	-27.3	0.4	-26.9	1.0	-30.7	0.8	-30.3	0.6	-42.5	0.6	-3.8	2.1	32.7	1.4	29.8	1.2	29.6	1.5	178.2	2.2	198.4	1.4	210.3	3.3
8	-22.1	0.6	-24.8	1.2	-26.7	2.1	-19.9	0.7	-51.7	0.8	-25.6	1.4	46.0	0.6	40.9	0.8	43.6	0.9	172.2	1.5	179.1	3.3	180.5	4.3
9	-22.3	2.1	-21.2	1.2	-5.9	2.3	-21.4	1.3	-35.5	1.7	-2.8	3.7	44.5	1.3	31.6	1.7	32.0	2.8	155.9	6.2	158.4	6.2	165.5	5.9
10	-26.5	1.4	-11.8	0.8	-24.4	1.7	-26.4	1.8	-35.5	1.4	-13.9	1.2	41.5	1.5	27.5	1.7	32.4	2.2	157.3	1.5	179.1	2.3	173.7	2.7
11	-27.6	0.5	-30.5	0.5	-15.9	1.0	-23.6	0.6	-41.7	0.6	-11.3	0.8	35.6	1.0	38.4	2.0	38.5	2.1	162.1	3.5	166.9	3.7	167.6	4.1
12	-26.1	0.5	-30.4	0.8	-16.8	2.5	-19.1	1.0	-44.9	0.6	-14.9	2.0	43.2	1.6	38.9	2.2	43.1	2.4	175.8	4.3	175.1	4.2	165.7	3.6
13	-19.3	0.8	-25.0	1.0	-24.2	0.7	-20.6	0.5	-52.7	1.0	-22.0	0.9	42.1	0.7	35.3	0.9	35.2	1.3	161.0	4.4	152.6	4.1	150.8	3.9
14	-31.9	0.4	-31.3	1.1	-27.2	1.4	-27.9	0.6	-42.0	1.3	-18.6	1.9	37.6	1.9	30.1	1.6	35.0	2.0	170.2	3.3	164.2	2.3	157.3	2.5
15	-23.1	0.9	-24.1	0.8	-36.7	0.9	-19.6	0.7	-37.0	0.8	-29.0	0.5	36.5	2.2	33.9	1.1	19.7	0.8	160.8	2.4	180.4	2.5	170.3	2.0
16	-25.8	0.4	-18.7	0.7	-4.4	0.4	-21.0	0.6	-37.1	1.3	-19.2	2.0	49.9	0.5	35.7	0.7	45.5	0.6	176.6	2.4	167.8	1.5	151.8	2.0
17	-20.1	1.5	-27.2	1.3	-33.9	1.1	-25.3	1.0	-44.7	0.7	-22.5	1.6	54.6	1.4	35.4	1.5	28.9	2.4	166.6	1.3	159.2	3.1	166.8	3.0
18	-30.2	0.8	-19.6	0.8	-9.7	1.2	-28.6	1.0	-39.5	0.7	-4.4	0.8	42.5	1.1	29.0	1.1	33.0	1.7	164.4	2.5	171.0	2.4	161.8	2.4
19	-17.3	0.6	-29.9	1.8	-23.6	0.9	-22.4	1.0	-38.3	2.3	-12.1	1.9	34.7	0.9	38.1	0.6	24.1	0.9	172.1	2.0	176.2	2.2	161.3	2.6
Mean ± SD	-25.3	5.3	-23.9	7.2	-20.1	10.5	-24.6	4.6	-41.4	8.4	-13.1	9.4	41.1	6.2	31.5	6.9	30.8	8.0	167.2	12.5	171.6	11.6	169.0	15.1

Table G.3. Mean and SD of posture balance values at the swing events TA, TB and IMP for nineteen golfers.

Golfer ID	Posture Parameter																							
	Posture Balance																							
	%COG (M-L)						%COG (A-P)						%COP (M-L)						% COP (A-P)					
	TA		TB		IMP		TA		TB		IMP		TA		TB		IMP		TA		TB		IMP	
1	48.5	1.1	37.2	1.2	50.7	1.2	71.8	0.7	74.0	1.5	65.6	1.3	60.5	1.8	41.4	1.5	40.0	3.1	69.8	0.9	57.9	1.5	72.1	1.9
2	52.8	0.9	44.1	1.0	70.5	1.0	68.2	2.1	65.0	2.1	53.8	2.1	69.9	1.2	47.3	1.9	71.9	2.2	61.1	2.8	49.5	2.7	41.2	2.1
3	42.8	1.7	29.8	3.6	52.0	3.6	67.8	1.0	72.1	1.2	66.4	1.3	55.3	4.5	33.4	29.0	28.1	16.0	58.6	1.5	53.7	3.1	74.5	2.7
4	51.1	1.3	32.9	2.1	61.7	0.7	54.7	1.0	73.9	1.7	76.0	1.1	61.4	1.0	24.6	2.3	83.9	2.8	45.0	0.6	52.6	3.5	81.2	0.7
5	47.4	2.7	32.8	2.3	61.2	2.0	78.4	1.7	78.1	3.0	79.6	1.8	55.7	2.7	28.4	3.2	64.1	2.8	73.6	1.1	59.7	5.3	86.5	1.2
6	47.5	1.1	46.2	0.9	68.1	1.3	81.8	0.9	77.4	1.6	72.1	2.0	48.9	1.1	25.0	2.1	92.3	2.8	69.7	1.3	52.2	2.1	80.0	1.7
7	46.8	1.2	32.5	0.7	51.2	0.6	70.8	1.1	72.0	2.0	75.7	1.8	65.1	1.8	18.0	3.8	27.8	1.4	61.8	1.1	38.5	4.2	82.8	0.9
8	52.7	0.3	54.7	0.7	64.8	0.7	66.0	1.3	74.6	1.5	67.3	2.3	57.0	0.6	68.4	4.0	89.1	1.7	59.5	1.0	65.4	2.0	63.2	0.6
9	49.5	1.1	35.7	1.2	58.1	2.4	58.8	2.5	62.4	2.5	63.4	2.1	57.5	2.3	23.7	2.6	48.9	14.4	51.6	2.5	41.1	5.1	71.7	3.7
10	51.8	1.3	43.4	0.9	62.4	1.5	67.0	1.6	73.5	1.4	70.7	1.4	53.4	1.0	30.4	4.3	92.6	3.8	58.6	0.9	55.7	1.8	78.9	2.0
11	48.0	0.7	44.5	0.5	57.3	0.5	58.2	0.3	62.8	0.3	58.2	0.4	54.0	1.0	33.5	2.2	59.1	5.3	51.5	0.9	39.1	1.4	76.2	1.6
12	47.7	1.2	40.2	1.7	56.8	1.2	67.3	4.5	67.7	2.7	64.8	3.3	49.7	2.5	34.4	2.2	34.3	4.4	55.1	5.1	50.0	2.4	66.5	5.2
13	50.6	0.4	45.3	0.6	60.2	0.6	60.2	1.8	65.3	2.1	59.0	1.7	60.8	0.6	9.3	1.7	93.3	1.3	56.0	1.7	63.6	3.6	54.4	1.7
14	49.3	1.3	36.2	1.2	53.8	1.6	70.1	2.1	70.0	1.3	64.5	2.5	53.9	1.9	18.2	3.5	60.9	2.8	59.0	2.9	51.4	2.0	73.8	3.6
15	44.8	1.6	32.9	0.8	53.0	0.5	73.1	0.6	69.9	1.2	66.4	1.2	48.2	4.0	24.8	1.0	76.0	2.2	63.4	1.3	48.8	1.7	51.0	1.7
16	50.4	0.5	42.2	0.6	68.6	0.4	72.5	0.6	60.9	1.2	54.9	1.4	53.3	0.8	29.0	2.0	91.8	1.8	65.9	0.8	43.8	2.5	52.8	4.2
17	53.0	0.5	41.4	1.0	56.4	0.8	68.6	0.8	69.5	1.8	69.5	2.0	53.0	0.4	15.2	2.5	76.1	2.0	63.0	1.3	43.8	2.1	64.8	5.5
18	47.5	0.5	35.2	0.5	53.5	0.6	71.3	1.2	70.2	1.1	61.4	1.1	49.8	0.7	16.2	1.9	3.8	1.3	62.9	0.9	51.7	2.2	74.5	1.6
19	44.6	0.7	40.1	1.2	57.2	0.7	69.5	1.5	72.7	2.0	68.9	1.4	56.4	1.1	50.3	5.4	75.2	4.4	57.3	1.8	48.6	2.3	73.0	3.0
Mean ± SD	48.8	2.9	39.3	6.3	58.8	6.0	68.2	6.7	70.1	5.0	66.2	7.0	56.0	5.7	30.1	14.1	63.6	26.5	60.2	6.9	50.9	7.6	69.4	12.1

Quality of Retained PC Scores

To assess the quality of the retained PC's, the data was reconstructed from these PC's and compared to the original data. An example of this comparison is presented for Lumbar flexion where two principal components were retained to explain 90% of the variance.

The retained PC scores, for example PC1 and PC2 for lumbar flexion, were firstly multiplied by the transpose of the weighting factor matrix (Weighting Factor ^{T}) of the retained principal components. The mean value of lumbar flexion across all golfers and trials for each time point were then added to multiplication between retained PC scores and weighting factors.

$$Reconstructed\ Data = (Retained\ PC\ score\ \times Weighting\ Factor^{\,T}) + Mean$$

An example of the comparison between reconstructed and original data is shown in Figure G.2. From qualitative inspection of the curve, there appeared to be good agreement between the curves from TA to IMP. However, following IMP there was slight greater disparity between the data curves. This could be rectified by including more PC's account for variation following IMP. Nevertheless, it was deemed that the number of PC's retained was adequate to represent original data.

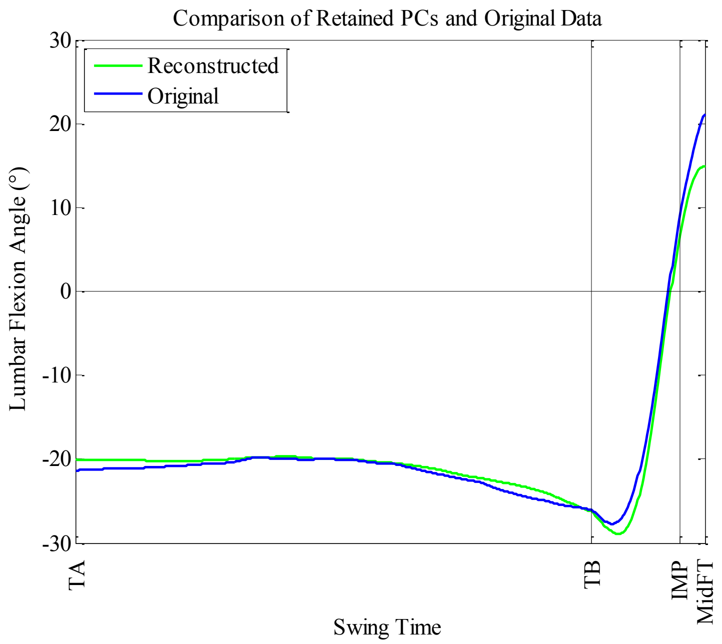


Figure G.2. Reconstructed (PC1 & PC2) and original lumbar flexion angles for a single golfer and trial.

PCA Results – Weighting Factors and Mean Curves

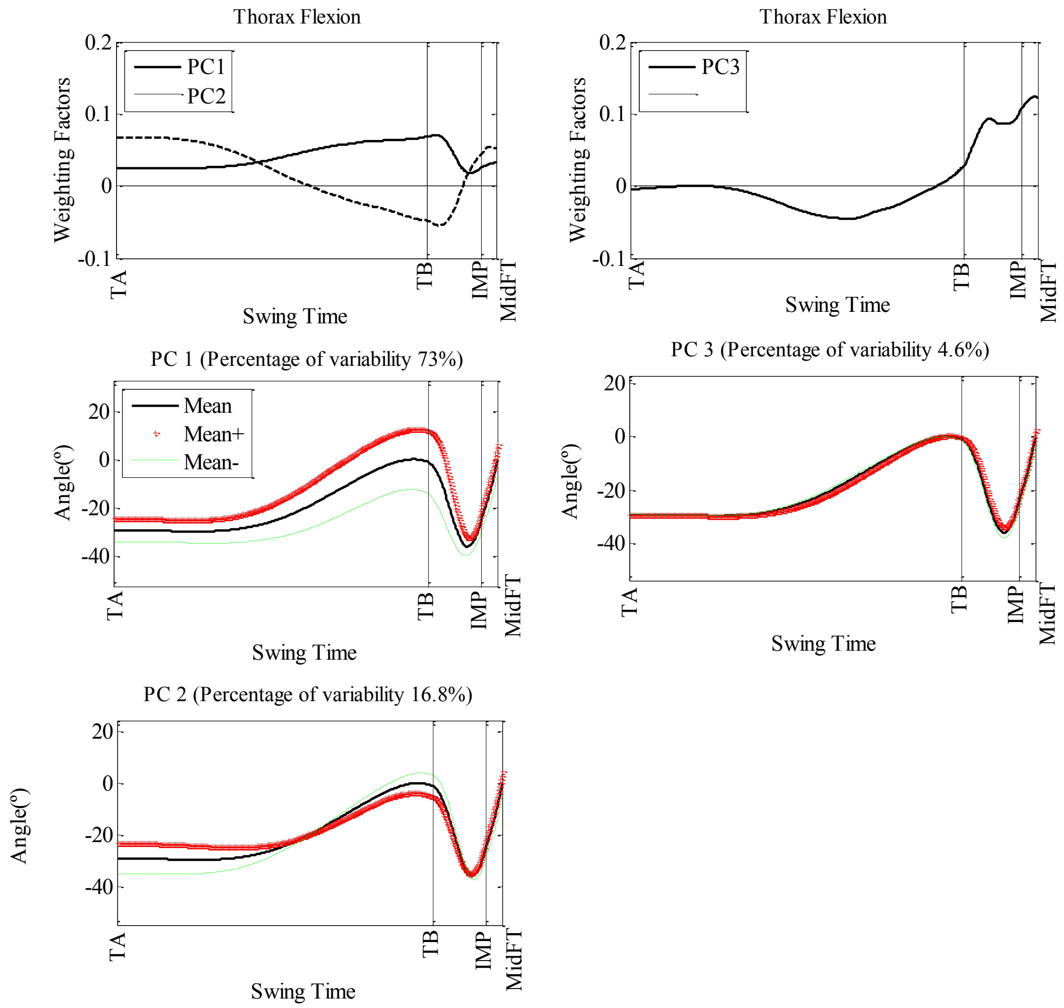


Figure G.3. (a) The weighting factors for the first three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean thorax flexion curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean thorax flexion curve (black line) with a multiple of PC2 added (red) and subtracted (green) from mean curve.

