THE ROLE OF BIOMECHANICS IN ACHIEVING DIFFERENT SHOT TRAJECTORIES IN GOLF

A Doctoral Thesis submitted in partial fulfilment of the requirement for the award of Doctor of Philosophy of Loughborough University

by

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For Dad

ABSTRACT

In golf, a range of shot types are necessary for successful performance, with driving and iron-play constituting the “long-game”. It is possible to vary “long-game” shots through altered trajectory, for example, by utilising right-to-left or left-to-right ball flight curvature, providing course management advantages. However, how golfers vary their biomechanics to achieve different trajectories is not scientifically understood. Therefore, the purpose of this thesis was to biomechanically investigate different trajectories hit with the same club.

To investigate shot trajectories, accurate measures of performance were necessary. Launch monitors (TrackMan Pro IIIe and Foresight GC2+HMT) are bespoke technologies capable of tracking the clubhead and ball through impact. However, their accuracy for scientific research has not been independently validated. Therefore, a novel purpose-designed tracking method was developed using a three-dimensional optical tracking system (GOM). The accuracy of this method was validated and the system used as the benchmark to which the two launch monitors were compared through limits of agreement. The results showed, in general, the launch monitors were in closer agreement to the benchmark for ball parameters than clubhead. High levels of agreement were found for ball velocity, ball path, total spin rate and backspin. However, poorer agreement was shown for ball sidespin and spin axis as well as clubhead velocity, clubhead path and clubhead orientation. Consequently, the launch monitors were deemed unsuitable for inclusion in scientific research across a range of impact parameters.

Draw and fade trajectories with a driver and draw, fade and low trajectories with a 5-iron were investigated biomechanically. The clubhead and ball were tracked using the optical method developed in this thesis. Key biomechanical variables (address position and whole-swing) were defined based on coaching theory. Statistically, analysis of variance (address) and principal components analysis (whole-swing), were used to compare draw against fade and low against natural trajectories. Multivariate correlation was used to identify swing pattern similarities between golfers.

The group-level comparison showed draw-fade address differences whereby for draw trajectories, the ball was positioned further away from the target, the lead hand further towards the target and the pelvis, thorax and stance openness closed relative to the target line. Over the whole-swing, the draw when compared to the fade demonstrated a pelvis rotation, more rotated away from the target with later rotation; lumbar forward flexion, with slower extending in the downswing; lumbar lateral flexion, with more flexion towards the trail throughout and prolonged trail flexing through ball contact; thorax lateral flexion, with greater, slower lead flexing in the backswing and greater, more prolonged trail flexing in the downswing; pelvis translation further towards the target throughout, with earlier forward translation and centre of pressure, with an earlier, quicker, greater forward shift. Cluster differences were evident, with both *Clusters I* (57% of golfers with the driver) and *II* (71% of golfers with the 5-iron) showing greater, earlier thorax rotation towards the target and a tendency for greater lumbar forward flexion over the whole-swing (*Cluster II*) and backswing (*Cluster I*).

For the group-level low-natural comparison, golfers positioned the ball further away from the target and their lead hand further towards the target for low trajectories. Further, *Cluster IV* (45% of golfers), narrowed their stance width and laterally flexed their thorax towards the lead, for the same trajectories. Over the whole-swing, the low when compared to the natural showed the pelvis translated towards the target throughout, with later, lesser forward shift for the low trajectories. Furthermore, centre of pressure displayed a greater forward shift for the same shots. Finally, both clusters (*Cluster III* – 36% of golfers – and *Cluster IV*) differed in lumbar forward flexion when playing low trajectories; over the backswing, *Cluster III* extended, whereas *Cluster IV* flexed. *Cluster IV* also showed greater extending in the downswing. Finally, *Cluster IV* showed more lumbar lateral flexion towards the lead throughout.

The results of this study have implications for scientific researchers as well as golf coaches, club-fitters and professionals. Commercially available launch monitors appear accurate enough for coaching applications, however caution is needed for scientific research when tracking a range of clubhead and ball parameters. Furthermore, changes in biomechanics when playing different trajectories has implications for future research and interpretation of published work, as well as for coaching theory. Future work following this thesis could utilise the optical tracking method to validate further commercial systems and for more detailed experimental investigation of clubhead-ball impacts. Furthermore, additional biomechanical investigation into a wider range of shot trajectories across more variables could be conducted, with a more in-depth understanding gained from principal components analysis and golfer clustering.

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PUBLICATIONS

Journal articles

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Conference Proceedings

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Oral Conference Presentations

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Leach, R. J., Roberts, J. R., & Forrester, S. (2017). Golfers alter their whole-swing biomechanics to achieve successful draw and fade shots with the driver. In *The Proceedings of BASES Biomechanics Interest Group Meeting 2017.* (Oral communication).

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CHAPTER ONE

INTRODUCTION TO THE THESIS

1.1. Introduction

Golf is a historic sport, the origin of which dates back hundreds of years. During on-course play, the ball sits stationary on a tee or on the ground from where it is struck with a club towards a target. The overarching aim is to get the ball from the tee into the hole in the fewest shots possible. To do so, a range of clubs are available to the golfer and for each shot, one is selected depending on the shot requirements. Typically, performance is measured by the total number of shots taken across multiple holes giving an overall score. To achieve a low score golfers are required to perfect different types of shot, encompassing the "long-game" of driving and iron-play and the "short-game" of pitching, chipping and putting. Within a golfer's "long-game" there is more than one way of playing a shot; in particular, a golfer may attempt to alter the trajectory of their shot. For example, by manipulating ball spin, a golfer can generate lateral movement in the ball flight, and the resultant shot is typically referred to as fade or draw (see Section 2.2.2; Figure 2-4). depending on the direction of motion. Control over shot trajectories can be considerably advantageous to golfers who are more easily able to overcome the challenges of the course, such as fading or drawing the ball around a dogleg, allowing more effective management of the golf course.

Achieving a given shot trajectory involves biomechanical changes of a golfer's swing to control the path and orientation of the clubhead leading up to its impact with the ball. Physical theory and experimentation, possibly due to recent technological advances, provide insight into the motion of the clubhead that is necessary to achieve each trajectory. The swing changes required to achieve these relevant motions are often professed by coaches, and include a combination of most simple changes in address position to more complex alterations of movements during the swing. The efficacy of these biomechanical swing changes to achieve the required trajectory have yet to be demonstrated scientifically.

1.2. The research scope

1.2.1. Current scientific research

Currently, there is a wide range of scientific research within the golf biomechanics area, the majority of which focuses on performance, relating biomechanical variables to measures of shot performance or ability, such as clubhead velocity and handicap (Okuda et al., 2010;

Brown et al., 2011; Meister et al., 2011; Fedorcik et al., 2012; Joyce et al., 2013a). There is little direct investigation of golfer biomechanics in relation to different shot trajectories using the same club. Those that have, have tended to focus on full and partial swings, with the aim of reduced shot distance (Tinmark et al., 2010; McNitt-Gray et al., 2013). However, other trajectories, such as draw and fade curvatures, have featured as part of article discussions, as potential factors influencing the results (e.g. Coleman & Anderson, 2007). Therefore, there is a need for further investigation across shot trajectories.

1.2.2. Thesis boundaries

At present, the lack of scientific biomechanical investigation into different shot trajectories presents a large gap in knowledge. Therefore, to address this gap, the overall purpose of this thesis was to investigate the biomechanics and impact characteristics of different shot trajectories. Specifically, trajectories related to the "long-game" were chosen as the scope of the research, namely, draw, fade, high and low trajectories.

Achieving this research purpose would increase knowledge in the area of golf biomechanics. Much of the existing research is based on the "'long-game", however, the majority focuses on clubhead velocity, ball velocity and shot distance. Whilst, unquestionably, these factors are important for the success of a shot, they are not necessarily the sole focus of a golfer when addressing the ball on the tee. Previous studies, therefore, may be limited by not controlling or ignoring the differences elicited by the type of trajectory a golfer has chosen to play during data collection. This thesis, therefore, fits a niche within golf biomechanics literature.

The outcomes of a biomechanical investigation into shot trajectories are important to both the scientific and coaching communities. Scientifically, implications can be drawn for future golf data collection methodology, as well as in the interpretation of existing findings, the results of which may be due to differences in shot trajectories. For coaches, the identification of key coaching points could offer guidance, that when teaching a specific shot trajectory, could form the basis of their lessons. These key coaching points would have scientific backing in terms of successfully achieving the shot trajectory.

1.2.3. Research questions

To achieve the overall purpose of the thesis, two research questions were defined:

> *Research Question 1*: Do measurable biomechanical differences exist when a golfer plays different types of shot trajectory with the same club? If so, what are the differences?

To address *Research Question 1*, suitable measurement systems are required to quantify biomechanical motion and shot outcomes. Biomechanical assessments of the golf swing are well established using existing motion analysis technologies available at the time of this thesis. Furthermore, a number of different launch monitor technologies have emerged in recent years, two of which, potentially available for use in scientific research, were available for this thesis: the TrackMan Pro IIIe (TrackMan A/S, Denmark) and Foresight GC2+HMT (Foresight Sports, San Diego, CA). These systems track a number of relevant shot parameters; however, the launch monitors had not previously been independently validated to assess their suitability to track the clubhead and ball. Therefore, a second research question was defined:

> *Research Question 2:* How suitable are commercially available clubhead-ball impact measurement technologies for use in scientific biomechanical investigation to measure performance outcomes?

The two research questions were complex to answer as standalone questions, so were broken down into more specific chapter-level aims:

> *Aim 1:* To gain an understanding of the scientific theory of the clubhead and ball during impacts as well as the biomechanical literature relating to different types of trajectory in hitting sports.
>
> *Aim 2:* To validate the accuracy of the impact parameters output by the TrackMan Pro IIIe and Foresight GC2+HMT launch monitor systems.
>
> *Aim 3:* To provide evidence based recommendations regarding the use of launch monitors within biomechanics scientific research.
>
> *Aim 4:* To understand coaching points behind different types of golf shot with the same club and to identify key coaching parameters for each shot.
>
> *Aim 5:* To determine the measurable differences that exist between different shot trajectories on a group and individual basis.

Specific hypotheses relevant to the two research questions are outlined within the relevant chapters.

1.3. Thesis breakdown

1.3.1. Chapter two

Chapter 2 consists of a literature review and focused on addressing *Aim 1*. The chapter is split into two sections. The first half involves insight into golf impacts as well as the technology used to track the clubhead and ball. The second details biomechanical literature relating to achieving different shot trajectories in hitting sports. The limited literature regarding the scope of the thesis in golf meant that relevant sources from similar hitting sports were included within this chapter.

1.3.2. Chapters three & four

The validation of two commercially available launch monitor systems is detailed in these two chapters, focusing on addressing *Aims 2-3* and *Research Question 2*. Chapter 3 outlines the method, including development of a benchmark optical tracking system, insight into its accuracy and set-up of the laboratory to align all three systems. Chapter 4 outlines the results of the validation, using degree of agreement statistics to evaluate how closely the launch monitors agree with the benchmark system from which recommendations on the use of launch monitors in scientific research can be made. The chapter finishes with future research recommendations based on the launch monitor study.

1.3.3. Chapters five, six, seven & eight

These four chapters contain the main biomechanical investigation, addressing *Research Question 1*. The study is split across the chapters with Chapter 5 initially outlining the methods. The chapter begins with a brief investigation of coaching points through a literature search and coach interviews *(Aim 4)*. This is intended as a guide for the main biomechanical investigation and not as a qualitative study in its own right. The chapter then defines the biomechanical variables identified in the coaching search. Finally, the main investigation methodology is defined. Chapters 6 and 7 detail the results of the investigation *(Aim 5)*, on a group-basis (Chapter 6) and individual-basis (Chapter 7). Finally, Chapter 8 is a discussion of the results, in the context of coaching theory and scientific literature and finishes with recommendations for future biomechanical research in the area.

1.3.4. Chapter nine

This chapter includes the major conclusions of the thesis, reinforcing the answers to the two major research questions and other outcomes based on the main aims of this thesis.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Hitting or striking sports involve a competitor striking a projectile with their body or a purpose-designed implement in an attempt to achieve a desired outcome. The hitting motion involves complex coordination of body movements to ensure that an optimal strike is achieved. Popular sports of this kind are baseball, tennis, badminton, cricket and golf, which require a range of shot types, some of which are played for maximum velocity. Other types of shot involve more accurate placement. For example, a second serve in tennis is unlikely to involve a flat, maximum velocity ball trajectory but could involve a slice or right-to-left curvature through the air for a right-handed player. Similarly, in golf, fade and draw trajectories are used to “shape” the ball from left-to-right or right-to-left to achieve a better outcome.

To understand how a hitter in these sports achieves their desired trajectory, it is important to consider both the biomechanics of the movement itself and the mechanics of the implement-projectile collision. In golf, there is a breadth of information regarding the physics of the clubhead-ball impact, aided by the growth of interest within the golfing community in technology to measure impacts. However, regarding the biomechanics of shot trajectories there is much less information.

Therefore, this review aims to gain an understanding of the scientific theory of the clubhead and ball during impacts as well as the biomechanical literature relating to different types of trajectory in hitting sports (*Aim 1*; Section 1.2.3).

2.2. Clubhead-ball impacts

Clubhead-ball impacts involve a high-speed collision between the clubhead mass and the ball stationary on the ground or on a tee. A range of parameters that define the path and orientation of the clubhead, typically at the moment of impact, have been related to the initial launch parameters of the ball, which ultimately determine the shot outcome. Some commonly used parameters within golf are described in general terms in Table 2-1 and Table 2-2 to prepare the reader for the discussion to follow. Also shown are the common units for these parameters, which are not necessarily SI units. However, as will become evident the scientific definitions of these parameters are far more complex than the general descriptions in Tables 2-1 and 2-2.

Table 2-1: List of common clubhead impact parameters. Green shading indicates a view from above the impact.

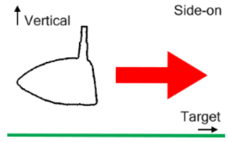
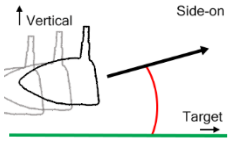
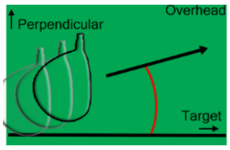
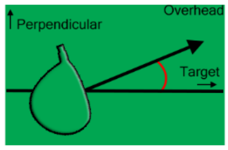
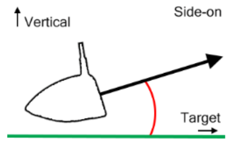
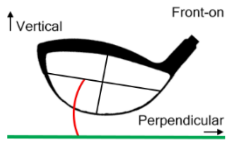
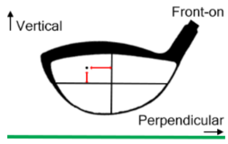
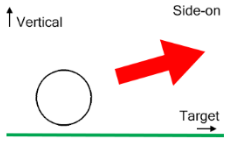
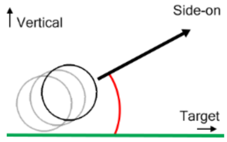
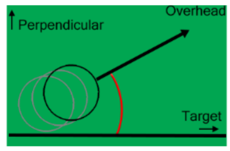
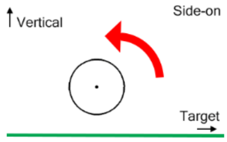
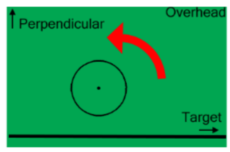
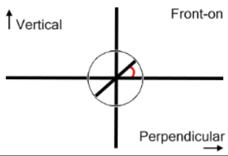
Parameter		Common unit	General description	
Clubhead speed		mph	Speed of the clubhead leading up to impact	
Clubhead path	Attack angle	°	Vertical angle of the clubhead trajectory	
	Club direction	°	Horizontal angle of the clubhead trajectory	
Clubhead orientation	Face angle	°	Horizontal angle of the clubface to target line	
	Dynamic loft	°	Vertical angle of the clubface to ground	
	Dynamic lie	°	Horizontal angle of the clubface to ground	
Impact location		mm	Vertical and horizontal distance from the centre of the clubface to the point at which the ball was contacted	

Table 2-2: List of common ball impact parameters. Green shading indicates a view from above the impact.

Parameter		Common unit	General description	
Ball speed		mph	Resultant speed of the ball post-impact	
Ball path	Launch angle	°	Angle of the ball at take-off relative to the ground	
	Launch direction	°	Angle of the ball at take-off relative to the target line	
Spin rate	Total spin	rpm	Total rotation rate of the ball post-impact	
	Backspin/ Topspin	rpm	Component of total spin about the horizontal axis, perpendicular to target line	
	Sidespin	rpm	Component of total spin about the vertical axis. When viewed from above, clockwise spin creates left-right-curvature and anticlockwise spin creates right-to-left curvature.	
Spin axis		°	Tilt of the axis around which the ball spins post-impact	

2.2.1. Tracking technology

In golf, the measurement of clubhead-ball impact parameters is of interest because ultimately, they determine the outcome of a shot. Both theory and experimental work have helped achieve an understanding of what happens during the impact period. Scientific investigation of the golf swing often uses impact parameters as measures of performance; typically, the case in biomechanical investigation (e.g. Ball & Best, 2007a; Tucker et al., 2013). There are various technologies available that measure impact parameters and normally, they involve either using launch monitors or motion analysis systems (Williams & Sih, 2002; Sweeney et al., 2013; Betzler et al., 2014).

Motion analysis

Motion capture systems, such as VICON (Oxford Metrics Group, Oxford, UK), Qualysis (Qualisys, Sweden) or Motion Analysis (Santa Rosa, CA, USA), are often the tool of choice for measuring golfer biomechanics and therefore are usually configured for biomechanical analysis. Motion analysis systems work by tracking markers located on the target object, whether it be a human or piece of equipment. Therefore, the clubhead can be tracked by attaching markers to the shaft and crown of the clubhead. Additionally, calibration markers can be attached to the clubface which are removed for testing and reconstructed during post-processing to create virtual markers that represent the clubface (Coleman & Anderson, 2007; Betzler et al., 2012; Sweeney et al., 2013; Morrison et al., 2017). The ball can be tracked by attaching retro-reflective tape to the surface. The time sampling frequency for biomechanical analysis is typically in the region of 200-500 Hz. The clubhead and ball reach speeds in excess of 100 and 150 mph (44.7 and 67.1 m/s) respectively (Cochran & Stobbs, 1968). Therefore, a sampling frequency in this range, whilst able to track the clubhead and ball, is too low for an in depth understanding; at a sampling rate of 500 Hz a clubhead travelling at 44.7 m/s will have translated linearly by approximately 90 mm between frames, during which time its orientation may have changed markedly. Ideally, for an in depth understanding of the clubhead and ball impact, time sampling rate would need to be several thousand hertz, due to the short duration the clubhead impacts the ball (less than one millisecond). Furthermore, during motion analysis, each camera's field of view is often set-up to focus on a large volume surrounding the golfer, not a smaller volume centring around the clubhead-ball impact, decreasing the spatial resolution. It not possible to track the clubhead and ball with more than a small cluster of markers. An increased spatial resolution, for example focusing on the volume centred around the tee, would increase accuracy of marker tracking. Studies have used three markers on the crown of the clubhead or shaft to define a coordinate system for the club. Williams & Sih, (2002) defined a coordinate system using three markers and manually manipulated clubface orientation angles. The motion analysis system measurements led to absolute differences in the three rotations of the clubhead of 0.39-0.60º when compared to the known angles.

Bespoke technology

Recently, launch monitor technologies for both indoor and outdoor use have become commercially available to coaches, professionals, club-fitters and researchers and represent a bespoke solution to measuring impact parameters. Such systems are designed to output clubhead and ball impact parameters immediately following a shot and for ease of set-up. The technologies typically utilise radar, optical or inertial measurement technology. Examples which may be suitable for scientific research are listed in Table 2-3. Radar launch monitors utilise the Doppler effect to directly measure clubhead and ball parameters. A signal (or multiple signals) is sent out at a given frequency, the signal then reflects off the clubhead and ball back to the unit. If the object is moving, the frequency of the reflected signal is different and the magnitude of change dependent on the velocity of the object. Based on this information, a range of clubhead and ball impact parameters can be determined. Optical systems take a series of images of the clubhead and ball at high sampling rates around the time of impact. The images are processed through, for example, threshold processing (Kiraly & Merloti, 2015), to identify features of the clubhead and ball, which are used to calculate the impact parameters. Inertial measurement technologies use an accelerometer and gyroscope to identify the orientation of the club. Signal processing can identify the point of impact and the orientation of the clubhead can be inferred at this time point, although signal processing has been shown to introduce errors when compared to motion analysis systems (Seaman & McPhee, 2012).

Table 2-3: Example launch monitor technologies that could be used in scientific research listed by the type of technology.

Method	Technology
Optical	Foresight Sports AccuSport Vector Pro Nam et al., (2014)
Radar	TrackMan FlightScope
Inertial measurement	Nam et al., (2014)

The TrackMan Pro IIIe and Foresight GC2+HMT systems are two of the more common launch monitors, being used at major golf tournaments and commercially by instructors and club-fitters across the world. The manufacturer’s stated accuracies for the output parameters are given in Table 2-4; however, the origin of these values is unclear and, to date, they have not been independently verified.

The TrackMan unit is positioned behind the tee facing down the target line meaning outdoors it can track the entire ball flight. Indoors however, algorithms are used to predict the entire ball flight. The system uses Doppler radar technology at a frequency of approximately 20000 Hz (TrackMan, 2015) to identify clubhead and ball motion. The application of this technology allows parameters relating to the motion path of the clubhead and ball, for example clubhead speed, to be measured directly but those relating to orientation are calculated from impact algorithms based upon related parameters, such as the club and ball paths and spin axis. This has implications for off-centre impacts where the gear effect occurs and limitations in the system’s algorithm can be exposed (see Section 2.2.2). Foresight is a stereoscopic optical system, capturing at up to 10000 frames per second (Foresight Sports, 2016). The GC2 unit tracks the ball, which when combined with the additional HMT (head measurement technology) unit the clubhead can also be tracked. The unit sits to the side of the tee, perpendicular to the target line, and directly measures impact parameters from images taken pre- and post-impact. Unique Foresight markers are required to be placed on the clubface for the HMT but are not required on the ball. By tracking the movement of these markers, the unit can measure the motion of the clubhead. Algorithms then predict the flight of the ball, both indoors and outdoors. There is no formal procedure for aligning the Foresight unit relative to the target line, raising questions over parameters related to the path and orientation of the clubhead and ball relative to the target line.

Table 2-4: Stated TrackMan Pro IIIe and Foresight GC2+HMT accuracies for the common parameters. Missing values indicate the system does not output the parameter. Launch direction and spin axis accuracies for TrackMan are unknown.

Parameter	TrackMan accuracy (TrackMan, 2015)	Foresight accuracy (Foresight Sports, 2016)
Clubhead speed (mph)	± 1.5	± 0.75
Attack angle (º)	± 1.0	± 0.5
Club direction (º)	± 1.0	± 0.5
Face angle (º)	± 0.6	± 0.5
Dynamic loft (º)	± 0.8	± 0.75
Dynamic lie (º)	-	± 0.25
Ball speed (mph)	± 0.1	± 0.5
Launch angle (º)	± 0.2	± 0.2
Launch direction (º)	N/A	± 1.0
Total spin (rpm)	± 15	± 50
Backspin (rpm)	-	± 50
Sidespin (rpm)	-	± 50
Spin Axis (º)	N/A	-

All the tracking technologies have limitations; therefore, it is important to understand how well the systems perform. Sweeney et al., (2009) compared the performance of the optical launch monitor AccuSport Vector Pro to the VICON motion analysis system, when measuring ball path and speed. The study found small mean differences and large correlation coefficients between the two systems for launch angle (0.5 ± 0.6º; $r = 0.96$), launch direction (1.1 ± 0.9º; $r = 0.93$) and ball speed (1.1 ± 1.0 m/s or 2.5 ± 2.2 mph; $r = 0.95$). The study concluded that the launch monitor could be used when a motion analysis system is unavailable but no statistical comparison other than mean differences and correlation are presented in the abstract. The lack of statistical validation, the fact that a strong correlation does not necessarily mean close agreement between the systems' measurements (Bland & Altman, 1986) and the reasons outlined for the limitations in motion analysis tracking above mean the study fell short of detailed clubhead and ball tracking and launch monitor validation.

A second TrackMan technology designed for baseball (TrackMan IIx) was evaluated by comparison to multi-camera three-dimensional high speed video (Martin, 2012). Radar measurements for baseball hit speed were found to be within less than 3.1 m/s of the high speed video and trajectory angles within 1.2º.

Novel technology

Ellis, (2013) used a system called GOM (GOM mbH, Germany), originally developed for aeronautical and automotive industries, to measure clubhead-ball impacts. The technology is an optical three-dimensional dynamic measurement system (GOM, 2015) that comprises associated software capable of analysing an object's displacement through point tracking (PONTOS; INSPECT; CORRELATE, Table 2-5). The system is compatible with high speed video cameras so, as long as the images are of good quality (i.e. well-focused, well contrasted, etc.), sampling frequencies up to the limits of the cameras used can be analysed, making it suitable for capturing the rapid impact of a golf shot, lasting less than a millisecond (Cochran & Stobbs, 1968). As a general rule, the system is accurate to 25 microns per metre field of view (GOM, personal communication, March 4th, 2016). Ellis, (2013) placed markers on the golf clubhead so when a swing was recorded and images imported into the software they were automatically identified. Processing allowed the definition of a local coordinate system on the clubface. Its orientation could then be calculated to give clubhead orientation angles, and the trajectory of its origin tracked to calculate clubhead speed and path. Alternatively, any marker on the clubhead could be used to calculate clubhead speed and trajectory. The method was demonstrated by tracking the clubhead and ball from shots hit by human participants. The results for clubhead orientation were compared to the TrackMan system with mean differences between the systems in the region of 2-5º. No further analysis of the data was conducted or any other parameters compared.

Overall, the method developed by Ellis, (2013) provides a means to gain a deeper understanding of the impact with scope for further development and use in scientific research. However, it still has limitations, including, hardware cost, data processing time and the complexity of the hardware set-up procedure and processing, making the method inaccessible for the wider golf community. Furthermore, the system has methodological limitations; for example, a driver clubface is curved and placing markers on the clubface only allows for a prediction of this curvature by fitting a surface to the markers. The method also placed markers on the ball for the purposes of calculating impact location. Further development could enable ball tracking to be fully included in the analysis process.

Table 2-5: The family of GOM software available (as of August, 2016).

Software	Version	Release	Purpose
PONTOS	6.3	2010	Dynamic 3D measurement software
TRITOP	6.3	2010	3D coordinate measurement software
ARAMIS	6.3	2010	3D deformation measurement software
ATOS	6.3	2010	3D digitising and scanning software
INSPECT	V8	2015	3D dimensional analysis software
CORRELATE*	V8 SR1	2016	3D dimensional analysis software

**GOM CORRELATE was introduced part way through this thesis and does essentially the same job as GOM Inspect. Therefore, when Inspect is mentioned throughout, it could refer to either Inspect or Correlate, depending on the chronology of the analysis.*

2.2.2. The impact & ball flight

The clubhead-ball impact period is a crucial point during the golf swing in determining the shot outcome. The duration of the impact is as little as half a millisecond (Cochran & Stobbs, 1968) and the normal force which acts on the golf ball can reach 10 kN (Penner, 2002). The kinematics of the clubhead have been imparted by the golfer long before the impact itself, and once the latter stages of the golfer’s downswing have begun, the period of time is too short for the golfer to adjust the clubhead approach. Following initiation of the impact, the duration is far too short for the golfer to react and make adjustments (Cochran & Stobbs, 1968). Indeed, golfers cannot even perceive the impact duration (Roberts et al., 2001).

Theory

The rapid nature of the impact makes it difficult to investigate. Theoretical assessment with a physical basis has provided some insight. The D-plane theory is an example (Figure 2-1; Jorgensen, 1999), essentially describing the relationship between two vectors, the normal to the clubface and the direction the clubhead is moving at impact. These two vectors form a plane and the trajectory at which the ball leaves the clubface lies on this plane (Figure 2-1b). When this plane is tilted, i.e. the clubhead trajectory and the clubface normal are not parallel, the ball no longer flies straight (Figure 2-1b). To achieve a shot that flies directly at the target the clubhead normal, its velocity vector and the target line must all be in the same vertical plane. To achieve a shot that curves from left-to-right during flight it doesn't necessarily matter whether the club direction is parallel to the target. For a centre clubface impact with no gear effect, if the clubface normal is angled to the right of the club direction it will produce a left-to-right spin component with the ball taking off on the plane formed by the two vectors.

a.

b.

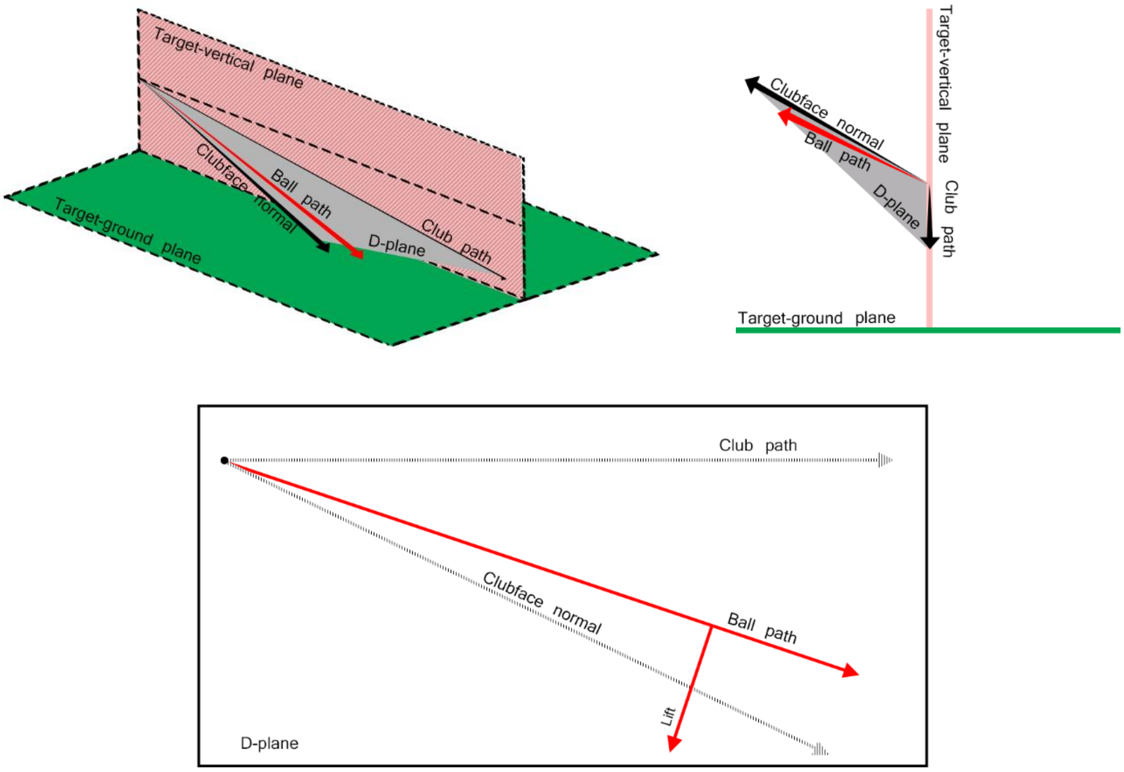


Figure 2-1: The d-plane theory (Jorgensen, 1999): a. based on Jorgensen, (1999) Figure 9.1 and b. based on Jorgensen, (1999) Figure 9.2. Due to the complexity of the Jorgensen, (1999) Figure 9.1, an additional perspective (right) has been included in a. showing the d-plane as viewed from the fairway looking back towards the tee. The shot depicted here represents a push-slice shot (defined in the shot trajectories section) with the ball starting right of target and curving left-to-right in the air. The lift force lies within the d-plane and is perpendicular to the ball path. It acts to lift the ball and curve the ball from left-to-right. Note, club path encompasses club direction and attack angle and ball path encompasses ball direction and launch angle.

Impact parameters

Experimentally and statistically, clubhead parameters have been related to the ball parameters. Neglecting environmental factors and ball design, the outcome of a shot is a result of the ball speed, the vertical and horizontal launch angles, spin rate of the ball, spin axis and the tee height. Clubhead delivery determines these and the relationships between the clubhead and ball has received a lot of attention in scientific literature.

Clubhead & ball speed

The most obvious connection has linked ball speed to clubhead speed (Joyce et al., 2013b; Sweeney et al., 2013; Betzler et al., 2014). Both clubhead speed (e.g. Hume et al., 2005; Ball & Best, 2007b; Kwon et al., 2013; Sinclair et al., 2014) and ball speed (e.g. Myers et al., 2008; Healy et al., 2011; Tucker et al., 2013) have been widely used as a measure of performance in previous research.

The association between clubhead speed and ball speed is mechanical. Logically, if a golfer impacts the ball with a clubhead that is moving more rapidly the ball will leave the face quicker. However, the relationship is more complex (Equation 2-1; Penner, 2002):

$$BS = \frac{(1 + CoR)CHS}{1 + Mb/Mc} \tag{2-1}$$

where BS is the ball speed, CHS is the clubhead speed, CoR is the coefficient of restitution between the ball and clubhead, Mb is the mass of the ball and Mc is the mass of the clubhead.

Dynamic loft and impact location also affect ball speed (Williams & Sih, 2002; Sweeney et al., 2013; Betzler et al., 2014). To achieve the highest ball speed, the clubhead speed must be high but the impact must also be central, occurring at the clubface’s “sweet-spot” or centre of percussion (Harper et al., 2005), taking advantage of maximum energy and momentum transfer. In commercial golf terms, the relationship between the clubhead speed and ball speed has been described by the efficiency of impact or “smash” factor (Equation 2-2; Wallace et al., 2007; Brown et al., 2011; Betzler et al., 2012; Langdown et al., 2012; Betzler et al., 2014).

$$\text{"}Smash\text{"}\ factor = \frac{Ball\ speed}{Clubhead\ speed} \tag{2-2}$$

Collision theory states that the maximum smash factor, for the least lofted clubs, is approximately 1.5 (Jorgensen, 1999). Resultant clubhead speed alone has explained 75% of the variance in peak resultant ball speed; clubhead speed and impact location together explained 82% of the variance in peak resultant ball speed (Sweeney et al., 2013).

Clubhead speed appears a simple concept, however the reality is somewhat complex (Ellis, 2013). The clubhead is a finite rigid body, with complex motion in the lead-up to and during ball contact. The simplest clubhead motion would involve solely translation and would mean the entire clubface had equal velocity. However, this is not the case. The clubhead, attached to the shaft, swings in an approximate arc causing the clubhead to rotate as well as translate. The rotation of the clubhead means that the tangential velocity of points across the clubface differ, the slowest velocities at the heel and top of the clubface and the quickest at the toe and bottom, increasing with distance from the point of rotation.