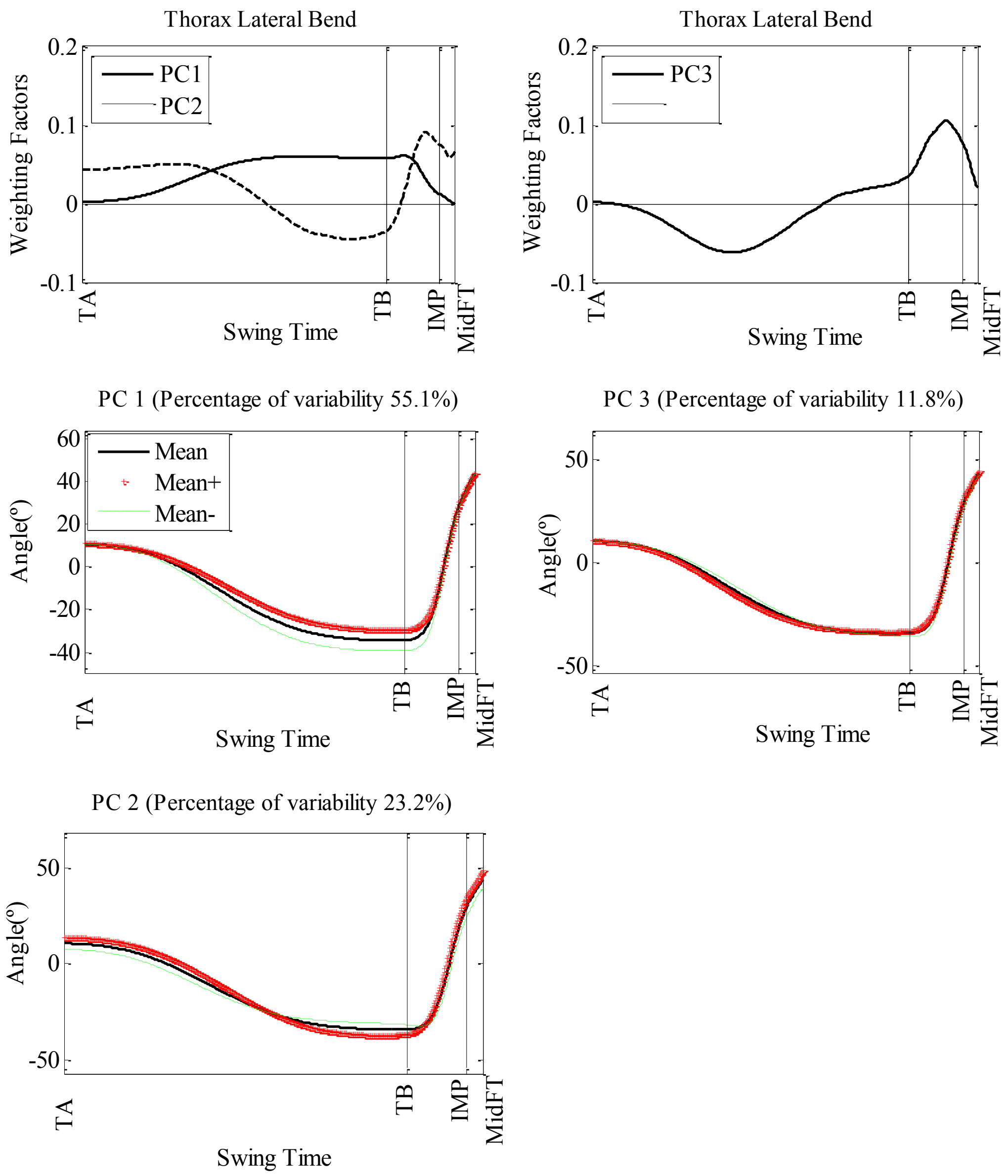


Figure G.4. (a) The weighting factors for the first three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean thorax lateral bend curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean thorax lateral bend curve (black line) with a multiple of PC2 added (red) and subtracted (green) from mean curve.

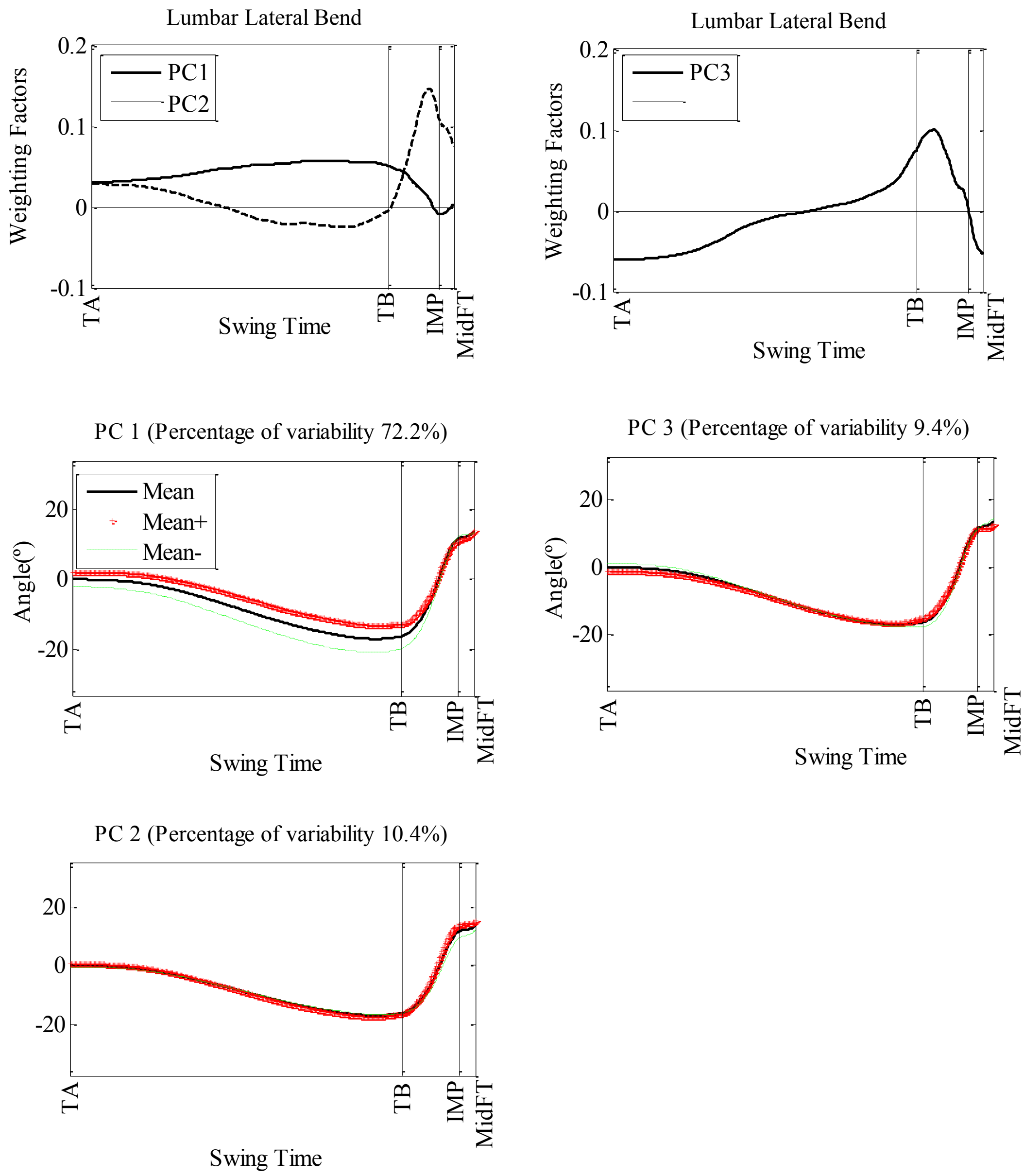


Figure G.5. (a) The weighting factors for the first four principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean lumbar lateral bend curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean lumbar lateral bend curve (black line) with a multiple of PC2 added (red) and subtracted (green) from mean curve.

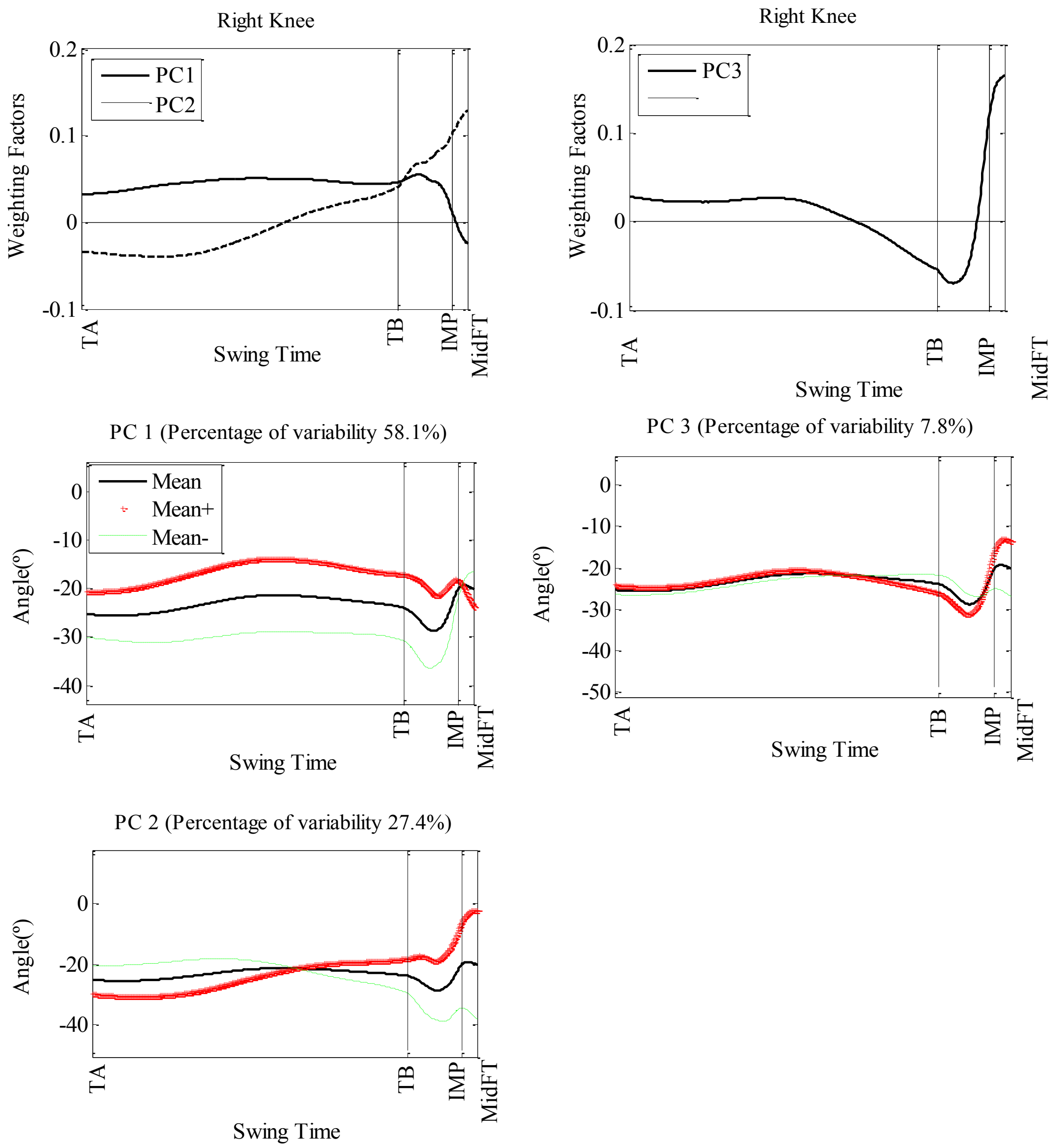


Figure G.6. (a) The weighting factors for the first three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean right knee flexion curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean right knee flexion curve (black line) with a multiple of PC2 added (red) and subtracted (green) from mean curve.

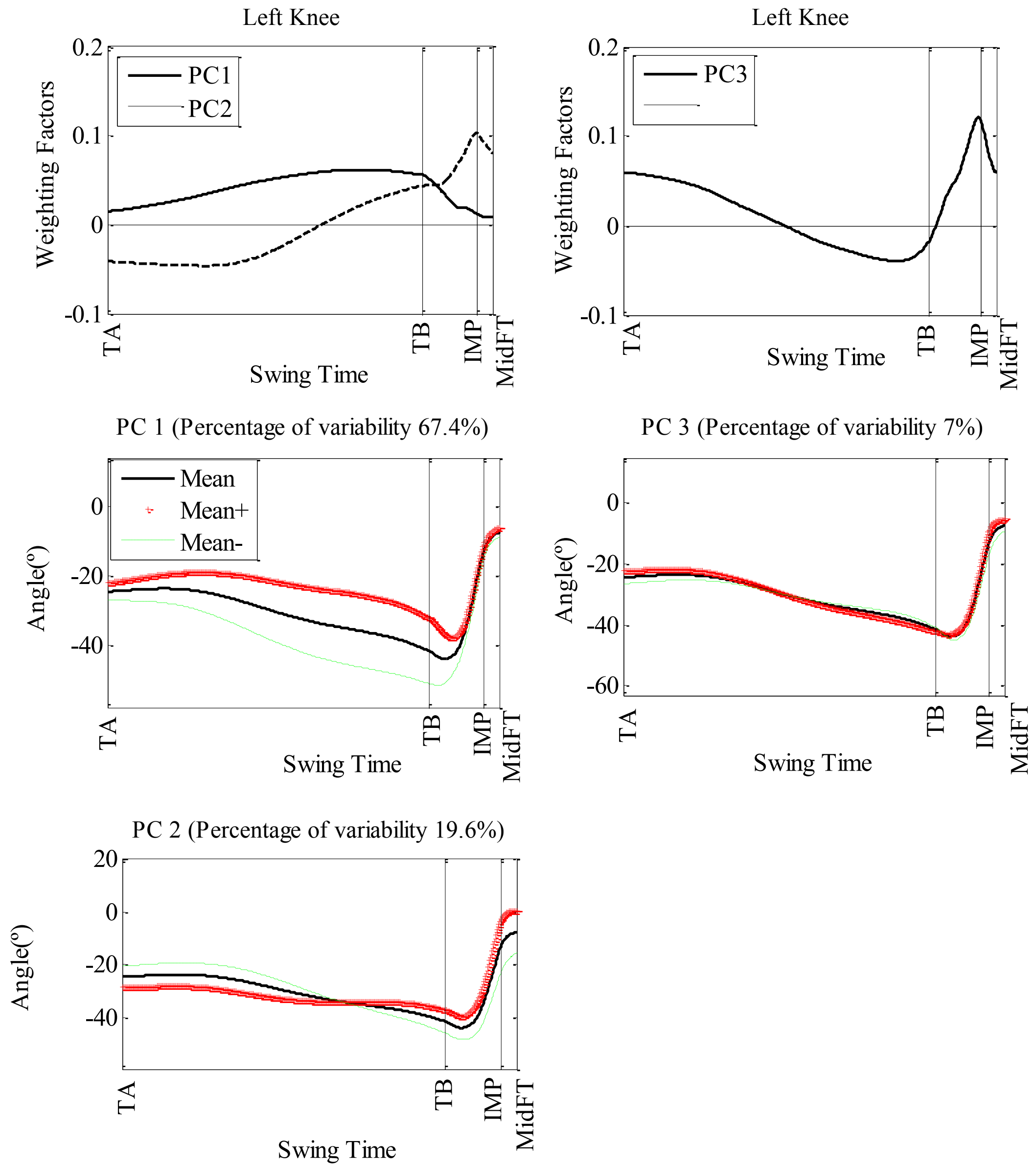


Figure G.7. (a) The weighting factors for the first three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean left knee flexion curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean left knee flexion curve (black line) with a multiple of PC2 added (red) and subtracted (green) from mean curve.

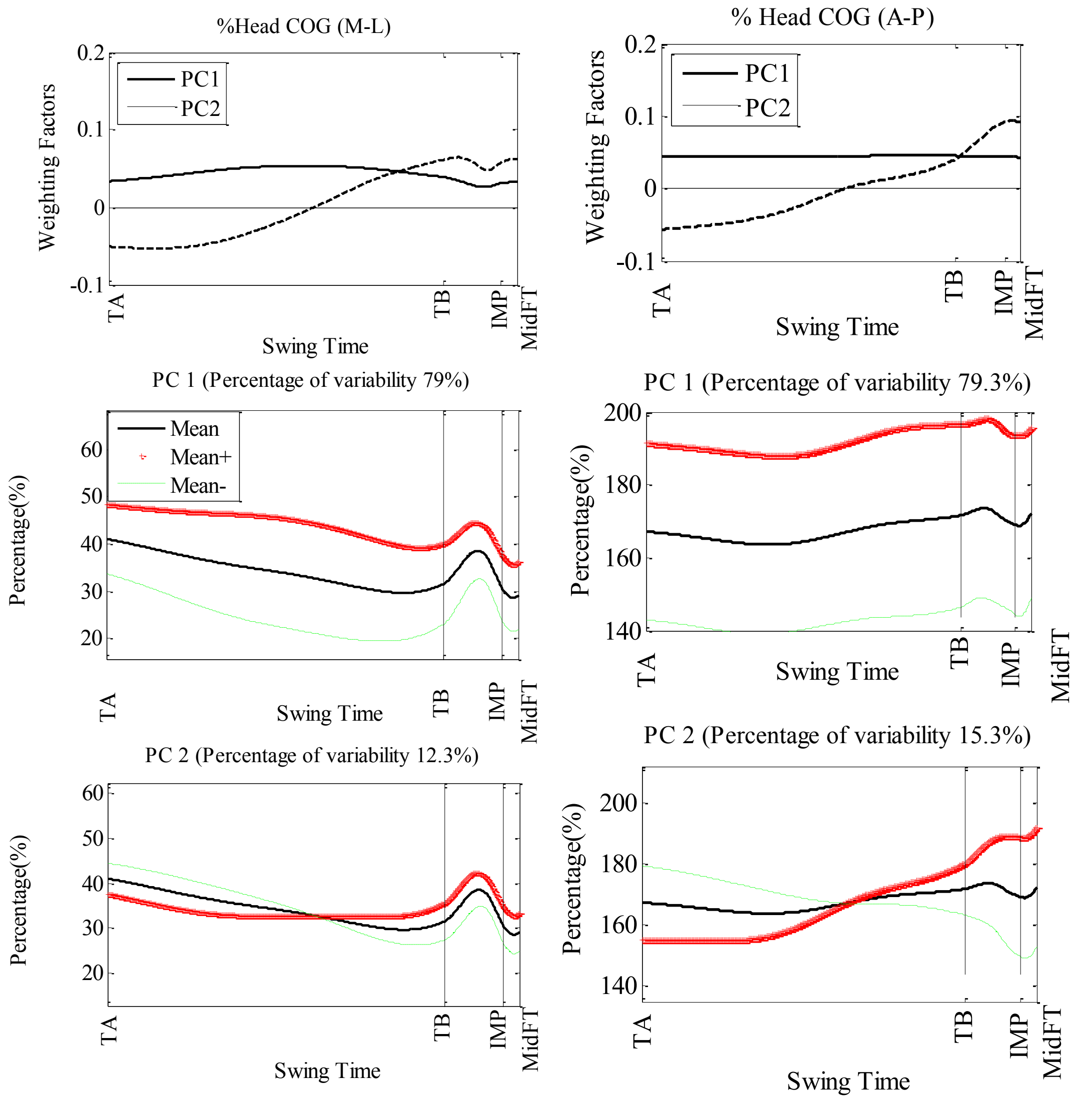


Figure G.8. (a) The weighting factors for the first two principal components for %Head COG (M-L) and %Head COG (A-P), PC1 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean curve (black line) with a multiple of PC1 and PC2 added (red) and subtracted (green) from mean curve.

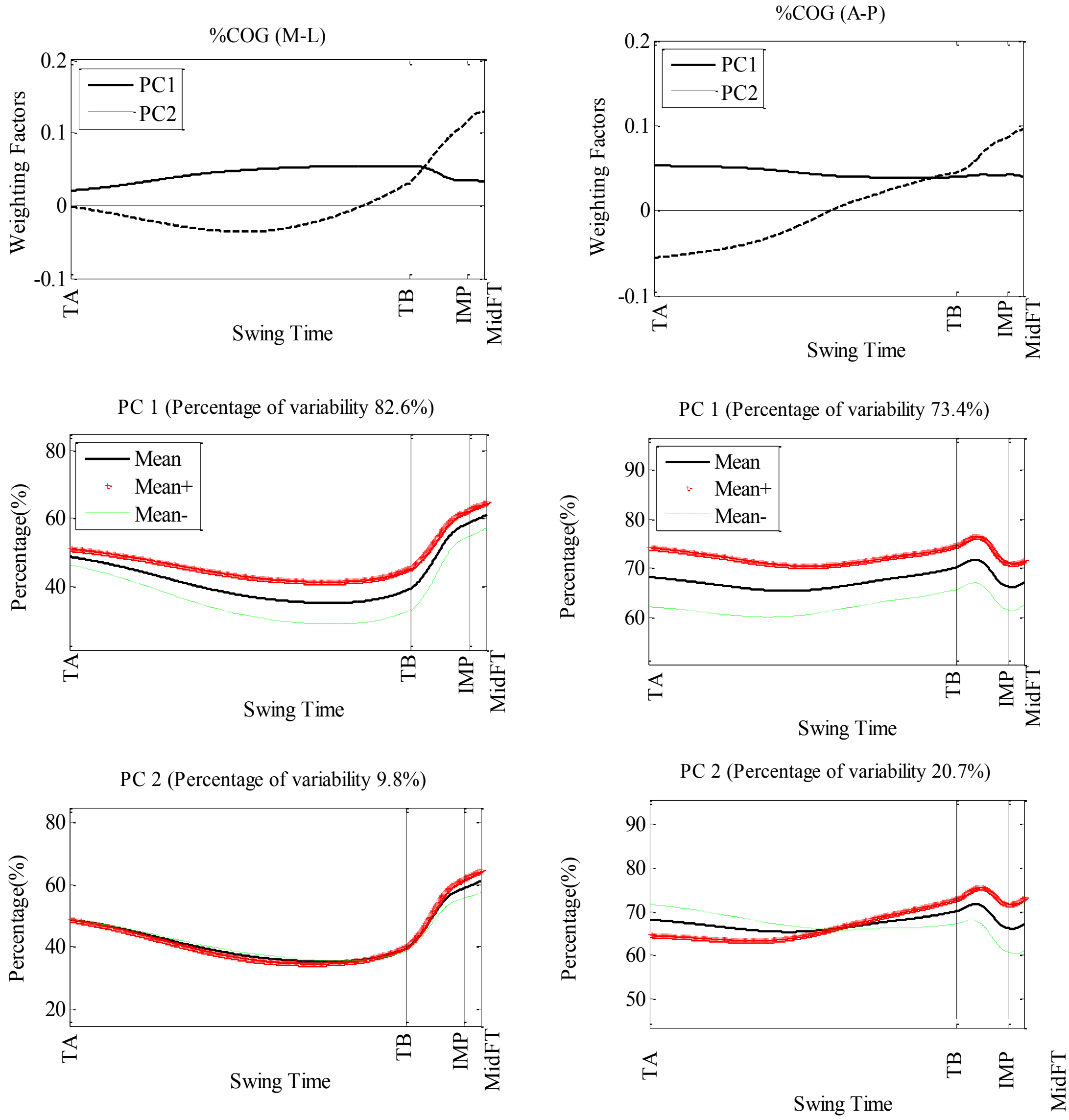


Figure G.9. (a) The weighting factors for the first two principal components, PC1 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean %COG $_{(M\text{-}L)}$ and %COG $_{(A\text{-}P)}$ curve (black line) with a multiple of PC1 added (red) and subtracted (green) from mean curve (c) Mean Mean %COG $_{(M\text{-}L)}$ and %COG $_{(A\text{-}P)}$ (black line) with a multiple of PC2 added (red) and subtracted (green) from mean curve.

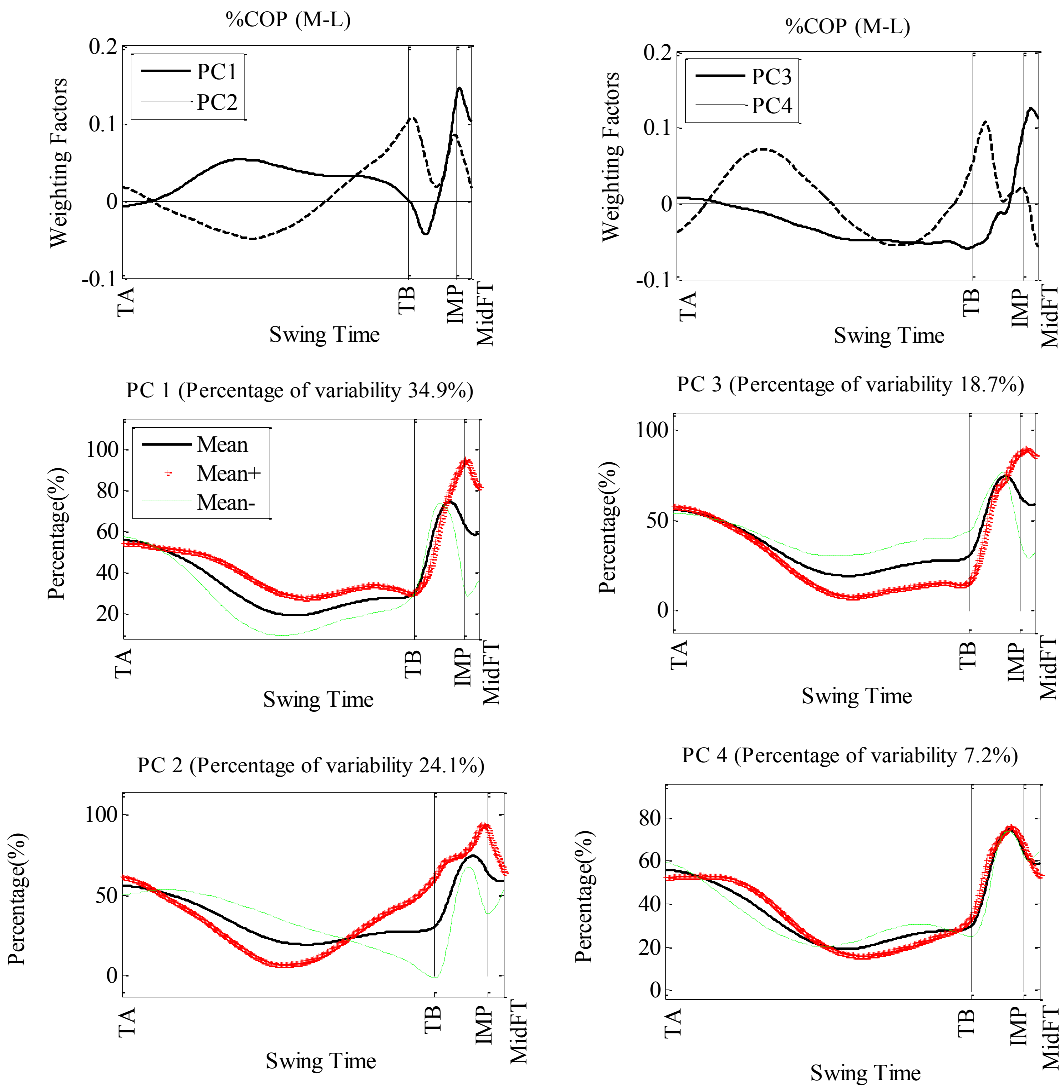


Figure G.10. (a) The weighting factors for the first four principal components, PC1 and PC3 (solid) and PC2 and PC4 (dashed) throughout the golf swing. (b) Mean %COP x curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean %COP $_x$ curve (black line) with a multiple of PC2 and PC4 added (red) and subtracted (green) from mean curve.