When measured using a launch monitor system clubhead speed is output as a single value. When using motion analysis systems, markers have been placed on the crown of the clubhead, and clubhead speed defined as the average of the individual markers (Williams &

Sih, 2002; Betzler et al., 2012; Worobets & Stefanyshyn, 2012; Sweeney et al., 2013; Betzler et al., 2014; Morrison et al., 2014). The method of Ellis, (2013) (described in Section 2.2.1) obtained differences from the toe to the heel in the lead up to impact of 5.7 m/s or 12.8 mph. Therefore, reporting the clubhead speed is not straightforward and should include the point on the clubhead to which the speed refers. Similar arguments can be made for all impact parameters and the complexity in measuring impact parameters is a feature of this thesis.

Clubhead orientation, clubhead path & ball path

Further relationships between clubhead and ball parameters relate to the path of the ball following the impact, comprising the vertical launch angle and the horizontal launch direction. Launch angle has been associated with the vertical attack angle of the clubhead, the dynamic loft of the clubface, the vertical impact location (Williams & Sih, 2002; Joyce et al., 2013b; Sweeney et al., 2013; Betzler et al., 2014) and ball position in the stance (Zhang & Shan, 2013). Interestingly, higher ball speeds have been associated with lower launch angles (and lower backspins) (Wallace et al., 2007). Likewise to launch angle, launch direction is influenced by horizontal club direction, the face angle and horizontal impact location (Sweeney et al., 2013; Betzler et al., 2014). Sweeney et al., (2013) stated that a 280 metre drive, if miss-hit by a 2º launch direction would land 10 metres offline, and similarly, a 120 metre wedge shot miss-hit by 2º would land 4 metres offline. Face angle is the most important influence on launch direction (Miura, 2002); explaining 82% of the variance in launch direction (Sweeney et al., 2013).

As indicated above, due to the combined translational and rotational rigid body motion of the clubhead, clubface orientation changes rapidly in the approach to impact. For example, driver face angle closing rate has been measured at 2.9 º/ms (Ellis et al., 2010). Furthermore, the rate of change of the face angle leading up to impact has been shown to be far quicker than the rate of change of the club path (Betzler et al., 2012). Therefore, timing of measurement of the parameter is key. Through impact itself, the location of the impact on the clubface causes clubhead rotation about an axis more or less parallel to the shaft axis (Williams & Sih, 2002).

The third clubhead orientation parameter is the dynamic lie or toe-up/ toe-down angle (Table 2-1). This parameter may be more influenced by the properties of the club, for example shaft flex, than the golfer's swing, however, the golfer's swing is likely to exert some influence (Worobets & Stefanyshyn, 2012). Worobets & Stefanyshyn, (2012) observed the conceptually probable result that more flexible shafts led to more toe-down dynamic lie angles, as these shafts were less able to resist the gravitational pull of the mass of the clubhead.

Clubhead orientation is particularly difficult to define for wooden (or now termed metal) clubs with curved clubfaces. The values for face angle, dynamic loft and dynamic lie will all depend on the point of the clubface that the orientation is measured from. This could, for example, be a clubface normal based at the impact location or at the geometric centre.

Perhaps as equally complex to define is attack angle; during the lead up to ball contact, the clubhead is travelling along an arc. Attack angle is a result of golfer kinematics (Tuxen, 2008). For example, a golfer intentionally playing for a high or a low trajectory could change attack angle with the same club. Similarly, for club direction, a golfer may vary their club direction from an “in-to-out” direction (where the club begins inside the target line and moves to outside during the late downswing) to an “out-to-in” (where the club begins outside the target line and moves to inside during the late downswing) direction to achieve a different result. It is thought that golfers control club direction and the attack angle-dynamic loft relationship (also known as spin loft) to influence spin rates.

Spin rates

Increased total spin has been associated with a more negative or downward trajectory of the vertical clubhead path, dynamic loft of the clubface, vertical impact location and friction (Penner, 2002; Williams & Sih, 2002; Corke et al., 2013; Joyce et al., 2013b; Sweeney et al., 2013; Betzler et al., 2014). It has been found to vary across different types of shot. Intentionally lower ball trajectories have been found to have a significantly lower spin rate than normal and higher trajectory shots (Corke et al., 2013). Other factors may be important as well as those outlined above. In a regression model clubhead speed was found to be a significant contributor of spin rate (Corke et al., 2013). Interestingly, the face-to-path angle, the difference between the face angle and the club direction, and the horizontal impact location were removed from the model because their contribution was found to be non-significant.

Two important spin parameters are backspin and sidespin. Backspin, as discussed below, and sidespin have important implications for the flight of the ball and have been linked to the path and the orientation of the clubhead as it strikes the ball (Sweeney et al., 2013) as well as ball speed (Wallace et al., 2007). The left-to-right sidespin produced in Figure 2-1 is a result of the tilted D-plane. The D-plane tilt is a result of the face angle being open (orientated right for a right-handed golfer) relative to the club direction. The opposite trend will result in right-to-left spin. The result is a tilting of the axis about which the ball rotates; the more tilted the axis the greater the sidespin component becomes and the more the ball moves from right-to-left or left-to-right in the air. For every 5º of spin axis tilt, the ball will curve sideways by 3.5 yards per 100 yards of ball travel towards the target (TrackMan, 2010). This could be a desired effect intentionally imparted by the golfer or a result of a shot error. Both backspin and sidespin are also influenced by impact location and therefore gear effect, discussed in the following sub-section.

Impact location

Previous work has emphasised the importance of impact location but it is not well understood (Joyce et al., 2013b; Sweeney et al., 2013; Betzler et al., 2014). Off-centre impacts cause the clubhead to rotate about its centre of gravity causing an effect known as the gear effect (Figure 2-2; Cochran & Stobbs, 1968; Penner, 2002). The ball and clubface, like two gears, act in opposition to one another which imparts spin on the ball (Cochran & Stobbs, 1968). For larger clubheads, such as the driver, rotation is greater due to the centre of gravity being situated further back from the clubface, therefore the effect is more pronounced. Consequently, there is a need for a curved clubface to counteract the effect. Sidespin has been shown to increase linearly with centre of gravity depth for off-centre impacts (McNally et al., 2016). Thus, manufacturers can actively alter the clubhead moment of inertia to influence the gear effect (Hocknell, 2002; McNally et al., 2016).

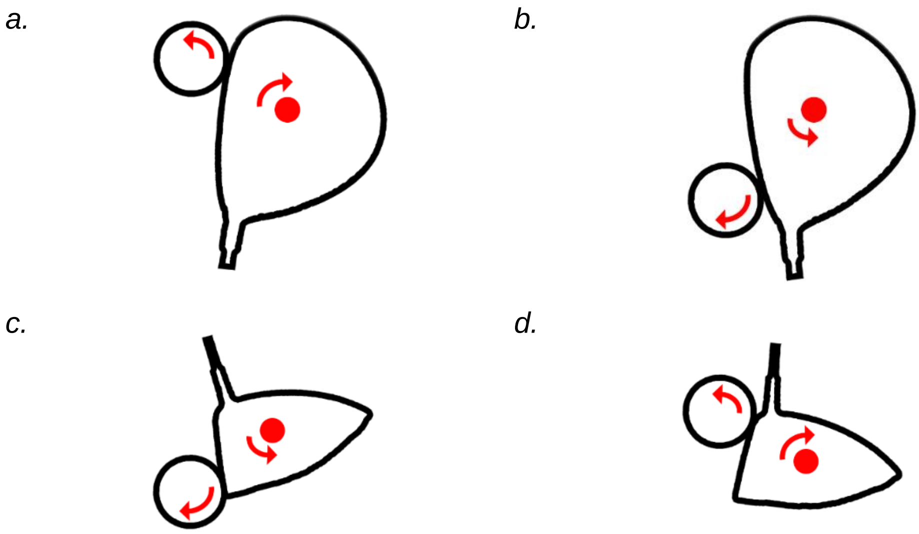


Figure 2-2: The gear effect: a. toe impact from above; b. heel impact from above; c. low impact from side-on and d. high impact from side-on. The red circle represents the centre of gravity and the arrows the respective body's direction of rotation due to the off-centre impact.

Gear effect has implications for tracking technologies, specifically radar technologies which cannot directly measure the face angle or the spin axis. Clubface orientation calculations for this type of technology are often based on other parameters such as club and ball path and spin axis. As an example, for a toe impact (Figure 2-2a), the gear effect would induce a launch direction further right of target and a more tilted spin axis indicating right-to-left spin.

Therefore, when the initial information is inputted into the algorithms to calculate face angle the calculation may produce an angle more closed relative to the club direction.

Carry distance

One of the most important outcomes of a golf shot is the carry, a factor that has been linked to clubhead speed and impact location (Betzler et al., 2014). Achieving the maximum distance possible is a complex relationship between the launch parameters of the ball. Ball speed is obviously important and an increase of one mile per hour can lead to an increased driver carry 1.83 yards (Betzler et al., 2014). Launch angle is also important for maximum carry. Based on a simple parabola with no atmospheric conditions the optimal launch angle is 45º; however, atmospheric conditions mean the optimum launch angle is much lower (Cochran & Stobbs, 1968). When a dimpled golf ball is struck, backspin imparted on the ball creates a lift force that acts perpendicular to the ball flight (Figure 2-3; Cochran & Stobbs, 1968; Penner, 2002). The force increases with spin rate (Smits & Smith, 1994) and can be altered through golf ball dimple design (Beasley & Camp, 2002; Penner, 2002; Chowdhury et al., 2016). In the presence of backspin, lift acts to raise the ball flight thus extending the carry, acting at 90º to the drag force produced by the spinning ball and helping to counteract the gravitational pull of the ball's mass (Figure 2-3). However, too much lift raises the ball too much effectively reducing the ball flight. This is the underlying principle behind the theory of long drives. The theory states that to achieve long drives the ball speeds must be high and spin rates must be low; for drives spin rates between 38 and 44 rev/s or 2280 and 2640 rpm are suggested (Wallace et al., 2007). This achieves some lift to extend the length of the drive but does not create too much to produce an early peak and decline in the trajectory. In elite golfers, optimal launch angle should be between 10 and 14º (Wallace et al., 2007). It was recommended that a launch angle of around 20º may lead to even longer drives, but would require golfers to "strike up" (a positive attack angle) extensively on the ball to achieve the same solid contact, rather than increasing the loft of the driver, which would reduce the strike to a more glancing blow and increase spin (Cochran & Stobbs, 1968).

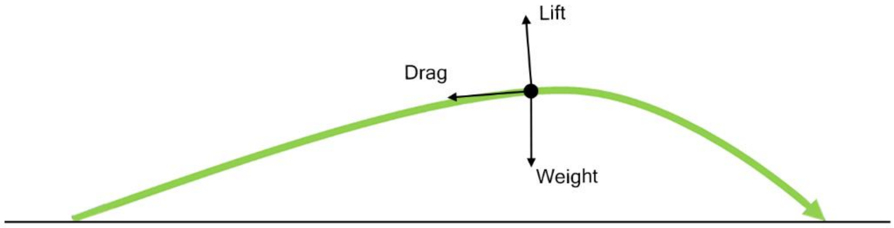
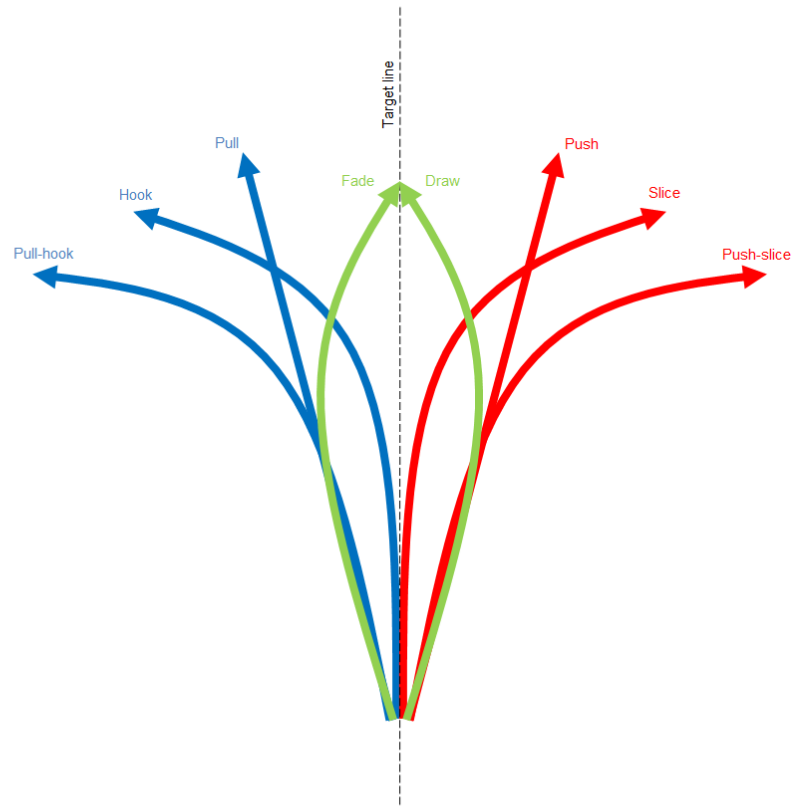


Figure 2-3: The forces acting on a golf ball during flight.

Shot trajectories

The factors discussed in this section define several common trajectories in golf (Figure 2-4). These typical definitions are discussed further in Section 5.3.4. The way impact parameters change due to different shots being struck was the focus of a conference paper (Robertson & Burnett, 2012). Shots were tracked using the TrackMan system and differences were seen in parameters such as face angle, club direction and spin axis for draw and fade trajectories. The authors highlighted the differences between draw and fade trajectories as a particular interest. The study however, did not incorporate any biomechanics.

a.



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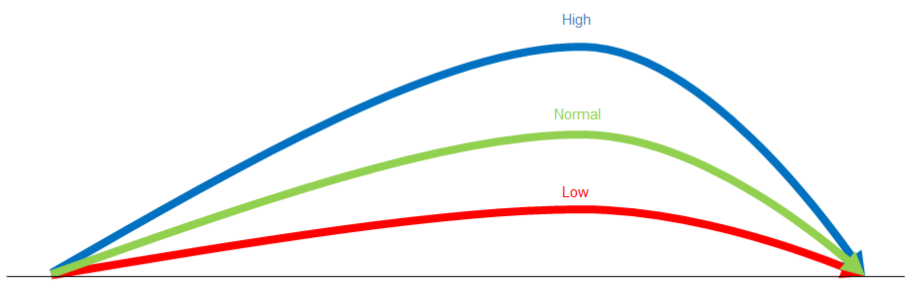


Figure 2-4: Typically defined shot trajectories: a. defined predominantly through curvature in the air (sidespin); b. defined predominantly through launch angle and peak height. Draw, fade, low and high trajectory shots are deliberately played shots, whereas push, pull, slice, hook, push-slice and pull-hook trajectories are considered errors.

Trajectory models

As previously mentioned in Section 2.2.1 launch monitor systems use trajectory models to predict the outcome of a golf shot when they are used indoors. However, the exact algorithms are not available in the wider public domain. Within the scientific literature there are numerous studies which have published models regarding ball flight across a number of hitting sports; for example in tennis (Steele, 2006; Sissler, 2012; Cross & Lindsey, 2014), football (Bray & Kerwin, 2003; Goff & Carré, 2009; Tuplin et al., 2012), badminton (Lin et al., 2015) and baseball (Alaways & Hubbard, 2001).

Golf ball aerodynamics have long been investigated (Tait, 1890; Davies, 1949; Bearman & Harvey, 1976; Aoyama, 1990; Libii, 2007) and scientific trajectory models based on the aerodynamics have been published (Lieberman, 1990; Smits & Smith, 1994; Beasley & Camp, 2002; Mizota et al., 2002; Quintavalla, 2002; Adams, 2004; Nauro & Mizota, 2006; Baek & Kim, 2013). The model parameters, lift and drag forces, are typically empirically validated by matching wind tunnel data across multiple golf ball models and through data from real shots. The coefficients are validated under different ball conditions, for example a range of spin rates, due to the travelling ball affecting lift and drag (Smits & Ogg, 2004). To add further complexity, golf ball design, dimple number, size and depth, affects the aerodynamic performance of the ball (Davies, 1949; Beasley & Camp, 2002; Ting, 2003; Aoki et al., 2010; Alam et al., 2011; Chowdhury et al., 2016) and environmental factors (temperature, humidity, pressure, altitude and wind) will also affect the flight. Trajectory models simplify these latter factors by removing or controlling them i.e. fixing them as a constant. Overall, this means there is a great deal of complexity to an aerodynamic model to predict ball flight across a range of spin rates and Reynolds numbers.

Between-model differences arise because experimental wind tunnel results can lead to different lift and drag coefficients. Furthermore, some models have extra added dimensions, such as Smits & Smith, (1994) who included a spin rate decay across a range of Reynolds numbers. The model suggested the results of the wind tunnel testing were generalisable to a range of golf balls, however, the model may only be applicable to driver shots. Baek & Kim, (2013) included changes in Reynolds number and dimple characteristics as well as environmental factors such as altitude. However, certain aspects, such as drag coefficients were similar to previous work (Bearman & Harvey, 1976). The complexity of the golf ball aerodynamics makes trajectory modelling difficult and any model must be treated with caution. Nevertheless, they are in wide use in the golf community and their inclusion in commercially available technology requires realistic outcomes.

2.2.3. Summary

Section 2.2 has provided an overview of the technology to measure golf clubhead-ball impacts and the key literature relating to theory and experimental investigation into the impact and ball flight.

Initially physical theory offered insight into what interactions may occur during clubhead impact with the ball, for example the D-plane theory. However, more recently experiments have been conducted to investigate the interactions further. Recently, bespoke technologies have become increasingly available to measure clubhead-ball impacts and some of these may be applicable to scientific research. However, more novel solutions have also been developed which could provide an alternative method. Finally, trajectory models can be used to predict the final outcome of shots hit indoors into a net.

2.3. The biomechanics of different ball trajectories in hitting sports

As stated at the beginning of the chapter, altering the trajectory of a projectile when hitting likely involves various biomechanical changes. There is little research relating to this topic in golf. Therefore, this section of the literature review provides an overview of the biomechanics of achieving different trajectories across a number of sports, encompassing kinetics, kinematics and swing plane. It must be noted that the breadth of hitting biomechanics is far greater than contained in the section; only that relevant to achieving specific shot trajectories has been considered.

Table 2-6: Typical trajectories relevant to this literature review, common across sports other than golf.

Trajectory	Definition
Flat	No spin axis tilt and limited spin, with the aim of maximum ball speed. As in the typical first serve in tennis.
Sidespin	A tilted spin axis so that there is a curvature of the ball from right-to-left or left-to-right in the air. As in tennis or table tennis slice trajectories.
Topspin	No spin axis tilt, however the ball spins in a manner that will cause the ball to dip in the air.
Backspin	No spin axis tilt, however the ball spins in a manner that will cause a floated trajectory.
Kickspin	A combination of topspin and sidespin cause by a tilted spin axis, that cause the ball to kick off the playing surface. This is common in second serves in tennis.

The shot trajectories that appear in other sports differ slightly from those of golf. To guide the reader relevant trajectories are outlined in Table 2-6. It must be noted that golf is unique in many ways. For example, the ball is stationary until impacted, unlike other sports such as tennis, where it is either thrown into the air, in the case of a serve or a moving ball returned in the case of ground strokes. Furthermore, during competition there are a number of club types available to the golfer. Therefore, different biomechanical patterns could be utilised when playing a certain trajectory shot with different club types. Finally, the golfer is not competing directly opposite an opponent who is trying to identify cues regarding what type of trajectory may be hit.

2.3.1. Challenges when comparing across studies

In conducting this literature review some key challenges emerged with regards to comparing the outcomes of different studies. Firstly, swing events are commonly termed identically but defined differently, thus in effect representing different events. As an example, Ball & Best, (2007a) defined the top of the backswing by club shaft position, whereas Horan et al., (2010) used pelvis rotation. This also applies to studies considering the entire swing where often phases are defined, separated by distinct swing events (e.g. Zheng et al., 2008).

A similar issue is seen in how certain kinematic variables are quantified, such as segment definition for X-factor and torso kinematics (Wheat et al., 2007; Kwon et al., 2013; Joyce et al., 2010; Brown et al., 2011; Smith et al., 2015a). For example, Brown et al., (2013) evaluated three previously used methods for X-factor computation: (1) difference between the axial rotations (Z component) of the pelvis and thorax segments relative to the global coordinate system, using the XYZ Cardan order (Horan et al., 2010); (2) difference between the pelvis and thorax orientations projected onto the global coordinate system transverse plane (Chu et al., 2010; Myers et al., 2008) and (3) orientation of the thorax segment coordinate system relative to the pelvis segment coordinate system (Aguinaldo et al., 2007; Brown et al., 2011). The study concluded the last of these (3) as the most appropriate method of X-factor computation. However, Smith, (2013) noted how the study had limitations with cardan rotation orders and homogeneity of golfers.

Finally, studies also differ in measures of performance. Commonly used are golfer handicap, clubhead speed at ball contact or ball speed and experience. An assumption used in many studies is that high clubhead speeds mean better players. Handicap has, indeed, been found to correlate well with clubhead speed ($r = 0.95$; Fradkin et al., 2004). Therefore, in terms of handicap at least the assumption may be reasonable. However, having a low handicap could be a result of different aspects of the game, such as the golfer's "short-game" and putting.

These challenges need to be considered when interpreting any biomechanical findings and, at times, they can be the reason for differences between studies.

2.3.2. The role of kinetics in achieving shot trajectories

Centre of pressure

The role of centre of pressure has often been of interest in hitting movements (Mason, 1987; Welch et al., 1995; Girard et al., 2007; Fu et al., 2009; Girard et al., 2010; Hu et al., 2015; Phomsoupha & Laffaye, 2015; Fu et al., 2016). For some sports, investigations have utilised plantar pressure measurement systems, such as in tennis (Girard et al., 2007; Girard et al., 2010). However, due to the more stationary nature, golf is more suited to investigations using embedded force plates, particularly in a laboratory environment.

For centre of pressure, there has been little investigation focused on shot trajectories. Fu et al., (2016), for example, examined centre of pressure patterns in table tennis, with particular focus on the topspin forehand loop trajectory; however, the focus was on comparison between player ability as opposed to shot trajectory and the study used an insole plantar pressure measurement system. Nevertheless, the study did find anterior-posterior and medio-lateral centre of pressure patterns beneath each individual foot that were common across both ability groups. It is unknown if patterns differ between different shot trajectories.

In golf, whole-body centre of pressure has commonly been used to investigate “weight transfer”. Coaches tend to perceive “weight transfer” via body movement (Smith et al., 2012; Smith et al., 2015b). Lateral shifts towards the target, medio-lateral, and perpendicular, anterior-posterior, correlate with both handicap and clubhead speed (Koenig et al., 1994; Mason et al., 1995; Rambarran & Kendall, 2001; Okuda, 2003; Williams, 2004; Ball & Best, 2011; Ball & Best, 2012; Smith et al., 2016). Elite golfers displace their centre of pressure further medio-laterally along the target line during the swing (Langdown et al., 2012), manifesting in further centre of pressure shift away from the target in the backswing and back towards the target from top of the backswing to ball contact.

Further evidence suggests individual golfers use different styles of centre of pressure pattern (Koslow, 1994; Neal, 1998; Ball & Best, 2007a). Specifically, two styles, “front foot” and “reverse”, styles have been identified (Ball & Best, 2007a) and golfers have been observed to use the same style across different club types (Ball & Best, 2012). These two clusters resulted from the analysis of centre of pressure at distinct events and are reflective of the sample of golfers used. Therefore, they may form parts of a continuum of centre of pressure patterns across golfers, as in the study of Smith et al., (2016).

Ground reaction force

Ground reaction forces across hitting sports have received a lot of attention in scientific research (Van Gheluwe & Hebbelinck, 1986; Payne, 1978; Mason, 1987; Koenig et al., 1994; Welch et al., 1995; Bahamonde & Knudson, 2001; Fu et al., 2009; Fortenbaugh, 2011; Huang et al., 2012; Hu et al., 2015; Fu et al., 2016). In golf, commonalities in vertical ground reaction force profiles are evident in the literature (Figure 2-5; Barrentine et al., 1994; Dillman & Lange, 1994; Robinson, 1994; Okuda et al., 2002; Williams, 2004; Hume et al., 2005; Worsfold et al., 2007; Okuda et al., 2010; Queen et al., 2013).

The majority of golf studies investigating ground reaction forces have related the variable to clubhead speed. To achieve high clubhead speeds ground reaction force magnitudes must be considerable; results for mid-range irons through to driver show peak ground reaction forces of 1.6-2, 0.4-0.6 and 0.2-0.3 bodyweights for vertical, anterior-posterior and medial-lateral respectively and studies have found large differences between lead and rear foot (Hume et al., 2005). Forces exceeding two bodyweights have been observed in tennis when hitting flat power serves aimed at generating high ball speed (Payne, 1978; Van Gheluwe & Hebbelinck, 1986; Girard et al., 2005). Lastly, kinetic timing is a consideration with differences in the timing of peak ground reaction forces (relative to impact) a potential differentiator between skill levels (Barrentine et al., 1994; Queen et al., 2013).

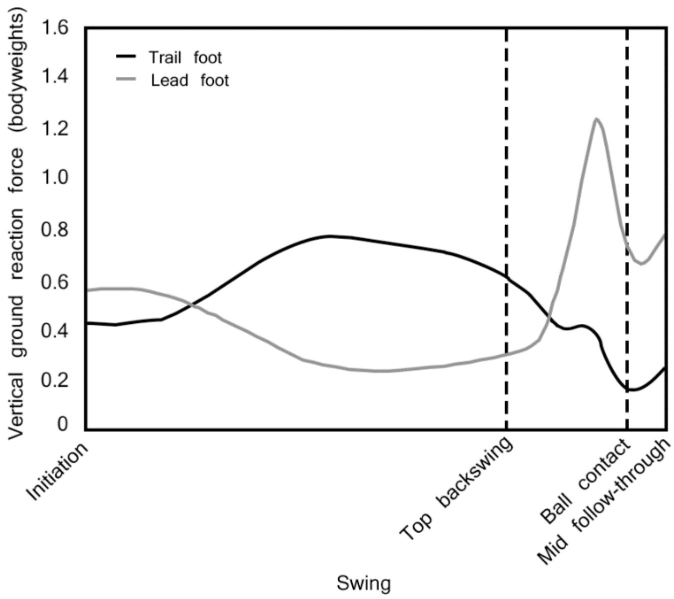


Figure 2-5: Example vertical ground reaction force trace, based on Koenig et al., (1994).

Specific ground reaction force traits with different clubs are evident. With the driver, at ball contact, the magnitudes of both lead and rear foot vertical ground reaction forces are lower than during late downswing, a result of the whole-body upward lifting to "uppercut" the ball for greater ball speed (Koenig et al., 1994; Worsfold et al., 2007; Chu et al., 2010). When hitting iron shots coaches teach golfers to hit down on the ball (e.g. Sorenstam, 2008). As a result, peak vertical ground reaction forces have been found to be significantly greater for 3-iron and 7-iron shots versus driver and hitting down was identified as causal (Worsfold et al., 2007), contrasting previous literature (Barrentine et al., 1994; Koenig et al., 1994). Worsfold et al., (2007) described previous theory, that forces are greater during driving, as anecdotal and stated that greater ground reaction force magnitudes for the driver, when evident (Barrentine et al., 1994), have been of small magnitude.

In terms of shot trajectory, McNitt-Gray et al., (2013) investigated the horizontal ground reaction forces in golf shots regulated by distance with the same club. Scaling of the magnitudes was tested using "normal" 6-iron shots against "half 6-iron" shots intended for lesser carry distance in 12 skilled golfers. Shot distance was regulated, in part, by selectively scaling the magnitude of the lead foot resultant horizontal ground reaction force, an alteration that occurred during the transition from backswing to downswing through to the early-downswing stage. Importantly, although the authors found decreased ground reaction forces for both feet in "half 6-iron" shots – significantly at the lead and non-significantly at the trail – there was no change in the direction in which the resultant horizontal ground reaction force acted.

In tennis, maximum forces were observed to be higher under the lead foot for the flat serves than for the slice, using a plantar pressure measurement system (Girard et al., 2010). However, using force platforms flat first and slice second serves have been shown to have a similar magnitude of ground reaction forces (Bahamonde & Knudson, 2001). This discrepancy between studies is perhaps evident because of the different methods of force measurement.

Joint loading

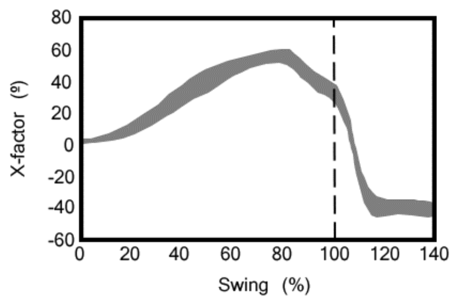
Joint loading is a lesser researched area in golf with only a few studies encompassing the area (Gatt et al., 1998; Nesbit, 2005; Stewart & Haigh, 2010; McNally et al., 2014). The area is more investigated in other sports such as tennis, perhaps because of the more obvious contribution of the main hitting limb and incidence of injury. Loading has been shown to vary with technique in tennis (Elliott et al., 2003). However, studies which have compared trajectories, specifically serve trajectory, have not shown any differences. (Chow et al., 2009; Abrams et al., 2011).

2.3.3. The role of kinematics in achieving shot trajectories

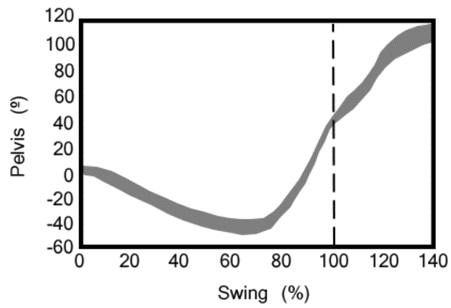
Central body

The role of central body segments in hitting movements is well investigated across hitting sports. Torso rotation plays a crucial role in hitting movements. Axial rotation of the thorax and pelvis segments and the differential between the two (Figure 2-6), commonly termed X-factor in golf literature, are often positively correlated to increased speed of the hitting implement and projectile (Cheetham et al., 2001; Fleisig et al., 2003; Teu et al., 2005; Gordon & Dapena, 2006; Myers et al., 2008; Chu et al., 2010; Healy et al., 2011; Meister et al., 2011; Sinclair et al., 2014; Genevois et al., 2015; Zhang et al., 2016). In golf, X-factor was advocated by Jim McLean (McLean, 1992) and is fairly well understood (e.g. Horan et al., 2009; Horan et al., 2010; Horan et al., 2011; Horan & Kavanagh, 2012; Beak et al., 2013). At the top of the backswing, the differential should be large and close rapidly during the downswing (Cheetham et al., 2001; Brown et al., 2011). Timing differences, with an earlier axial rotation of the pelvis back towards the target just prior to this time point increases X-factor stretch (the increase in X-factor in the early downswing), which has been shown to relate to golfer ability (Cheetham et al., 2001).

a.



c.



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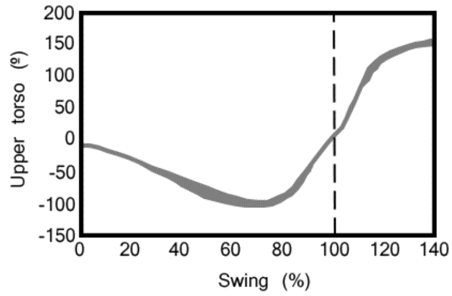


Figure 2-6: Example central body segment rotations, based on Meister et al., (2011). a. X-factor; b. upper torso [thorax] and c. pelvis. The bands represent the mean and standard deviation bands for ten professional golfers. The initiation of the swing occurred at 0%, ball contact occurred at 100%.

Other rotations of the torso, constituting forward and lateral flexion of the thorax and lumbar have also been investigated (McTeigue et al., 1994; Hume et al., 2005; Chu et al., 2010; Han et al., 2012). Morgan et al., (1997) emphasised how the golf swing is asymmetrical in terms of motions related to the torso; these motions are also considered a key part of postural kinematics (Smith et al., 2015b). Forward and lateral flexion variables have been related to clubhead speed (Joyce et al., 2013a) and ability (McTeigue et al., 1994). Their movements are potential contributors to altering the swing plane of the clubhead. The influence of swing plane, discussed in Section 2.3.4, has evidence to being an important factor in producing different shot trajectories. Consequently, the torso flexion movements may also be important.

In terms of individual shoulder and hip joint motion, shoulder motion has been linked to ball speed in golf (Healy et al., 2011). However, research is limited. It has been far more greatly investigated in tennis and badminton, perhaps unsurprisingly due to the one arm nature of certain shot types, such as the serve. Internal rotation of the hitting shoulder has been shown to be a major contributor to horizontal (directed towards the target) racket head speed when serving (Gowitzke & Waddell, 1979; Sakurai et al., 1987; Phomsoupha & Laffaye, 2015; Sprigings et al., 1994; Tanabe & Ito, 2007). It is unclear if there are differences in this variable between shot trajectories.

In golf, there may be inter-club differences in central body segments. Evidence suggests, for skilled golfers, different clubs are hit with the same power (Kenny et al., 2008). However, the driver swing has been shown to be distinguishable from that of iron clubs in terms of magnitude of thorax axial rotation angles (Egret et al., 2003) and torso flexion/ extension (Lindsay et al., 2002; Joyce et al., 2013a). These differences could be a result of club characteristics, such as shaft length and should be considered across shot trajectories.

Movements of the central body segments have not been investigated across shot trajectories in golf. However, in tennis, an increased thorax rotation has been found when hitting a backhand with more power (Fanchiang et al., 2013). Furthermore, the kick serve of an elite tennis player differed from the flat serve, via torso rotation, forward and lateral lumbar flexion as well as thorax and pelvis tilting (Vorobiev et al., 1993; Reid & Elliott, 2002; Lo et al., 2004; Abrams et al., 2011). Specifically, the flat serve showed more thorax rotation and shoulder tilt to the left and the kick more forward and lateral torso flexion at ball contact. Furthermore, peak velocity or velocity at ball contact of central segments were found to be non-different between the flat, kick and slice serves (Sheets et al., 2011). In terms of ground strokes, compared to flat strokes, topspin were shown to have significantly lesser X-factor at events during the swing. Furthermore, they had a more extended, backwards lean, thorax position at ball contact compared to the flat strokes (Reid & Elliott, 2002). Therefore, certainly for tennis, shot trajectories appear to be influenced by changes in the movements of central body segments.