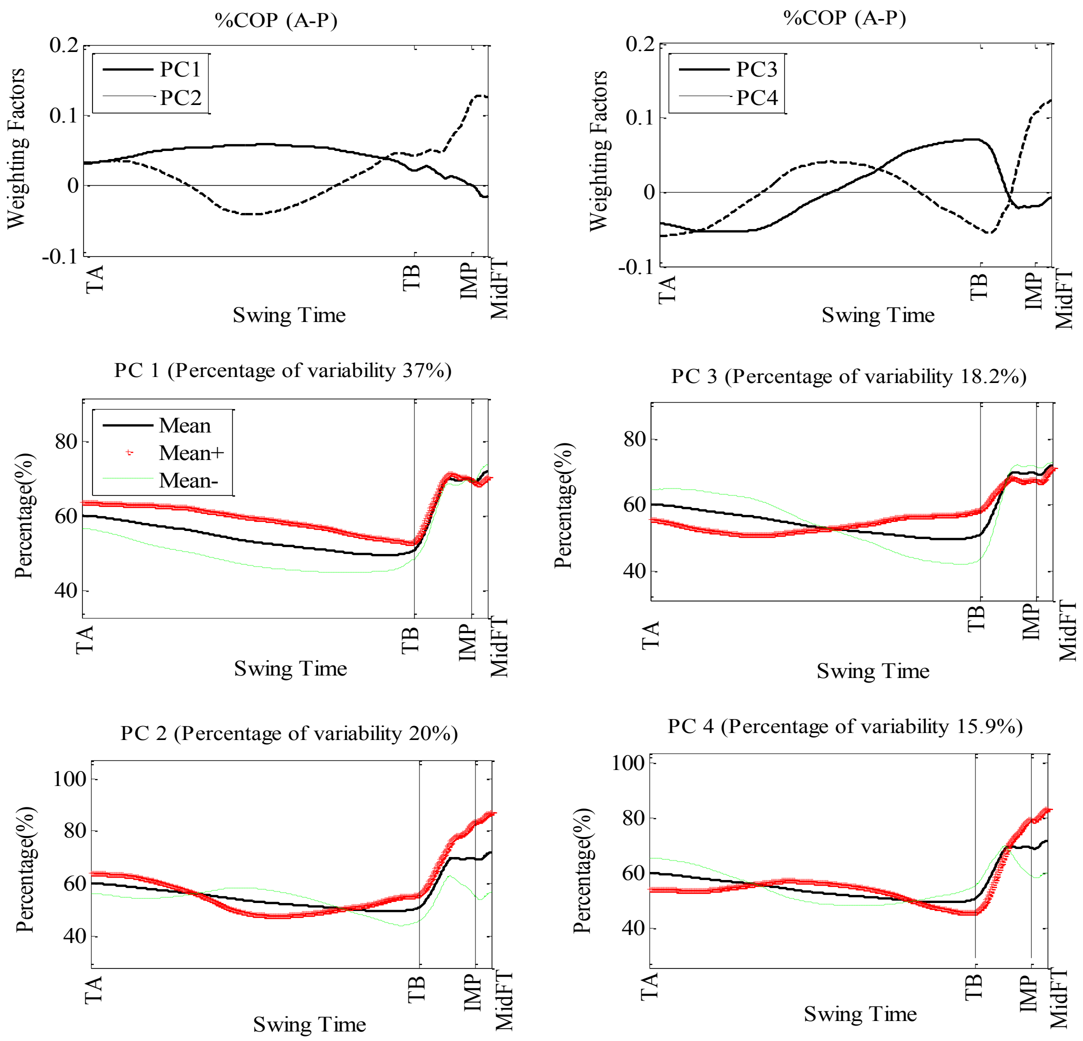


Figure G.11. (a) The weighting factors for the first four principal components, PC1 and PC3 (solid) and PC2 and PC4 (dashed) throughout the golf swing. (b) Mean %COP y curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean %COP y curve (black line) with a multiple of PC2 and PC4 added (red) and subtracted (green) from mean curve.

Appendix H Chapter 8 Results

PCA Results – Weighting Factors and Mean Curves

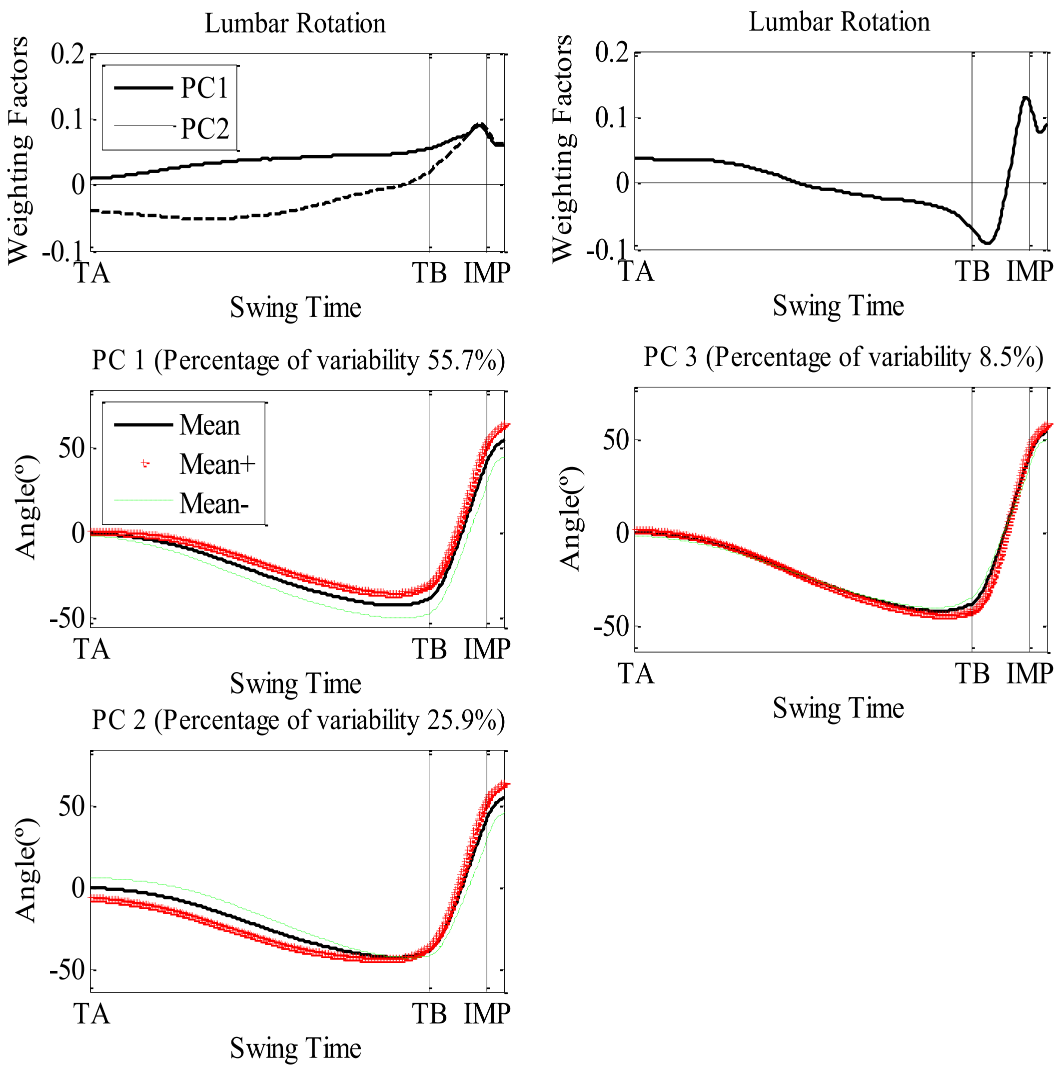


Figure H.1. (a) The weighting factors for the three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean lumbar rotation curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean lumbar rotation curve (black line) with a multiple of PC2 (red) and subtracted (green) from mean curve.

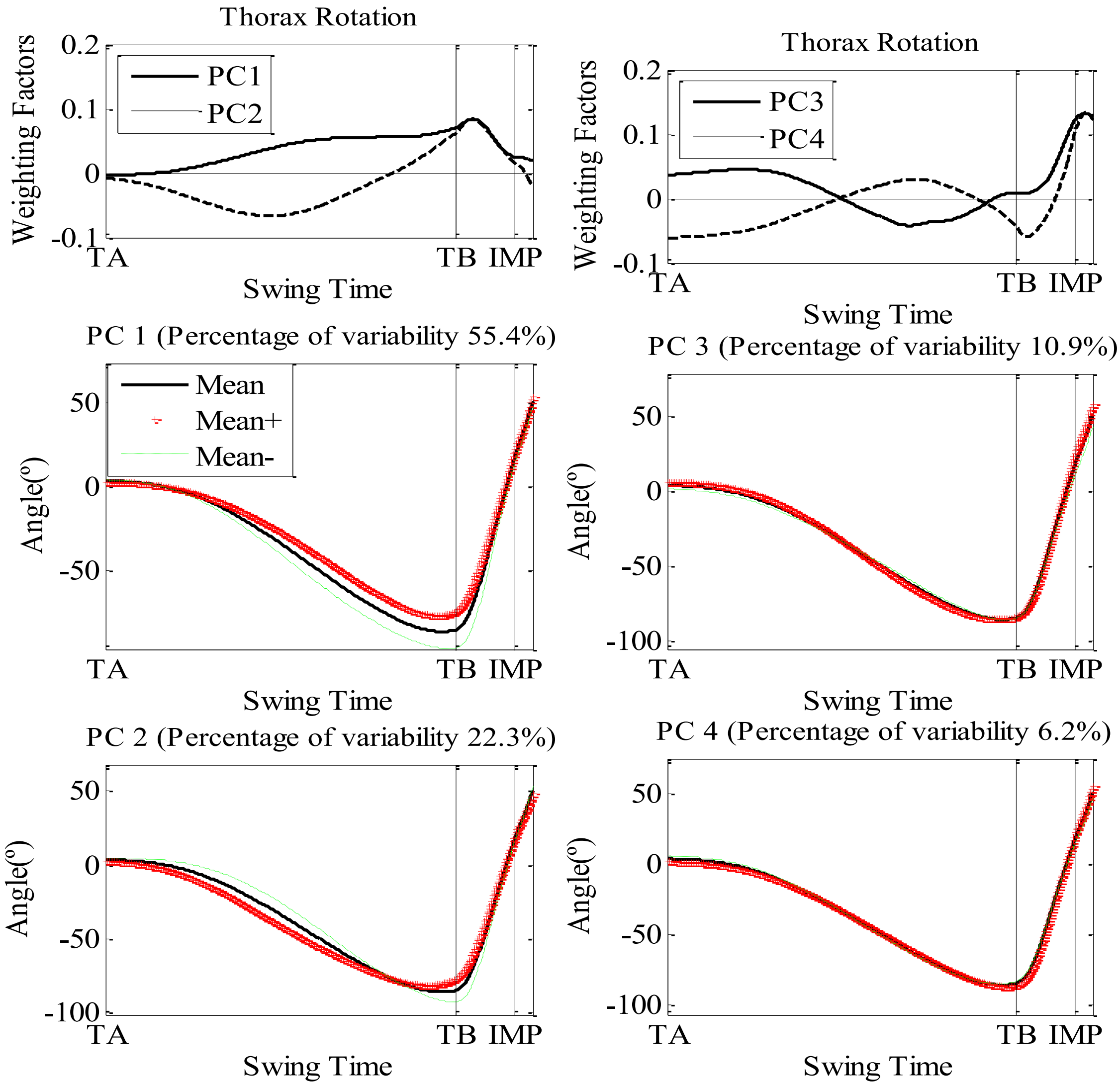


Figure H.2. (a) The weighting factors for the four principal components, PC1 and PC3 (solid) and PC2 and PC4 (dashed) throughout the golf swing. (b) Mean thorax axial rotation curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean thorax axial rotation curve (black line) with a multiple of PC2 and PC4 (red) and subtracted (green) from mean curve.

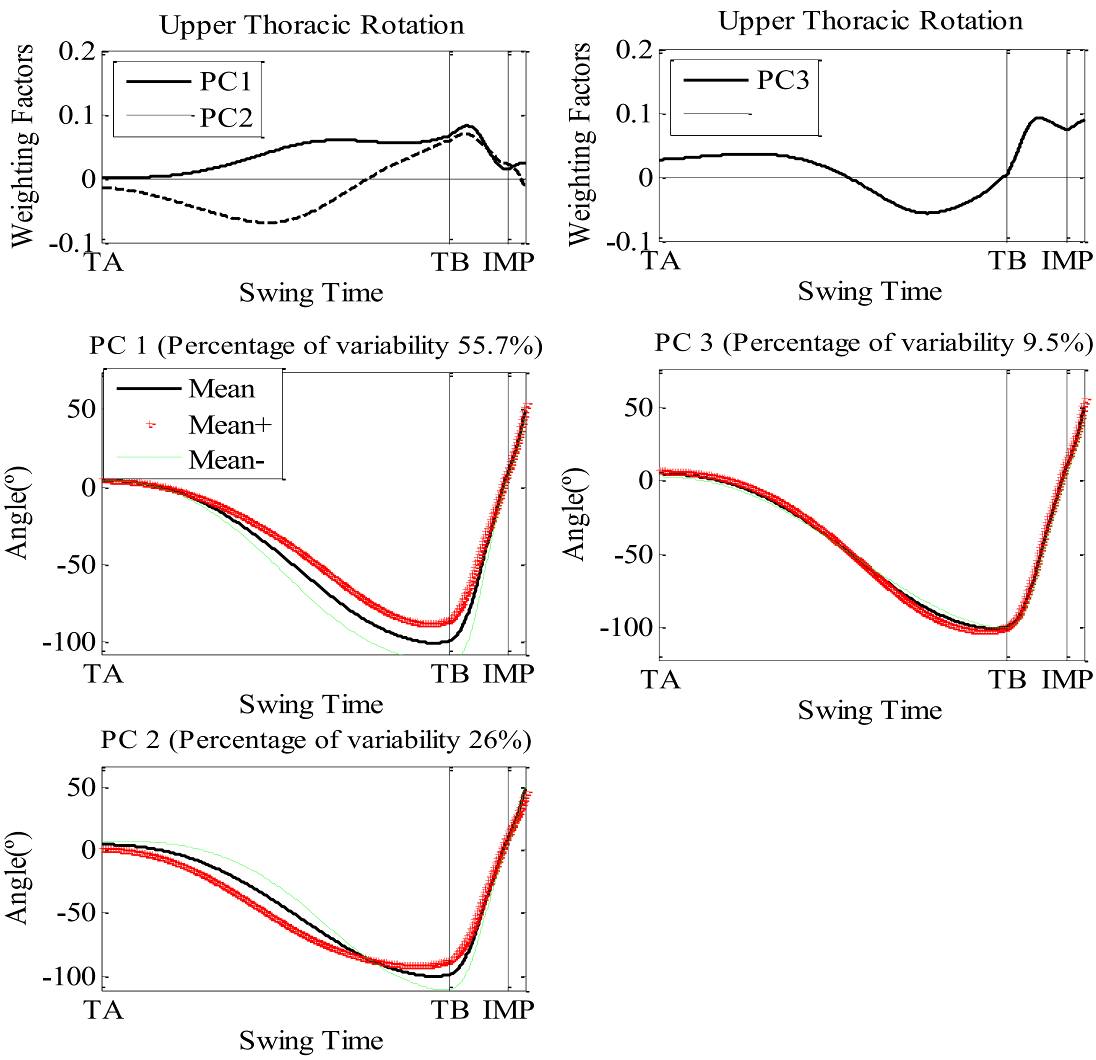


Figure H.3. (a) The weighting factors for the three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean upper thorax axial rotation curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean upper thorax axial curve (black line) with a multiple of PC2 (red) and subtracted (green) from mean curve.