Proximal-to-distal sequencing

The theory of proximal-to-distal sequencing is common across hitting sports to produce maximum speed of the hitting implement (Putnam, 1993). Examples of its application are in badminton (Phomsoupha & Laffaye, 2015; Zhang et al., 2016), tennis (Marshall & Elliott, 2000; Abrams et al., 2011; Sheets et al., 2011; Bingul et al., 2016), squash (Elliott et al., 1996), volleyball (Huang & Hu, 2007; Charalabos et al., 2013), baseball (Welch et al., 1995; Fortenbaugh, 2011) and golf (Putnam, 1993; McTeigue et al., 1994; Burden et al., 1998; Neal et al., 2007; Kenny et al., 2008, Vena et al., 2011b).

A version of the theory proposes that there is a summation of speed of the angular velocity of body segments (Figure 2-7). An example in golf is the interaction between the pelvis and thorax axial rotations. The earlier acceleration of the pelvis segment back towards the target in the late backswing and early downswing leads to a lag in the thorax axial rotation. As the movement continues, the thorax begins to rotate back towards the target gaining kinetic energy from the pelvis segment. In doing so, its rate of rotation is increased and the pelvis segment rotation decelerates. The overall pattern displays the peak angular velocity of the pelvis proceed that of the thorax. The chain then continues to the more distal segments of the arms and eventually the club.

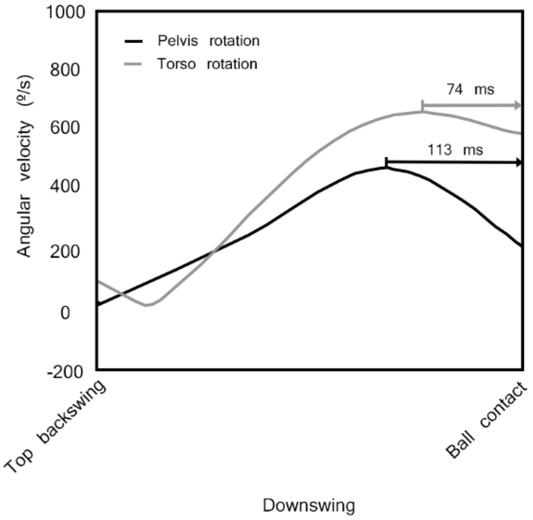


Figure 2-7: Example proximal-to-distal sequence, based on Neal et al., (2007). The example shows the pelvis rotation angular velocity peaking before that of the upper torso [thorax] segment.

In golf, interestingly, the proximal-to-distal sequencing has also been observed for partial swings, aimed at three different shorter distances rather than the maximum full distance (Tinmark et al., 2010). The findings were comparable across shot trajectories in tennis, which found the sequencing present in flat, kick and slice serves (Sheets et al., 2011).

Centre of gravity

The movement of whole-body centre of gravity of the player during hitting movements has been investigated with evidence that it may be important for performance (Gowitzke & Waddell, 1989; Vorobiev et al., 1993; Welch et al., 1995; Huang et al., 2002; Abrams et al., 2011; Ellabany & Attaallah, 2015).

In the golf downswing, the centre of gravity has been shown to shift medio-laterally towards the target and anterior-posteriorly forwards towards the target line (Figure 2-8; Burden et al., 1998; Smith et al., 2016). For performance, individual characteristics in centre of gravity movement have been identified (Smith et al., 2016) and associations made between patterns of centre of gravity movement and clubhead speed. For example, an earlier shift of the centre of gravity towards the lead foot in the backswing were likely to have a lower clubhead speed. Golf studies have also shown centre of gravity to be important for postural balance (Lindsay et al., 2008; Tsang & Hui-Chan, 2010; Smith et al., 2012; Wrobel et al., 2012; Smith et al., 2015b; Choi et al., 2015; Peterson et al., 2016; Smith et al., 2016) and have linked its movement to centre of pressure (Smith, 2013; Choi et al., 2015); principal components relating to the two variables were moderately-to-strongly correlated (Smith, 2013).

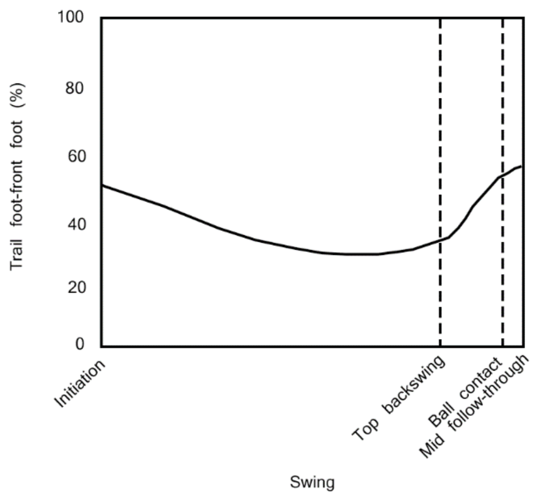


Figure 2-8: Example golfer medial-lateral centre of gravity pattern, based on Smith et al., (2016). The position is given as a percentage of the distance between the lead and trail foot, where 0% is the trail foot and 100% is the lead foot.

Away from golf, evidence has emerged for different centre of gravity patterns across shot trajectories in other sports, specifically tennis. At an individual-level an elite player showed greater horizontal linear velocity of the centre of gravity for flat serves, and greater vertical linear velocity for kick serves (Vorobiev et al., 1993; Abrams et al., 2011). This data was collected during competition from a two-camera video based system. Therefore, whilst swings were representative of in-play competition, in terms of data collection, the set-up has limitations.

Wrists

Wrists kinematics are a well investigated area of hitting biomechanics. They have been linked to the speed of the hitting implement (Gowitzke & Waddell, 1979; Sprigings et al., 1994; Elliott et al., 1995; Huang et al., 2002; Fleisig et al., 2003; Rambely et al., 2005; Gordon & Dapena, 2006; Tanabe & Ito, 2007; Genevois et al., 2015; Shan et al., 2015).

In golf the main movement, ulnar deviation (sometimes termed uncocking), has been linked to clubhead speed (Budney & Bellow, 1982; Milburn, 1982; McLaughlin & Best, 1994; Sprigings & Neal, 2000; Sprigings & Mackenzie, 2002; Lindsay et al., 2008). The wrist is radially deviated at top of the backswing (Hume et al., 2005) and as the downswing progresses the lead wrist should remain so until late in the downswing (Lampsa, 1975; Milburn, 1982; Neal et al., 2007). This is advised in order to take full advantage of the proximal-to-distal sequencing; wrist ulnar deviation should occur when the lead arm is approximately 30° below horizontal (Sprigings & Neal, 2000; Hume et al., 2005) corresponding to approximately 80-125 ms prior to ball contact (Milburn, 1982; Neal & Wilson, 1985; Dillman & Lange, 1994). The angle between the left forearm and the club at the point where the left arm is parallel to the ground has been found to be the most important determinant of clubhead speed between players accounting for 60.3% of the variance (Robinson, 1994). Additionally, high lead wrist angle velocities are important for clubhead speed (Sinclair et al., 2014). The lead wrist maintains approximately 35° of flexion at ball contact, allowing the clubhead to rotate around the wrist joint in the direction of the target (Cochran & Stobbs, 1968).

It is worth noting that a delayed uncocking of the wrists will lead to other swing consequences, one of these being a lower ball trajectory (Zhang & Shan, 2013). Therefore, it is possible golfers alter their wrist kinematics to achieve different types of shot, such as low trajectory shots.

Wrist mechanics have influences on shot trajectories in other hitting sports. For example, in tennis, greater velocities have been seen when comparing the topspin ground stroke to the backspin ground stroke. The latter had a relatively constant wrist angle over the forward swing phase (Elliott & Marsh, 1989). However, there was little difference in wrist angles at ball contact. Furthermore, the kick serve has shown differences in wrist velocity when compared to the flat, with a greater lateral component in order to produce sidespin by increasing the lateral racket velocity (Sheets et al., 2011). Finally, pronation, deviation and flexion movements of the wrist/ radioulnar joint have been shown to contribute to the flat and topspin ground strokes linear racket velocities in different ways (Takahaski et al., 1996).

Similarly, in table tennis, differences in wrist mechanics, namely an extension of the wrist, as ball contact approached led to backspin trajectories over topspin (Iino et al., 2008) and in badminton players altered wrist flexion angles to create a cut shot motion when compared to a drop shot (Sakurai et al., 1987).

2.3.4. Swing plane

The motion of the striking implement at the point of contact with the projectile determines the trajectory of the projectile's flight, controlling velocity and spin. Golf club swing plane is often discussed by golfers, coaches, commentators and researchers, perhaps because visually it is easy to interpret, unlike other sports such as tennis, where the planar motion is less evident.

Swing plane is a concept in golf that dates back a long time (Hogan & Wind, 1957). Initial theory suggested the clubhead and shaft follows a co-planar path during the backswing, downswing and follow-through. A double-pendulum model was developed to represent this (Figure 2-9; Cochran & Stobbs, 1968). However, the actual movement is more complex; for example, it has been found that only parts of the downswing and follow-through are co-planar (Lowe & Fairweather, 1994; Kwon et al., 2012). Within individual shots, an instantaneous club plane, formed by the motion of the shaft over consecutive three frames, has been defined and found to vary during the early stages of the downswing (Vaughan, 1981). It was stated however, that 0.1 seconds prior to impact the plane was "fairly well established". Therefore, whilst "swing plane" is a commonly used phrase, and in parts, it could be viable notion (Kwon et al., 2012), there is evidence that some aspects of a golf swing and some individual's swings are not planar (Coleman & Rankin, 2005; Coleman & Anderson, 2007).

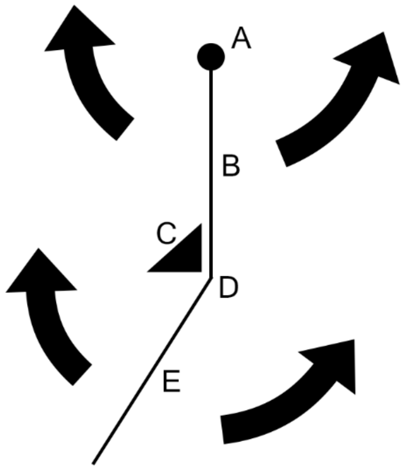


Figure 2-9: The double-pendulum model based on Cochran and Stobbs, (1968): A. a fixed pivot representing the centre of the shoulders; B. the upper lever corresponding to the upper and lower arms; C. a stop to prevent unnatural wrist deviation; D. the hinged wrist joint and E. the lower club lever. The arrows represent the direction of the lever rotation.

Two angles (vertical and horizontal) have been calculated from club swing planes (Figure 2-10). Across clubs, swing plane changes have been observed in these angles (Lindsay & Horton, 2002; Egret et al., 2003; Coleman & Anderson, 2007; Kwon et al., 2012). To highlight an example, Coleman & Anderson, (2007) identified swing plane differences between the driver, 5-Iron and pitching wedge. All three clubs significantly differed in horizontal swing plane, (7.8 ± 5.9º, 4.9 ± 5.7 and 5.9 ± 6.0º in-to-out for the driver, 5-Iron and pitching wedge respectively) and furthermore, the driver differed to the other two clubs in vertical swing plane (125.5 ± 3.0º, 117.1 ± 3.0º and 113.6 ± 2.7º for the three clubs). These differences resulted from planes fitted to the markers tracked throughout the downswing phase of the swing; the study also calculated the equivalent instantaneous swing planes over each consecutive pair of frames. Reasons discussed for the differences included differing club lengths, ball position at address and kinematic differences with shot trajectory (fade or draw). The authors suggested the differences in horizontal swing plane, a more in-to-out swing plane, could promote a draw trajectory with the driver, more than in the other two clubs. It is perhaps in this horizontal plane where differences may be elicited when playing draw and fade trajectories. It is likely that the horizontal swing plane shows similar, in-to-out and out-to-in patterns that club direction theoretically shows for these trajectories to begin the ball path right or left of target for the respective shot.

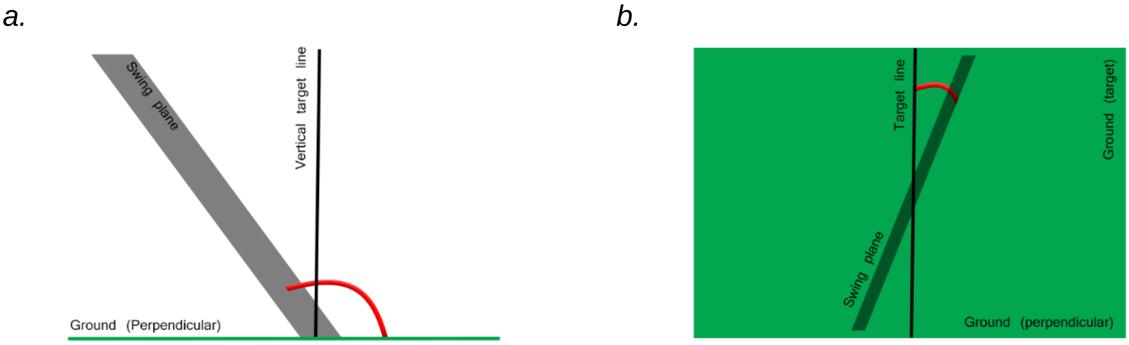


Figure 2-10: Instantaneous swing plane angles: a. vertical and b. horizontal.

Clubhead swing plane has been investigated for draw and fade trajectories directly (Collinson et al., 2012). However, the plane was not the instantaneous plane described above. It was fitted through the trajectory of a virtual marker at the clubface geometric centre from club parallel to the ground in the downswing to ball contact, which was tracked via motion analysis at 460 Hz, up-sampled to 2000 Hz. Draw trajectories were defined as curving 10-25 yards right-to-left in the air and fade correspondingly left-to-right and landing within 10 yards of the target line. High-level golfers hit draw and fade trajectories indoors, which were tracked by a launch monitor (Foresight); therefore, the inclusion of a successful draw or fade was dependent on the in-built algorithm. Swing plane differences were found between the draw and fade, even when address differences were accounted for. The article does not elaborate further on the nature of the differences, but does recommend research into the how clubhead motion relative to the golfer biomechanics affects the shot trajectory.

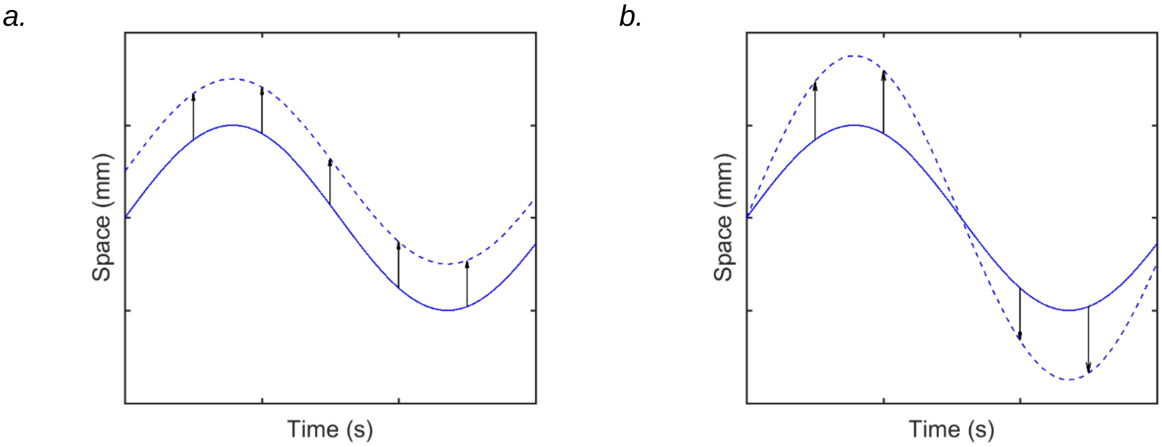
In tennis and table tennis, the motion of the hitting implement just prior to striking the ball when serving has been associated with spin production (Elliott & Wood, 1983; Iino et al., 2008; Sheets et al., 2011). Specifically, in tennis, the velocity vector direction has shown to differ between the topspin and backspin ground strokes, directed more down-to-up for the former and laterally for the latter (Elliott & Marsh, 1989; Chow et al., 2003; Reid, 2006), despite the resultant racket speed not changing. Similarly, for table tennis a significantly more upward trajectory was seen for backspin shots compared to topspin with the horizontal forward velocity showing no difference (Iino et al., 2008).

2.4. Statistical analysis in biomechanics

There are numerous methods of statistical analysis generally used in experimental biomechanics (Smith, 2013). Typically, the process starts by performing a variation of time-normalisation on the data of each participant to enable cross-comparisons. These temporal waveforms are then graphed and initial subjective interpretations drawn based on the data curves. Pre-defined key instances, such as peaks and troughs, can be identified and the data extracted at each instance. This is common in golf where events such as takeaway, top of the backswing, 40 ms prior to ball contact, ball contact, and follow-through are identified. Comparisons tests, such as t-tests and analysis of variance, or relationship statistics, such as correlation and regression, can then be used to compare test conditions, such as gender and ability. The disadvantage of this method is that the vast majority of the data is ignored and the key instances that are retained are done so subjectively by the researcher (Smith, 2013).

To overcome these limitations, whole-movement continuous data analysis techniques have been used in biomechanics. One of the goals of such techniques is to identify differences in waveforms without the subjective bias of researcher interpretation. Smith, (2013) reviewed the strengths and weakness of various continuous data analysis techniques, including discrete and continuous relative phase, vector coding, cross-correlations, normalised root-mean squared difference, statistical parametric mapping, curve clustering and principal components analysis.

The final technique and the one utilised by Smith, (2013) to investigate golf biomechanics was principal component analysis. The analysis can be used to explain variance within a data set (Ramsay & Silverman, 2005; Smith, 2013). It is used to reduce the dimensionality of the data from a large number of interrelated variables to a new set of uncorrelated variables, the principal components (Jolliffe, 2002). This is achieved through calculation of eigenvectors and eigenvalues of the covariance or correlation data matrix. The eigenvectors represent the coefficients or weighting of each principal component at each time point. The eigenvalues contain the relative contribution of each principal component to the total variation in the data set. The eigenvalues are ordered from the principal component explaining the most variation to the one explaining the least, then, typically, the principal components cumulatively explaining over 90% or 95% of the data are retained, whilst the remaining are disregarded. The biomechanical meaning of the principal components can be interpreted through plots (Ramsay & Silverman, 2005) and therefore, the biomechanical cause of the variation be identified. Principal components can be interpreted as representing offset, magnitude, timing and rate of change differences (Figure 2-11), useful when determining the characteristics of golfer biomechanics.



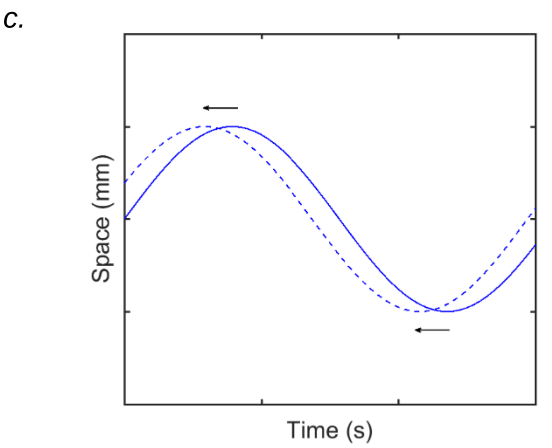


Figure 2-11: Different biomechanical principal component difference interpretations of a variable in space over time based on Ramsay & Silverman, (2005): a. offset; b. magnitude and c. timing. The solid line represents the original data and the dotted represents the respective difference. Arrows indicate the direction of the difference.

Across biomechanics principal component analysis has been used to compare more than one test conditions when performing a task. For example, Deluzio et al., (1997), Deluzio & Astephen, (2007), Muniz & Nadal, (2009) and Federolf et al., (2013) identified biomechanical differences between normal and pathological gait patterns. Similarly, Kobayashi et al., (2014) identified key gait joint kinematics related to risk of falling and Reid et al., (2010) investigated stair climbing in younger and older adults. Wrigley et al., (2005) and Wrigley et al., (2006) demonstrated the ability of principal component analysis to identify technique differences in lifting patterns between workers who did and did not develop lower back pain. The only golf related study to use principal components to compare conditions was Lynn et al., (2012). The study compared ground reaction forces between two conditions: novice and expert. In total, there were six significant differences in principal component scores between the groups, corresponding to vertical, anterior-posterior and medio-lateral differences at the lead foot and vertical and medio-lateral differences at the trail foot. Therefore, the ability of principal components analysis to differentiate between test conditions has been demonstrated both outside of and within golf biomechanics.

The principal component analysis studies identified above grouped participants based on the test conditions. For example, in the study of Lynn et al., (2012) the novice and the expert golfers were grouped. This is a common feature of biomechanical research. Often the data from one-group is averaged and compared to that of another. This has limitations, for example, individual participant characteristics are lost. In golf, this could mean that golfers who are perceived to have similar swings, such as those with similar handicaps, are grouped despite having individual swing idiosyncrasies. This individuality of golfers' swings is often commented upon (e.g. Jorgensen, 1999; Brown et al., 2011; Tucker et al., 2013). Also, the group-based findings may also be inapplicable for individual golfers when providing feedback, particularly the case in elite samples (Ball & Best, 2012). The usefulness for using individual-based analysis for elite athletes has been demonstrated to investigate more specifically the athlete's movements (e.g. Vorobiev et al., 1993; Okuda et al., 2002). Therefore, the case for the inclusion of at least a mixed group and individual-based analysis is strong.

Most golf biomechanics research is group-based. However, there are a few studies that have applied individual analysis techniques. For example, Ball & Best, (2012) found that centre of pressure shift was important on an individual-level for all golfers, the medio-lateral aspect being associated with clubhead speed, however, the nature of the shift was very much individual. The authors state how the study provides support for the inclusion of individual analysis in group-based studies.

2.5. Summary

This chapter, through a systematic literature review, has provided the reader with an overview of clubhead and ball impact mechanics as well as the biomechanics of shot trajectories in hitting sports.

Physical theories, such as D-plane, have provided an insight into the clubhead-ball impact during golf and new bespoke technologies to measure golf shot impact parameters are increasing in use; however, these have not been independently verified in terms of accuracy. Therefore, to use them in biomechanical investigation, confidence in the accuracy must first be gained. Otherwise, an alternative approach must be sought.

The biomechanics section highlighted how shot trajectories in golf have not been directly investigated scientifically. Although, at times, their influence has been acknowledged (e.g. Coleman & Anderson, 2007; Collinson et al. 2012). Information regarding shot trajectories can be gleamed from other hitting sports where altered trajectories are important for performance, predominantly tennis. Kinetic and kinematic differences found in other sports suggest the area is of interest in golf. Potential biomechanical variables of interest for golf trajectories include: lateral centre of pressure shift; vertical and horizontal ground reaction forces; velocity and magnitude of thorax, pelvis and X-factor axial rotation; lateral and forward flexion of the lumbar spine and thorax; individual shoulder joint motions; lateral centre of gravity shift and velocity and magnitude of wrist supination and deviation angles.

The review has demonstrated how more complex continuous data analysis techniques can provide deeper insight in biomechanics, some of which have been applied recently in golf. Principal component analysis is one such tool and the method may well be beneficial to shot trajectories.

CHAPTER THREE

METHODOLOGY FOR THE VALIDATION OF TWO COMMERCIALLY AVAILABLE LAUNCH MONITORS

3.1. Introduction

TrackMan and Foresight manufacture and develop commonly used launch monitors to measure golf performance. At the time of investigation their primary models were the TrackMan Pro IIIe and Foresight GC2+HMT. These launch monitors were discussed in Section 2.2.1; however, to recap, TrackMan uses Doppler radar technology to identify fast moving objects i.e. the clubhead and ball and uses the shift in radar signal, between the signal sent out and the signal that returns, to measure the impact parameters. Foresight is a stereoscopic optical system. The GC2 aspect tracks the ball, with the addition of the HMT or head measurement technology to track the clubhead. Both manufacturers state the accuracy of their systems in their technical specifications, however, the origin of these values is unclear and, to date, they have not been independently verified. Given the need for sufficiently accurate performance outcomes it is important to validate such systems for use in golf research.

To validate the systems, there is a need to compare the degree of agreement in outputs against a more accurate system. The GOM system introduced in Section 2.2.1 is one such system (Doebele et al., 2012). It is an optical tracking system and although not purposely designed for golf its application to clubhead and ball tracking has previously been demonstrated (Ellis, 2013). The hardware consists of multiple high-speed video cameras, allowing dynamic events to be investigated at high frame rates and in three dimensions thus making it suitable for capturing the rapid impact of a golf shot, lasting less than one millisecond (Cochran & Stobbs, 1968). The accuracy of the system is dependent on the setup, including the camera, lens, calibration, lighting and marker quality. The ingenuity of the GOM INSPECT system is in the software, which offers detailed three-dimensional dynamic analysis via a range of tools including point tracking, mesh fitting and coordinate system transformations. Despite demonstrating the system’s potential for use in golf investigation Ellis, (2013) did not attempt to quantify the uncertainty of the measurements. Therefore, to evaluate the TrackMan and Foresight systems, validation of the GOM system itself is needed.

Chapters 3 and 4 address the second research question: “how suitable are commercially available clubhead-ball impact measurement technologies for use in scientific biomechanical investigation to measure performance outcomes?" Chapter 3 outlines the methodology, whilst Chapter 4 contains the results and interpretation. The specific aims addressed in this investigation are *Aims 2* and *3* (Section 1.2.3): to validate the accuracy of the impact parameters output by the TrackMan Pro IIIe and Foresight GC2+HMT launch monitor systems and to provide evidence based recommendations regarding their use within biomechanics scientific research.

3.2. Methodology

3.2.1. Participants

When designing the methodology for the investigation two options were available: to use a robot to control and manipulate each impact parameter; or to use human participants to naturally create a random spread of each impact parameter. The latter of these options was decided upon for three main reasons. Firstly, the multitude of equipment used in the study would have proved difficult to optimise a set-up around a golf robot given the limited space around the location in the laboratory; secondly, a natural variation of impacts was desirable, rather than an artificial variation input into a robot; and lastly, the investigation set out to investigate the launch monitors as they were designed to be used in everyday settings i.e. by golf professionals with human golfers.

Eight right-handed golfers (age 26 ± 7 years; height 1.80 ± 0.07 m; mass 78 ± 12 kg; experience 10 ± 7 years) volunteered for the study. Handicaps ranged from zero through to recreational (no official handicap). The study met with approval by the University's Ethics Committee for studies involving human participants and all participants provided voluntary informed consent.

3.2.2. Equipment set-up

Data collection took place in the motion analysis laboratory at the Sports Technology Institute at Loughborough University. The GOM, TrackMan and Foresight systems were set-up and aligned (Figure 3-1) so that all three could be operated concurrently. Golfers hit from a mat placed centrally in the laboratory into a hitting net approximately four metres away. The underlying principle of the experimental design was to evaluate the launch monitors in a manner representative of how they would be used in practice, therefore: the two launch monitors were in frequent use within the laboratory and there was no specific reason behind the selection of the units nor were they configured specifically for the testing; manufacturers' guidelines were followed throughout the set-up; everything associated with the launch monitors was widely available to the general public and no non-standard or specialist items were employed to optimise their performance; and all three systems operated simultaneously to allow direct comparison of results.

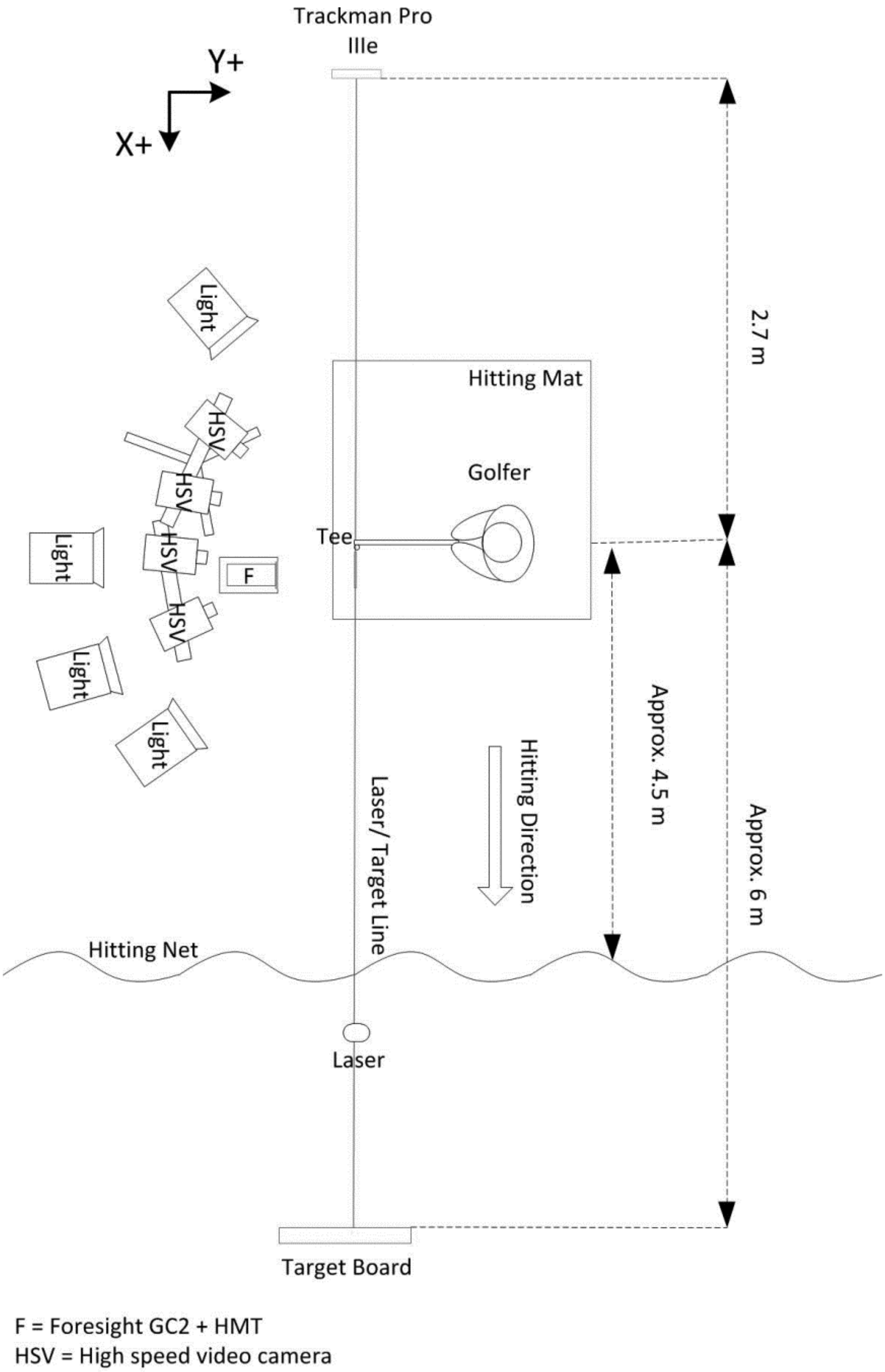


Figure 3-1: Plan view of the laboratory setup.

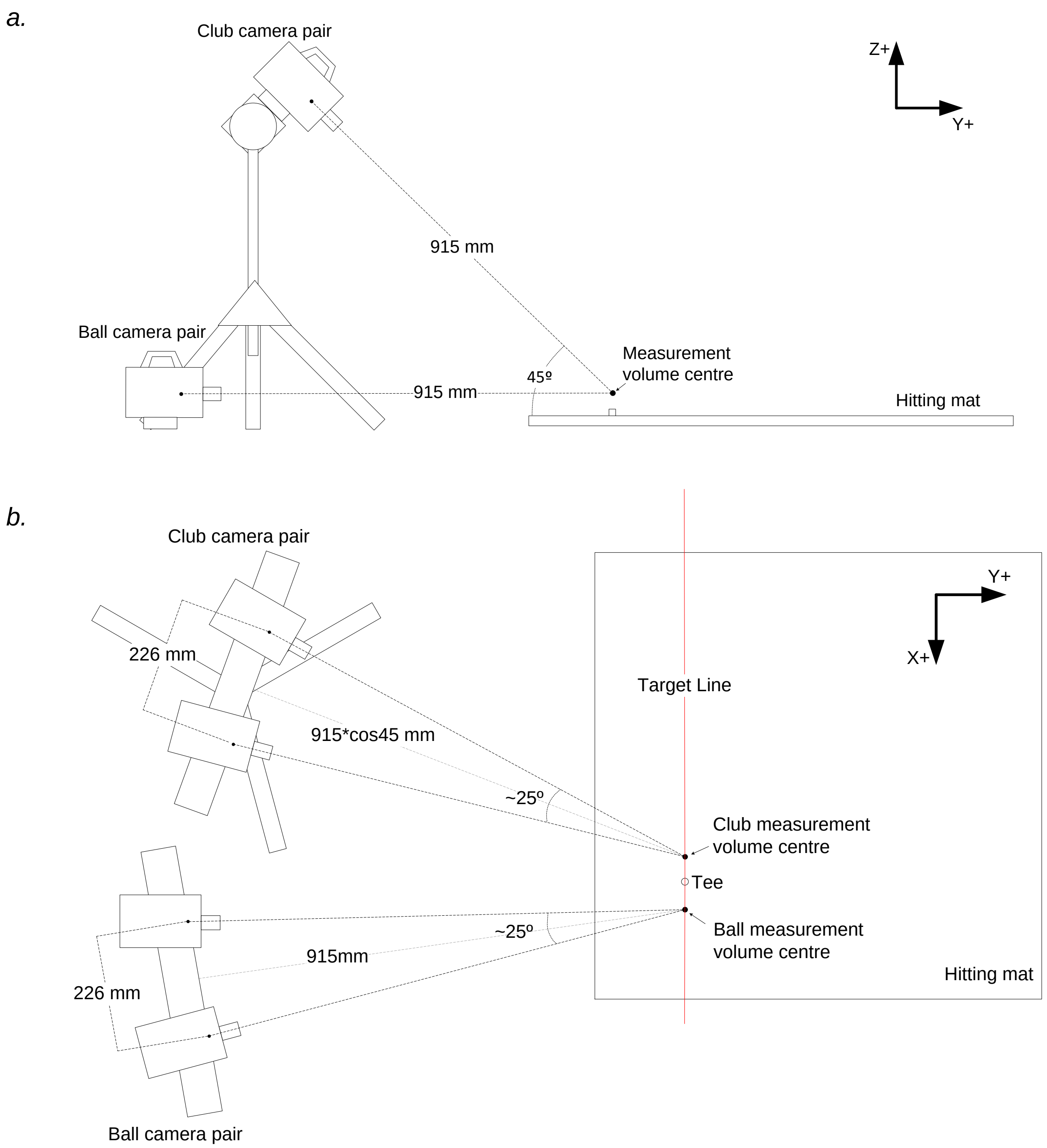


Figure 3-2: Diagram of the high speed camera set-up from a. down the target line and b. overhead.