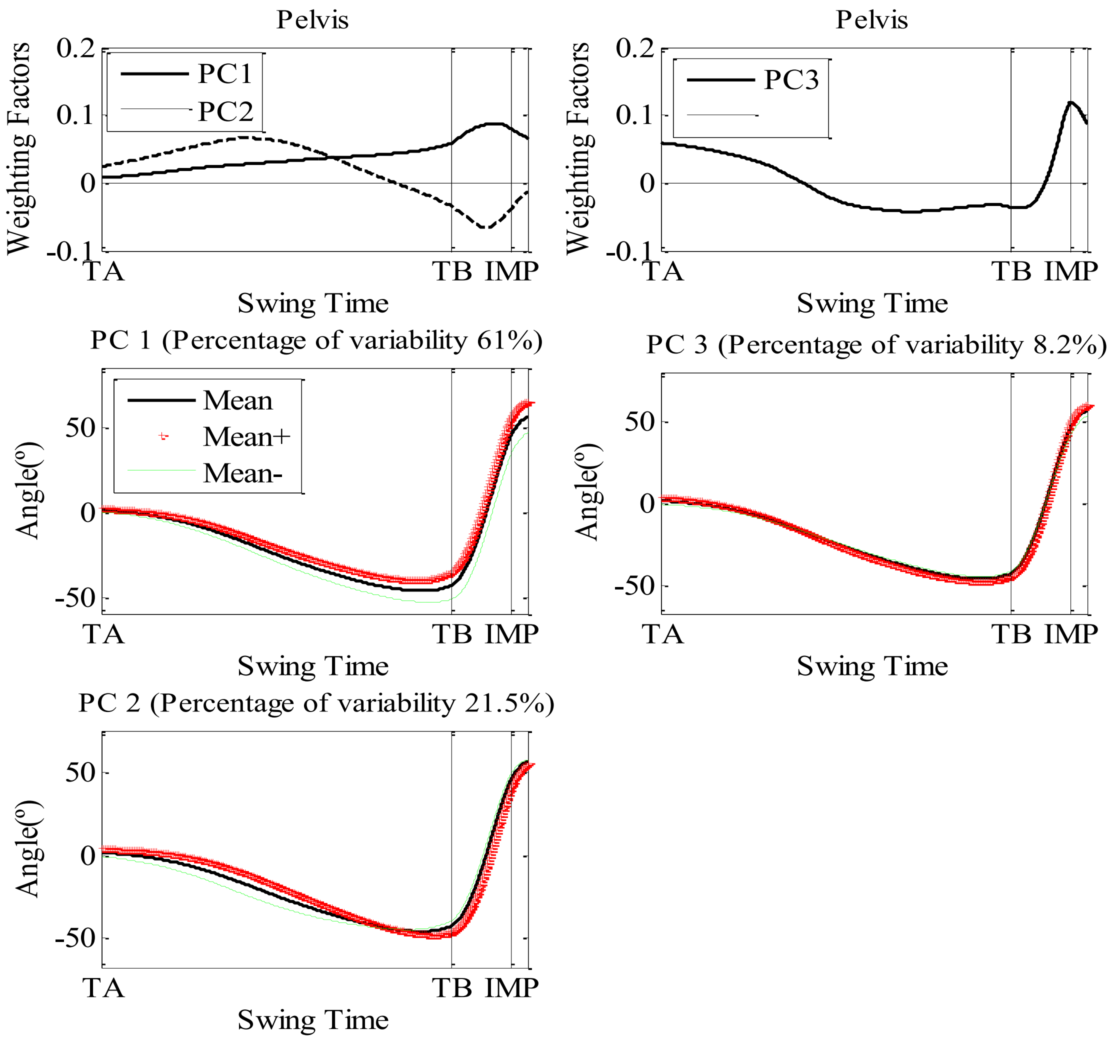


Figure H.4. (a) The weighting factors for the three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean pelvis axial rotation curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean pelvis axial rotation curve (black line) with a multiple of PC2 (red) and subtracted (green) from mean curve.

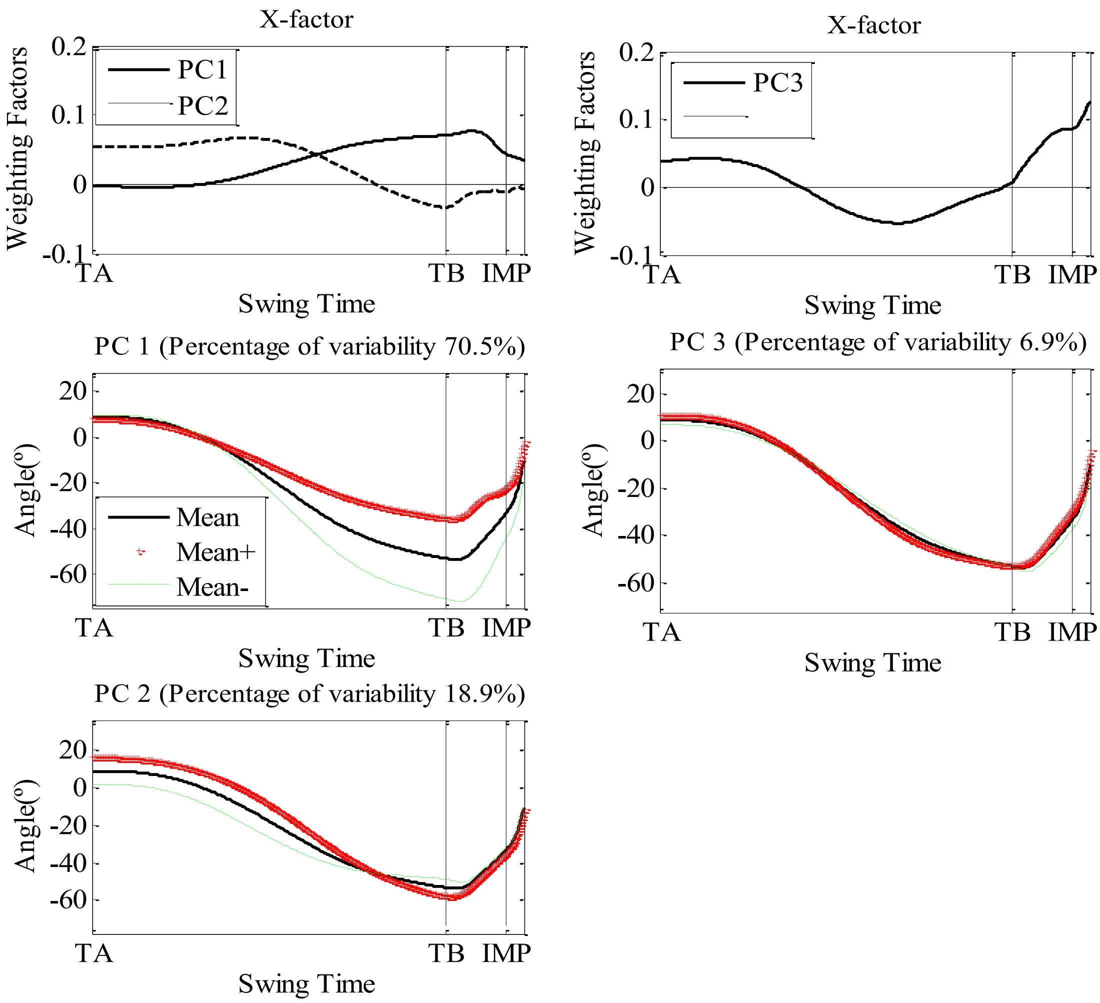


Figure H.5. (a) The weighting factors for the three principal components, PC1 and PC3 (solid) and PC2 (dashed) throughout the golf swing. (b) Mean X-factor curve (black line) with a multiple of PC1 and PC3 added (red) and subtracted (green) from mean curve (c) Mean X-factor curve (black line) with a multiple of PC2 (red) and subtracted (green) from mean curve.

Cluster determination

Using the Matlab functions ‘kmeans’ and ‘silhoutte’ the number of clusters required to adequately capture patterns in golfers body rotation PC scores were deduced. A try and tested method was used whereby the number of clusters was varied from one to six. Initially, kmeans was performed on PC scores data set, after which a silhouette plot was produced and the mean of the silhouette plot was calculated. An example of the Matlab code and silhouette analysis outputs is presented below.

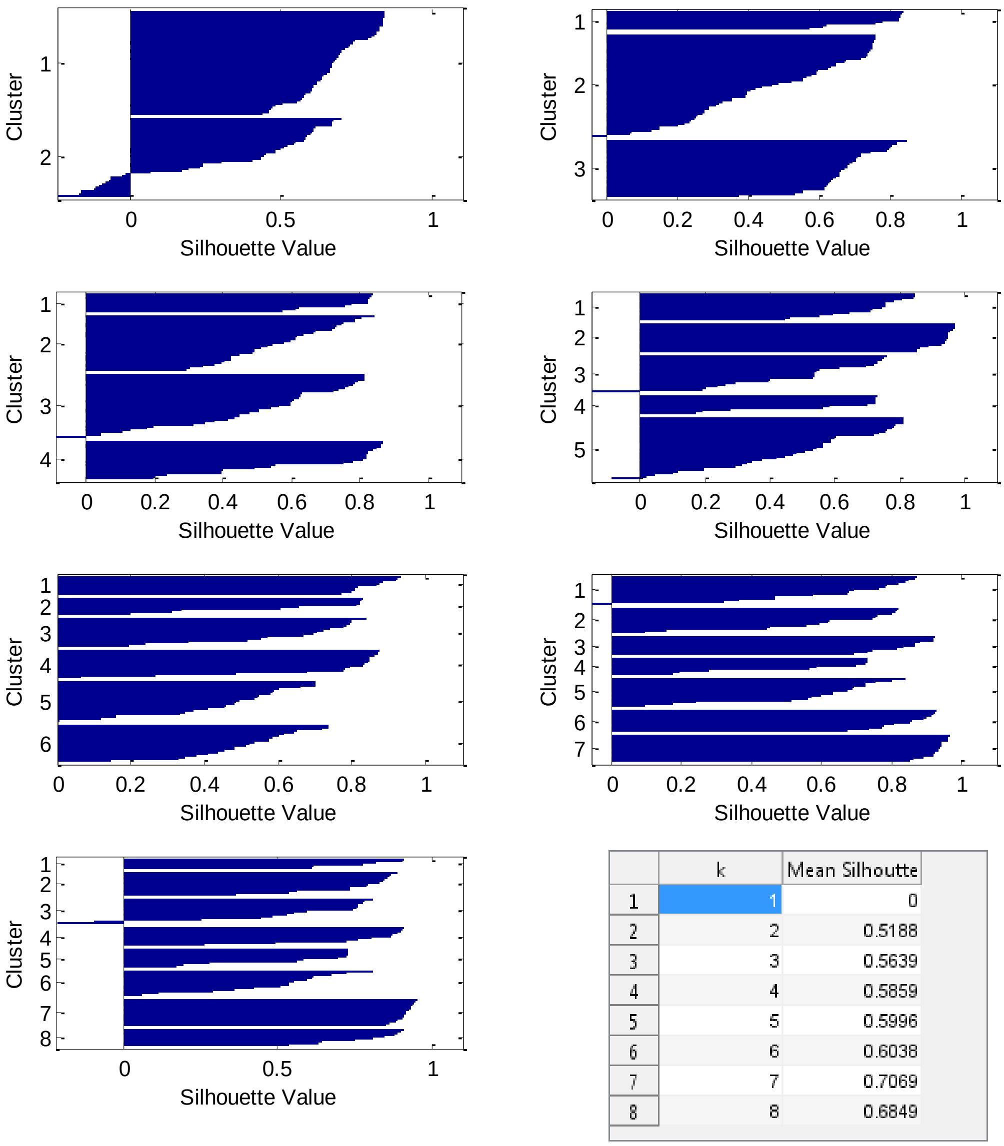
```
for clust=2:8;

[IDX,C]=kmeans(SCORE(:,1:2),clust,'display','iter');
cluster_groups(:,:,clust)=IDX;
centroids(:,:,clust) = [0 0;0 0;0 0;0 0;0 0;0 0;0 0;0 0;0 0];
centroids(1:clust,:,clust)=C;

figure(1);
subplot(4,2,clust-1);
[silh,h]=silhouette(SCORE(:,1:2),IDX);
silmean(clust,1)=mean(silh);

end

cnames = {'k','Mean Silhoutte'};
kno=[1;2;3;4;5;6;7;8];
t = uitable('Data',[kno silmean],'ColumnName',cnames,'Position',[340 60
200 160]);
```



	k	Mean Silhoutte
1	1	0
2	2	0.5188
3	3	0.5639
4	4	0.5859
5	5	0.5996
6	6	0.6038
7	7	0.7069
8	8	0.6849

Figure H.6. Silhoutte output for determining the appropriate number of clusters for k-means cluster analysis of PC scores.