GOM

The GOM set-up involved finding a balance of various hardware and software requirements. Four Photron Fastcam SA1.1 (Photron, San Diego, CA) high speed video cameras were placed to the side of the hitting mat, each fitted with a Titanar 50 mm focal length lens. The cameras operated as two pairs, one pair tracking the clubhead, the other the ball; the ball camera pair sat at ground level and the clubhead camera pair atop a tripod tilted 45º down towards the tee (Figure 3-2). The exact set-up was guided by GOM recommendations. Each camera was set-up for a capture volume around the tee of 300×300×300 mm^3. All four high speed video cameras were synchronised to the same external trigger and set to record at 5400 Hz, the highest frame rate allowing full resolution (1024×1024 pixels), with a shutter speed of $\frac{1}{50000}$ seconds. The fast shutter speed reduced image blur; the clubhead and ball can travel in excess of 100 mph (approximately 45 m/s) and 150 mph (approximately 67 m/s) respectively around impact (Cochran & Stobbs, 1968). The resultant problem of reduced light exposure was resolved by additional lighting; four flicker free Arri (Arri Group, Munich, Germany) lights were directed at the tee. Camera apertures were altered to ensure good contrast between white and black, although they were not set below f/5.6 as recommended by GOM. This set-up allowed a balance, whereby enough high speed images of suitable quality (contrast, focus, spatial resolution, etc.) within the GOM capture volume could be recorded, whilst the system operated alongside the two launch monitors.

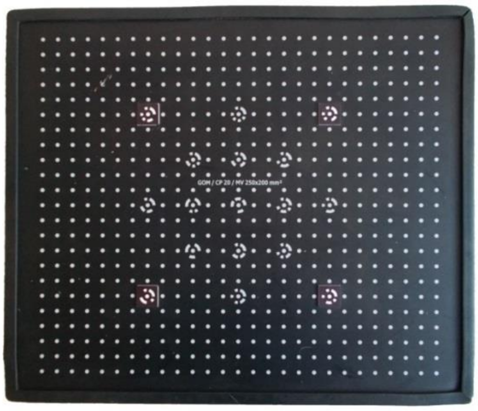


Figure 3-3: GOM calibration object.

Each camera pair operated as an independent system. Therefore, each volume was calibrated independently. This was done in accordance with the GOM instructions by imaging a specific calibration object (Figure 3-3), supplied with the system, in multiple positions and orientations within the capture volume. The object had previously been independently certified (Appendix A). Calibration images were imported into GOM software (PONTOS V6.3), where an in-built calibration process was followed. The result of the process was a calibration file. Due to the independent calibrations, a separate file was saved for each camera pair. Along with the calibration file, results were produced for each calibration. The calibration results for this investigation are displayed in Section 4.3.1; to achieve a satisfactory calibration a calibration deviation of less than 0.04 pixels is recommended by the manufacturer. Further inspection of the intersection deviation for multiple trials across each session provided added confirmation of a successful scientific set-up. The intersection deviation, representing the nonconformity in the identification of points on each camera image, is a unitless value that like the calibration deviation gives an indication of the quality of set-up; it should be small and consistent from frame-to-frame, somewhere in the region of 0.03.

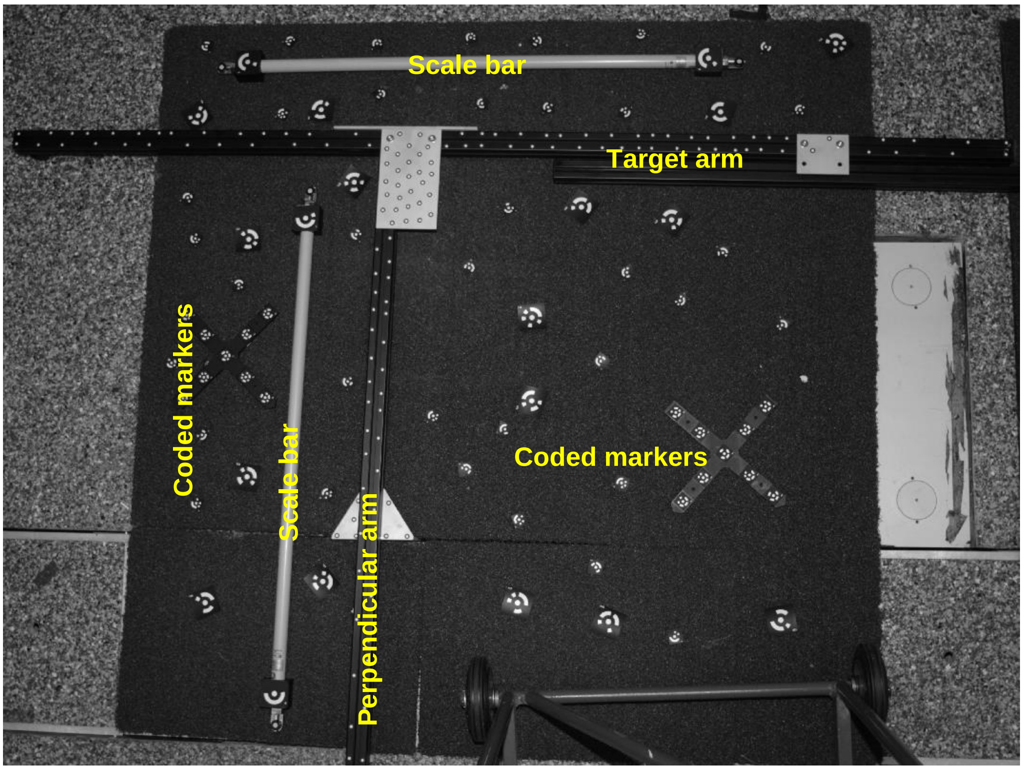


Figure 3-4: Annotated image of the global coordinate system rig (taken using the Nikon D2Xs camera).

The GOM calibration procedure outlined above generated an independent local coordinate system for each camera pair. In order to identify a common global coordinate system a subsequent transformation was required to align each pair. To achieve this transformation a purpose-designed rig was built. The rig consistent of two perpendicular arms, termed the target arm and perpendicular arm (Figure 3-4). Adjustable feet were attached to the ends of each arm. A metal attachment projected downwards so the rig could be aligned to the edges of the forces plates in the centre of the laboratory. To define a visible target line for the golfers to focus on a vertical plane of laser light was projected from a self-levelling Leica Lino L360. The plane passed through the tee and the target arm of the rig was carefully aligned to the plane of the laser beam. The legs were then adjusted with the aid of a spirit level so that the arms formed a horizontal plane. Beforehand, multiple 5 mm GOM markers were placed randomly on the rig and the three-dimensional coordinates were measured using the GOM three-dimensional optical coordinate measurement software (TRITOP). The process involved taking approximately 50 images of the rig using a Nikon D2Xs camera from different orientations and importing them into the software, which identified the three-dimensional positions of the markers on the rig (Figure 3-5a). The images also included coded markers surrounding the rig which the software could also identify (Figure 3-5b). Coded markers had a unique pattern and corresponding number. In each image the coded markers were used to identify the relative position of the point markers on the rig. All images were then computed together to produce a three-dimensional point cloud of the rig (Figure 3-5). Two scale bars of known length were also placed in close proximity to the rig so that the software could scale the measurement volume. From the point cloud markers each surface of the rig was selected and used to create best-fit planes which would define the global coordinate system. The following three best-fit orthogonal planes were created (Figure 3-6), intersecting at an origin subsequently forming the global coordinate system:

- *Plane I:* A horizontal plane through all the markers on the upper surface of the two arms of the rig.
- *Plane II:* A vertical plane, perpendicular to *Plane I*, passing through the points on the vertical face of the target arm.
- *Plane III:* A vertical plane, perpendicular to *Planes I* and *II*, passing through the points on the vertical face of the perpendicular arm.

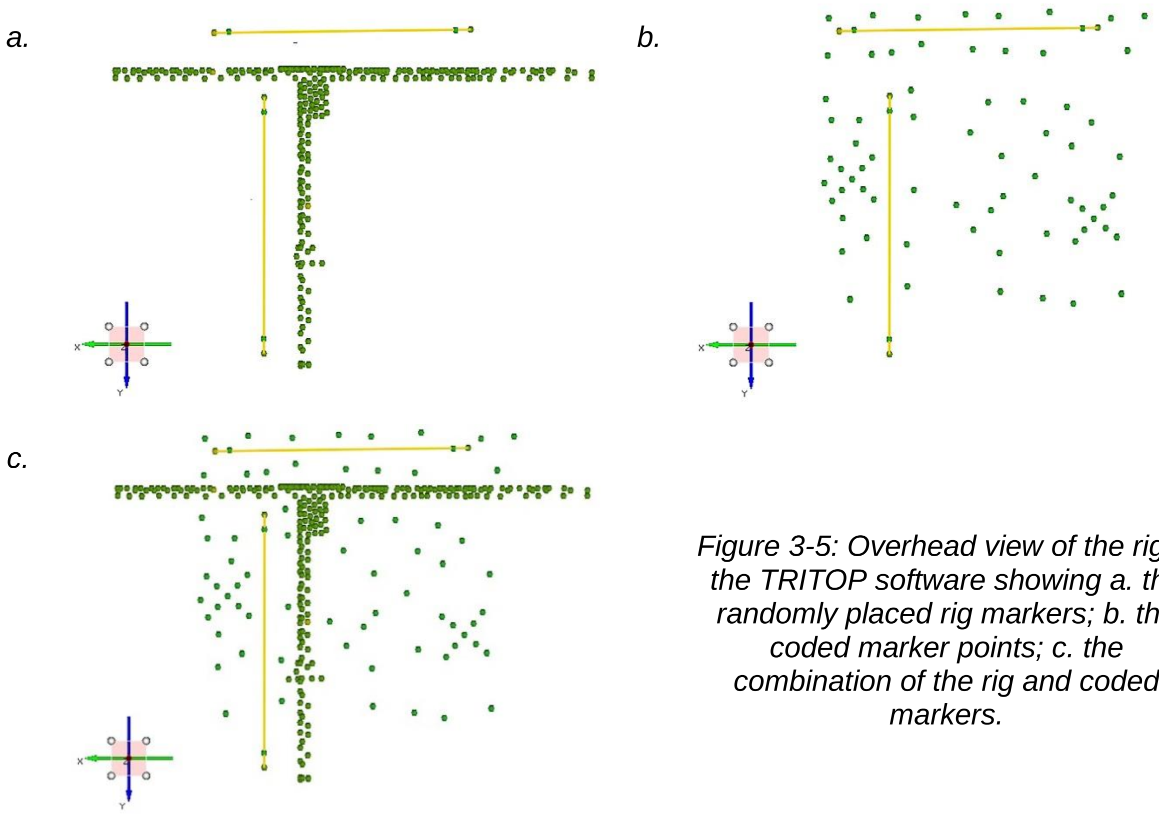


Figure 3-5: Overhead view of the rig in the TRITOP software showing a. the randomly placed rig markers; b. the coded marker points; c. the combination of the rig and coded markers.

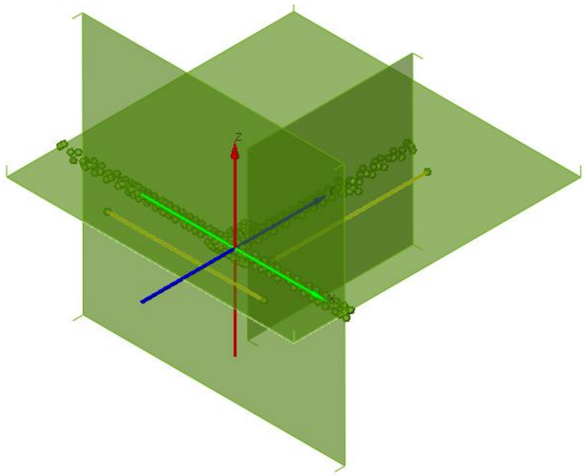


Figure 3-6: Three planes defined in the TRITOP software forming the basis of the global coordinate system.

All planes were created as best-fit planes using 95.5% of points to discount outliers. Despite best efforts to ensure the planes were mutually orthogonal, small errors (< 0.5°; Table 3-1) resulted from the manufacture and assembly of the rig, marker identification in TRITOP and the thickness and placement of the markers. Despite these small errors a 3-2-1 transformation in TRITOP created an orthogonal global coordinate system.

Table 3-1: The error in angle between the three created planes in TRITOP.

Plane comparison	Error in angle (°)
I-II	0.462
I-III	0.160
II-III	0.137

To quantify the offset between the planes and the coordinate system axes plane-line angles were created (Table 3-2). *Plane I* was aligned perfectly with the coordinate system; however, the other two planes were not. It was desirable for *Plane I* to match as it was created from the top surface of the rig, which was carefully positioned using the spirit level to lie flat. The offsets in *Planes II* and *III* were accounted for via corrections to the relevant impact parameters following their calculation at the end of the analysis process. The point cloud of rig marker locations was exported as reference points to support the transformation of the local coordinate system of each measurement volume to the common global coordinate system.

Table 3-2: The angle between each created plane and the axis lines of the global coordinate system.

Plane	Line	Angle (°)
I	X	0
	Y	0
	Z	90
II	X	0.005
	Y	89.538
	Z	0.462
III	X	89.792
	Y	0.133
	Z	0.16

The transformation was a three-step process. Firstly, images of the rig were taken with the high speed video cameras. The points in view of the camera were then identified in GOM software (INSPECT). Lastly, two best-fit transformations were applied to match the points from each high speed camera pair to the reference points. This transformed each local coordinate system into the common global coordinate system.

TrackMan & Foresight

Extensions to the global coordinate system rig were secured to align the TrackMan and Foresight units (Figure 3-7). Set-up of the units followed each manufacturer's guidelines (TrackMan, 2014; Foresight Sports, 2012a). An extension to the rig enabled the front face of the TrackMan unit to be aligned perpendicularly to the target arm of the rig. The laser beam bisected the vertical line in the 'k' of the TrackMan logo, corresponding to the centre of the TrackMan unit(TrackMan 2015a)(TrackMan 2015a) (TrackMan, 2015a), at a distance of 2.7 m behind the tee. Software alignment was performed using the TrackMan Performance Studio 3.2 (TPS 3.2) software; the laser beam was visible to a built-in camera and was selected as the target line in the software (Figure 3-8). Apart from a built-in accelerometer which enables self-levelling, Foresight has no formal alignment procedure. However, a requirement was that the ball must sit within the hitting zone when on the tee. The alignment rig ensured the front edge of the Foresight unit was parallel to the target arm of the rig (Figure 3-7). Following setup of the launch monitors and imaging of the rig, the rig itself was no longer required and thus removed from across the hitting mat.

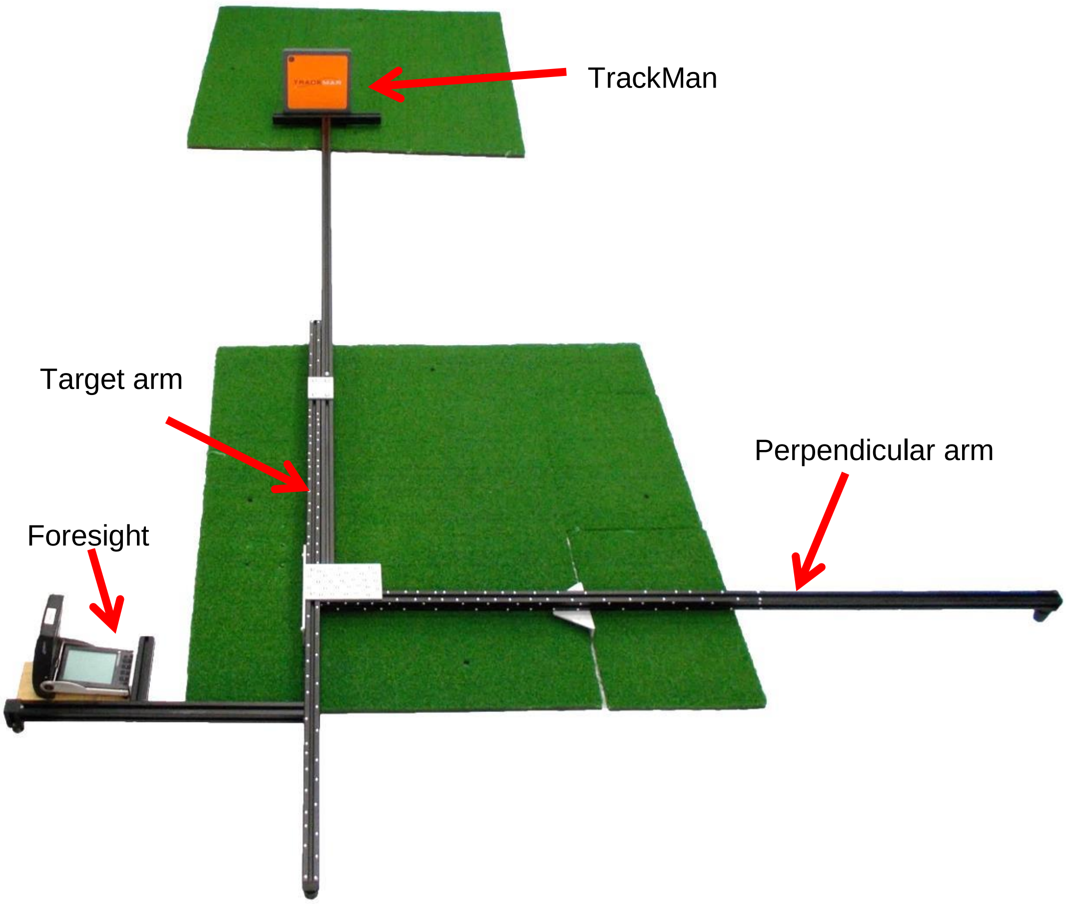


Figure 3-7: The rig including the additional sections to align the TrackMan and GC2.

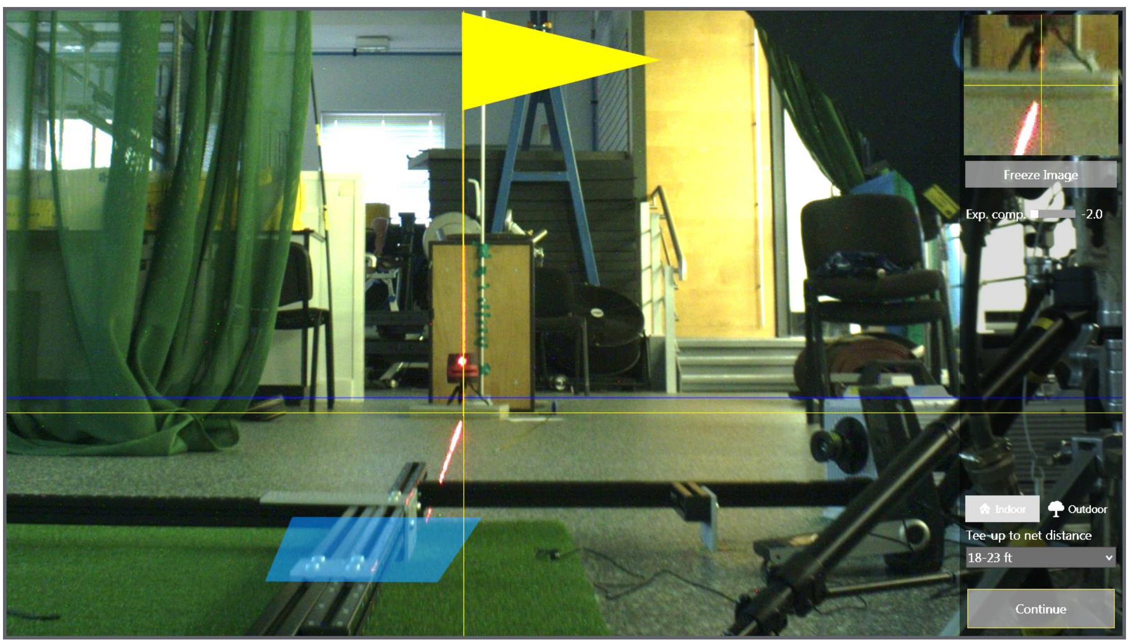


Figure 3-8: The set-up screen in the TrackMan TPS 3.2 software illustrating the alignment of the TrackMan target line (the yellow flag) to the laser target line.

Details of the club and ball preparation

Three clubs were prepared to ensure a range of clubhead and ball impact parameters (Table 3-3). The make and models were chosen because of the size of the clubhead allowed for the placement of sufficient markers to aid the tracking process. Five mm diameter GOM markers were placed on the driver (Figure 3-9a) and 3 mm diameter markers placed on the 7-iron (Figure 3-9b) and wedge (Figure 3-9c). The GOM system requires the markers to be a minimum of 10 pixels in diameter to identify as a marker. The markers used were of sufficient size to achieve this with the camera set-up and measurement volume. Finally, markers unique to Foresight were placed on each clubface (Figure 3-10), according to the manufacturer's instructions (Foresight Sports, 2012b), so that the HMT unit could track the clubhead.

Table 3-3: Details of the three clubs used for the study.

Club	Make/ Model	Loft (º)	Length (inches)	Offset (inches)	Lie (º)	Bounce (º)	Head mass (grams)	Head size (cc)	Swing Weight
Driver	Ping G25	9.5	45.75	No	58	-	205	460	D3
7-Iron	Ping K15	32	36.75	0.24	62.25	6	-	-	D0
UW	Ping K15	50	35.5	0.15	64	11	-	-	D2

Figure 3-9: GOM marker placement on a. the driver; b. the 7-iron and c. the utility wedge.

Figure 3-10: Foresight HMT markers placed on the driver clubface.

Srixon Z-Star golf balls were chosen for the study (Table 3-4) with a different ball used for each subject. The balls were sandblasted to minimise glare resulting from the additional lighting which would affect the high speed video image quality for GOM (Figure 3-11a). The ball was Srixon's premier ball and had premium ball classification by TrackMan. The golf ball's dimples proved large and flat enough to stick 1.5 mm GOM markers within ensuring the best chance of being identified (Figure 3-11b). To further increase the chances of identification the markers were filled black increasing the ellipse size to three millimetres, ensuring at least 10 pixels covered the diameter (Figure 3-11c); the software identifies black on white as well as white on black markers. Marker placement was a random non-repeated pattern. Wear and tear of the markers on each ball was monitored throughout the testing and repaired if necessary. The ball manufacturer's stated compression value of 90 unit corresponds to low deformation, therefore minimises relative marker movement upon impact which was beneficial for tracking of the ball using GOM. A metallic dot supplied by TrackMan was placed on the ball to enhance the radar signature (Figure 3-11d), as recommended by the manufacturer to improve spin rate tracking. If TrackMan is not confident in this measurement it provides a calculated value; these data were excluded from the study.

Table 3-4: Details of the golf ball used for the study.

Make/ Model	Srixon Z-Star
Handicap range	Mid-Low
Swing speed	90-105 mph
Cover hardness rating	27
Cover thickness	0.508 mm
Compression rating	90
Dimple number	324

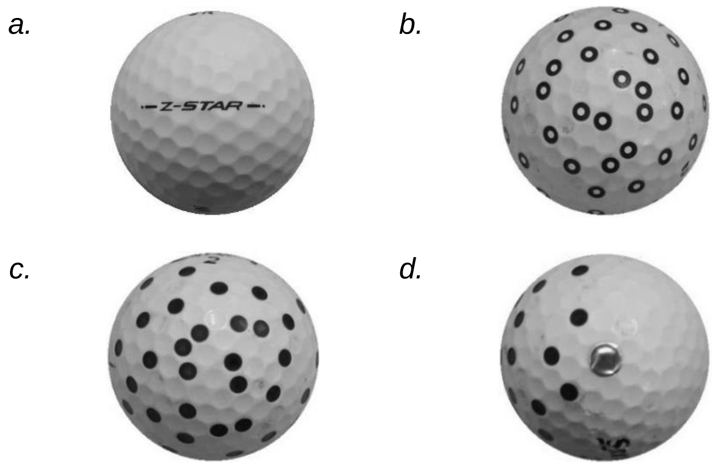


Figure 3-11: Golf ball used in the study: a. Sandblasted Srixon Z-Star ball; b. marked sandblasted Srixon Z-Star ball; c. fill-marked sandblasted Srixon Z-Star ball and d. metallic dot placed on the ball.

All three clubheads and the ball were scanned using a GOM scanner (ATOS Core) and associated software to create a surface mesh of each. Further to the mesh; the markers on the surface were identified during each scan. The purpose of the meshes and associated points is detailed in the system outputs sub-section.

Data collection

Golfers conducted a self-guided warm-up, using separate clubs and balls, to minimise risk of marker damage pre-testing, until they felt comfortable to swing. Golfers were permitted to hit in their own time. It was emphasised that the quality of shot was not of critical importance, as long as the ball contacted the clubface reasonably well; a variety of impacts was not discouraged. Ten shots were hit with each club with trials being repeated if the equipment did not track. TrackMan and Foresight automatically detected each shot; the high speed video cameras were externally triggered at the top of the backswing. High speed videos were cropped to include only the impact period. The cropping process following each individual trial gave the golfer time to recover between shots. Images were saved in TIFF format and the Bayer save option was checked so the images saved as greyscale. Each camera's images were saved in separate folders denoted by the camera number ready for post-processing. All shots were included in the analysis regardless of impact location or shot outcome.

System outputs

GOM

The clubhead and ball data were processed in GOM software (INSPECT) and MATLAB 2015a (The Mathworks, Natick, MA). An estimation of the golf ball radius was gained by fitting a sphere to the ball mesh giving a value of 21.3 mm (Figure 3-12; INSPECT). For each trial, the ball markers were reconstructed in the global coordinate system (Figure 3-13a). The ball centre was determined as the centre of a virtual best-fit sphere of radius 21.3 mm fitted to the surface markers, using 95.5% of the points (Figure 3-13b; INSPECT). The three-dimensional coordinates of the sphere centre and tracked points were exported and a MATLAB script written to compute the ball parameters listed in Table 3-5.

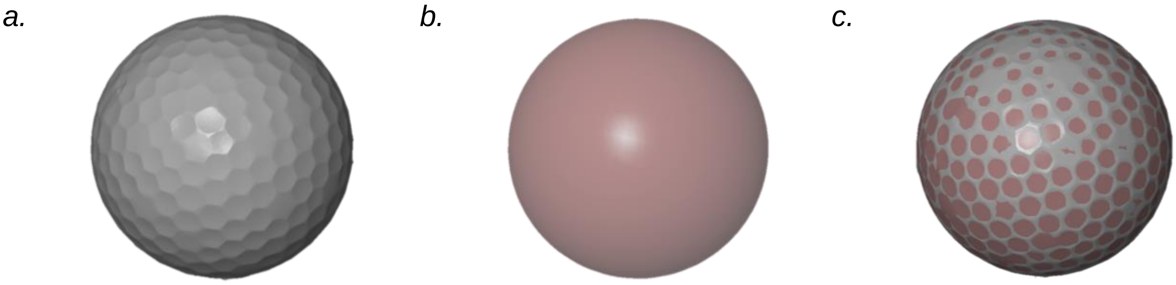


Figure 3-12: Use of a. the scan mesh to create b. a virtual sphere representation of the golf ball by c. best-fit.

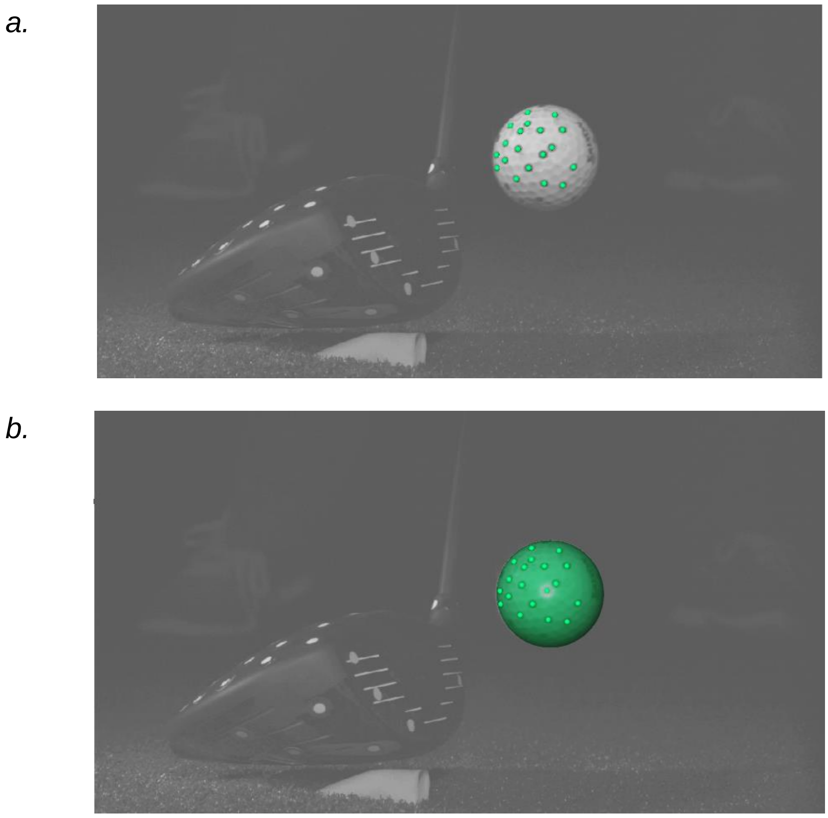


Figure 3-13: Sphere fitting to the tracked ball surface points in GOM INSPECT involving a. the identification of the points and b. a sphere of best-fit of radius 21.3 mm fitted to the points.

Total spin along with the components of spin and spin axis, were calculated from the point data. Rotation matrices from frame-to-frame were computed (Soderkvist & Wedin, 1993; Challis, 1995) and differentiated using the finite difference method (Robertson et al., 2013). The cardan rotation order was considered; the order of the GOM software was fixed at YXZ. Therefore, the global coordinate system was rotated within the GOM software to give the rotations in a desired order. Barrel spin was ordered as first rotation, due to its implications for spin axis, followed by sidespin and finally backspin, ordered last because of its prominent role as a component of total spin rate.

The use of the scan meshes along with the associated points identified in the scans was key to the clubhead analysis. Each clubhead mesh was best-fitted to the tracked points using the associated points on the clubhead identified during the scanning process. The location of the centre of gravity locations for each clubhead was provided by the manufacturer and the scan mesh enabled a virtual marker to be created at this point (INSPECT). The three-dimensional coordinates of the centre of gravity were exported. The impact location for each trial was calculated by projecting the virtual sphere centre, representing the centre of the ball, the shortest distance onto the mesh representing the clubface for the frame of first ball contact. This provided a normal to the clubface mesh at the projected impact location point. A MATLAB script calculated the clubhead parameters listed in Table 3-6.

One challenge was defining the clubface orientation. The definitions of face angle and dynamic loft appeared to differ between the TrackMan and Foresight systems. For this reason, two measures of face angle were calculated from the GOM data. The first, used for comparison with the TrackMan data, involved the impact location normal. Face orientation was defined as the angle between the normal and *Plane* II for face angle and *Plane* I for dynamic loft. The second measure, used for comparison to the Foresight data, was based upon the geometric centre of the clubface. The geometric centre of the clubface was defined horizontally at the mid-point of the face grooves and vertically level with the centre groove or half way between the two centre grooves if there was an even number of grooves. Face angle and dynamic loft could once again be calculated relative to the same global planes as before.

TrackMan & Foresight

One of the advantages of the launch monitor systems is the automatic recording and immediate feedback of the impact parameters. Therefore, for TrackMan and Foresight the parameters from each trial were automatically recorded and saved in the respective system shot library. Following data collection, the data was exported to MATLAB to be compared to the GOM data. The data was collected in January 2015, using the latest software and firmware.

Table 3-5: Definition of the ball impact parameters compared in this study.

Parameter	Unit	Definition	TrackMan definition and stated accuracy (TrackMan, 2015)		Foresight definition and stated accuracy (Foresight Sports, 2013; Foresight Sports, 2016)	
Ball velocity[1]	mph	Rate of change in position of the centre of a sphere fitted to the ball markers.	The speed of the golf ball's centre of gravity immediately after separation from the clubface.	± 0.1	The measurement of the golf ball's velocity measured just after impact.	± 0.5
Launch Angle[1]	º	Angle formed between a line of best fit through the coordinates of the ball centre and *Plane I* in the direction of the ball flight.	The vertical angle relative to the horizon of the golf ball's centre of gravity movement immediately after leaving the clubface.	± 0.2	The initial vertical angle of ascent [of the ball] relative to the ground plane.	± 0.2
Launch Direction[1]	º	Angle formed between a line of best fit through the *Plane I* coordinates of the ball centre and *Plane II*, therefore representing a projected angle onto the horizontal *Plane I*. A positive value meant a launch direction right of target.	The initial direction of the ball relative to target line.	-	The initial horizontal angle [of the ball] relative to the target line.	± 1.0
Total Spin Rate[1]	rpm	Total angular velocity of the ball, calculated from the 3D positions of the markers of the ball surface using the finite differences method (Robertson et al., 2013).	The rate of rotation of the golf ball around the resulting rotational axis of the golf ball immediately after the golf ball separates from the clubface.	± 15	The total amount of spin around the tilt axis (the axis the golf ball rotates around).	± 50
Backspin[1]	rpm	Component of the total angular velocity of the ball about the global Y axis, calculated from the 3D positions of the markers of the ball surface using the finite differences method (Robertson et al., 2013).	-	-	A component of total spin.	± 50
Sidespin[1]	rpm	Component of the total angular velocity of the ball about the global Z axis, calculated from the 3D positions of the markers of the ball surface using the finite differences method (Robertson., et al 2013).	-	-	A component of total spin.	± 50
Spin axis[1]	º	Angle of the spin axis unit vector relative to the horizontal *Plane I*. A negative angle indicated the ball spinning with right-to-left curvature in the air, a positive with left-to-right.	The tilt angle relative to the horizon of the golf ball's resulting rotational axis immediately after separation from the clubface (post impact).		The axis that the golf ball rotates around to create shot curvature and lift.	-

[1]All ball parameters were calculated over 15 frames post impact

Table 3-6: Definition of the clubhead impact parameters compared in this study.

Parameter	Unit	Definition	TrackMan definition and stated accuracy (TrackMan, 2015)		Foresight definition and stated accuracy (Foresight Sports, 2013; Foresight Sports, 2016)	
Clubhead Velocity[1]	mph	Rate of change in position of the centre of gravity of the clubhead.	The linear speed of the clubhead's centre of gravity at first contact with the golf ball	± 1.5	The velocity the clubhead travels measured just prior to ball contact.	± 0.75
Attack Angle[2]	º	Angle between the second order polynomial curve fitted through the *Plane II* coordinates of the clubhead COG[2] and *Plane I*, therefore this represented attack angle projected onto *Plane II*. A negative angle meant a descending clubhead centre of gravity.	The vertical direction of the clubhead's centre of gravity movement at maximum compression of the golf ball.	± 1.0	The descending or ascending path of the clubhead.	± 0.5
Club Direction[2]	º	Angle between the second order polynomial curve fitted through the *Plane I* coordinates of the clubhead COG[2] and *Plane II*, therefore this represented the club direction projected onto *Plane I*. A positive value meant a club direction moving to the right of the target line, an in-to-out path for a right-handed golfer.	The horizontal direction of the clubhead's centre of gravity movement at maximum compression of the golf.	± 1.0	The swing path measured in a horizontal plane relative to target-line.	± 0.5
Face Angle[3] (Impact Location)	º	Angle between the normal to the clubface at the impact location and the target vertical *Plane II*.	The horizontal clubface orientation at the centre-point of contact between clubface and golf ball at the maximum compression of the golf ball.	± 0.6	The dynamic measurement of the clubhead's face plane position at a right angle 90 degrees perpendicular relative to the target line.	± 0.5
Face Angle[3] (Geometric Centre)		Angle between the normal to the clubface at the geometric clubface centre and the target vertical *Plane II*.				
		A positive value indicates an open face, pointing to the right of the target line for a right-handed golfer.				
Dynamic Loft[3] (Impact Location)	º	Angle between the normal to the clubface at the impact location and the horizontal *Plane I*.	The vertical clubface orientation at the centre-point of contact between the clubface and golf ball at the maximum compression of the golf ball.	± 0.8	The dynamic measurement in degrees of the clubhead's face plane position vertically relative to the ground plane.	± 0.75
Dynamic Loft[3] (Geometric Centre)		Angle between the normal to the clubface at the geometric clubface centre and the horizontal *Plane I*.				
Dynamic Lie[3]	º	Angle between the line of the face grooves and the horizontal *Plane I*.	-	-	The dynamic measurement in degrees of the clubhead's face plane position horizontally relative to the ground plane.	± 0.25
Face-to-path[3] (Impact Location)	º	Difference between face angle (impact location) and the club direction.	The angle difference between face angle and club path as defined (face angle minus club path).	-	The face angle relative to the club path.	-
Face-to-path[3] (Geometric Centre)	º	Difference between face angle (geometric centre) and the club direction.				
		Face angle minus club direction. A positive angle meant the face angle was open (pointing right for a right-handed golfer) to the club direction.				
Horizontal Impact Location[3]	mm	Horizontal distance (parallel to the clubface grooves, of the impact location from the geometric face centre. A positive value indicated a toe impact.	-	-	The measurement (in millimetres) of the contact point of the golf ball on the clubface relative to face centre.	-
Vertical Impact Location[3]	mm	Horizontal distance (perpendicular to the clubface grooves, of the impact location from the geometric face centre. A positive value indicated a high impact.		-		-

[1]Over 20 frames pre-impact [2]Immediately before impact [3]At ball contact

3.3. Accuracy of the GOM method

It is difficult to quantify the accuracy of a three-dimensional point tracking system such as GOM to measure clubhead and ball impact parameters. What makes it particularly difficult, as outlined above, is the chain of steps that must be taken to calculate clubhead and ball parameters. However, to get some measure of accuracy a number tests on the system were performed. These comprised of four parts: point tracking, fitting and element creation, the effect of ball oscillation post-impact and spin rate validation.

3.3.1. Point tracking

Point tracking accuracy was investigated by comparing GOM measurements to those of an independent “gold standard” system. A high speed camera pair was set-up in the same way as outlined in the equipment set-up section. Fifty images of a GOM calibration object, unrelated to the calibration object used during the high speed video camera set-up, (Figure 3-14), covering a range of orientations were taken. The images were imported into GOM software (INSPECT) and the three-dimensional coordinates of the larger central markers (A-E; Figure 3-14) were exported to MATLAB. The three-dimensional coordinates were used to calculate distances and angles between the points across all 50 images. These measurements were validated against a “gold standard” system, the SmartScope Flash 200 (OPG, Rochester, NY; www.ogpnet.com). The SmartScope is also an optical measurement system, which works in a similar way to the GOM system, identifying circular edges via background contrast. The system however uses just one camera and thus its accuracy in the third dimension is slightly diminished; the XY accuracy is stated as $2.5 \pm \frac{5L}{1000}$ microns, where L is the measuring length in millimetres, whilst the Z accuracy is stated as $3 \pm \frac{6L}{1000}$ microns (www.ogpnet.com). For this reason, the flat calibration object was used in the XY plane. The three-dimensional coordinates of the same five larger central markers were obtained and each measurement was repeated six times. The coordinates were exported to MATLAB and the same distance and angle measurements calculated. Comparisons were then made between the measurements from the GOM system and those of the SmartScope.

Table 3-7 shows the results of the measurements taken using the GOM system and those taken using the SmartScope system. Distances and angles differed on average by -3 ± 33 microns and 0.00 ± 0.08 degrees respectively. These values indicate good agreement in point tracking accuracy between the GOM system and the “gold standard” SmartScope.

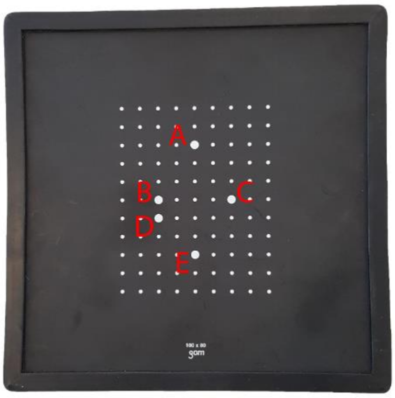


Figure 3-14: The second artefact used to investigate the accuracy of the GOM system. Letters A-E indicate the points used in the accuracy investigation.

Table 3-7: Mean values for each distance and angle measurement.

Distance	SmartScope (mm)	GOM (mm)	Difference (mm)	Angle	SmartScope (º)	GOM (º)	Difference (º)
AC	36.0013	36.0222	0.0209	BC-BD	89.9284	89.8108	-0.1176
AD	44.6700	44.6231	-0.0469	BC-CD	14.0658	14.0706	0.0048
AE	59.9759	59.9964	0.0205	BD-BE	33.5952	33.6185	0.0233
BC	39.9302	39.9440	0.0138	BD-DC	76.0058	76.1186	0.1128
BD	10.0013	10.0034	0.0021	BD-DE	135.1083	135.0833	-0.0250
BE	36.0221	35.9547	-0.0674	BE-DE	11.2965	11.2982	0.0017
CE	36.0342	36.0521	0.0179	CE-CD	42.2963	42.3536	0.0573
CD	41.1515	41.1455	-0.0060	CE-DE	78.6012	78.6818	0.0806
DE	28.2508	28.2697	0.0189	DC-DE	59.1025	58.9647	-0.1378
Mean			-0.0029	Mean			0.0000
SD			0.0325	SD			0.0841
Range			-0.0674 to 0.0209	Range			-0.1378 to 0.1128

3.3.2. Fitting & element creation

As part of the GOM analysis process the golf ball was represented virtually by fitting a sphere of fixed radius to the tracked surface points. To investigate the goodness of the fit of the sphere, for three golfers, the mean RMS error and RMS error range across trials were exported and examined. The movement error of the ball centre whilst stationary on the tee was also identified. Multiple golfers were used to ensure the fit quality was not affected by the placement of markers on the ball; a different ball was used for each golfer. Additionally, for two golfers the driver was used, for the other the 7-iron. Similarly, for the club analysis a best-fit transformation of the mesh scans, which also contained the coordinate locations of the points on each clubhead, to the tracked points was performed. The equivalent values as for the sphere fit were computed for each club to give an idea of quality of mesh fitting, only the maximum RMS error was accessible as opposed to the range. This was simply because the process within the software (INSPECT) followed slightly different steps to that of the sphere creation and fit. The values were from three golfers; each club was examined from a separate golfer, across testing days to account for the independent day-to-day set-up.

For the sphere fitting, across the three golfers the RMS error and RMS error range were 54 ± 38 microns and 255 ± 196 microns respectively. Whilst stationary on the tee the fit appeared to be better than following ball impact when the ball was in flight – not including frames where the ball was in contact with the clubface (Table 3-8). Pre-impact mean RMS error was 47 ± 34 microns. Whilst the ball was stationary on the tee mean frame-to-frame difference in ball centre position was 20 ± 23 microns. The post-impact RMS error was 71 ± 43 microns. The mean RMS error range was 226 ± 180 microns pre-impact and 327 ± 212 microns post-impact.

Table 3-8: Pre and post-impact mean RMS error and RMS error ranges for the sphere fitting.

	Pre-impact	Post-impact
Mean RMS error (μm)	47 (34)	71 (43)
Mean RMS error range (μm)	226 (180)	327 (212)

For the club mesh fitting, the results for each club are shown in Table 3-9. The results suggest the mesh fitting was much better for the driver than both the 7-iron and the utility wedge. This is probably because the driver had far more points available to create the best-fit than the iron clubs. Even for the 7-iron, the club with the largest mean deviation, the error was 102 microns. The maximum deviation for the same club was 156 microns. This could be considered the worst possible error.

Table 3-9: Pre and post-impact mean RMS error and RMS error maximum for the club mesh fitting.

	Driver	7-Iron	Utility wedge
Mean RMS error (μm)	35 (48)	102 (25)	70 (7)
Mean maximum RMS error (μm)	82 (17)	156 (43)	137 (32)

3.3.3. Ball oscillation

To investigate whether the ball deformed post-impact, distances between surface points were calculated. This was done for one golfer’s driver data whose clubhead velocity calculated from the GOM data was fastest. The distances were output across the whole of each trial, including both when the ball was stationary on the tee and when the ball was in flight following impact. Frame-to-frame differences for each distance were calculated.

Increases in differences following impact could be attributed to changing ball shape through oscillation.

An increased mean difference between points was observed following impact. Overall the mean difference was 41 ± 111 microns. However, pre-impact the mean difference was 19 ± 85 microns; whilst post-impact it was 70 ± 97 microns. The evident ball deformation could be a reason for the greater RMS error values for sphere fitting post-impact. Given the shot selection stated above, it is likely these shots would see the greatest ball deformation post-impact or represent the worst scenario. The mean difference could therefore be considered at their largest in the sub-set of data used. It is worth noting that the ball used in this study was a hard ball with a compression rating of 90 purposely chosen to reduce post-impact deformation.

3.3.4. Spin rates

The GOM method outlined in this chapter calculates golf ball spin rates from the three-dimensional ball surface point data through differentiation of rotation matrices (Robertson et al., 2013). To validate this method one camera pair was set-up and calibrated in the same way as for the main investigation (Section 3.2.2). At the same sampling frequency and shutter speed as during the main data collection, images were captured of a GOM markered, purpose-made sphere spinning via a custom device (Figure 3-15). The sphere was manufactured to be the same diameter as the golf ball and was secured on an axis so that the sphere-axis structure formed one system. GOM markers on the sphere surface were visible to each camera. The spinning device was connected to a power supply and oscilloscope. By adjusting the input voltage, the angular velocity of the rotation could be adjusted. Three repetitions of various rotational velocities from nominally 3000 rpm through to 9500 rpm were recorded. Firstly, the ball was begun spinning, then the cameras and the oscilloscope were triggered simultaneously. The images were processed in the same way as the main investigation data; the three-dimensional coordinates of the ball surface points were exported to MATLAB where the pre-existing script was run in order to calculate total spin rate. These values were compared to the angular velocity measured directly from the device. The device axis was marked so that each time the axis rotated it was detected by a tachometer sensor. The sensor altered the electrical signal, generating a pulse with each rotation (Figure 3-16). The lead edge of the pulse could be used to determine the frequency of rotation. Two cursors were positioned at matching points on the waveform (the orange line; Figure 3-16) across five signals or rotations so the angular velocity measurement was based upon multiple rotations. The cursors were then positioned to align with the time of trigger (Figure 3-16); a decrease in the trigger signal pin-pointed the exact time. The average frequency (one over the period of rotation) was output for the five rotations. This value could be multiplied by 60 to calculated the angular velocity in revolutions per minute. The results were compared directly to the values calculated from MATLAB.

Figure 3-15: Purpose-built spinning device designed to validate the GOM method spin rate calculations.

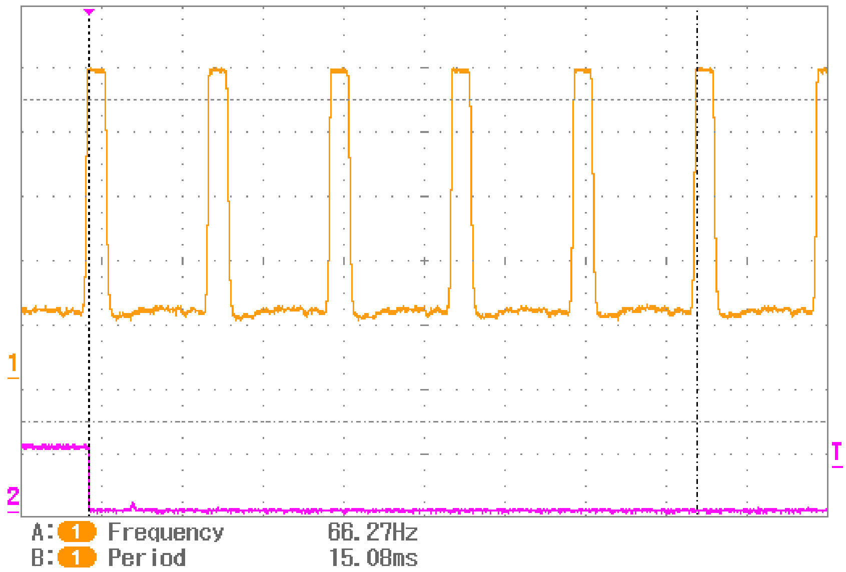


Figure 3-16: Example waveform from the oscilloscope, showing multiple rotations (the orange line), the trigger signal (the purple line), the average frequency over the five revolutions and the average period over the five revolutions.

Table 3-10 displays the spin rates generated from the oscilloscope and those calculated from GOM. The mean difference was -2 ± 6 rpm. The extremely close agreement between the two sets of results, over a wide range of spin rates, indicates that the GOM spin rate calculation method used provided realistic spin rate numbers.

Table 3-10: Mean (& SD) differences in spin rates given by the spinning device and the GOM system (GOM system value – oscilloscope value).

Nominal angular velocity (rpm)		Difference (rpm)
3000		2 (3)
3500		0 (4)
4000		2 (1)
4500		3 (2)
5000		0 (2)
5500		-2 (2)
6000		4 (5)
6500		-5 (11)
7000		1 (4)
7500		-4 (3)
8000		-9 (4)
8500		-2 (9)
9000		-6 (5)
9500		-12 (4)
	Mean difference	-2 (6)

3.4. Summary

This chapter has developed a methodology for simultaneously tracking the clubhead and ball using the GOM system alongside the two launch monitors. It has also investigated the GOM system accuracy, including point tracking, element fitting and spin rate calculation.

The GOM method developed in this chapter built on previous work conducted by Ellis et al., (2010), notably including full tracking and analysis of the ball through the addition of a second separate GOM system, analysis of the clubhead through mesh fitting and development of a rig to define the common global coordinate system. Additional sections to the rig enabled all three systems (GOM, TrackMan and Foresight) to be aligned to a common global coordinate system. The set-up was optimised so all three systems could operate simultaneously, crucial to validating the launch monitors.

The accuracy of the GOM system was investigated at various stages of the analysis process, from the initial point identification through to the calculation of spin rates. From the results point tracking accuracy could be considered good, with small mean differences in distances between points when compared to the “gold standard” SmartScope system (-3 ± 33 microns). Furthermore, the sphere fitting RMS errors were shown to be small, although they did increase post-impact suggesting ball deformation may play a role in the goodness of the fit (mean RMS error of 47 ± 34 microns pre-impact and 71 ± 43 microns post-impact. Finally, the spin rate calculation method was shown to produce spin rates of extremely close agreement to those measured directly from a spinning axis via an oscilloscope (mean difference -2 ± 6 rpm over the range of 3000-9500 rpm). From the results, confidence can be gained that the GOM system is an appropriate tool to assess the accuracy of the TrackMan and Foresight launch monitors.

CHAPTER FOUR

THE VALIDATION OF TWO COMMERCIALLY AVAILABLE GOLF LAUNCH MONITORS

4.1. Introduction

Background information regarding the Trackman Pro IIIe and Foresight GC2+HMT launch monitors is detailed in Sections 2.2.1 and 3.1. These systems are occasionally used as bespoke performance measurement methods in scientific golf studies (e.g. Collinson et al., 2012; Betzler et al., 2014; Smith et al., 2016). However, their suitability for this purpose and the origin of their stated tracking accuracies are unknown. To gain confidence in their suitability for inclusion in future scientific investigation, results of a validation investigation are necessary.

Following the development of a suitable methodology (Chapter 3), this chapter presents and discusses the results for the comparison of the impact parameters from the Trackman Pro IIIe and Foresight GC2+HMT, against the GOM optical tracking system. In doing so, the chapter aims to validate the accuracy of the impact parameters output by the launch monitor systems and provide evidence based recommendations regarding their use within scientific biomechanics research (*Aims 2* and *3*; Section 1.2.3). The chapter, therefore, addresses the second thesis research question: "how suitable are commercially available clubhead-ball impact measurement technologies for use in scientific biomechanical investigation to measure performance outcomes?"

The chapter begins by outlining the statistical analysis used to compare the launch monitors to the GOM system, followed by the results for each launch monitor. Relevant methodological considerations are then discussed, and recommendations made for the use of launch monitors in biomechanical studies based on the results of this investigation.

4.2. Statistical analysis of the outputs

All statistical analysis was conducted in MATLAB 2015a. The clubhead and ball parameters from TrackMan and Foresight were independently compared against those calculated from GOM. Difference data was generated by subtracting the GOM measurement from the launch monitor measurement. Therefore, a negative difference value would indicate the launch monitor underestimated the respective value when compared to GOM. The difference data was checked for normality by conducting Kolmogorov-Smirnov with Lilliefors correction checks and it was concluded that non-parametric methods of data analysis were most suitable due to the frequency of non-normally distributed data sets. Median values along with interquartile ranges were therefore deemed the most suitable measures of central tendency and dispersion within the data. Median differences significantly different from zero ($\alpha = 0.05$), indicating a systematic bias, were assessed using Wilcoxon signed rank tests. The agreement was then further explored using limits of agreement analysis (Bland & Altman, 1986). Lower and upper quartiles gave an indication of the spread or random variability in the difference data. Additional analysis used the first non-parametric method outlined by Bland & Altman, (1999). The method involves pre-defining reference values which when added to and subtracted from the median define an acceptable range. The proportion of points lying within this range was then identified. In this investigation two grades were defined, research and coaching; both were pre-defined by the author. Research grade being what was considered the criteria for use in scientific research, and similarly coaching grade was considered suitable for use by a golf professional. When pre-defining the grades the range of values typically encountered, the differences in values between each club and golfer as well as the sensitivity of shot outcomes to small changes in each parameter were considered. The analysis process was first of all conducted on an all-club group basis and subsequently broken down into a club-by-club basis.

To aid the interpretation of the results two hypotheses were outlined beforehand:

> *Hypothesis 1:* Comparison of the launch monitors' outputs to the GOM system would show close agreement.
>
> *Hypothesis 2:* Comparison of the launch monitors' outputs to the GOM system would lead to a judgement that they are suitable for their use as measures of performance in biomechanical scientific research.

The hypotheses were considered when forming an evidence based recommendation on the suitability of the launch monitors in Section 4.5. A rejection of the second hypothesis would mean an alternative solution for clubhead and ball tracking would be required for further scientific investigation.

4.3. Results

4.3.1. GOM calibration results

To help confirm the successful set-up of the GOM system hardware over the period of testing, the calibration results for the measurement volumes are displayed (Table 4-1). Notably, a calibration deviation of ≤ 0.03 pixels was achieved for each calibration; a value equating to less than nine microns in the capture volume. Also achieved was a measurement volume around the tee of suitable size. Not included in the table but undertaken during the data collection process, additional inspection of the intersection error for multiple trials across each testing day showed low and consistent values, in the region of 0.01-0.04 suggesting adequate set-up and calibration.

Table 4-1: GOM calibration results.

Camera Pair	Testing Day	Calibration Deviation (Pixels)	Measuring Volume (mm×mm×mm)
Ball	1	0.025	310×315×315
	2	0.028	310×315×315
Club	1	0.028	310×315×315
	2	0.030	310×315×315

4.3.2. Launch monitor success rate

A total of 240 trials were struck and tracked simultaneously across all golfers and clubs. Foresight successfully tracked the clubhead and ball in 75% and 90% of trials respectively. TrackMan tracked the ball parameters (except spin axis) in 98% of trials; spin axis was tracked in 62%. TrackMan faced challenges when tracking the clubhead; specifically, for the utility wedge where attack angle, club direction, face angle and dynamic loft were only tracked in 19% of shots. Overall, this meant clubhead velocity was tracked in 98% of shots with the remaining clubhead parameters being tracked in 62%. Consequently, individual analysis of the utility wedge for TrackMan for all club parameters except clubhead velocity was removed from the study; the data remained in the overall analysis. Shots with the utility wedge were also the reason for lower spin axis tracking. Again, for this club, analysis was omitted but remained in the overall analysis.

4.3.3. Mean impact parameter values

To help put the degree of agreement results into context, the mean and standard deviation of each parameter across each club and system is shown in Table 4-2. Here the differences between clubs can be seen. For example, as would be expected, the total spin rate can be seen to increase from driver, to 7-iron through to the utility wedge.

Table 4-2: Mean (& SD) GOM, TrackMan and Foresight values for each parameter across the driver (D), the 7-iron (7) and the utility wedge (UW).

Parameter	Club	GOM	TrackMan	Foresight
Ball velocity (mph)	D	146.2 (15.6)	147.1 (15.9)	147.6 (14.7)
	7	111.5 (16.6)	111.1 (17.0)	111.6 (16.8)
	UW	88.1 (12.0)	88.0 (11.8)	87.7 (12.3)
Launch angle (º)	D	11.2 (4.1)	11.6 (3.7)	11.6 (4.0)
	7	16.7 (3.6)	16.9 (3.7)	16.8 (3.5)
	UW	27.8 (4.3)	28.0 (3.8)	27.9 (4.2)
Launch direction (º)	D	2.3 (4.1)	2.3 (3.8)	2.0 (4.1)
	7	0.5 (4.2)	0.4 (4.5)	-0.95 (4.1)
	UW	-1.1 (3.0)	-1.1 (3.2)	-3.5 (3.5)
Total spin rate (rpm)	D	3140 (677)	3189 (1001)	3189 (639)
	7	5916 (1506)	5938 (1591)	5750 (1592)
	UW	8571 (1842)	8624 (2044)	8270 (2122)
Backspin (rpm)	D	2731 (1271)	-	3027 (683)
	7	5718 (1635)	-	5602 (1587)
	UW	8179 (2418)	-	8319 (1894)
Sidespin (rpm)	D	12 (860)	-	-93 (827)
	7	-511 (1087)	-	-664 (1179)
	UW	-769 (936)	-	-1149 (1145)
Spin axis (º)	D	-1.1 (18.4)	-6.3 (12.7)	-
	7	-5.1 (13.3)	-5.2 (6.5)	-
	UW	-5.7 (7.5)	-6.5 (3.8)	-
Clubhead velocity (mph)	D	100.8 (10.8)	101.1 (10.8)	105.8 (11.1)
	7	83.4 (11.3)	82.0 (10.5)	85.8 (11.7)
	UW	76.5 (11.2)	76.4 (10.4)	77.1 (11.9)
Attack angle (º)	D	3.9 (5.2)	0.3 (4.0)	3.1 (4.8)
	7	-3.0 (3.4)	-3.8 (2.3)	-2.1 (4.4)
	UW	-3.4 (3.6)	-4.8 (3.2)	-2.6 (3.3)
Club direction (º)	D	1.9 (4.0)	3.7 (4.3)	2.8 (4.3)
	7	2.1 (4.5)	3.3 (3.9)	2.9 (4.7)
	UW	1.8 (4.5)	4.2 (2.4)	2.9 (3.9)
Face angle (Impact Location) (º)	D	2.1 (3.9)	2.0 (4.1)	-
	7	-1.3 (4.0)	-0.3 (3.2)	-
	UW	-2.6 (2.8)	-3.2 (2.7)	-
Face angle (Geometric Centre) (º)	D	0.8 (4.0)	-	3.3 (5.5)
	7	-1.3 (4.0)	-	-1.3 (4.8)
	UW	-2.6 (2.8)	-	-5.2 (5.4)
Dynamic loft (Impact Location) (º)	D	13.7 (4.1)	13.6 (4.1)	-
	7	24.2 (3.1)	22.5 (3.4)	-
	UW	40.3 (3.4)	35.0 (4.5)	-
Dynamic loft (Geometric Centre) (º)	D	14.0 (4.1)	-	18.8 (6.7)
	7	24.2 (3.1)	-	26.2 (4.0)
	UW	40.3 (3.4)	-	42.8 (3.5)
Dynamic lie (º)	D	-2.1 (2.2)	-	0.6 (4.4)
	7	-3.0 (2.4)	-	-4.2 (3.1)
	UW	-3.9 (2.8)	-	-5.5 (3.5)
Face-to-path (Impact Location) (º)	D	-1.5 (6.1)	-1.7 (4.3)	-
	7	-3.6 (5.0)	-3.5 (4.4)	-
	UW	-4.5 (5.1)	-7.5 (4.2)	-
Face-to-path (Geometric Centre) (º)	D	-0.5 (4.3)	-	0.4 (5.7)
	7	-3.6 (5.0)	-	-4.5 (4.3)
	UW	-4.5 (5.1)	-	-8.0 (7.4)
Horizontal impact location (mm)	D	-3.6 (15.5)	-	-8.4 (19.8)
	7	-5.1 (16.3)	-	-7.3 (49.6)
	UW	-3.8 (15.1)	-	-9.2 (13.2)
Vertical impact location (mm)	D	0.9 (10.2)	-	-2.4 (10.8)
	7	-6.5 (6.6)	-	-6.3 (17.9)
	UW	-9.6 (6.8)	-	-9.4 (8.0)

4.3.4. Agreement between systems

Overall median differences and upper and lower quartiles for both TrackMan and Foresight for each impact parameter are shown in Table 4-3, Figure 4-1 and Figure 4-2; the data broken down by club are shown in Table 4-4, Table 4-5 and Table 4-6. The systematic bias is indicated by median differences and the interquartile ranges give an indication of random variability in the data. Finally, the percentage of difference values that satisfied the pre-defined research and coaching grades are presented for each system in Table 4-7. It can be seen from Table 4-3, Table 4-4, Table 4-5 and Table 4-6 that many of the median differences emerged as statistically significant but when interpreted from a practical perspective could be considered negligible.

Ball velocity was measured well by both systems across all clubs; the results indicated strong agreement with the GOM data. The overall small significant systematic bias was the same for both systems (0.2 mph) but negligible from a practical perspective. Additionally, the grouping of measurements around the median range is small, although there are three wider outlying values for Foresight. Finally, over 80% of ball velocity measurements met the research grade agreement level (± 1 mph) for both systems (Table 4-7).

Ball launch angle and launch direction together can be considered as constituting ball path. These two parameters were also generally measured well across all clubs, although there was a notable systematic bias of 1-2° in the launch direction measurements from the Foresight system across all clubs. Despite this systematic bias over 70% of measurements satisfied the research grade (± 1°) for both systems. For both systems, the random variability in the launch direction measurements was greater than for the launch angle, although for TrackMan the difference was small; there were outliers for both systems (Figure 4-1). Launch angle was measured particularly well by the Foresight system with an interquartile range of just 0.3°. The value for TrackMan was slightly larger at 0.8°. Both had a very small but significant systematic offset (0.1°), however well over 80% of trials met the research grade agreement for both systems.

Less variability was observed in the TrackMan spin rates compared to Foresight, with over 80% of values falling within ± 50 rpm of the median value measured, the pre-defined research grade. What is noticeable from Figure 4-1 are the outlying points for the driver trials for both launch monitors. These are more pronounced for TrackMan. Furthermore, there was greater systematic bias in the TrackMan data, with the system typically underestimating spin rates by ~50 rpm across all clubs.

Table 4-3: Overall median differences and interquartile ranges for T (TrackMan minus GOM) and F (Foresight minus GOM) for all parameters. The p-value is the probability that the median difference differs from zero, calculated using the Z-value (MATLAB, 2017).

	Variable	System	Median difference	Z-value	p-value	Lower quartile	Upper quartile
Ball Parameters	Ball velocity (mph)	T	0.2	6.19	*<0.0001*	-0.1	0.5
		F	0.2	3.20	*0.0013*	-0.3	0.6
	Launch angle (º)	T	0.1	3.36	*0.0008*	-0.3	0.5
		F	0.1	6.38	*<0.0001*	0.0	0.3
	Launch direction (º)	T	0.0	-0.21	0.8290	-0.5	0.5
		F	-1.6	-12.24	*<0.0001*	-2.3	-1.0
	Total spin rate (rpm)	T	-47	-11.12	*<0.0001*	-73	-26
		F	-20	-2.91	*0.0036*	-60	30
	Backspin (rpm)	T	-	-	-	-	-
		F	-22	-3.53	*0.0004*	-79	32
	Sidespin (rpm)	T	-	-	-	-	-
		F	-230	-9.96	*<0.0001*	-399	-97
	Spin axis (º)	T	0.6	0.10	0.9207	-5.2	5.4
		F	-	-	-	-	-
Club Parameters	Clubhead velocity (mph)	T	-1.1	-6.55	*<0.0001*	-1.9	0.1
		F	2.8	9.08	*<0.0001*	1.4	4.5
	Attack angle (º)	T	-1.4	-7.77	*<0.0001*	-3.7	-0.5
		F	0.5	5.34	*<0.0001*	-0.3	1.0
	Club direction (º)	T	0.8	3.99	*<0.0001*	-0.3	1.9
		F	0.2	1.86	0.0624	-0.3	1.3
	Face angle (º)	T	0.0	0.76	0.4445	-0.6	0.8
		F	-0.8	-1.94	0.0530	-3.0	1.8
	Dynamic loft (º)	T	-0.9	-7.44	*<0.0001*	-1.7	-0.2
		F	2.2	8.15	*<0.0001*	0.8	4.0
	Dynamic lie (º)	T	-	-	-	-	-
		F	-0.8	-2.90	*0.0038*	-1.5	0.4
	Face-to-Path (º)	T	-0.8	-3.45	*<0.0001*	-2.2	0.9
		F	-1.9	-5.50	*<0.0001*	-4.1	0.5
	Horizontal impact location (mm)	T	-	-	-	-	-
		F	-5.5	-8.03	*<0.0001*	-8.1	-2.6
	Vertical impact location (mm)	T	-	-	-	-	-
		F	-1.9	-5.88	*<0.0001*	-4.1	0.3

$\alpha = 0.05$

The backspin component of the Foresight data shows similar agreement to the total spin rate greement and a similar percentage of trials (48%) met the ± 50 rpm research grade. The systematic offset appears to increase for the utility wedge compared to the other two clubs along with the random variability in the data. Sidespin however, showed a much larger, over ten-fold, overall systematic bias, with a much larger interquartile range and therefore random variability. Foresight had a tendency to underestimate the sidespin rate and the agreement was worst for the utility wedge, consequently the percentage of trials meeting the ± 50 rpm research grade was greatly reduced.

Similarly to Foresight's sidespin, TrackMan had a wide interquartile range for spin axis (10.6º). Furthermore, a similar percentage of points met the pre-defined ± 2º research grade agreement (26%). An overall non-significant systematic offset of 0.6º was also present.

Finally, at a club-level, the driver showed a wide distribution of data points, reflected in an interquartile range of 15.3º.

Compared to ball velocity and path parameters, for both systems, weaker agreement was found for almost all clubhead parameters. There were significant systematic offsets for clubhead velocity, TrackMan underestimated, Foresight overestimated, which were larger than for ball velocity. Outlying values were present for both systems (Figure 4-2) and greater random variability in the clubhead velocity measurements resulted in only 54% of TrackMan values and just 29% of Foresight values satisfying the pre-defined research grade of ± 1 mph.

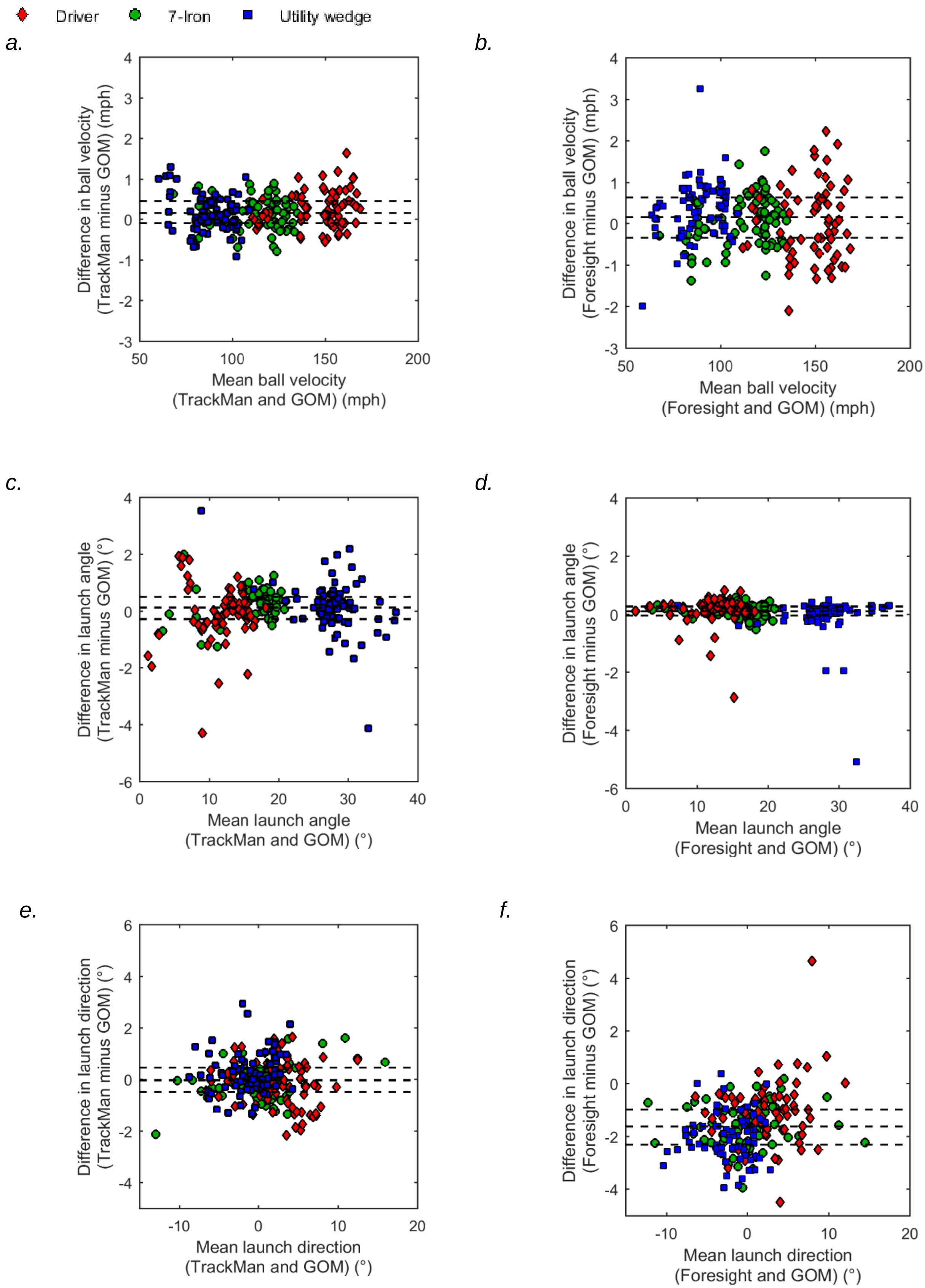
Measurements of clubhead path (attack angle and club direction) were in closer agreement for the Foresight data with smaller overall systematic offsets and interquartile ranges. Furthermore, more points satisfied the research grade (± 1°) for this system. The majority of Foresight data that fell outside of this range were likely to have been from driver shots due to the increased interquartile range for this club. TrackMan tended to underestimate attack angle particularly with the driver (-3.5°) when compared to the 7-iron (-0.6°).