Appendix I Visual 3D Pipeline

##Visual3D Script used to process and calculate data for biomechanical report written by Aimee Smith, 2011 – 2013 ##

```
Create_Hybrid_Model
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! /SUFFIX=
/RANGE=1+200
;
Apply_Model_Template
! /MODEL_TEMPLATE=
! /CALIBRATION_FILE=
;
Set_Subject_Weight
! /CALIBRATION_FILE=
! /WEIGHT=
;
Set_Subject_Height
! /CALIBRATION_FILE=
! /HEIGHT=
;
Save_Model_Template
! /CALIBRATION_FILE=
! /MODEL_TEMPLATE=
;
File_Open
! /FILE_NAME=
;
Assign_Tags_To_Files
! /MOTION_FILE_NAMES=
! /QUERY=
/TAGS=Report
;
Assign_Tags_To_Files
! /MOTION_FILE_NAMES=
/TAGS=Driver
;
Assign_Tags_To_Files
! /MOTION_FILE_NAMES=
/TAGS=5-iron
;
Assign_Tags_To_Files
! /MOTION_FILE_NAMES=
/TAGS=COG
;
Assign_Model_File
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! /MOTION_FILE_NAMES=
! /REMOVE_EXISTING_ASSIGNMENTS=FALSE
;
Lowpass_Filter
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TAREGT+TAREGT+TAREGT+TARGET+TARGE
T+TARGET+TAGRET+TARGET+TARGET+TAR
GET+TARGET+TARGET+TARGET+TARGET+T
ARGET+TARGET+TARGET+TARGET+TARGET
+TARGET+TARGET+TARGET+TARGET+TARG
ET+TARGET+TARGET+TARGET+TARGET+TA
RGET+TARGET+TARGET+TARGET+TARGET+
TARGET+TARGET+TARGET+TARGET+TARGE
T+TARGET+TARGET+TARGET+TAGRET+TAR
GET+TARGET+TAGRET+TARGET+TARGET+T
ARGET+TARGET+TARGET+TARGET+TARGET
+TARGET+TARGET+TARGET+TARGET+TARG
ET+TARGET+TARGET+TARGET+TARGET+TA
RGET+TARGET+TARGET+TARGET+TARGET+
TARGET+TARGET+TARGET+TARGET+TARGE
T+TARGET+TARGET+TARGET+TARGET+TAR
GET+TARGET
/SIGNAL_NAMES=LTOE+RFHD+LFHD+RBHD+
LBHD+C7+T10+RBAK+CLAV+RAC+LAC+RSHO
+LUP1+LUP2+LLELB+LMELB+LFA+LSHO+RUP
1+RUP2+RLELB+RMELB+RFA+LRAD+LULN+L
HA+RRAD+RULN+RHA+RASI+LASI+RPSI+LPSI
+LTH1+LTH2+LTH3+LLK+LMK+RTH1+RTH2+R
TH3+RLK+RMK+LSK1+LSK2+LLA+LMA+LTOE
+LHEEL+RSK1+RSK2+RLA+RMA+RTOE+RHEE
L+STRN+RAC+RASIS+RHA2+LHA2+RBK+LBH
D+RBHD+LPSIS+RPSIS+LASIS+LSHK1+T8+T2+
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K2+LSHK3+LSHK4+LHA1
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
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! /TIME=
;
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```

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! /RESULT_TYPES=
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! /RESULT_SUFFIX=
;
First_Derivative
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/SIGNAL_NAMES=BALL
/SIGNAL_FOLDER=ORIGINAL
/RESULT_NAMES=BALL_VEL
/RESULT_TYPES=TARGET
/RESULT_FOLDER=PROCESSED
! /RESULT_SUFFIX=
;
Event_Threshold
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/SIGNAL_NAMES=CLUBVEL
/SIGNAL_FOLDER=PROCESSED
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! /SELECT_Z=FALSE
! /SELECT_RESIDUAL=FALSE
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/FRAME_WINDOW=10
! /FRAME_OFFSET=0
! /ASCENDING=FALSE
! /DESCENDING=FALSE
!
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OLD_CROSSING=FALSE
!
/ENSURE_RANGE_FRAMES_AFTER_THRESHO
LD_CROSSING=FALSE
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! /END_AT_EVENT=
/EVENT_INSTANCE=1
;
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! /SELECT_RESIDUAL=FALSE
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! /FRAME_WINDOW=8
! /FRAME_OFFSET=0
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OLD_CROSSING=FALSE
!
/ENSURE_RANGE_FRAMES_AFTER_THRESHO
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! /END_AT_EVENT=
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;
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! /FRAME_OFFSET=0
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! /DESCENDING=FALSE
!
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!
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ACKSWING+ENDFOLLOW
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Metric_Minimum
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/AXIS3=X
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! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
;
!!!!3D Xfactor!!!!!
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/SEGMENT=Shoulder
/REFERENCE_SEGMENT=RPV_2
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! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
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! /NEGATEX=FALSE
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! /AXIS2=Y
/AXIS3=X
;
!!!3D X-factor at events!!!!
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=3DXFACTOR_STUP
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=3DXFACTOR
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=3DXFACTOR_TB
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=3DXFACTOR
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=3DXFACTOR_FT
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=3DXFACTOR
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=ENDFOLLOW
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=3DXFACTOR_IMPA
CT
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=3DXFACTOR
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Compute_Model_Based_Data
/RESULT_NAME=PELVIS_COG
/FUNCTION=SEG_CGPOSITION
/SEGMENT=RPV
! /REFERENCE_SEGMENT=LAB
! /RESOLUTION_COORDINATE_SYSTEM=LAB
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
;
!!!!Thorax/ab rotation!!!!
Compute_Model_Based_Data
/RESULT_NAME=THORAX/AB ROTATION
/FUNCTION=JOINT_ANGLE
/SEGMENT=Shoulder
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
/AXIS1=Z
! /AXIS2=Y
/AXIS3=X
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=THOR/AB_STUP
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=THORAX/AB ROTATION
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=THOR/AB_TB
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=THORAX/AB ROTATION
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=THOR/AB_IMPACT
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=THORAX/AB ROTATION
```

```
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=THOR/AB_FT
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=THORAX/AB ROTATION
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=ENDFOLLOW
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
!!! Pelvis rotation!!!!!!
Compute_Model_Based_Data
/RESULT_NAME=PELVIS ROTATION
/FUNCTION=JOINT_ANGLE
/SEGMENT=RPV_2
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
/AXIS1=Z
! /AXIS2=Y
/AXIS3=X
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=PEL_STUP
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=PELVIS ROTATION
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=PEL_TB
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=PELVIS ROTATION
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=PEL_IMPACT
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=PELVIS ROTATION
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=IMPACT
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=PEL_FT
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=PELVIS ROTATION
! /SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=ENDFOLLOW
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
!!!!Left arm rotation!!!!
Compute_Model_Based_Data
/RESULT_NAME=LEFT ARM ROTATION
/FUNCTION=JOINT_ANGLE
/SEGMENT=LAR
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
/AXIS1=Z
! /AXIS2=Y
/AXIS3=X
;
!!!!!Left forearm rotation!!!!
Compute_Model_Based_Data
/RESULT_NAME=LEFT FOREARM ROTATION
/FUNCTION=JOINT_ANGLE
/SEGMENT=LFA
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
/AXIS1=Z
! /AXIS2=Y
/AXIS3=X
;
!!!!Joint velocities!!!!!
```

```
Compute_Model_Based_Data
/RESULT_NAME=THORAX/AB VELOCITY
/FUNCTION=JOINT_VELOCITY
/SEGMENT=RTA
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=RTA
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
;
Metric_Maximum
/RESULT_METRIC_NAME=MAX_THORAX_VE
L
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=THORAX/AB VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/SIGNAL_COMPONENTS=Z
/EVENT_SEQUENCE=TAKEAWAY+ENDFOLLO
W
/EXCLUDE_EVENTS=
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
! /CREATE_GLOBAL_MAXIMUM=FALSE
;
Event_Global_Maximum
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=THORAX/AB VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=MAX_TRUNK VELOCITY
! /SELECT_X=FALSE
! /SELECT_Y=FALSE
/SELECT_Z=TRUE
/START_AT_EVENT=TAKEAWAY
/END_AT_EVENT=ENDFOLLOW
;
Compute_Model_Based_Data
/RESULT_NAME=PELVIS VELOCITY
/FUNCTION=JOINT_VELOCITY
/SEGMENT=RPV_2
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=RPV_2
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
;
Metric_Maximum
/RESULT_METRIC_NAME=MAX_PELVIS_VEL
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=PELVIS VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/SIGNAL_COMPONENTS=Z
/EVENT_SEQUENCE=TAKEAWAY+ENDFOLLO
W
/EXCLUDE_EVENTS=
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
! /CREATE_GLOBAL_MAXIMUM=FALSE
;
Event_Global_Maximum
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=PELVIS VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=MAX_PEL VELOCITY
! /SELECT_X=FALSE
! /SELECT_Y=FALSE
/SELECT_Z=TRUE
/START_AT_EVENT=TAKEAWAY
/END_AT_EVENT=ENDFOLLOW
;
Compute_Model_Based_Data
/RESULT_NAME=LEFT UPPER ARM VELOCITY
/FUNCTION=JOINT_VELOCITY
/SEGMENT=LAR
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=LAR
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
;
Metric_Maximum
/RESULT_METRIC_NAME=MAX_LEFTUPA_VE
L
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT UPPER ARM
VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/SIGNAL_COMPONENTS=Z
/EVENT_SEQUENCE=TAKEAWAY+ENDFOLLO
W
/EXCLUDE_EVENTS=
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
! /CREATE_GLOBAL_MAXIMUM=FALSE
;
Event_Global_Maximum
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT UPPER ARM
VELOCITY
/SIGNAL_FOLDER=ORIGINAL
```

```
/EVENT_NAME=MAX_LUPA VELOCITY
! /SELECT_X=FALSE
! /SELECT_Y=FALSE
/SELECT_Z=TRUE
/START_AT_EVENT=TAKEAWAY
/END_AT_EVENT=ENDFOLLOW
;
Compute_Model_Based_Data
/RESULT_NAME=LEFT FOREARM VELOCITY
/FUNCTION=JOINT_VELOCITY
/SEGMENT=LFA
! /REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=LFA
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
;
Metric_Maximum
/RESULT_METRIC_NAME=MAX_LFA_VEL
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT FOREARM VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/SIGNAL_COMPONENTS=Z
/EVENT_SEQUENCE=TAKEAWAY+ENDFOLLO
W
/EXCLUDE_EVENTS=
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
! /CREATE_GLOBAL_MAXIMUM=FALSE
;
Event_Global_Maximum
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT FOREARM VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=MAX_LFA VELOCITY
! /SELECT_X=FALSE
! /SELECT_Y=FALSE
/SELECT_Z=TRUE
/START_AT_EVENT=TAKEAWAY
/END_AT_EVENT=ENDFOLLOW
;
Signal_Magnitude
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=PELVIS VELOCITY
! /SIGNAL_FOLDER=ORIGINAL
/RESULT_NAMES=PELVIS VELOCITY
! /RESULT_TYPES=
! /RESULT_FOLDER=PROCESSED
! /RESULT_SUFFIX=
;
Signal_Magnitude
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=THORAX/AB VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/RESULT_NAMES=THORAX/AB VELOCITY
! /RESULT_TYPES=
/RESULT_FOLDER=PROCESSED
! /RESULT_SUFFIX=
;
Signal_Magnitude
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT FOREARM VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/RESULT_NAMES=LEFT FOREARM VELOCITY
! /RESULT_TYPES=
/RESULT_FOLDER=PROCESSED
! /RESULT_SUFFIX=
;
Signal_Magnitude
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT UPPER ARM
VELOCITY
/SIGNAL_FOLDER=ORIGINAL
/RESULT_NAMES=LEFT UPPER ARM
VELOCITY
! /RESULT_TYPES=
/RESULT_FOLDER=PROCESSED
! /RESULT_SUFFIX=
;
Average_Filter
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=PELVIS
VELOCITY+THORAX/AB VELOCITY+LEFT
FOREARM VELOCITY+ LEFT UPPER ARM
VELOCITY
/SIGNAL_FOLDER=PROCESSED+PROCESSED+
PROCESSED+PROCESSED
/RESULT_NAMES=PELVIS
VELOCITY+THORAX/AB VELOCITY+LEFT
FOREARM VELOCITY+LEFT UPPER ARM
VELOCITY
! /RESULT_TYPES=
/RESULT_FOLDER=PROCESSED+PROCESSED+
PROCESSED+PROCESSED
! /RESULT_SUFFIX=
/NUM_WINDOW_FRAMES=5
;
!!!!!Swing Time!!!!!!

Metric_Time_Between_Events
/RESULT_METRIC_NAME=Swing Time
! /RESULT_METRIC_FOLDER=PROCESSED
/EVENT_SEQUENCE=TAKEAWAY+IMPACT
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Time_Between_Events
/RESULT_METRIC_NAME=Backswing
! /RESULT_METRIC_FOLDER=PROCESSED
/EVENT_SEQUENCE=TAKEAWAY+TOPBACKS
WING
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Time_Between_Events
/RESULT_METRIC_NAME=Downswing
! /RESULT_METRIC_FOLDER=PROCESSED
/EVENT_SEQUENCE=TOPBACKSWING+IMPAC
T
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
```

```
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=(TARGET::ORIGINAL::LHEEL::X
-TARGET::ORIGINAL::BALL::X)*100
/RESULT_NAME=BALL_POSITION
! /RESULT_TYPE=DERIVED
! /RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=BALL_POSITION_T
A
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=BALL_POSITION
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+TARGET+TARGET