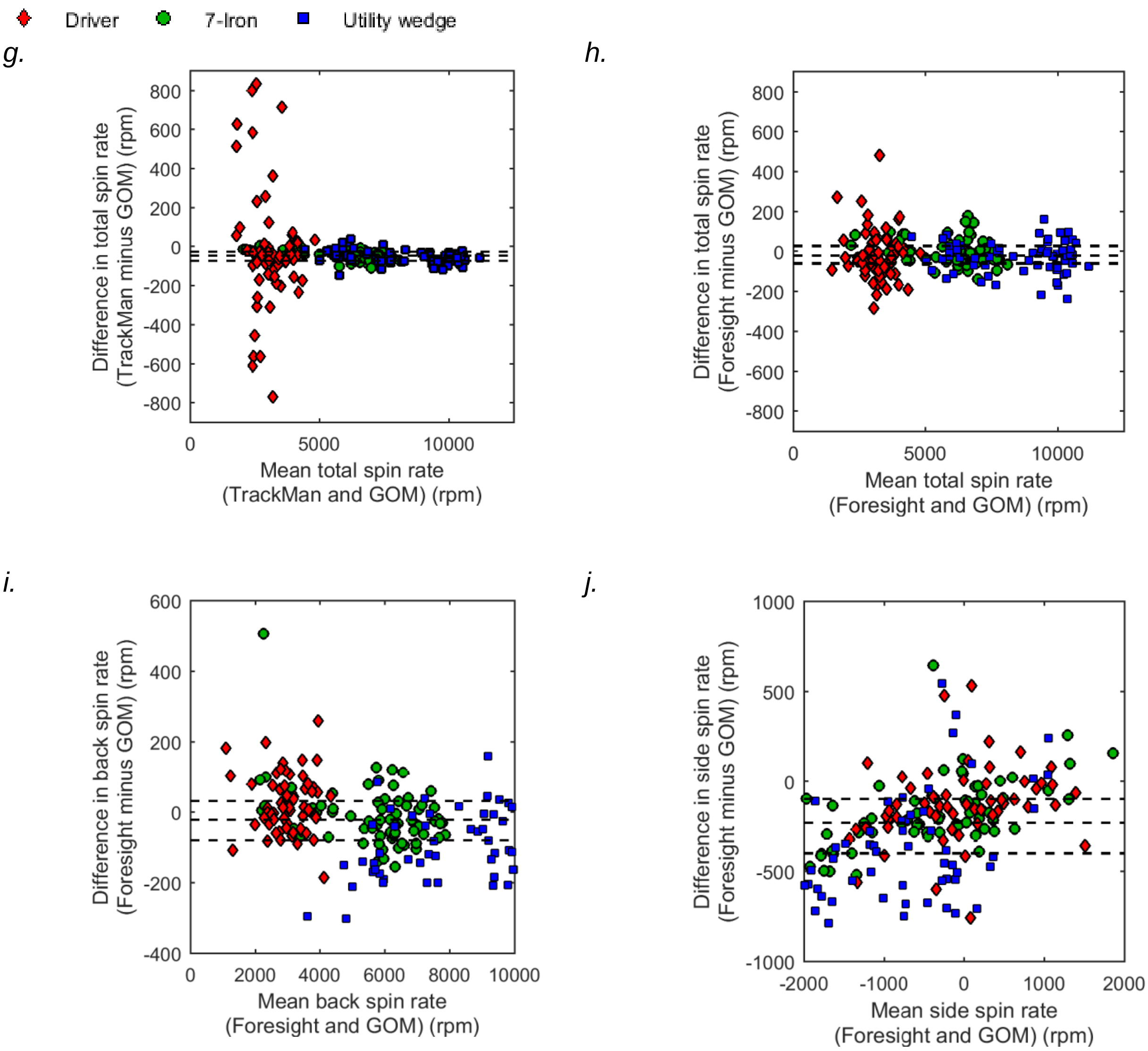
In contrast to the clubhead path results, measurements of clubhead orientation, face angle and dynamic loft – TrackMan didn't output a value for dynamic lie – were in closer agreement for the TrackMan data. Overall face angle was calculated well by TrackMan with no systematic offset and a narrow interquartile range; there was a non-significant median offset and larger interquartile range for Foresight. These were reflected in a higher percentage of data points meeting both pre-defined grades for TrackMan than Foresight. Significant systematic bias was evident in the dynamic loft values from both systems. TrackMan tended to underestimate the parameter by ~1° across the 7-iron and driver. Foresight overestimated by 1-2° with the 7-iron and utility wedge and showed marked overestimation of as much as 5° with a driver. Again, TrackMan had a higher percentage of points meeting both research grades for dynamic loft; however, Foresight was more successful at meeting the research grades when it came to dynamic loft than face angle. The final clubhead orientation parameter, dynamic lie, was only output by Foresight and there was a significant underestimation bias of 0.8º overall, although the interquartile range was smaller than for face angle and dynamic loft. Moreover, a greater percentage of points met both research grades than for the other face orientation parameters. On a club-by-club basis again the driver fared worse than the 7-iron and utility wedge.

Face-to-path angle represents the relationship between the clubhead path and orientation. The overall median offsets and interquartile ranges suggest poorer agreement for the

Foresight system than TrackMan; however, from Figure 4-2 the overall distribution of the values appears similar for both systems. Both systems performed similarly when it came to the research grade agreement with just under a third of the trials meeting the ± 1° grade.

The final parameters, solely output by Foresight were horizontal and vertical impact location. Both had a significant overall systematic offset, although greater for the horizontal (-5.5 mm versus -1.9 mm for vertical), which suggested Foresight measured impacts as lower and closer to the heel compared to GOM. The horizontal offsets were reasonably consistent across clubs, however for the vertical the driver offset was of greater magnitude. Despite the offsets and random variability, a high percentage, 73% and 86%, met the research grade agreement for the horizontal and vertical impact locations respectively.


Driver
7-Iron
Utility wedge
a.
Difference in ball velocity (TrackMan minus GOM) (mph)
Mean ball velocity (TrackMan and GOM) (mph)
b.
Difference in ball velocity (Foresight minus GOM) (mph)
Mean ball velocity (Foresight and GOM) (mph)
c.
Difference in launch angle (TrackMan minus GOM) (°)
Mean launch angle (TrackMan and GOM) (°)
d.
Difference in launch angle (Foresight minus GOM) (°)
Mean launch angle (Foresight and GOM) (°)
e.
Difference in launch direction (TrackMan minus GOM) (°)
Mean launch direction (TrackMan and GOM) (°)
f.
Difference in launch direction (Foresight minus GOM) (°)
Mean launch direction (Foresight and GOM) (°)



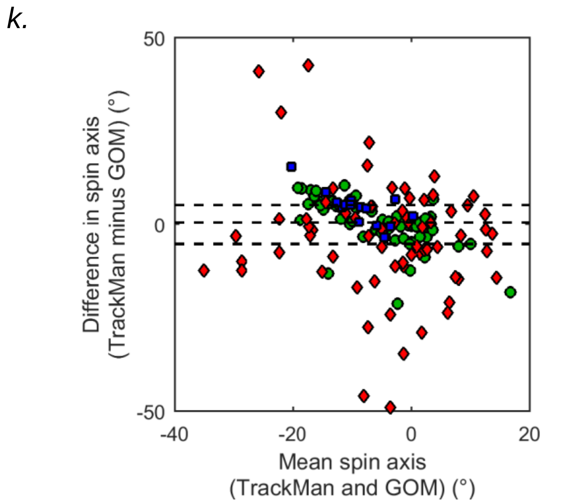
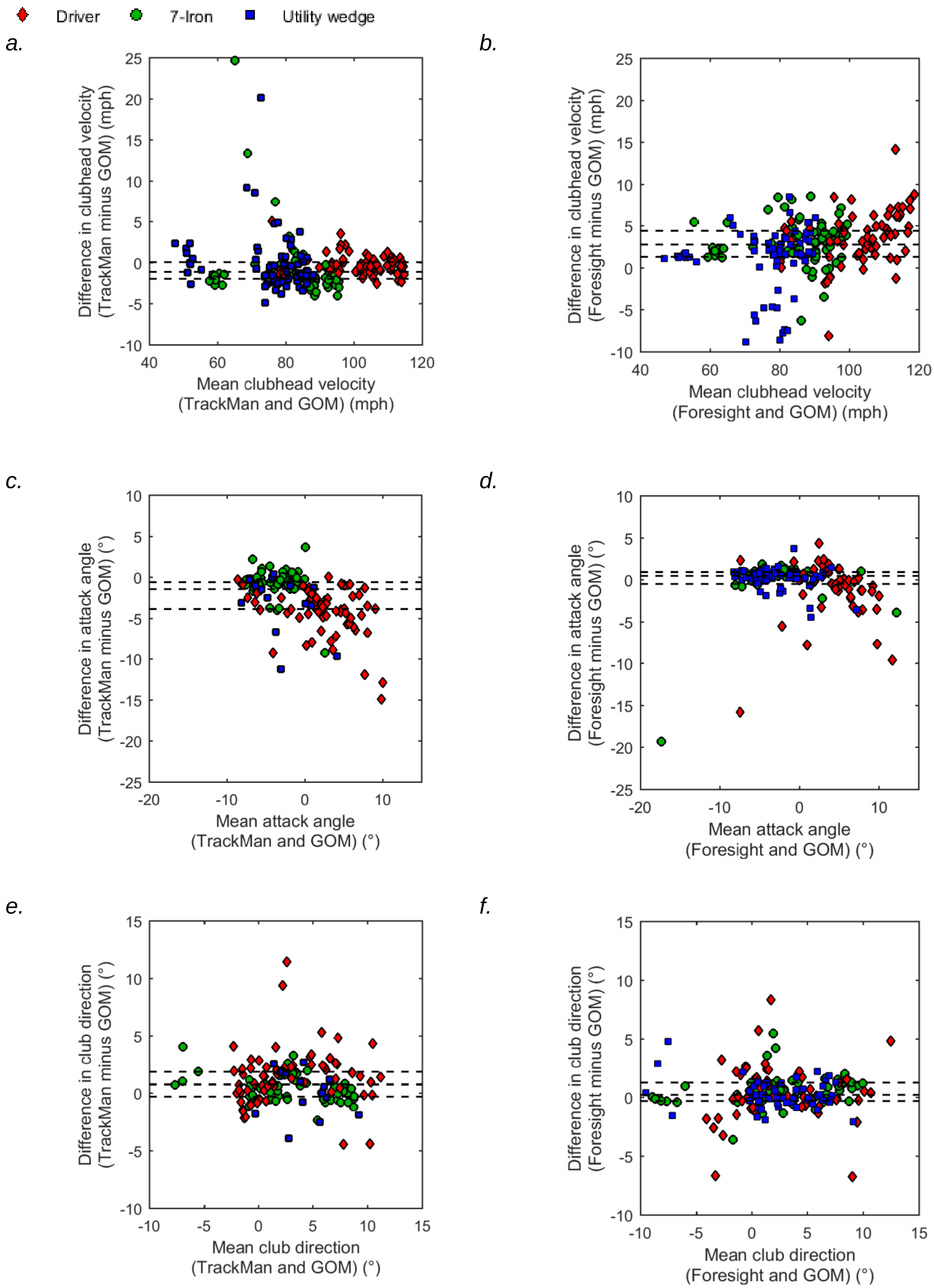
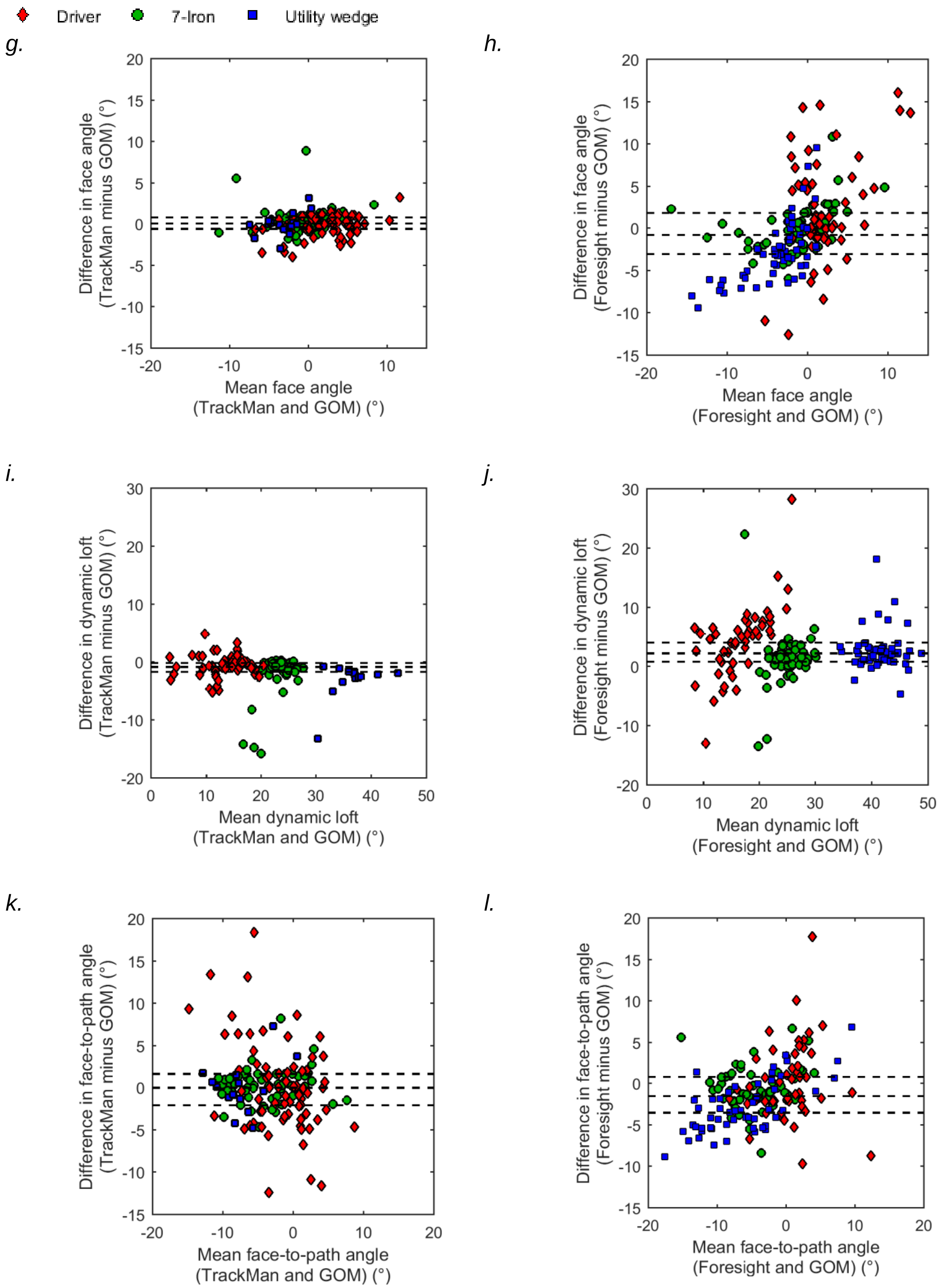
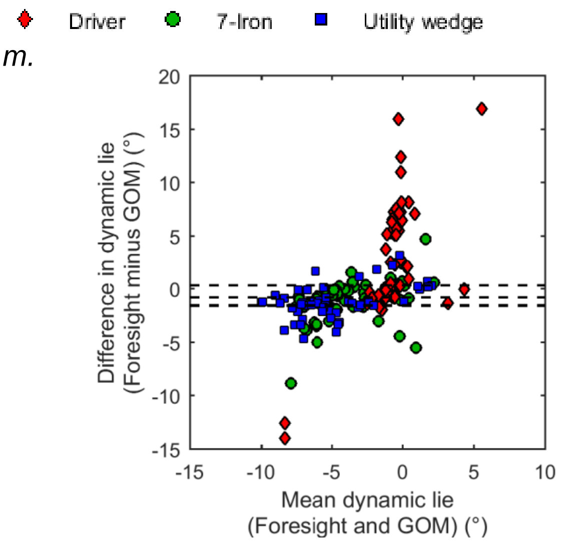


Figure 4-1: Bland-Altman plots for all ball parameters: a. ball velocity TrackMan; b. ball velocity Foresight; c. launch angle TrackMan; d. launch angle Foresight; e. launch direction TrackMan; f. launch direction Foresight; g. spin rate TrackMan; h. spin rate Foresight; i. backspin Foresight; j. sidespin Foresight and k. spin axis TrackMan. The three clubs are indicated by different marker characteristics on each plot.

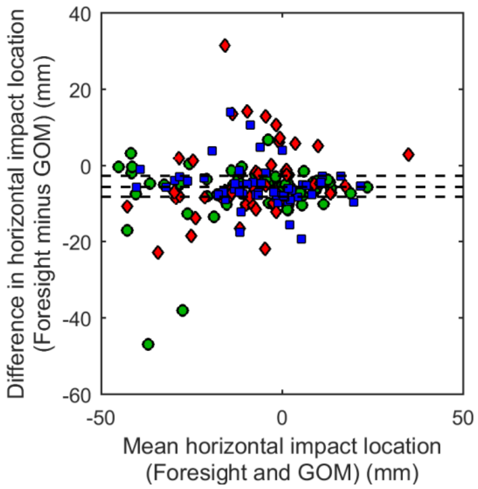

Driver
7-Iron
Utility wedge
a.
Difference in clubhead velocity
(TrackMan minus GOM) (mph)
Mean clubhead velocity
(TrackMan and GOM) (mph)
b.
Difference in clubhead velocity
(Foresight minus GOM) (mph)
Mean clubhead velocity
(Foresight and GOM) (mph)
c.
Difference in attack angle
(TrackMan minus GOM) (°)
Mean attack angle
(TrackMan and GOM) (°)
d.
Difference in attack angle
(Foresight minus GOM) (°)
Mean attack angle
(Foresight and GOM) (°)
e.
Difference in club direction
(TrackMan minus GOM) (°)
Mean club direction
(TrackMan and GOM) (°)
f.
Difference in club direction
(Foresight minus GOM) (°)
Mean club direction
(Foresight and GOM) (°)


Driver
7-Iron
Utility wedge
g.
Difference in face angle (TrackMan minus GOM) (°)
Mean face angle (TrackMan and GOM) (°)
h.
Difference in face angle (Foresight minus GOM) (°)
Mean face angle (Foresight and GOM) (°)
i.
Difference in dynamic loft (TrackMan minus GOM) (°)
Mean dynamic loft (TrackMan and GOM) (°)
j.
Difference in dynamic loft (Foresight minus GOM) (°)
Mean dynamic loft (Foresight and GOM) (°)
k.
Difference in face-to-path angle (TrackMan minus GOM) (°)
Mean face-to-path angle (TrackMan and GOM) (°)
l.
Difference in face-to-path angle (Foresight minus GOM) (°)
Mean face-to-path angle (Foresight and GOM) (°)

m.



n.



o.

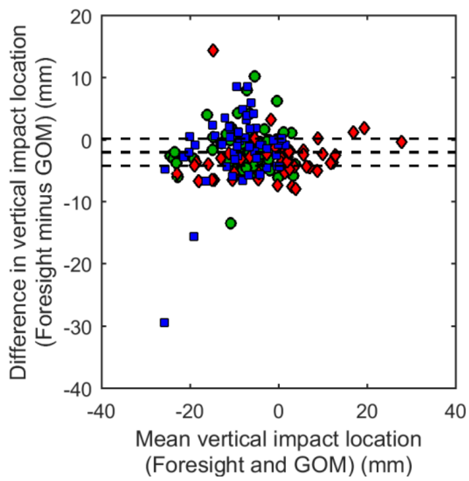


Figure 4-2: Bland-Altman plots for all clubhead parameters: a. clubhead velocity TrackMan; b; clubhead velocity Foresight; c. attack angle TrackMan; d. attack angle Foresight; e. club direction TrackMan; f. club direction Foresight; g. face angle TrackMan; h. face angle Foresight; i. dynamic loft TrackMan; j. dynamic loft Foresight; k. face-to-path angle TrackMan; l. face-to-path angle Foresight; m. dynamic lie Foresight; n. horizontal impact location Foresight and o. vertical impact location Foresight. The three clubs are indicated by different marker characteristics on each plot.

Table 4-4: Driver median differences and interquartile ranges for T (TrackMan minus GOM) and F (Foresight minus GOM) for all parameters. The p-value is the probability that the median difference differs from zero, calculated using the Z-value (MATLAB, 2017).

	Variable	System	Median difference	Z-value	p-value	Lower quartile	Upper quartile
Ball Parameters	Ball velocity (mph)	T	0.2	4.64	*<0.0001*	0.0	0.6
		F	0.0	0.17	0.8677	-0.6	0.6
	Launch angle (º)	T	0.0	-0.57	0.5655	-0.4	0.4
		F	0.3	4.96	*<0.0001*	0.1	0.4
	Launch direction (º)	T	0.0	-1.55	0.1216	-0.9	0.5
		F	-1.1	-5.91	*<0.0001*	-1.7	-0.5
	Total spin (rpm)	T	-63	-4.59	*<0.0001*	-110	-18
		F	-31	-1.46	0.1438	-92	50
	Backspin (rpm)	T	-	-	-	-	-
		F	12	1.86	0.0636	-34	75
	Sidespin (rpm)	T	-	-	-	-	-
		F	-135	-4.56	*<0.0001*	-218	-17
	Spin axis (º)	T	-3.1	-2.15	*0.0316*	-11.2	4.1
		F	-	-	-	-	-
Club Parameters	Clubhead velocity (mph)	T	-0.4	-2.80	*0.0051*	-1.2	0.3
		F	3.9	6.12	*<0.0001*	1.6	5.9
	Attack angle (º)	T	-3.5	-7.00	*<0.0001*	-4.5	-2.0
		F	-0.3	-0.22	0.8283	-1.4	0.7
	Club direction (º)	T	1.5	3.65	*0.0003*	0.3	2.4
		F	0.1	-0.38	0.7067	-0.8	1.5
	Face angle (º)	T	-0.1	-1.02	0.3083	-0.9	0.6
		F	0.8	2.42	*0.0154*	-1.1	5.8
	Dynamic loft (º)	T	-0.5	-2.92	*0.0035*	-1.1	0.1
		F	5.2	4.68	*<0.0001*	1.3	7.0
	Dynamic lie (º)	T	-	-	-	-	-
		F	2.1	3.04	*0.0024*	-0.7	6.4
	Face-to-path (º)	T	-0.4	-0.37	0.7078	-3.4	2.5
		F	-0.9	-0.08	0.9347	-2.3	3.5
	Horizontal impact location (mm)	T	-	-	-	-	-
		F	-5.6	-2.85	*0.0044*	-8.7	-0.8
	Vertical impact location (mm)	T	-	-	-	-	-
		F	-3.1	-5.35	*<0.0001*	-5.0	-1.9

$\alpha = 0.05$

Table 4-5: 7-Iron median differences and interquartile ranges for T (TrackMan minus GOM) and F (Foresight minus GOM) for all parameters. The p-value is the probability that the median difference differs from zero, calculated using the Z-value (MATLAB, 2017).

	Variable	System	Median difference	Z-value	p-value	Lower quartile	Upper Quartile
Ball Parameters	Ball velocity (mph)	T	0.2	3.58	*0.0003*	-0.1	0.4
		F	0.1	1.12	0.2614	-0.3	0.5
	Launch angle (º)	T	0.3	4.52	*<0.0001*	0.0	0.6
		F	0.1	3.08	*0.0021*	0.0	0.2
	Launch direction (º)	T	-0.1	-1.61	0.1079	-0.5	0.4
		F	-1.6	-7.60	*<0.0001*	-2.2	-1.0
	Total spin (rpm)	T	-44	-7.51	*<0.0001*	-55	-28
		F	-8	-0.76	0.4453	-43	29
	Backspin (rpm)	T	-	-	-	-	-
		F	-23	-2.04	*0.0416*	-62	19
	Sidespin (rpm)	T	-	-	-	-	-
		F	-234	-6.49	*<0.0001*	-296	-97
	Spin axis (º)	T	1.3	1.9	0.0567	-1.7	5.6
		F	-	-	-	-	-
Club Parameters	Clubhead velocity (mph)	T	-1.6	-5.26	*<0.0001*	-2.4	-0.7
		F	2.7	6.56	*<0.0001*	1.8	4.4
	Attack angle (º)	T	-0.6	-1.53	0.1257	-1.1	0.1
		F	0.7	5.66	*<0.0001*	0.4	1.0
	Club direction (º)	T	0.4	1.83	0.0668	-0.5	1.1
		F	0.5	3.48	*0.0005*	-0.1	1.2
	Face angle (º)	T	-0.4	2.36	*0.0185*	-0.4	1.0
		F	-0.3	-1.07	0.2850	-2.1	1.7
	Dynamic loft (º)	T	-0.9	-6.40	*<0.0001*	-1.4	-0.2
		F	1.6	4.35	*<0.0001*	0.2	2.5
	Dynamic lie (º)	T	-	-	-	-	-
		F	-0.9	-4.92	*<0.0001*	-1.7	-0.1
	Face-to-path (º)	T	0.2	0.51	0.6115	-1.0	1.2
		F	-1.0	-2.74	*0.0061*	-1.9	0.8
	Horizontal impact location (mm)	T	-	-	-	-	-
		F	-4.9	-6.13	*<0.0001*	-7.4	-2.9
	Vertical impact location (mm)	T	-	-	-	-	-
		F	-1.3	-3.21	*0.0013*	-3.6	0.1

$\alpha = 0.05$

Table 4-6: Utility wedge median differences and interquartile ranges for T (TrackMan minus GOM) and F (Foresight minus GOM) for all parameters. The p-value is the probability that the median difference differs from zero, calculated using the Z-value (MATLAB, 2017).

	Variable	System	Median difference	Z-value	p-value	Lower quartile	Upper Quartile
Ball Parameters	Ball velocity (mph)	T	0.1	2.49	*0.0128*	-0.1	0.4
		F	0.4	4.51	*<0.0001*	-0.1	0.8
	Launch angle (º)	T	0.1	2.18	*0.0293*	-0.2	0.6
		F	0.1	2.20	*0.0277*	-0.1	0.2
	Launch direction (º)	T	0.2	2.52	*0.0116*	-0.3	0.8
		F	-2.1	-7.40	*<0.0001*	-2.6	-1.6
	Total spin (rpm)	T	-56	-7.08	*<0.0001*	-74	-37
		F	-21	-2.64	*0.0082*	-74	17
	Backspin (rpm)	T	-	-	-	-	-
		F	-81	-5.1	*<0.0001*	-162	-4
	Sidespin (rpm)	T	-	-	-	-	-
		F	-458	-6.1	*<0.0001*	-577	-216
	Spin axis (º)	T	-	-	-	-	-
		F	-	-	-	-	-
Club Parameters	Clubhead velocity (mph)	T	-1.3	-2.79	*0.0053*	-2.0	0.6
		F	1.7	2.94	*0.0033*	0.9	3.4
	Attack angle (º)	T	-	-	-	-	-
		F	0.5	3.83	*0.0001*	0.1	1.0
	Club direction (º)	T	-	-	-	-	-
		F	0.1	0.46	0.6421	-0.4	0.9
	Face angle (º)	T	-	-	-	-	-
		F	-3.1	4.55	*<0.0001*	-5.7	-0.9
	Dynamic loft (º)	T	-	-	-	-	-
		F	2.2	5.63	*<0.0001*	1.1	3.1
	Dynamic lie (º)	T	-	-	-	-	-
		F	-1.3	-4.55	*<0.0001*	-1.9	-0.5
	Face-to-path (º)	T	-	-	-	-	-
		F	-3.5	-4.94	*<0.0001*	-5.3	-0.9
	Horizontal impact location (mm)	T	-	-	-	-	-
		F	-5.9	-5.14	*<0.0001*	-7.8	3.9
	Vertical impact location (mm)	T	-	-	-	-	-
		F	-0.7	-1.36	0.1742	-2.94	1.8

$\alpha = 0.05$

Table 4-7: The percentage of all data points within the pre-defined reference grade ranges for each parameter and system.

	Parameter	Reference grade range	TrackMan (%)	Foresight (%)
Research grade	Ball Velocity	± 1 mph	98	84
	Launch Angle	± 1º	87	97
	Launch Direction	± 1º	76	71
	Spin Rate	± 50 rpm	83	54
	Backspin	± 50 rpm	-	48
	Sidespin	± 50 rpm	-	20
	Spin Axis	± 2º	26	-
	Clubhead Velocity	± 1 mph	54	29
	Attack Angle	± 1º	38	67
	Club Direction	± 1º	45	58
	Face Angle	± 1º	66	26
	Dynamic Loft	± 1º	65	33
	Dynamic Lie	± 1º	-	52
	Face-to-Path	± 1º	32	31
	Horizontal Impact Location	± 5 mm	-	73
	Vertical Impact Location	± 5 mm	-	86
Coaching grade	Ball Velocity	± 2.5 mph	100	99
	Launch Angle	± 2º	97	98
	Launch Direction	± 2º	98	95
	Spin Rate	± 150 rpm	97	91
	Backspin	± 150 rpm	-	88
	Sidespin	± 150 rpm	-	50
	Spin Axis	± 4º	42	-
	Clubhead Velocity	± 2.5 mph	87	67
	Attack Angle	± 2º	65	83
	Club Direction	± 2º	82	86
	Face Angle	± 2º	89	46
	Dynamic Loft	± 2º	83	59
	Dynamic Lie	±2º	-	68
	Face-to-Path	± 2º	55	46
	Horizontal Impact Location	± 10 mm	-	86
	Vertical Impact Location	± 10 mm	-	95

4.4. Methodological considerations & challenges

4.4.1. Launch monitor & other considerations

This study assessed the performance of TrackMan and Foresight in the laboratory environment. TrackMan has the ability to track the full ball flight when used outdoors in outdoor mode. The Foresight unit, positioned side on to the tee is limited in the period of the flight it can track post-impact. The reader should bear in mind the results apply when the systems are set-up in an indoor environment. This is a common case in research and for professionals and clubfitters. Within the TrackMan software the distance from the tee to the net can be set. Therefore, the distance may impact the tracking. For example, at the mean ball speed for the driver 146.2 mph (approximately 65 m/s) and a net located five metres in front of the tee the ball is in flight for approximately 0.08 seconds before hitting the net. If the ball is spinning at the mean spin rate for the driver, 3140 rpm or approximately 52 rev/s it means that TrackMan has just over four revolutions to measure the spin rate. This could be a factor in the poorer driver spin rate tracking for TrackMan.

The two systems used in this study take a very different approach to alignment. TrackMan has self-levelling legs and a built-in video camera which enables a target line to be selected. Foresight needs to be placed in a specific region relative to the ball but has no formal means of target line alignment, although it does have an accelerometer for self-levelling. Whilst care was taken to align all three measurement systems relative to each other and the target line through the purpose-built rig and use of a laser, small discrepancies are inevitable. This may have contributed to the systematic bias in the Foresight launch direction data; a similar offset, however, is not observed in other data that is measured relative to the same target line (e.g. face angle and club direction) although it should also be noted that ball and clubhead parameters are measured by different units bolted together. Errors in dynamic loft are unlikely to be due to alignment issues, as the system was placed and self-levelled on a level laboratory floor and no such issues were observed in related measurements such as launch angle. The Foresight HMT unit uses markers on the clubface to track the clubhead. Placement is thus influential so effort was made to follow guidelines as accurately as possible.

Data collected from radar systems, such as TrackMan, contain information on the motion of every moving object within their field of view. As a result, the motion of the clubhead has to be distinguished from the motion of the ball. At impact their paths coincide and separating club data from ball data becomes increasingly difficult as the difference in their respective velocities reduces. With the utility wedge, ball velocity is more similar to clubhead velocity than it is with a driver and this is a possible cause of the poor success rate in measuring clubhead parameters with the club. Furthermore, in the region of impact, both clubhead and ball are travelling close to the ground and a radar system will not only receive a signal reflected directly back from each moving object but will also receive a signal reflected back via the ground. Again, this will add noise to the data, which may have contributed to less than 50% of TrackMan measurements of clubhead path (attack angle and clubhead direction) satisfying the research grade. Clubhead geometry could also influence TrackMan results. For example, the TrackMan attack angle offset for the driver was potentially the result of the clubhead geometry. This study used only one driver, 7-iron and utility wedge.

It was considered important to collect data from all three systems simultaneously for direct comparison of results from each shot. A consequence of this approach, however, is the potential for interference between systems. The presence of large metallic tripods and lights close to the tee may have affected the quality of the radar data. The high intensity lighting required for the high speed cameras could have affected the quality of Foresight images. Non-metallic, non-retroreflective, markers placed on both the clubhead and ball for the GOM system in addition to the metallic dot on the ball for the TrackMan system, may have affected the Foresight algorithms. Compromises had to be made in marker placement and light intensity to find a balance where all systems appeared to function together effectively. This may be a reason for a lower percentage of shots tracked and, therefore, the data collected cannot be considered as originating from an optimal setup for each individual system, but rather for the combination of all three systems.

One final factor is the ball deformation post-impact. This has been shown to influence the sphere fitting (Section 3.3.2) although the RMS errors were low. The ball, a premium quality model, was specifically chosen because of its hardness and therefore reduced deformation. The method, if applied to alternative balls may see larger RMS errors. Furthermore, clubhead deformation on impact may be present. This study measured parameters such as face angle at ball contact, which could be affected should any clubhead deformation occur.

4.4.2. Challenges with parameter definitions

A challenge of the study was to measure equivalent parameters so that a like-for-like comparison could be made. The motion of the clubhead and ball during the period around impact is anything but simple (Section 2.2) and there are no standardised definitions for any of the impact parameters. Differences between the systems existed. TrackMan, for example, reports face angle and dynamic loft at the location of impact on the face, whereas the Foresight definition involves the geometric clubface centre. Consequently, two different face angles were generated from the GOM data. TrackMan also specifies that several parameters are measured ‘at maximum compression of the golf ball’, whereas most systems tend to report these values at the instant of ball contact. It is not clear how TrackMan determines the point of maximum ball compression, nor how this point would be identified in the GOM data, and so GOM measurements were determined at ball contact. Certainly, differences in the timing of a measurement can lead to discrepancies in the data. Furthermore, it is acknowledged that some comparisons may be subject to systematic bias, such as the use of centre of gravity to measure clubhead velocity, a point which the launch monitors cannot measure. However, when interpreted with the methodological challenges in mind the comparisons are meaningful. Clubhead velocity is anything but a simple concept; centre of gravity is the most obvious way to define a body’s translational motion. The fact that systematic bias can be interpreted in such a way may explain some of the results, but the random variability seen in some parameters are far more difficult to explain and not a result of the parameter definitions.

4.4.3. Statistical considerations

Limits of agreement analysis is a widely-used technique to compare measurement systems. This method was chosen over regression type statistics because the aim of the investigation was to compare the degree of agreement between the launch monitors and the GOM system. The advantage of the application of the method was the enabling of pre-defined grades of agreement to identify the percentage of data points falling in acceptable ranges. Subjective conclusions could then be drawn as to whether the agreement was acceptable for the launch monitors use in scientific biomechanical research. The results could also be interpreted by other researchers for their own needs.

For the limits of agreement analysis itself, many of the difference data sets across the parameters in this investigation were non-normally distributed. The decision was made therefore to apply non-parametric statistics across all parameters, even when found to be normally distributed. It is acknowledged that this method is less reliable than using parametric methods (Bland & Altman, 1999). However, it is less likely to be influenced by extreme outlying values. The interpretation of the Bland-Altman statistics is very much dependent on the reader’s needs. This investigation defined research and coaching grades of agreement, based upon what the author considered to be sufficient agreement. For the scientific investigation in the succeeding sections of this thesis the research grade agreement was of primary interest.

4.5. Recommendation on the suitability of launch monitors for research

From a practical perspective, the results suggest that the ball velocity and path parameters measured by both systems would be, in general, suitable for use in golf research; caution however, would need to be exercised for launch direction when using the Foresight system.

Ball velocity is a key performance parameter and an increase in ball velocity of one mile per hour can lead to an increase in driving distance of 1.83 yards (or one metre per second increases distance by 3.75 metres), depending on environmental conditions (Betzler et al., 2014). TrackMan’s own research suggests an increase in ball velocity of 1 mph, in neutral conditions, will result in up to two yards (1.8 metres) more carry with a driver (TrackMan, 2015). Therefore, the errors seen in this study equate to relatively small carry distances. Similarly, in regard to launch angle when aiming for distance during driving, a launch angle between 10º and 14º is considered optimal for elite golfers (Wallace et al., 2007). Therefore, there is suggestion of a relatively wide window for optimal launch angle compared to the errors produced in this investigation.

The launch direction for Foresight was an outlying result, producing a notable systematic bias of 1-2° in the launch direction measurement across clubs, possibly due to the lack of target line alignment. Future launch direction values output by the system could be adjusted retrospectively based upon this offset. An initial difference in launch direction of a shot of the magnitude seen here may have some meaningful influence on the final result of the shot; for a straight 280 metre drive a change of 2º can lead to the ball landing nearly 10 metres offline (Sweeney et al., 2013).

There was discrepancy in the degree of agreement between the spin rate variables. Total spin rate and the backspin component agreed reasonably well across both systems. Both systems demonstrated a much wider spread of data for total spin rate for the driver, which could be due to methodological reasons (Section 4.4), including the fewer rotations of the ball before striking the net. The version of TrackMan at the time of the investigation did not output the components of spin; rather it provided a spin axis value. Foresight, on the other hand, provided the back and sidespin components. When sidespin for Foresight and spin axis for TrackMan were considered the agreement became poorer. The components of total spin and the spin axis could be considered most important. It has been suggested optimal backspin rates for driving distance are between 2280 and 2640 revolutions per minute (Wallace et al., 2007). As with, launch angle, this represents a larger window than the error seen in the Foresight agreement in this investigation. However, the sidespin component represents a far smaller proportion of the total spin rate. Sidespin and spin axis can act to produce either left-to-right fade or right-to-left draw spin on the golf ball. Ultimately, the degree of agreement at the research grade in this study were detrimental to the both systems' use in scientific research for the sidespin and spin axis parameters.

The results suggest caution would be required for any of the clubhead parameters. In general, clubhead velocity and clubhead path showed weaker agreement to GOM for both launch monitors systems than the equivalent ball parameters counterparts. Clubhead velocity is probably the most common measure of performance in golf biomechanics research (e.g. Hume et al., 2005; Ball & Best, 2007a; Kwon et al., 2013; Sinclair et al., 2014) for the reason that faster clubhead velocity typically means better golfing ability (Fradkin et al., 2004). The significant systematic offsets for this parameter were much greater than for ball velocity and likely relate to the point tracked on the clubhead (Section 4.4.2).

Clubhead path and orientation were of interest for the investigation following the current study in this thesis. The results of this investigation cast doubt into the clubhead orientation measurements. A 2º difference in face angle corresponds to 10 m in lateral dispersion of a 280m drive (Sweeney et al., 2013). Differences in the timing of when measurements are taken could contribute to discrepancy in the data. Similarly, the curvature of driver clubface could have caused the poorer Foresight agreement. It was beyond the scope of this thesis to investigate the relationship between the impact location and the degree of agreement, but it is certainly possible using the GOM method that has been developed.

The D-plane theory suggests resultant spin axis tilt and ball sidespin arise from face-to-path angle (Jorgensen, 1999). Face-to-path angle is therefore pivotal for golfers in creating intentional right-to-left draw spin and left-to-right fade spin (Chapter 2). However, the results of this investigation casts doubt on the systems' ability to measure the parameter in scientific investigation. In general, the percentage of data points meeting the research agreement grade was lower than for face angle and club direction alone, except for face angle for Foresight.

The final clubhead parameter is dynamic lie. This was outputted by Foresight only. Previous findings have suggested this parameter is more influenced by the club, i.e. the shaft flex, than the golfer's swing (Worobets & Stefanyshyn, 2012). Foresight appeared to track dynamic lie fairly well; however, the role of dynamic lie in the clubhead-ball impact may be less important than the remaining clubhead parameters.

Foresight was the only launch monitor to track impact location. It did so with an overall systematic offset in both the horizontal and vertical aspects of impact location, suggesting it tended to measure impacts as more towards the heel and lower on the clubface than GOM. However, the interquartile range was narrow and the system showed good agreement with the pre-defined research grade for both horizontal and vertical impact locations. The measurements for Foresight were based on specific Foresight markers, placed at specific points on each clubface. To guide this Foresight recommendations were followed (Foresight Sports, 2012b). It must be considered that error in the placement of the markers may have introduced some systematic offset into the measurement; the GOM impact location was based upon the face centre, halfway along the face grooves horizontally and midway between the top and bottom face grooves vertically.

The subsequent chapters of this thesis involve a scientific biomechanical investigation into different trajectory golf shots. Therefore, being able to measure a wider range of clubhead-ball impact parameters to a high level of accuracy was imperative. For example, when playing a lower trajectory shot the dynamic loft of the clubface is an important parameter. The results of this investigation lead to a partial rejection of hypothesis one. However, the mixed level of agreement across parameters mean it could not be completely rejected. Regardless, the only partial rejection of hypothesis one determined that the launch monitors were inadequate for inclusion in scientific investigation into different shot trajectories, thus hypothesis two was rejected and therefore, an alternative approach to measuring impact parameters going forward was necessary.

4.6. Future work

There are several avenues for further investigation. This study only considered a single clubhead of each type and differences in clubhead geometry may influence the measurements. The testing was carried out indoors in a laboratory environment as this is often where biomechanical research is conducted. TrackMan's capability of tracking the whole ball flight could be investigated with the possibility that the quality of ball parameters would improve further if more of the ball's trajectory was measured. The Foresight system requires markers to be attached to the clubface and their guidance was followed in the positioning of these markers. It was beyond the scope of this study however, to investigate the sensitivity of clubhead parameters to small changes in marker position. Furthermore, both systems provide more parameters than have been reported in this paper, and these could be similarly investigated. Perhaps importantly, since the completion of the investigation both TrackMan and Foresight have released new software and hardware updates, aimed at greater accuracy across a wider spectrum of shot types. These could be evaluated in a similar manner; some of the issues with the current models discussed in this chapter may have been addressed.

There is a lot of interest in the golfing community regarding clubhead-ball impacts. What exactly happens is not well understood in the fraction of a second when the clubhead contacts the ball. Interestingly, at 5400 Hz, the high speed video typically captured two frames of ball contact for the driver. The launch monitors offer some insight into the impact mechanics but it takes a system capable of more in-depth analysis, such as the GOM method presented in Chapter 3, to understand impacts more thoroughly. One particularly interesting area is the role of impact location and how, through the gear effect, this influences the resultant ball parameters and shot outcome as well as its potential influence on golfer biomechanics, such as wrist kinematics and risk of injury.

Finally, face-to-path angle has implications for shot trajectories. However, as highlighted within this study, its definition is far from clear. Therefore, future work could highlight whether club direction should be defined through the centre of gravity of the clubhead, as done here, or by tracking alternative points on the clubhead, such as impact location. Indeed, definition of all impact parameters needs some consensus to provide much needed clarity to the golfing community.

4.7. Summary

This chapter has presented the statistical methodology and results of the comparison of the launch monitors to the GOM system developed in Section 3.2. Comparisons were made through limits of agreement analysis and by pre-defining two grades of agreement (research and coaching).

The results show that, in general, most ball parameters showed closer agreement to the GOM system than the clubhead parameters. In fact, high levels of agreement, showing small systematic offsets and narrow inter-quartile ranges, were found for ball velocity and path, although a notable systemic offset in launch direction was uncovered for Foresight. Good agreement was also found for the magnitude of total spin for both systems and backspin for Foresight. Inferior agreement, in the form of larger systematic offsets and wider inter-quartile ranges were shown for sidespin, spin axis and clubhead parameters.

In regard to the pre-defined grades of agreement, a high percentage of points met the research grade for ball velocity and ball path, suggesting the launch monitors would be useful tools to measure these for scientific research. However, the percentages were lower for spin rates and clubhead parameters. Therefore, it was determined that the launch monitors were unsuitable for use in scientific research to measure a wide range of impact parameters. For coaches and clubfitters, however, the comparisons at the coaching grade level were largely of sufficient quality for their needs, although they should be watchful for occasional erroneous measurements.

The chapter also highlights methodological considerations that may impact on the study, including launch monitor considerations, parameter definitions and statistical considerations, as well as providing future research recommendations that would naturally follow based upon the work conducted.

CHAPTER FIVE

METHODOLOGY FOR ASSESSING GOLFER BIOMECHANICS FOR ACHIEVING DIFFERENT SHOT TRAJECTORIES WITH THE SAME CLUB

5.1. Introduction

Golfers who can achieve different trajectories with a golf club are at a course management advantage. Scientific biomechanical knowledge of the changes in a golfer's swing elicited by varying the shot trajectory is not known. Therefore, the scope of the biomechanical research in this thesis, defined in Chapter 1, focuses on the "long-game" and specifically how golfers achieve draw, fade, low and high trajectories with the same club.

Golf biomechanics has the power to investigate a large range of variables related to the swing. Therefore, a narrowing of the focus was required, along with the definition of relevant biomechanical variables to be investigated. Furthermore, a methodology needed to be laid out prior to conducting the main investigation. Therefore, this chapter focuses on the methodological development required to address the first research question: "do measurable biomechanical differences exist when a golfer plays different types of shot trajectory with the same club? If so, what are the differences?"

This chapter covers two topics relevant to the development of the methodology. The first is to understand coaching points behind the relevant shot trajectories, to identify the potentially key biomechanical variables and narrow the focus of the investigation (*Aim 4*; Section 1.2.3). Based on this a number of testable hypotheses were developed to form a focus for the main investigation, the full methodology of which is outlined.

5.2. Coaching Literature

5.2.1. Introduction

A search of the coaching literature was used as a starting point for the biomechanical investigation to gain an initial understanding of key coaching variables associated with different types of golf shot.

5.2.2. Literature search

The literature searched included internet and text sources. Each trajectory type (draw, fade, high and low) were searched for independently, with specific reference to golf. Sources were excluded if they contained no new coaching points or didn't refer to these shots with reference to the same club. Internet sources were saved and imported into NVivo 10 (QSR International Pty Ltd; Australia), whereas text sources were manually entered into the software. Coding identified key coaching arguments that recurred as themes throughout (Table 5-1). Themes were split depending on whether they were based on the club and ball or on the golfer and whether they related to the draw and fade trajectories or the high and low trajectories. Each theme was then populated with coaching points. The results helped form a list of key variables which informed the development of the questioning framework used in the coach interviews as well as a post-interview questionnaire.

The clubhead and ball outcomes were consistent with scientific theory and were well understood before the investigation commenced (see Section 2.2). For example, to get the ball to draw from right-to-left in the air the face-to-path theme was populated with the coaching point of a closed clubface relative to the club direction. Similarly, for low trajectories the spin loft theme was populated with the actions of the dynamic loft and the attack angle leading up to and through ball contact. However, of more interest were the outcomes of the search relating to the golfer. Based upon the coaching literature the biomechanics was broken down into the address position and the swing (Table 5-2). The themes, along with the associated coaching points, were carried forward to the interviews detailed in Section 5.3.

Table 5-1: Key coaching arguments emerging from the initial coaching literature search.

	Draw/ Fade	High/ Low
Club & Ball	Ball spin Face-to-Path Swing plane	Ball Position Spin loft Swing plane
Golfer	Arms Feet Pelvis Shoulders Weight transfer Wrists & hands	Arms Feet Grip Lumbar spine Shoulders Weight transfer Wrists/ Hands

Table 5-2: Coaching points for each shot trajectory.

Draw		Fade	
Address	Swing	Address	Swing
Feet closed to the target Loose top hand grip Pelvis closed to the target Pelvis shifted towards the target Shoulders closed to the target	Forearm/ wrist rotation Pelvis shifts towards the target Thorax rotation held back as long as possible Weight shifts towards the target Lead hand rotates under trail	Feet open to the target Firm top hand grip Pelvis open to the target Shoulders open to the target	Minimal forearm/ wrist rotation Fast lumbar rotation Fast pelvis rotation Fast shoulders rotation Weight shifted back from the target Minimal wrist rotation
High		**Low**	
Address	Swing	Address	Swing
Feet slightly open to the target Lumbar spine tilts away from target Weight towards the trail Hands slightly back	Minimal forearm/ wrist rotation Lumbar spine tilts away from target Fast lumbar spine rotation Fast pelvis rotation Fast thorax rotation Trail shoulder low No lead hand rotation under trail Additional lead wrist release	Narrow stance Feet slightly open Grip down the club Weight towards lead foot Hands ahead of the ball	Forearm/ wrist rotation Slow lumbar spine rotation Slow pelvis rotation Slow thorax rotation Limited weight shift No lead wrist release Hands forward at impact

5.3. Interviews

5.3.1. Introduction

Following on from the coaching literature search face-to-face interviews were conducted to delve deeper into coaching points related to shot trajectories and thereby to aid the design of the biomechanical investigation. The aim of this was to produce a list of hypotheses relating to golfer biomechanics that could be investigated explicitly. The initial coaching literature search gave some coaching points which populated key themes giving an indication of expected responses from the coaches. The search was used to shape the questions used; but not limit the outcomes, allowing for any new coaching points to be identified. The results of the interviews are discussed throughout Section 5.3.4. For the purposes of keeping the reporting concise key discussion points have been selected.

5.3.2. Participants

Five Professional Golf Association (PGA) qualified coaching professionals (age 29 ± 7, coaching experience 6 ± 3 years) were interviewed. Ethical approval was gained from the Loughborough University Ethics Committee and all participants gave informed consent prior to being interviewed.

5.3.3. Interview Structure & analysis

A question framework was used as the basis for each interview. The framework acted only as a guide, allowing flexibility for the interviews to take any route. Although it also ensured the interview could be brought back on topic had the conversation wandered to unrelated areas of discussion. More targeted questions were answered through a follow-up questionnaire to ensure that anything omitted because of the flexibility of the interviews was covered. Interviews were conducted at each coach's golf course or facility of affiliation. Each interview lasted between 30 minutes and one hour and were documented using a dictation recorder.

To analyse the interviews for post-processing, the following pre-defined themes partly based upon the initial literature were used as a basis for transcribing the interviews:

- Definition of shot trajectories;
- Clubhead and ball;
- Address position;
- Swing biomechanics and ball contact position;
- Natural shots.

The themes were populated with quotes from each interview and related to each individual shot trajectory. When a coach spoke generally about shot shape or trajectory the quote was inserted into both the related shot trajectories. Any new themes that emerged when playing back the interviews were added as extra. Using the quotes, key variables relating to each theme were identified and were then defined biomechanically.

5.3.4. Results & discussion

Definition of shot trajectories

All coaches defined each respective shot trajectory based upon the ball flight as opposed to the golfer's movements. A draw was defined as right-to-left (anticlockwise spin when viewed from above) ball curvature during flight, whilst a fade was defined as left-to-right curvature (clockwise spin when viewed from above), for a right-handed golfer by all coaches. These definitions were expected and are universal across those with an interest in golf. For draw and fade trajectories it was emphasised by each coach that the ball finishes on the target line; if a draw finishes left of the target line "that's not a draw, because a draw starts right and finishes on the target." Draw and fade trajectories are achieved through a controlled, deliberate spin axis tilt, rather than the outcome being achieved purely by chance. This raised interesting issues for a biomechanical investigation, including the margin of error for a trajectory, likely to be different for different levels of golfers. The amount of curvature or spin axis tilt of a draw or a fade trajectories was not specifically defined.

High or low shot trajectory was not conclusively defined; a high or low trajectory was defined by either the “trajectory it [the ball] takes off at” or “the peak height of the shot”, definitions which were considered when finalising the main biomechanical investigation methodology.

Clubhead and ball

All coaches spoke about the clubhead and ball interaction to achieve different trajectories, a possible reflection of their education as PGA qualified coaches. The same principles were spoken about for a draw and fade and for a high and low trajectory. “The only way you hit a draw is if … the swing path [club direction] has got to be in-to-out [left-to-right of the target line for a right-handed golfer] and the clubface has got to be open [right of for a right-handed golfer] to the target line but closed [left of for a right-handed golfer] to the swing path (see Table 2-1).” An in-to-out (left-to-right of the target line for a right-handed golfer) path was highlighted by coaches as important for a draw trajectory. A fade, in terms of the clubhead and ball interaction, was believed to be achieved in the opposite way to a draw. Ultimately, the important parameters were considered to be the club path and the face angle for achieving each trajectory. Similarly, for control of low trajectory with the same club, the important clubhead parameter identified by the coaches was spin loft. Spin loft is the relationship between attack angle and dynamic loft (see Table 2-1) and has implications for backspin. “[Golfers] are trying to put less spin on the ball, less backspin, so it doesn’t ride up on the wind as much ... to play it lower, the spin loft has got to be down”. This means the trajectory of the clubhead (attack angle) pre-impact should be as parallel to the ground as possible, with a low dynamic loft.

Address

Deeper questioning attempted to understand how coaches believe the changes in clubhead and ball parameters are achieved by the golfer. These were broken down into address and the swing itself. Whilst one coach acknowledged it is “not all down to address” every coach outlined principles which are common when playing a draw, fade, high or low trajectory at this time point of the swing. For example, for a fade a common theme was that of an open stance, meaning the feet, pelvis and thorax orientate to the left of the target line, put simply by one coach for a right-handed golfer “aim left of the target with your body.” Another elaborated, “to hit a fade I would withdraw my left foot, so I’d step back a couple of inches, because I know that’s going to get my left side out the way and I am going to find it easier to cut across, to create that swing path that we’re looking for.” Again, the coaches outlined the opposite principles for a draw. The open and closed address stance for a draw and a fade was a common theme. However, other factors appeared in individual interviews. For example, one coach noted how it appears golfers who draw the ball have “low hands” at address but couldn’t explain why. It could be related to the concept of swing plane formed by the motion of the clubhead and shaft, helping to create the in-to-out or out-to-in path described above.

For low trajectories one coach started with the simple premise of reducing the distance from the hands to the base of the grip However, others dug a bit deeper into the mechanics, one sighting kinetics as playing a role, “put the ball further back in the stance, [with a] bit of weight on the front (lead) foot”, effectively saying the centre of pressure should be distributed further forward, towards the target, in low trajectories at address. Another coach highlighted the need to understand that putting the ball back in the stance could lead to a more negative attack angle (a greater angle of the clubhead path relative to the ground), thus imparting extra spin on the ball causing it to rise. Another feature that emerged was “pushing [the] hands forward at address”, but the same coach stated it is important to coach low trajectories on an individual-level. The coach also highlighted the D-plane theory (Jorgensen, 1999). A final outcome from the coaches was that of a narrower stance (a reduced distance between the feet centres), “posture would near enough be the same, apart from you might stand a little bit closer to the ball … [the] stance would be narrower”. The coaches were less certain over high shots. Two coaches cited moving the ball forward slightly in the stance in the opposite manner to low trajectories. However, another coach argued it is not worth pushing the hands backward as it is “not worth it because of the timing [difficulties]”.

Swing biomechanics and ball contact

Interview questioning targeted the actual swing itself; coaches were asked what swing changes golfers make to achieve each shot trajectory. Firstly, they were asked about fade and draw trajectories. One coach highlighted the impact position in relation to the address position for draw and fade trajectories. Specifically, “what the shoulders [thorax] are doing at impact, open [orientated left of target line] [or] shut [orientated right of target line].” The coach went on to highlight the importance of pelvis and thorax rotation in creating both draw and fade shapes. Interestingly the coach did highlight the importance of concentrating on getting in the right position at impact rather than concentrating on the swing itself. A separate coach highlighted potential biomechanical parameters with sentences such as “I’d feel like my right elbow was more tucked”, i.e. shoulder adduction, when referring to a draw. A different coach used the term “covering the golf ball” when referring to a fade. When asked to explain the term in more detail they described it as “my body weight [centre of pressure] and my spine [lumbar] go further forward in the downswing than what it was at address.” There is also some suggestion that timing of movements play a role in fade and draw trajectories. One coach noted how "people who try and hit it too hard tend to be faders". This could suggest timing of their body movements (e.g. rotation of central body segments) may not be optimal. The coach continued with "… you know they'll turn [the] upper body over, rather than using the lower half to turn underneath". The same coach also attributed natural fades to a loss of posture with the golfer's head rising throughout the downswing.

Following fade and draw trajectory questioning the coaches were asked about low trajectory shots. Again, some factors that were regarded important at address were highlighted as important at impact. For example, "pushing your hands a little bit forward, especially at impact, gets less loft on the club." Reduced dynamic loft will in theory contribute to a lower ball flight. However, coaches explained it is not as simple as simply reducing dynamic loft to create a lower ball flight. As discussed earlier spin loft is an important parameter for creating backspin and therefore lift on the golf ball. It was widely acknowledged that a slower, softer swing will produce less backspin on the ball. Speculation suggests this could manifest in the rotational velocities of large body segments. One coach touched on other aspects of biomechanics, for example: "… get that left shoulder low … you'll find golfers generally stack their weight on their left-hand side [for a right-handed golfer]".

Coaches were less confident when asked what biomechanical parameters are important for high trajectory shots. One coach highlighted that making changes opposite to what was stated for a low trajectory, meaning hands away from the target at impact and/ or centre of pressure towards the trail foot was "not worth it because of the timing [difficulties]." In the coach's opinion making the shot hard to time would lead to inconsistent ball striking. Whilst the same coach spoke about the height of each shoulder, citing the opposite pattern to what is quoted above; other coaches were less able to provide biomechanical information. Interestingly, the coach related this biomechanical change in the swing to the impact parameter of attack angle stating, "a drill that I use quite a lot to hit it high is get the left shoulder higher than the right shoulder. That generally creates a shallower angle of attack [more perpendicular to the ground], which is going to help hit it in the air". Another coach suggested the length of the swing [more backswing and follow-through] would be longer for a high trajectory shot and that the golfer may "keep a lot stiller over the shot". They explained a bit further by stating "the movement backwards and forwards [translation towards and away from the target] will be a lot less."

Natural shot shapes

The intention of this section was to establish if coaches thought golfers had a preferred shot trajectory (draw or fade) and would they resort to this when on the course. Across coaches there was a consensus that golfers tend to have a preferred or natural shot trajectory i.e. they are more comfortable drawing or fading the golf ball. Generally, it was felt that golfers don't really try to achieve a perfect straight shot. One coach said how under the pressure of competition a golfer will return to their preferred trajectory shot for psychological reasons. There was some discussion by each coach as to why a golfer does have a preferred trajectory. Physical characteristics were highlighted as a potential reason. For example, a taller golfer will be able to achieve a different clubhead path prior to impact, thus the coach felt they would more easily be able to play a fade. Coaches did however, feel that physical characteristics aren't the be all and end all and that individual golfers do have idiosyncrasies or characteristics which could lead them to favour one shot trajectory. One of the coaches stated how the majority of golfers he coaches (mixed ability levels), for whatever reason, tended to fade the ball; the fade could well be the more common shot trajectory amongst the golfing population.

5.3.5. Key Outcomes

The interviews gave a deeper insight into the coaching points behind different trajectories of golf shot. Whilst it was impossible to conclude a saturation of theory (the identification of all coaching points related to the shot trajectories) had been reached it was felt important coaching points recurred throughout. Coaches in the main felt that golfers have a preferred shot trajectory or trajectories. Definitions of shot trajectories were consistent across coaches, the exception being for high and low trajectories; defined either based off the initial launch angle or the peak height of the shot. The reasons for utilising different trajectories of golf shot for a successful round of golf were predominantly environmental, however one coach highlighted psychological reasons as a factor. High shots were considered less important by coaches. For this reason, they were regarded of less interest and were excluded from this study. Low driver trajectories were also excluded, but were retained when it came to the 5-iron. For not dissimilar reasons, Robertson et al., (2012) based their methodology around a 5-iron.

The coaches all had a similar understanding of the clubhead mechanics that lead to different shots. The coaches go through a three-year course to become qualified at a PGA level. Therefore, they are all taught the same theories, which are consistent with published scientific literature, including theories such as the D-plane (Jorgensen, 1999). Clubhead-ball parameters that are considered important for each shot trajectory are shown in Table 5-3. Questioning pressed harder to prise out biomechanical factors, most of which were consistent across coaches, however, there were a few unique to individual coaches; these were also included in the main investigation. The ones that were described were broken into address and the swing itself and are defined biomechanically in Section 5.5.2.

Table 5-3: The clubhead-ball impact parameters considered important for each shot trajectory (based on a right-handed golfer).

Shot trajectory	Clubhead parameters		Ball Parameters
Draw	Negative face-to-path angle	Face angle Club direction	Negative sidespin Negative spin axis Right launch direction
Fade	Positive face-to-path angle		Positive sidespin Positive spin axis Left launch direction
Low	Lower spin loft	Dynamic loft Attack angle	Low backspin Low launch angle
High	Higher spin loft		Higher backspin Higher launch angle

5.4. Methodological rationale

Much thought was given to the design of the methodology for the biomechanical investigation into shot trajectories. Commonly, golfer biomechanics are measured using motion analysis systems (e.g. Egret et al., 2003; Langdown et al., 2013; Horan et al., 2014). In this study, a VICON motion analysis system was used (Figure 5-1). This is an optical passive marker system whereby, small, lightweight, retroreflective markers are placed on body landmarks to track a golfer's motion. Multiple cameras are placed around the target volume, which is calibrated, typically using a supplied wand, waved around the volume until each camera has recorded the wand for a predefined number of frames. The known distances between the wand markers then enable the system to build a three-dimensional representation of the laboratory with relative positions of each camera known. The cameras emit and receive light of infra-red wavelength, each creating a two-dimensional image of the markers. The associated software (Nexus 1.8.5) can build up a three-dimensional view by triangulating the cameras' images and therefore, the three-dimensional coordinates of each retroreflective marker can be obtained. The VICON system used is a highly accurate system when reconstructing tracking markers in three-dimensional space. Provided adequate calibration and camera set-up and environmental factors, accuracy is expected to be below 1 mm in a volume of 3×3×3 m (Peploe, 2016).

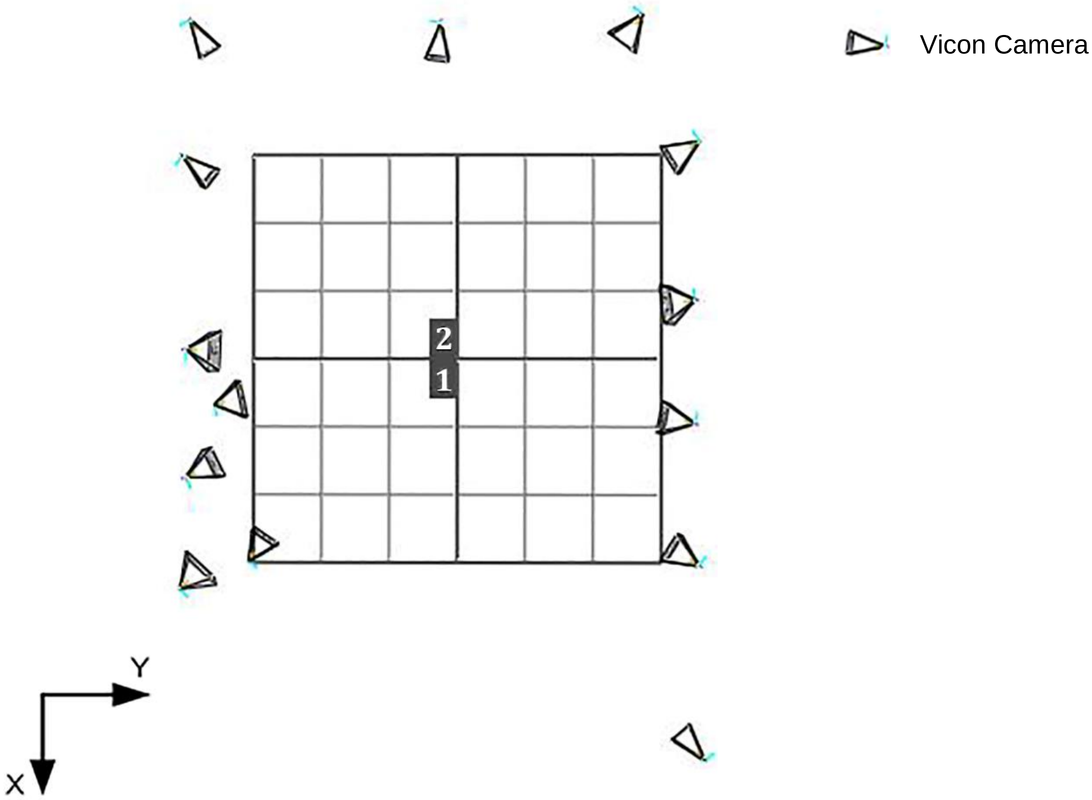


Figure 5-1: The VICON camera and force plate set-up. The positive X-axis corresponds to the target direction, the Y-axis corresponds to the perpendicular horizontal axis and the Z-axis (not shown) corresponds to the vertical. The force plates are shown as one and two. Note, the triangular shapes represent the cameras (see legend), which have slightly different geometries due to the camera orientations in the laboratory.

A disadvantage of passive marker systems is that each marker is unknown to the system, therefore must be identified by the user. Whilst models within the software can be built to automatically identify markers, it can be a laborious process to ensure the labelling is done correctly. An optimal camera set-up along with optimisation of software settings aids the automatic labelling of markers.

On top of golfer biomechanics, to analyse how shot trajectories are achieved, knowing the outcome of a shot was important thus providing an immediate argument for outdoor testing. However, there were factors that made this difficult to achieve. For example, the sheer amount and size of the equipment would have made creating an outdoor set-up complicated. The VICON motion analysis system involves multiple cameras and associated computer. Setting this up at a driving range or on a course in an optimal set-up would have proven challenging. Additionally, following the results of Chapter 4, the launch monitors couldn't be used during the investigation. The GOM system was therefore used simultaneously with VICON to track the clubhead and ball. This meant further equipment demands would be needed, including high speed video cameras and lighting. Furthermore, despite having the whole ball flight, control of conditions would have been difficult, for example, wind may have obscured the spin of the ball whilst in flight. Moreover, changing sunlight may have been a factor which could have influenced both the quality of high speed video images and motion analysis tracking; quality of images is imperative for GOM processing and sunlight can create unwanted noise for motion analysis systems. Taking all of this into consideration the decision was made to conduct the testing in the more controllable environment of the laboratory.

Data collection in the laboratory allowed for the integration to the VICON camera hardware of two adjacent 600×400 mm force plates (Kistler, 9281C, Kistler instrumente AG, Winterthur, Switzerland), embedded centrally in the laboratory (Figure 5-1). These enabled individual foot and combined feet kinetics to be measured in synchronisation with the kinematic marker movement. Piezoelectric force transducers located towards each corner of either force plate can measure both combined and individual force plate ground reaction forces in three dimensions through changes in the electrical charge. Furthermore, combined and individual force plate centre of pressure is calculated from the dimensions of each force and the relative application of force. The force plates can be zeroed allowing placement of separate sections of artificial turf on the surface of each force plate to create more realistic golf hitting conditions.