/SIGNAL_NAMES=LHEEL+BALL+LTOE
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORI
GINAL
/RESULT_NAME=BALL_ANGLE
! /RESULT_FOLDER=PROCESSED
! /COMPUTE_3PT_ANGLE=TRUE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
! /PROJECTION_PLANE=XY
! /USE_RIGHT_HAND_RULE=TRUE
! /USE_0_TO_360_DEGREES=TRUE
;
Evaluate_Expression
/EXPRESSION=360-
DERIVED::PROCESSED::BALL_ANGLE
/RESULT_NAME=BALL_ANGLE_360
! /RESULT_TYPE=DERIVED
! /RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=distance(TARGET::ORIGINAL::LH
EEL,TARGET::ORIGINAL::RHEEL)
/RESULT_NAME=HEEL_DISTANCE
! /RESULT_TYPE=DERIVED
! /RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=distance(TARGET::ORIGINAL::LT
OE,TARGET::ORIGINAL::RTOE)
/RESULT_NAME=TOE_DISTANCE
! /RESULT_TYPE=DERIVED
! /RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=DERIVED::PROCESSED::MID_LF
OOT_DIST_X-
DERIVED::PROCESSED::MID_RFOOT_DIST_X
/RESULT_NAME=STANCE_DIST
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=STANCE_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=STANCE_DIST
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=METRIC::PROCESSED::STANCE
_TA*-100
/RESULT_NAME=STANCE_TACM
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Metric_Mean
/RESULT_METRIC_NAME=STANCE_TCM
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=STANCE_TACM
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Lowpass_Filter
/SIGNAL_TYPES=ANALOG+ANALOG+ANALO
G+ANALOG+ANALOG+ANALOG+ANALOG+A
NALOG+ANALOG+ANALOG+ANALOG
+ANALOG
/SIGNAL_NAMES=Fz2+Fx2+Fy2+Mx1+Mx2+My1
+My2+Mz1+Mz2+Fx1+Fy1+Fz1
! /SIGNAL_FOLDER=ORIGINAL
! /RESULT_SUFFIX=
! /RESULT_FOLDER=PROCESSED
! /FILTER_CLASS=BUTTERWORTH
/FREQUENCY_CUTOFF=25
! /NUM_REFLECTED=6
! /TOTAL_BUFFER_SIZE=6
! /NUM_BIDIRECTIONAL_PASSES=1
;
Set_Use_Processed_Analog
/USE_PROCESSED=TRUE
;
Modify_Force_Structure_Parameters
/USED=3
/TYPE=0+0+0
/NUM_FP_IN=1+1+2
/FP_INDEX=1+2+1+2
/NUM_SURFACES_OUT=1+1+1
/SPEED_VALUES=0+0+0
! /SPEED_CHANNELS=
! /SPEED_SCALES=
/CORNER1=0+0+20+0+400+20+-600+0+20
```

```
/CORNER2=0+400+20+0+0+20+600+0+20
/CORNER3=600+400+20+-600+0+20+600+400+20
/CORNER4=600+0+20+-600+400+20+-600+400+20
/USE_FORCES_FOR_KINETICS=FALSE+TRUE+
FALSE
/COMBINE_INPUT_FORCES=FALSE+FALSE+TR
UE
! /UPDATE_C3D_FILE=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=BODY_WEIGHT
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=FORCE
/SIGNAL_NAMES=FS3_1
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=(FORCE::ORIGINAL::FP1::Z)/(ME
TRIC::PROCESSED::BODY_WEIGHT::Z)
/RESULT_NAME=FP1_BW
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Mean
/RESULT_METRIC_NAME=_MEAN
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=TRU
E
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=FP1_BW
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=(FORCE::ORIGINAL::FP2::Z)/(ME
TRIC::PROCESSED::BODY_WEIGHT::Z)
/RESULT_NAME=FP2_BW
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Mean
/RESULT_METRIC_NAME=_MEAN
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=TRU
E
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=FP2_BW
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=(FORCE::ORIGINAL::FS3_1::Z)/(
METRIC::PROCESSED::BODY_WEIGHT::Z)
/RESULT_NAME=FP3_BW
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Mean
/RESULT_METRIC_NAME=_MEAN
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=TRU
E
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=FP3_BW
/SIGNAL_FOLDER=PROCESSED
/SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LFZ_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=FORCE
/SIGNAL_NAMES=FP2
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RFZ_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=FORCE
/SIGNAL_NAMES=FP1
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=(METRIC::PROCESSED::LFZ_TA
_MEAN/METRIC::PROCESSED::BODY_WEIGHT
)*100
/RESULT_NAME=LFZ_TA_NORM
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=(METRIC::PROCESSED::RFZ_TA
_MEAN/METRIC::PROCESSED::BODY_WEIGHT
)*100
/RESULT_NAME=RFZ_TA_NORM
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LFZ_TB
/RESULT_METRIC_FOLDER=PROCESSED
```

```
/SIGNAL_TYPES=FORCE
/SIGNAL_NAMES=FP2
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RFZ_TB
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=FORCE
/SIGNAL_NAMES=FP1
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=(METRIC::PROCESSED::LFZ_TB
_MEAN/METRIC::PROCESSED::BODY_WEIGHT
)*100
/RESULT_NAME=LFZ_TB_NORM
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=(METRIC::PROCESSED::RFZ_TB
_MEAN::Z/METRIC::PROCESSED::BODY_WEIG
HT)*100
/RESULT_NAME=RFZ_TB_NORM
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LFZ_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=FORCE
/SIGNAL_NAMES=FP2
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RFZ_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=FORCE
/SIGNAL_NAMES=FP1
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=(METRIC::PROCESSED::LFZ_IM
P_MEAN::Z/METRIC::PROCESSED::BODY_WEI
GHT)*100
/RESULT_NAME=LFZ_IMP_NORM
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=(METRIC::PROCESSED::RFZ_IM
P_MEAN/METRIC::PROCESSED::BODY_WEIGH
T)*100
/RESULT_NAME=RFZ_IMP_NORM
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Metric_Mean
/RESULT_METRIC_NAME=FFTA_BW%
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=LFZ_TA_NORM
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=BFTA_BW%
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=RFZ_TA_NORM
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=FFTB_BW%
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=LFZ_TB_NORM
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=FFIMP_BW%
```

```
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=LFZ_IMP_NORM
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=BFTB_BW%
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=RFZ_TB_NORM
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=BFIMP_BW%
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=RFZ_IMP_NORM
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=LANDMARK::ORIGINAL::MID_L
FOOT::X
/RESULT_NAME=MID_LFOOT_DIST_X
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=LANDMARK::ORIGINAL::MID_R
FOOT::X
/RESULT_NAME=MID_RFOOT_DIST_X
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=
/RESULT_NAME=
! /RESULT_TYPE=DERIVED
! /RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=MID_LFOOT_DIST_
TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=MID_LFOOT_DIST_X
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=MID_RFOOT_DIST_
TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=MID_RFOOT_DIST_X
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=((COFP::ORIGINAL::FS3_1::X-
METRIC::PROCESSED::MID_RFOOT_DIST_TA)/
(METRIC::PROCESSED::MID_LFOOT_DIST_TA-
METRIC::PROCESSED::MID_RFOOT_DIST_TA))
*100
/RESULT_NAME=COP_PERX
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=((COFP::ORIGINAL::FS3_1::X-
METRIC::PROCESSED::MID_RFOOT_DIST_TA)/
(METRIC::PROCESSED::MID_LFOOT_DIST_TA-
METRIC::PROCESSED::MID_RFOOT_DIST_TA))
/RESULT_NAME=COP_X
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RTOE_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=TARGET
/SIGNAL_NAMES=RTOE
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LTOE_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=TARGET
/SIGNAL_NAMES=LTOE
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
! /GENERATE_MEAN_AND_STDDEV=TRUE
```

```
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=METRIC::PROCESSED::RTOE_T
A::Y>METRIC::PROCESSED::LTOE_TA::Y
/RESULT_NAME=RTOE_GREATER
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=METRIC::PROCESSED::LTOE_T
A::Y>METRIC::PROCESSED::RTOE_TA::Y
/RESULT_NAME=LTOE_GREATER
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=DERIVED::PROCESSED::LTOE_
GREATER*METRIC::PROCESSED::LTOE_TA::Y
+DERIVED::PROCESSED::RTOE_GREATER*ME
TRIC::PROCESSED::RTOE_TA::Y
/RESULT_NAME=ANTERIOR_TOE
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RHEEL_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=TARGET
/SIGNAL_NAMES=RHEEL
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LHEEL_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=TARGET
/SIGNAL_NAMES=LHEEL
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
! /GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=METRIC::PROCESSED::RHEEL_
TA::Y<METRIC::PROCESSED::LHEEL_TA::Y
/RESULT_NAME=RHEEL_FURTHER_BACK
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=METRIC::PROCESSED::LHEEL_T
A::Y<METRIC::PROCESSED::RHEEL_TA::Y
/RESULT_NAME=LHEEL_FURTHER_BACK
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=DERIVED::PROCESSED::LHEEL_
FURTHER_BACK*METRIC::PROCESSED::LHEE
L_TA::Y+DERIVED::PROCESSED::RHEEL_FURT
HER_BACK*METRIC::PROCESSED::RHEEL_TA:
:Y
/RESULT_NAME=POSTERIOR_HEEL
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=((COFP::ORIGINAL::FS3_1::Y-
DERIVED::PROCESSED::POSTERIOR_HEEL)/(D
ERIVED::PROCESSED::ANTERIOR_TOE-
DERIVED::PROCESSED::POSTERIOR_HEEL))*1
00
/RESULT_NAME=COP_PERY
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=((COFP::ORIGINAL::FS3_1::Y-
DERIVED::PROCESSED::POSTERIOR_HEEL)/(D
ERIVED::PROCESSED::ANTERIOR_TOE-
DERIVED::PROCESSED::POSTERIOR_HEEL))
/RESULT_NAME=COP_Y
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=COP_PERX_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=COP_PERX
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=COP_PERY_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=COP_PERY
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=COP_PERX_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=COP_PERX
/SIGNAL_FOLDER=PROCESSED
```

```
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=COP_PERY_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=COP_PERY
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+TARGET+TARGET
/SIGNAL_NAMES=LTH1+LLK+LLA
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORI
GINAL
/RESULT_NAME=LEFT_KNEE
! /RESULT_FOLDER=PROCESSED
! /COMPUTE_3PT_ANGLE=TRUE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
/PROJECTION_PLANE=YZ
! /USE_RIGHT_HAND_RULE=TRUE
! /USE_0_TO_360_DEGREES=TRUE
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+TARGET+TARGET
/SIGNAL_NAMES=RTH1+RLK+RLA
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORI
GINAL
/RESULT_NAME=RIGHT_KNEE
! /RESULT_FOLDER=PROCESSED
! /COMPUTE_3PT_ANGLE=TRUE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
/PROJECTION_PLANE=YZ
! /USE_RIGHT_HAND_RULE=TRUE
! /USE_0_TO_360_DEGREES=TRUE
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+TARGET+TARGET
/SIGNAL_NAMES=LTH1+LLK+LLA
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORI
GINAL
/RESULT_NAME=LEFT_KNEE_AB/AD
! /RESULT_FOLDER=PROCESSED
! /COMPUTE_3PT_ANGLE=TRUE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
/PROJECTION_PLANE=XZ
! /USE_RIGHT_HAND_RULE=TRUE
! /USE_0_TO_360_DEGREES=TRUE
;
Compute_Model_Based_Data
/RESULT_NAME=LEFT_KNEE_XYZ
/FUNCTION=JOINT_ANGLE
/SEGMENT=LSK
/REFERENCE_SEGMENT=LTH
/RESOLUTION_COORDINATE_SYSTEM=
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
/AXIS1=X
/AXIS2=Y
/AXIS3=Z
;
Compute_Model_Based_Data
/RESULT_NAME=RIGHT_KNEE_XYZ
/FUNCTION=JOINT_ANGLE
/SEGMENT=RSK
/REFERENCE_SEGMENT=RTH
/RESOLUTION_COORDINATE_SYSTEM=
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
/AXIS1=X
/AXIS2=Y
/AXIS3=Z
;
Metric_Mean
/RESULT_METRIC_NAME=LKNEE
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=TAKEAWAY+ENDFOLLO
W
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=RKNEE
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=RIGHT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=TAKEAWAY+ENDFOLLO
W
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
```

```
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LKNEE_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RKNEE_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=RIGHT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LKNEE_TB
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RKNEE_TB
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=RIGHT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=LKNEE_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=LEFT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=RKNEE_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=RIGHT_KNEE_XYZ
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+LANDMARK+LAND
MARK+LANDMARK
/SIGNAL_NAMES=T2+Mid_PSIS+Lab_origin+Lab
_z
/SIGNAL_FOLDER=PROCESSED+ORIGINAL+O
RIGINAL+ORIGINAL
/RESULT_NAME=SPINE_2D_flexion
! /RESULT_FOLDER=PROCESSED
/COMPUTE_3PT_ANGLE=FALSE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
/PROJECTION_PLANE=YZ
! /USE_RIGHT_HAND_RULE=TRUE
/USE_0_TO_360_DEGREES=FALSE
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+LANDMARK+LAND
MARK+LANDMARK
/SIGNAL_NAMES=T2+Mid_PSIS+Lab_origin+Lab
_z
/SIGNAL_FOLDER=PROCESSED+ORIGINAL+O
RIGINAL+ORIGINAL
/RESULT_NAME=SPINE_2D_lateral
! /RESULT_FOLDER=PROCESSED
/COMPUTE_3PT_ANGLE=FALSE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
/PROJECTION_PLANE=XZ
! /USE_RIGHT_HAND_RULE=TRUE
/USE_0_TO_360_DEGREES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=2D_SPINE_FLEXION
_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=SPINE_2D_flexion
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
```

```
!
/GENERATE_VECTOR_LENGTH_METRIC=FALSE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=2D_SPINE_LB_TA
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=SPINE_2D_lateral
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FALSE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=2D_SPINE_FLEXION_TB
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=SPINE_2D_flexion
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FALSE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=2D_SPINE_FLEXION_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=SPINE_2D_flexion
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FALSE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=2D_SPINE_LB_TB
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=SPINE_2D_lateral
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=TOPBACKSWING
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FALSE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=2D_SPINE_LB_IMP
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=SPINE_2D_lateral
/SIGNAL_FOLDER=PROCESSED
/EVENT_NAME=IMPACT
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FALSE
! /RETAIN_NO_DATA_VALUES=FALSE
;
First_Derivative
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=3DXFACTOR
/SIGNAL_FOLDER=ORIGINAL
! /RESULT_NAMES=
! /RESULT_TYPES=
/RESULT_FOLDER=PROCESSED
/RESULT_SUFFIX=_RATE
;
Evaluate_Expression
/EXPRESSION=(METRIC::PROCESSED::3DXFACTOR_TB::Z)-(METRIC::PROCESSED::3DXFACTOR_MAX::Z)
/RESULT_NAME=XFACTOR_STRETCH
/RESULT_TYPE=METRIC
/RESULT_FOLDER=PROCESSED
;
Metric_Minimum
/RESULT_METRIC_NAME=_MAX
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=TRUE
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=LINK_MODEL_BASED
/SIGNAL_NAMES=3DXFACTOR
/SIGNAL_FOLDER=ORIGINAL
/SIGNAL_COMPONENTS=Z
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
! /CREATE_GLOBAL_MINIMUM=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=_MEAN
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=TRUE
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=XFACTOR_STRETCH
/SIGNAL_FOLDER=PROCESSED
!/SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=EVENT_LABEL::ORIGINAL::MAX_TRUNK VELOCITY-EVENT_LABEL::ORIGINAL::MAX_PEL VELOCITY
/RESULT_NAME=TRUNK_LAG
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
```

```
/EXPRESSION=EVENT_LABEL::ORIGINAL::MA
X_LUPA VELOCITY-
EVENT_LABEL::ORIGINAL::MAX_TRUNK
VELOCITY
/RESULT_NAME=LUPA_LAG
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=EVENT_LABEL::ORIGINAL::MA
X_LUPA VELOCITY-
EVENT_LABEL::ORIGINAL::MAX_LFA
VELOCITY
/RESULT_NAME=LFA_LAG
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Metric_Mean
/RESULT_METRIC_NAME=TRUNK_LAG
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=TRUNK_LAG
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=LUPA_LAG
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=LUPA_LAG
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Mean
/RESULT_METRIC_NAME=LFA_LAG
!
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=FALS
E
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=LFA_LAG
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Metric_Signal_Value_At_Event
/RESULT_METRIC_NAME=BALL_POSITION
/RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=TARGET
/SIGNAL_NAMES=BALL
/SIGNAL_FOLDER=ORIGINAL
/EVENT_NAME=TAKEAWAY
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
!
/GENERATE_VECTOR_LENGTH_METRIC=FAL
SE
! /RETAIN_NO_DATA_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=LINK_MODEL_BASED::ORIGIN
AL::COG-
METRIC::PROCESSED::BALL_POSITION
/RESULT_NAME=COG_DIST
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Evaluate_Expression
/EXPRESSION=COFP::ORIGINAL::FS3_1-
METRIC::PROCESSED::BALL_POSITION
/RESULT_NAME=COP_DIST
/RESULT_TYPE=DERIVED
/RESULT_FOLDER=PROCESSED
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+TARGET+TARGET
/SIGNAL_NAMES=RLELB+RRAD+OBJ1
/SIGNAL_FOLDER=PROCESSED+PROCESSED+
ORIGINAL
/RESULT_NAME=RIGHT_WRIST
! /RESULT_FOLDER=PROCESSED
! /COMPUTE_3PT_ANGLE=TRUE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
/PROJECTION_PLANE=3D
! /USE_RIGHT_HAND_RULE=TRUE
! /USE_0_TO_360_DEGREES=TRUE
;
Lowpass_Filter
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=RIGHT_WRIST
/SIGNAL_FOLDER=PROCESSED
! /RESULT_SUFFIX=
/RESULT_FOLDER=PROCESSED
! /FILTER_CLASS=BUTTERWORTH
/FREQUENCY_CUTOFF=10
! /NUM_REFLECTED=6
! /TOTAL_BUFFER_SIZE=6
! /NUM_BIDIRECTIONAL_PASSES=1
;
First_Derivative
/SIGNAL_TYPES=DERIVED
/SIGNAL_NAMES=RIGHT_WRIST
/SIGNAL_FOLDER=PROCESSED
! /RESULT_NAMES=RIGHT_WRIST_VELOCITY
/RESULT_TYPES=DERIVED
/RESULT_FOLDER=PROCESSED
/RESULT_SUFFIX=_VELOCITY
;
Compute_Planar_Angle
/SIGNAL_TYPES=TARGET+TARGET+TARGET
/SIGNAL_NAMES=LSHO+LLELB+LULN
/SIGNAL_FOLDER=PROCESSED+PROCESSED+
PROCESSED
/RESULT_NAME=LEFT_ELBOW_ANGLE
```

```
! /RESULT_FOLDER=PROCESSED
! /COMPUTE_3PT_ANGLE=TRUE
! /NORMALX=
! /NORMALY=
! /NORMALZ=
! /REFERENCE_SEGMENT=LAB
/PROJECTION_PLANE=YZ
! /USE_RIGHT_HAND_RULE=TRUE
! /USE_0_TO_360_DEGREES=TRUE
;
Compute_Model_Based_Data
/RESULT_NAME=RIGHT_ARM_ANGLE
/FUNCTION=JOINT_ANGLE
/SEGMENT=RAR
/REFERENCE_SEGMENT=RTA
/RESOLUTION_COORDINATE_SYSTEM=
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
;
! Prompt the user for the Folder containing the cmo files
   ! In this case Sub Folders will be searched as well

   Set_Pipeline_Parameter_To_Folder_Path
   /PARAMETER_NAME=MAINFOLDER
   !/PARAMETER_VALUE= E:\Visual3DImages\
   ;
!!!!DRAW SHAFT PLANE!!!!!
Set_Animation_Draw_Size
/SIGNAL_TYPES=TARGET+TARGET+TARGET+
TAREGT+TAREGT+TAREGT+TARGET+TARGE
T+TARGET+TAGRET+TARGET+TARGET+TAR
GET+TARGET+TARGET+TARGET+TARGET+T
ARGET+TARGET+TARGET+TARGET+TARGET
+TARGET+TARGET+TARGET+TARGET+TARG
ET+TARGET+TARGET+TARGET+TARGET+TA
RGET+TARGET+TARGET+TARGET+TARGET+
TARGET+TARGET+TARGET+TARGET+TARGE
T+TARGET+TARGET+TARGET+TAGRET+TAR
GET+TARGET+TAGRET+TARGET+TARGET+T
ARGET+TARGET+TARGET+TARGET+TARGET
+TARGET+TARGET+TARGET+TARGET+TARG
ET+TARGET+TARGET+TARGET+TARGET+TA
RGET+TARGET+TARGET+TARGET+TARGET+
TARGET+TARGET+TARGET+TARGET+TARGE
T+TARGET+TARGET+TARGET+TARGET+TAR
GET+TARGET
/SIGNAL_NAMES=RSHK1+RFHD+LFHD+RBHD
+LBHD+C7+T10+RBAK+CLAV+RAC+LAC+RSH
O+LUP1+LUP2+LLELB+LMELB+LFA+LSHO+R
UP1+RUP2+RLELB+RMELB+RFA+LRAD+LULN
+LHA+RRAD+RULN+RHA+RASI+LASI+RPSI+L
PSI+LTH1+LTH2+LTH3+LLK+LMK+RTH1+RTH
2+RTH3+RLK+RMK+LSK1+LSK2+LLA+LMA+L
TOE+LHEEL+RSK1+RSK2+RLA+RMA+RTOE+R
HEEL+STRN+RAC+RASIS+RHA2+LHA2+RBK+
LBHD+RBHD+LPSIS+RPSIS+LASIS+LSHK1+T8+
T2+C7+L4+L5+RHA1+RSHK4+RSHK3+RSHK2+L
SHK2+LSHK3+LSHK4+LHA1
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL
/DRAW_SIZE=DON'T DRAW
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&SETUP.
JPG
/FRAME=TAKEAWAY
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&TB.JPG
/FRAME=TOPBACKSWING
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Set_Camera_Perspective
/USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=2
/CAMERA_PAN=-90
/CAMERA_TILT=0
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&IMPAC
T.JPG
/FRAME=IMPACT
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Set_Camera_Perspective
/USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=2
/CAMERA_PAN=-90
/CAMERA_TILT=0
;
Export_3D_Animation_To_Image
```

```
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&IMP_FR
ONT.JPG
/FRAME=IMPACT
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Set_Camera_Perspective
/USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=2
/CAMERA_PAN=0
/CAMERA_TILT=0
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&IMP_SI
DE.JPG
/FRAME=IMPACT
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Set_Camera_Perspective
! /USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=2
/CAMERA_PAN=-90
/CAMERA_TILT=90
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&IMP_TO
P.JPG
/FRAME=IMPACT
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Set_Camera_Perspective
! /USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=2
/CAMERA_PAN=90
/CAMERA_TILT=0
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&IMP_BA
CK.JPG
/FRAME=IMPACT
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&FT.JPG
/FRAME=ENDFOLLOW
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
End_For_Each
  /ITERATION_PARAMETER_NAME=INDEX
  ;
Switch_to_Report_Mode
! /SHOW_ANIMATION=FALSE
! /PAGE_NUMBER=
;
Open_Report_Template
! /REPORT_TEMPLATE=
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&IMP_FRONT.JP
G
/PAGE_NUMBER=2
/COLUMN_NUMBER=1
/ROW_NUMBER=1
! /COLUMN_SPAN=1
! /ROW_SPAN=1
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&IMP_SIDE.JPG
/PAGE_NUMBER=2
/COLUMN_NUMBER=1
/ROW_NUMBER=2
! /COLUMN_SPAN=1
! /ROW_SPAN=1
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&IMP_BACK.JPG
/PAGE_NUMBER=2
/COLUMN_NUMBER=2
/ROW_NUMBER=1
! /COLUMN_SPAN=1
! /ROW_SPAN=1
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&IMP_TOP.JPG
/PAGE_NUMBER=2
/COLUMN_NUMBER=2
/ROW_NUMBER=2
! /COLUMN_SPAN=1
! /ROW_SPAN=1
;
Set_Camera_Perspective
/USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=2
/CAMERA_PAN=-90
/CAMERA_TILT=0
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&SETUP_
FRONT.JPG
/FRAME=TAKEAWAY
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Set_Camera_Perspective
! /USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
```

```
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=2
/CAMERA_PAN=0
/CAMERA_TILT=0
;
Export_3D_Animation_To_Image
/FILE_NAME=::FOLDER&*.C3D
/IMAGE_FILE_NAME=::MAINFOLDER&SETUP_
SIDE.JPG
/FRAME=TAKEAWAY
/OUTPUT_WIDTH=700
/OUTPUT_HEIGHT=500
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&SETUP_FRONT.
JPG
/PAGE_NUMBER=3
/COLUMN_NUMBER=1
/ROW_NUMBER=1
! /COLUMN_SPAN=1
/ROW_SPAN=2
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&SETUP_SIDE.JP
G
/PAGE_NUMBER=3
/COLUMN_NUMBER=1
/ROW_NUMBER=3
! /COLUMN_SPAN=1
/ROW_SPAN=2
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&IMP_FRONT.JP
G
/PAGE_NUMBER=4
/COLUMN_NUMBER=1
/ROW_NUMBER=1
! /COLUMN_SPAN=1
/ROW_SPAN=2
;
Make_Image_Item
/IMAGE_FILE=::MAINFOLDER&IMP_SIDE.JPG
/PAGE_NUMBER=4
/COLUMN_NUMBER=1
/ROW_NUMBER=3
! /COLUMN_SPAN=1
/ROW_SPAN=2
;
Set_Animation_Draw_Size
/SIGNAL_TYPES=TARGET+TARGET
/SIGNAL_NAMES=OBJ2+OBJ1
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL
/DRAW_SIZE=LARGE
;
!!!!DRAW SHAFT PLANE!!!!!
Set_Animation_Draw_Size
/SIGNAL_TYPES=TARGET+TARGET+TARGET+
TAREGT+TAREGT+TAREGT+TARGET+TARGE
T+TARGET+TAGRET+TARGET+TARGET+TAR
GET+TARGET+TARGET+TARGET+TARGET+T
ARGET+TARGET+TARGET+TARGET+TARGET
+TARGET+TARGET+TARGET+TARGET+TARG
ET+TARGET+TARGET+TARGET+TARGET+TA
RGET+TARGET+TARGET+TARGET+TARGET+
TARGET+TARGET+TARGET+TARGET+TARGE
T+TARGET+TARGET+TARGET+TAGRET+TAR
GET+TARGET+TAGRET+TARGET+TARGET+T
ARGET+TARGET+TARGET+TARGET+TARGET
+TARGET+TARGET+TARGET+TARGET+TARG
ET+TARGET+TARGET+TARGET+TARGET+TA
RGET+TARGET+TARGET+TARGET+TARGET+
TARGET+TARGET+TARGET+TARGET+TARGE
T+TARGET+TARGET+TARGET+TARGET+TAR
GET+TARGET
/SIGNAL_NAMES=RSHK1+RFHD+LFHD+RBHD
+LBHD+C7+T10+RBAK+CLAV+RAC+LAC+RSH
O+LUP1+LUP2+LLELB+LMELB+LFA+LSHO+R
UP1+RUP2+RLELB+RMELB+RFA+LRAD+LULN
+LHA+RRAD+RULN+RHA+RASI+LASI+RPSI+L
PSI+LTH1+LTH2+LTH3+LLK+LMK+RTH1+RTH
2+RTH3+RLK+RMK+LSK1+LSK2+LLA+LMA+L
TOE+LHEEL+RSK1+RSK2+RLA+RMA+RTOE+R
HEEL+STRN+RAC+RASIS+RHA2+LHA2+RBK+
LBHD+RBHD+LPSIS+RPSIS+LASIS+LSHK1+T8+
T2+C7+L4+L5+RHA1+RSHK4+RSHK3+RSHK2+L
SHK2+LSHK3+LSHK4+LHA1
/SIGNAL_FOLDER=ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
GINAL+ORIGINAL+ORIGINAL+ORIGINAL+ORI
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GINAL+ORIGINAL
/DRAW_SIZE=DON'T DRAW
;
Set_Camera_Perspective
! /USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=1.5
/CAMERA_PAN=-90
/CAMERA_TILT=0
;
Set_Camera_Perspective
! /USE_STATIONARY_CAMERA=TRUE
! /SEGMENT=
/CAMERA_X_CENTER=-0.263
/CAMERA_Y_CENTER=-0.11
/CAMERA_Z_CENTER=-0.926
/CAMERA_ZOOM=1.5
/CAMERA_PAN=0
/CAMERA_TILT=0
;
###Example of code written to generate average data
###Generate Mean Data

Metric_Mean
/RESULT_METRIC_NAME=_GLOBAL
```

```
/APPLY_AS_SUFFIX_TO_SIGNAL_NAME=TRU
E
! /RESULT_METRIC_FOLDER=PROCESSED
/SIGNAL_TYPES=METRIC
/SIGNAL_NAMES=Downswing_MEAN
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_COMPONENTS=ALL_COMPONENTS
/EVENT_SEQUENCE=
/EXCLUDE_EVENTS=
/GENERATE_MEAN_AND_STDDEV=TRUE
! /APPEND_TO_EXISTING_VALUES=FALSE
;
Evaluate_Expression
/EXPRESSION=GLOBAL::METRIC::PROCESSED
::Downswing_MEAN_GLOBAL_MEAN
/RESULT_NAME=GLOBAL::Downswing_Mean_G
lobal
/RESULT_TYPE=P2D
/RESULT_FOLDER=NORM
;
;
!!!!!!Run after all globals have been calculated
Evaluate_Expression
/EXPRESSION=P2D::NORM::Downswing_Mean_G
lobal
/RESULT_NAME=GLOBAL::Downswing_Mean_G
lobal
/RESULT_TYPE=METRIC
/RESULT_FOLDER=TEMP
;
```