Despite the advantage of being able to collect accurate kinetic data, it is acknowledged that laboratory data collection brings associated limitations, such as the inability to track the whole ball flight and the golfers performing in an alien environment with no target in the distance to aim at. Lacking the entire flight meant the peak height of the low trajectories could not be measured along with the final outcome. This presented a limitation because the coaches defined fade and draw trajectories partly due to finishing on the target line. A trajectory model, described in Section 5.6.4, was used to calculate the outcome of the shots but of course as with any model was a prediction.

5.5. Biomechanical variable definitions & hypotheses

5.5.1. Biomechanical model

The biomechanical investigation utilised the model developed by Smith, (2013), consisting of a VICON marker set and associated Visual3D model. The full-body marker set comprised sixty-six 14 mm retroreflective markers (Figure 5-2; Smith, 2013) and formed the basis of the Visual3D model distance, landmark (virtual locations) and segment definitions (Table 5-4). Table 5-4 details the proximal and distal markers or landmarks used to define each segment as well as markers used for tracking and provides the origin of each segment's coordinate system. The model is visualised in Appendix B.

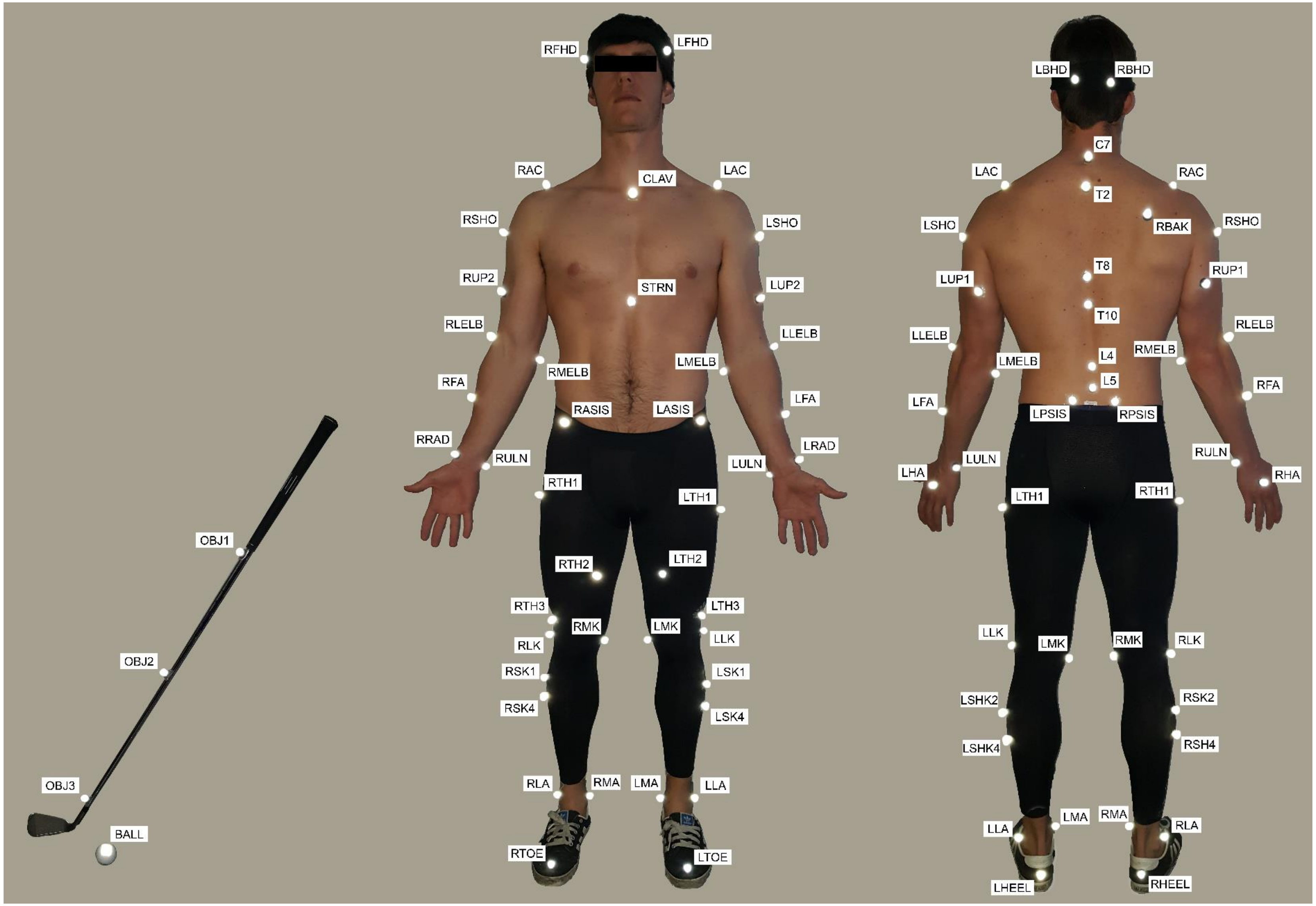


Figure 5-2: The golfer biomechanical marker set (Smith, 2013). Note that during testing markers were placed directly onto the skin, not clothing.

Table 5-4: Distance, landmark and segment definitions of the Visual3D model (Smith, 2013).

Distance	Definition
RAC_RSHO	RAC to RSHO divided by 2
LAC_LSHO	LAC to LSHO divided by 2
ASIS_Distance	RASIS to LASIS

Landmark	Starting Point	Ending Point	Segment*	Offset
RT_SHOULDER	RAC	-	Thorax_ab (Appendix B)	Z: -RAC_RSHO/2
LT_SHOULDER	LAC	-	Thorax_ab (Appendix B)	Z: -LAC_LSHO/2
Mid_ACROMION	LAC	RAC	-	50%
SH_origin	Mid_ACROMION	T10	-	50%
RIGHT_HIP	-	-	CODA pelvis (Appendix B; C-Motion, 2016a)	X: 0.36×ASIS_Distance Y: -0.19×ASIS_Distance Z: -0.3×ASIS_Distance (Bell et al., 1989)
LEFT_HIP	-	-	CODA pelvis (Appendix B; C-Motion, 2016a)	X: -0.36×ASIS_Distance Y: -0.19×ASIS_Distance Z: -0.3×ASIS_Distance (Bell et al., 1989)
RT_ILLIAC	RIGHT_HIP	-	Global	Z: 0.5×ASIS_Distance
LT_ILLIAC	LEFT_HIP	-	Global	Z: 0.5×ASIS_Distance
MID_RFOOT	RHEEL	RTOE	-	50%
MID_LFOOT	LHEEL	LTOE	-	50%

Segment	Defining markers			Local coordinate system*
	Proximal	Distal	Tracking	Origin
Head	LFHD / RFHD	LBHD / RBHD	LFHD / RFHD LBHD / RBHD	Mid-proximal
Right Upper Arm	RT_SHOULDER	RLELB / RMELB	RSHO / RUP1 / RUP2	RT_SHOULDER
Left Upper Arm	LT_SHOULDER	LLELB / LMELB	LSHO / LUP1 / LUP2	LT_SHOULDER
Right Lower Arm	RLELB / RMELB	RRAD / RULN	RLELB / RMELB / RFA / RRAD / RULN	Mid-proximal
Left Lower Arm	LLELB / LMELB	LRAD / LULN	LLELB / LMELB / LFA / LRAD / LULN	Mid-proximal
Right Hand	RRAD / RULN	RHA	RRAD / RULN / RHA	Mid-proximal
Left Hand	LRAD / LULN	LHA	LRAD / LULN / LHA	Mid-proximal
Thorax	SH_origin	LAC / RAC	C7 / T2 / CLAV	SH_origin
Lumbar	RT_ILLIAC / LT_ILLIAC	T8	L4 / L5 / T8 / T10	Mid-proximal
Pelvis	RT_ILLIAC / LT_ILLIAC	LEFT_HIP / RIGHT_HIP	LASIS / LPSIS / RASIS / RPSIS	Mid-ASIS
Right Upper Leg	RIGHT_HIP	RLK / RMK	RLK / RMK / RTH1 / RTH2 / RTH3	RIGHT_HIP
Left Upper Leg	LEFT_HIP	LLK / LMK	LLK / LMK / LTH1 / LTH2 / LTH3	LEFT_HIP
Right Lower Leg	RLK / RMK	RLA / RMA	LSHK1 / LSHK2 / LSHK3 / LSHK4	Mid-proximal
Left Lower Leg	LLK / LMK	LLA / LMA	RSHK1 / RSHK2 / RSHK3 / RSHK4	Mid-proximal
Right Foot	RLA / RMA	RTOE	RLA / RMA / RHEEL / RTOE	Mid-proximal
Left Foot	LLA / LMA	LTOE	LLA / LMA / LHEEL / LTOE	Mid-proximal
Club Shaft	RHA	OBJ3	OBJ1 / OBJ2 / OBJ3	RHA

**Visual3D calculates the positive Z-axis of each segment coordinate system as the vector from the distal mid-point or landmark to the proximal, representing the longitudinal axis (C-Motion, 2016b). A frontal plane (least-squares) is then defined based on proximal and distal markers. This enables definition of a positive Y-axis, in the anterior direction. The X-axis is defined perpendicularly to Y and Z, using the right-hand rule.*

Table 5-5: Swing event definitions used in Visual3D.

Event	Definition
Takeaway (TA)	The point at which the marker (OBJ3; Figure 5-2) in the global coordinate system X-direction crossed below a -0.25 m/s (-0.6 mph) threshold.
Mid-backswing (MDBS)	Point at which the club shaft coordinate system Z-axis (Table 5-4) is closest to parallel to the global coordinate system XY plane after takeaway.
Top of the Backswing (TB)	Point at which the clubhead (OBJ3; Figure 5-2) has zero X-direction velocity following mid-backswing.
Mid-downswing (MDDS)	Point at which the club shaft coordinate system Z-axis (Table 5-4) is closest to parallel to the global coordinate system XY plane after top of the backswing.
Ball contact (BC)	Point at which the golf ball (BALL; Figure 5-2) has a velocity in the global coordinate system X-axis exceeding a 1 m/s (2.2 mph) threshold.
Mid-follow through (MDFT)	Point at which the club shaft coordinate system Z-axis (Table 5-4) is closest to parallel to the global coordinate system XY plane after ball contact

5.5.2. Biomechanical variable definitions

The biomechanical model detailed above (Section 5.5.1) allowed calculation of biomechanical variables based on coaching points (Table 5-6, Table 5-7 and Table 5-8). Variables related to address, ball contact and the whole-swing. Some coaches considered the address variables important at ball contact; for example, lead hand forwardness for low trajectories. Others such as stance width were considered as solely address parameters.

Table 5-6: Address outcomes of the literature search and coach interviews defined biomechanically. For the relevant variables the rotational axis and cardan rotation order based on Smith, (2013) and Wu et al., (2005) is shown.

Parameter	Unit	Definition	Rotational axis	Cardan order
Pelvis rotation	º	Axial rotation of pelvis coordinate system (Table 5-4) relative to the global coordinate system (Figure 5-1). Zero degrees corresponds to the pelvis segment X-axis lying parallel to the global XZ plane. A negative angle corresponds to the pelvis coordinate system rotated clockwise (closed) when viewed from above, a positive angle corresponds to the pelvis coordinate system rotated anticlockwise (open) when viewed from above.	Z	ZXY
Thorax rotation	º	Axial rotation of thorax coordinate system (Table 5-4) relative to the global coordinate system (Figure 5-1). Zero degrees corresponds to the thorax segment X-axis lying parallel to the global XZ plane. A negative angle corresponds to the thorax coordinate system rotated clockwise (closed) when viewed from above, a positive angle corresponds to the thorax coordinate system rotated anticlockwise (open) when viewed from above.	Z	ZXY
Stance openness	º	The angle between the vector originating at the lead foot centre (MID_LFOOT for a right-handed golfer) to the trail foot centre (MID_RFOOT for a right-handed golfer) projected onto the XY plane, and the global coordinate system X-axis (Figure 5-1). Zero degrees indicates the vector is parallel to the global X-axis. A negative angle means a closed stance, a positive angle means an open stance.	-	-
Ball position	mm	Length of the vector, parallel to the global coordinate system X-axis (Figure 5-1), originating at the lead foot centre (MID_LFOOT for a right-handed golfer) to the BALL (Figure 5-2). A negative distance corresponds to the ball translated away from the lead foot centre towards the trail foot centre, a positive corresponds to the ball translated towards the target.	-	-
Stance width	mm	Length of the vector originating at the lead foot centre (MID_LFOOT for a right-handed golfer) to the trail foot centre (MID_RFOOT for a right-handed golfer), projected onto the XY plane. A greater distance indicates a wider stance width.	-	-
Grip distance	mm	Length of the vector, parallel to the club shaft coordinate system Z-axis (Table 5-4), originating at the trail hand segment centre of gravity (right hand for a right-handed golfer) to the marker at the top of the shaft (OBJ1; Figure 5-2). A greater distance corresponds to a higher grip position.	-	-
Lead hand forwardness	mm	Length of the vector, parallel to the global coordinate system X-axis (Figure 5-1), originating at the lead hand segment centre of gravity (left hand for a right-handed golfer) to the BALL (Figure 5-1). Zero distance corresponds to the lead hand centre of gravity X coordinate equal to the BALL X coordinate. A negative distance corresponds to the lead hand centre of gravity towards the target relative to the ball. A positive distance corresponds to the opposite.	-	-
Lead hand height	mm	Length of the vector, parallel to the global coordinate system Z-axis (Figure 5-1), originating at the lead hand segment centre of gravity (left hand for a right-handed golfer) to the XY plane. A greater distance corresponds to a higher lead hand position.	-	-
Thorax lateral flexion	º	Rotation of the thorax segment coordinate system (Table 5-4) relative to the global coordinate system (Figure 5-1). Zero corresponds to the thorax segment X-axis lying parallel to the global XY plane. A negative angle indicates anticlockwise rotation when viewed from front-on or flexion of the thorax towards the trail side, a positive angle means clockwise rotation when viewed from front-on or flexion of the thorax towards the lead.	Y	ZXY
Centre of pressure	%	Position of the centre of pressure parallel to the global coordinate system X-axis (Figure 5-1). Fifty percent corresponds to the centre of pressure located equidistant between the lead and trail foot centres (MID_LFOOT and MID_RFOOT). Zero percent corresponds to the trail foot centre and 100% corresponds to the lead foot centre.	-	-

Table 5-7: Ball contact outcomes of the literature search and coach interviews defined biomechanically. For the relevant variables the rotational axis and cardan rotation order based on Smith, (2013) and Wu et al., (2005) is shown.

Parameter	Unit	Definition	Rotational axis	Cardan order
Pelvis rotation	º	See Table 5-6.	Z	ZXY
Thorax rotation	º	See Table 5-6.	Z	ZXY
Lead hand forwardness	mm	See Table 5-6.	-	-
Lead hand height	mm	See Table 5-6.	-	-
Thorax lateral flexion	º	See Table 5-6.	Y	ZXY
Centre of pressure	%	See Table 5-6.	-	-
Instantaneous swing plane horizontal	º	The angle between the normal of the plane formed by the club shaft (OBJ1 & OBJ2; Figure 5-2) over the three consecutive frames immediately before ball contact, projected onto the global coordinate system XY plane, relative to the global coordinate system Y-axis (see Section 2.3.4; Coleman & Rankin, 2005; Coleman & Anderson, 2007; Mackenzie, 2012). A negative angle indicates the swing plane is orientated to the left (out-to-in) of the global coordinate system XZ plane, a positive angle indicates it was orientated to the right (in-to-out).	-	-
Instantaneous swing plane vertical	º	The obtuse angle between the normal of the plane formed by the club shaft (OBJ1 & OBJ2; Figure 5-2) over the three consecutive frames immediately before ball contact, projected onto the global coordinate system YZ plane, relative to the global coordinate system Z-axis (see Section 2.3.4; Coleman & Rankin, 2005; Coleman & Anderson, 2007; Mackenzie, 2012). A larger angle indicates a flatter orientated plane.	-	-

Table 5-8: Whole-swing outcomes of the literature search and coach interviews defined biomechanically. For the relevant variables the rotational axis and cardan rotation order based on Smith, (2013) and Wu et al., (2005) is shown.

Parameter	Unit	Definition	Rotational axis	Cardan sequence
Pelvis rotation	º	See Table 5-6.	Z	ZXY
Thorax rotation	º	See Table 5-6.	Z	ZXY
X-factor	º	Axial rotation of thorax coordinate system (Table 5-4) relative to the pelvis coordinate system Z-axis (Table 5-4). Zero angle corresponds to the thorax segment X-axis lying on the pelvis coordinate system XZ plane. A negative angle corresponds to the thorax coordinate system rotated anticlockwise (closed) when viewed from above, a positive angle corresponds to the thorax coordinate system rotated clockwise (open), when viewed from above.	Z	ZXY
Lumbar forward flexion	º	Rotation of the lumbar spine coordinate system (Table 5-4) relative to the global coordinate system X-axis (Figure 5-1). Zero angle corresponds to the lumbar coordinate system Y-axis lying on the global XY plane. A negative angle corresponds to a flexed lumbar spine. The more negative the angle the more flexed the lumbar spine.	X	ZYX
Lumbar lateral flexion	º	Rotation of the lumbar spine coordinate system (Table 5-4) relative to the global coordinate system Y-axis (Figure 5-1). Zero corresponds to the lumbar coordinate system X-axis lying on the global XY plane. A negative angle means anticlockwise rotation or flexion of the lumbar towards the trail side, a positive angle means clockwise rotation or flexion of the lumbar towards the lead.	Y	ZYX
Thorax lateral flexion	º	See Table 5-6.	Y	ZXY
Pelvis translation	mm	Length of the vector, parallel to the global coordinate system X-axis (Figure 5-1), originating at the pelvis segment centre of gravity (Table 5-4), to the lead foot (left foot for a right-handed golfer) centre (mid-point of the TOE and HEEL markers) at address. A zero value means the pelvis centre of gravity was located at the lead foot centre. A positive value corresponds to translation towards the trail foot centre away from the target.	-	-
Trail shoulder abduction	º	Rotation of the trail upper arm (right arm for a right-handed golfer) segment coordinate system (Table 5-4) relative to the thorax coordinate system Y-axis. A negative angle corresponds to shoulder abduction. A greater negative angle corresponds to greater abduction.	Y	YXY
Lead wrist/ radioulnar deviation	º	Rotation of the lead hand segment (left hand for a right-handed golfer) coordinate system (Table 5-4) relative to the lead forearm segment coordinate system Y-axis. A negative angle corresponds to ulnar deviation, a positive corresponds to radial deviation.	Y	YXZ
Lead wrist/ radioulnar supination	º	Rotation of the lead hand segment (left hand for a right-handed golfer) coordinate system (Table 5-4) relative to the lead forearm segment coordinate system Z-axis. A negative angle corresponds to pronation, a positive corresponds to supination	Z	YXZ
Centre of pressure	%	See Table 5-6.	-	-
Instantaneous horizontal swing plane	º	The angle between the normal of the plane formed by the club shaft (OBJ1 & OBJ2; Figure 5-2) over each three consecutive frames, projected onto the global coordinate system XY plane, relative to the global coordinate system Y-axis (see Section 2.3.4; Coleman & Rankin, 2005; Coleman & Anderson, 2007; Mackenzie, 2012). A negative angle means the swing plane is orientated left of the global coordinate system XZ plane, a positive means it is orientated right of the global coordinate system XZ plane.	-	-
Instantaneous vertical swing plane	º	The obtuse angle between the normal of the plane formed by the club shaft (OBJ1 & OBJ2; Figure 5-2) over each three consecutive frames, projected onto the global coordinate system YZ plane, relative to the global coordinate system Z-axis (see Section 2.3.4; Coleman & Rankin, 2005; Coleman & Anderson, 2007; Mackenzie, 2012). A larger angle means a flatter orientated plane.	-	-

5.5.3. Hypotheses

Following the definition of variables, hypothesised outcomes based upon the coaching points could be outlined for investigation. Initially, a general testable hypothesis was generated. This was then broken down into specific hypothesised changes for each individual variable (Table 5-9 and Table 5-10):

Hypothesis: A golfer will significantly alter their swing biomechanics to achieve different shot trajectories.

Table 5-9: Hypothesised changes in the biomechanical variables between the draw and fade at address, ball contact and over the whole-swing. Hypotheses are given by referring to the draw relative to the fade.

Variable	Address	Ball contact	Whole-swing
Pelvis rotation	A more negative, less positive (closed or more rotated away from the target) pelvis rotation in draw trajectories		
Thorax rotation	A more negative, less positive (closed or more rotated away from the target) thorax rotation in draw trajectories		
X-factor	N/A	N/A	A more negative, less positive (closed or more rotated away) X-factor in draw trajectories
Stance openness	A negative stance openness in draw trajectories, a positive stance openness in fade trajectories	N/A	N/A
Lead hand height	Smaller lead hand height distance for draw trajectories		N/A
Lumbar forward flexion	N/A	N/A	More lumbar forward flexion (greater negative angle) in draw trajectories
Lumbar lateral flexion	N/A	N/A	More flexing away from the target, towards the trail side (less positive, more negative angles) in draw trajectories
Thorax lateral flexion	Lesser flexing of the thorax, so it’s flexed towards the lead (positive angle) in draw trajectories		
Pelvis translation	N/A	N/A	Greater pelvis translation (lower value) towards the target in draw trajectories
Trail shoulder abduction	N/A	N/A	Greater trail shoulder abduction (greater negative angle) in draw trajectories
Lead wrist supination	N/A	N/A	A more supinated wrist (less negative, more positive angle) in draw trajectories
Lead wrist deviation	N/A	N/A	Lesser wrist deviation angles in draw trajectories
Centre of pressure	Distributed further towards the target (greater percentage) in draw trajectories		
Instantaneous swing plane horizontal	N/A	A more in-to-out horizontal swing plane (greater positive angle) in the downswing in draw trajectories	
Instantaneous swing plane vertical	N/A	A flatter (greater angle) vertical swing plane in the downswing in the draw trajectories	

Table 5-10: Hypothesised changes in the biomechanical variables between the low and natural trajectories at address, ball contact and over the whole-swing. Hypotheses are given by referring to the low relative to the natural.

Variable	Address	Ball contact	Whole-swing
Pelvis rotation	N/A	N/A	Slower rotation in low trajectories
Thorax rotation	N/A	N/A	Slower rotation in low trajectories
X-factor	N/A	N/A	Slower rotation in low trajectories
Ball position	Ball further back in the stance (more negative value) for low trajectories	N/A	N/A
Stance width	Narrower distance (smaller value) in the low trajectories	N/A	N/A
Grip distance	Grip down the club (lesser distance) for low trajectories	N/A	N/A
Lead hand forwardness	Hands further in front of the ball (more negative value) at address and ball contact for the low trajectories		N/A
Lumbar lateral flexion	N/A	N/A	Less flexing away from the target, towards the trail side (more positive, less negative angles) in the low trajectories
Thorax lateral flexion	Lesser flexion of the thorax, so it's flexed towards the lead (positive angle) in the low trajectories		
Lead wrist deviation	N/A	N/A	Lesser wrist deviation angles in low trajectories
Centre of pressure	Distributed further towards the target (greater percentage) in low trajectories		

5.6. Main investigation

5.6.1. Introduction

The aim of the main investigation was to determine whether measurable differences exist between shot trajectories (*Aim 5)*. The investigation was broken down into two sections; one focused on the driver, the other on the 5-iron.

5.6.2. Participants

Thirteen participants (27 ± 11 years, 1.80 ± 0.08 metres, 81.0 ± 8.4 kilograms, 1.6 ± 1.7 handicap) volunteered for the study. Two golfers completed the driver session only, five golfers completed the iron session only, whilst six completed both. Prior to testing participants gave informed consent based on ethical approval gained from the Loughborough University Ethics Committee. The procedure was explained and the golfers were offered the opportunity to ask any questions.

5.6.3. Test clubs

Four club conditions were used for the testing: a standardised driver and 5-iron (Table 5-11) and each golfer's equivalent driver and 5-iron. A driver and 5-iron was chosen because the literature suggests biomechanical differences occur between driver and 5-iron swings and the clubs are longer; theory suggests longer clubs are more suited to manipulating shot trajectories (e.g. PGA, 2010; BBC, 2017a). Standardised clubs were used as a necessity for the GOM analysis (Section 3.2.2); scan meshes were an integral part of the analysis and were fitted to the tracked points so the entire clubhead could be tracked. Shots were taken with the golfer's own clubs to establish the influence of the standardised club on the golfers' swing biomechanics.

Table 5-11: Details of the standardised clubs used for the study.

Club	Make/ Model	Loft (º)	Length (mm)	Offset (mm)	Lie (º)	Bounce (º)	Head Weight (grams)	Head size (cc)	Swing Weight
Driver	Ping G25	9.5	1162	No	58	-	205	460	D3
5-Iron	Ping G	24.0	971	7	61.5	6.0	-	-	D0

5.6.4. Data collection

Prior to either data collection session, as for the pilot investigation, the sixty-six full-body marker set was placed on pre-designated landmarks on each participant (Figure 5-2; Smith, 2013). Following marker placement participants were permitted a self-guided warm-up to familiarise themselves with the laboratory environment and standardised club. Participants warmed up with a separate ball to avoid damage to the testing ball. When the participant was content testing begun using a GOM markered ball.

The driver session

Seven of the eight golfers who completed the driver session were right-handed. Golfers followed the procedure outlined below. Firstly, a static trial was taken in the anatomical position. Afterwards, four sets of 10 shots were completed by the golfer covering the following shot types:

- Draw trajectories with the standardised driver,
- Fade trajectories with the standardised driver,
- Their perceived natural trajectories with the standardised driver,
- Their perceived natural trajectories with their own driver.

The order of the shot types was randomised for each golfer. When changing club, the golfer was allowed to familiarise before shots were recorded. Golfers were asked to aim so the ball finished on a target line, defined by a laser line projected onto the hitting net. After each shot the golfers were asked for a rating from one to ten based on the quality of the strike (one equalled the worst possible shot, ten equalled the best possible shot). For the draw and fade trajectories it was emphasised the shot shape should be controlled, as if standing on a tee-box, to avoid hooking or slicing the ball. For the natural shots, golfers were asked prior to the testing how they prefer to drive the ball. They were asked to replicate this shot. Forty shots were specified to avoid golfer fatigue. Shots not tracked by the equipment or rated poorly by the golfer were repeated.

The iron session

The iron session followed the same procedures as the driver session. A static trial with the golfer in the anatomical position was initially taken. Sets of ten different shot sets were struck:

- Draw trajectories with the standardised iron,
- Fade trajectories with the standardised iron,
- Low trajectories with the standardised iron,
- Natural trajectories with the standardised iron,
- Natural trajectories with their own iron.

As with the driver, shot type order was randomised across golfers, familiarisation was allowed with each change of club and the target line was defined by a laser line projected onto the hitting net. The golfers were asked to produce a controlled draw or fade for the respective sets of shots and the shots were repeated if rated poorly or if they were not tracked by the equipment. Golfers were instructed to play low trajectory shots as if attempting to ensure initially ball flight was low. Finally, golfers' natural trajectories were based on how they would normally hit a 5-iron shot off the tee during course play.

Clubhead and ball tracking

The clubhead and ball were tracked across both sessions using the GOM system. This was due to the conclusions drawn from the study detailed in Chapters 3 and 4; the launch monitors were not suitable for use in scientific research when it came to measuring the clubhead-ball impact parameters identified as important for defining fade, draw and low trajectories (Table 5-3). The GOM process was the same for both sessions. Four Photron high speed cameras were used, operating in pairs; two to track the ball and two to track the clubhead

(Section 3.2). The high speed cameras were synchronised and for each swing triggered manually at the top of each subject's backswing. The camera images were then cropped to the region of interest – just before and after the club-ball impact. The cropping process and data save allowed the golfer time to recover between shots.

The images were processed in the way described in Section 3.2.2. Different parameters were of interest when determining the success of a shot. The important parameters for each type of trajectory, based upon scientific research and coaching points relating to impacts and ball flights were discussed in the earlier sections in this chapter (Table 5-3).

A ball flight algorithmic model allowed prediction of the outcome of each shot. The model was based on that of Smits & Smith, (1994) and gave an indication of the final landing position of the ball relative to the target line. A successful shot outcome was determined as landing on a theoretical fairway defined by an angle so that as the length of the shot increased, the width of the fairway increased. The width was controlled so that at a length of 300 yards (approximately 274 metres) the fairway had a width of 30 yards.

Motion analysis

As with the GOM system the motion analysis process was the same for each session. Fourteen VICON MX-T, eight VICON MX-T20 and six MX-T40, cameras captured each trial, set-up as in Figure 5-1. The cameras were aimed at the volume from which the golfer would hit. Individually, the cameras were focused and software thresholds adjusted to optimise the light entering each camera. Due to the presence of the GOM system there was a lot of light focused on the tee. This meant a part of the VICON volume was illuminated whilst the rest was not. This was problematic for each camera, particularly those facing the additional lighting. A result of this was more VICON noise than optimal around the tee. Camera focusing and threshold adjustments could not eliminate all noise and keep the rest of the volume optimised. Therefore, the noise was masked. The downside to this is data could be missed should a marker move through the mask. This could have implications for event definitions; for example, should the ball marker be obscured when its velocity exceeds 1 m/s, the event of ball contact could be miss-defined (Table 5-5). The VICON system was calibrated with the GOM lighting switched on, as it would be for data collection. Following calibration, the volume origin and coordinate axes was defined based on the two adjacent force plates in the centre of the laboratory, in a way that the target line was aligned equal to the GOM system. The forces plates were each covered in a piece of artificial turf and synchronised with the VICON system to capture kinetic data simultaneously. Data was then collected, including a static trial for each golfer as well as the dynamic movement swing trials. The VICON cameras operated at 250 Hz; whilst the force plates operated at 1000 Hz. Raw trials were saved for post-processing.

Each trial was reconstructed in VICON Nexus 1.8.5. For each golfer, the pre-defined VICON model was applied to the static trial. The static trial was then used to apply the auto-label function to the dynamic movement trials. Where mistakes occurred in labelling, these were manually corrected following the auto-labelling process. Additionally, gaps were filled through either the spline fill function or pattern fill function, in-built into the software. The pattern fill was used when there was a marker with similar trajectory to base the fill upon, for example the markers on the lateral and medial wrist (R/LULN and R/LRAD; Figure 5-2). The spline fill was used when there was no similar marker. Post-processing of the static and dynamic trials created a .c3d file to be used for further analysis. For each golfer in turn, the static trial .c3d file was imported into a new Visual3D workspace. A pre-built Visual3D model (Table 5-4) was applied to the static trial, following which the dynamic movement trials for the particular golfer were imported and the static trial assigned to the dynamic trials. For each segment of the model a local coordinate system was generated. This process enabled calculation of the biomechanical variables through a pre-written Visual3D pipeline across the whole-swing. For the kinematic data, initially, raw body marker positions were Butterworth low-pass filtered at 15 Hz. A Butterworth low-pass filter frequency of 20 Hz was applied to the club marker positions and 25 Hz was applied to the raw force data. These filter frequencies were subjectively based on knowledge of the data signal (Robertson et al., 2013) and on the frequency spectra analysis conducted by Smith, (2013). Swing events were then identified (Table 5-5) and manually checked to ensure the correct points of the swing had been identified. Once swing events were confirmed and all variables were calculated the data was exported to MATLAB for statistical analysis. In MATLAB, the data for each shot was normalised from swing event to swing event to make comparisons across shots possible. Data was time normalised based on a number of points that represented the approximate average relative timings for each phase.

5.6.5. Statistical Analysis

Biomechanically, the comparisons of interest were the draw against fade, the natural against low and the natural against the golfer's own club. The third comparison gave an indication of whether the standardised clubs influenced the golfers' natural swing. Statistical analysis was carried out in two parts, at address and ball contact as well as over the whole-swing.

Shot selection

Draw-fade analysis

Draw-fade analyses were based on spin axis, launch direction and face-to-path angle impact parameters. The draw-like negative spin axis and face-to-path angle and positive launch direction shots could be compared against the fade-like opposites. A final category included the trajectory model shot outcome of each shot trajectory. The shot characteristics were ordered in terms of perceived importance for the respective shot trajectory. Spin axis was considered most important due to its importance in draw or fade curvature during flight (Section 2.2.2), then whether the ball landed on the trajectory model fairway (i.e. the shot was successful). Of next importance was the launch direction of the ball, as coaches often referred to a draw starting right of target and a fade left. Finally, of least importance was the face-to-path angle of the clubhead, due to it being a club parameter. With the addition of each sequential characteristic, the percentage of successful shots was calculated (Figure 5-3 and Figure 5-4). To ensure multiple trials for each golfer were included in the analyses a cut-off of 40% was set. For the driver analysis, often when the third characteristic, launch direction, was included the success percentage for one of or both draw and fade trajectories fell below 40%. Therefore, it was decided to include only shots that had the correct spin axis and the trajectory model shot outcome. On this basis, golfer two was removed from the driver analysis. Similarly, for the 5-iron analysis, spin axis and trajectory model shot outcome were used as the basis for the analysis. Consequently, golfers five, six, ten and eleven were removed from the 5-iron analysis. For the analysis, the shots with the most extreme results for each golfer were included, for example the most negative spin axis against the most positive that also landed on the trajectory model fairway.

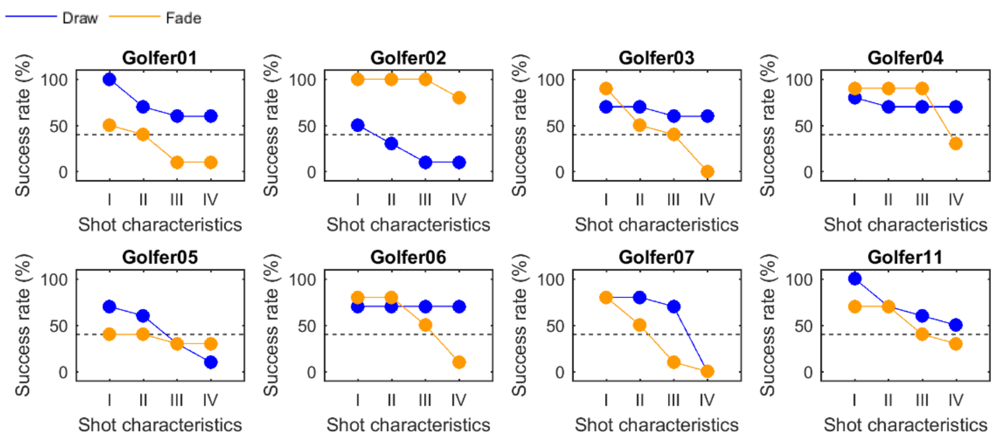


Figure 5-3: Driver draw-fade success rates with the inclusion of each characteristic by golfer. The X-axis contains the shot characteristics, ordered by importance (I = spin axis, II = shot outcome, III = launch direction and IV = face-to-path angle).

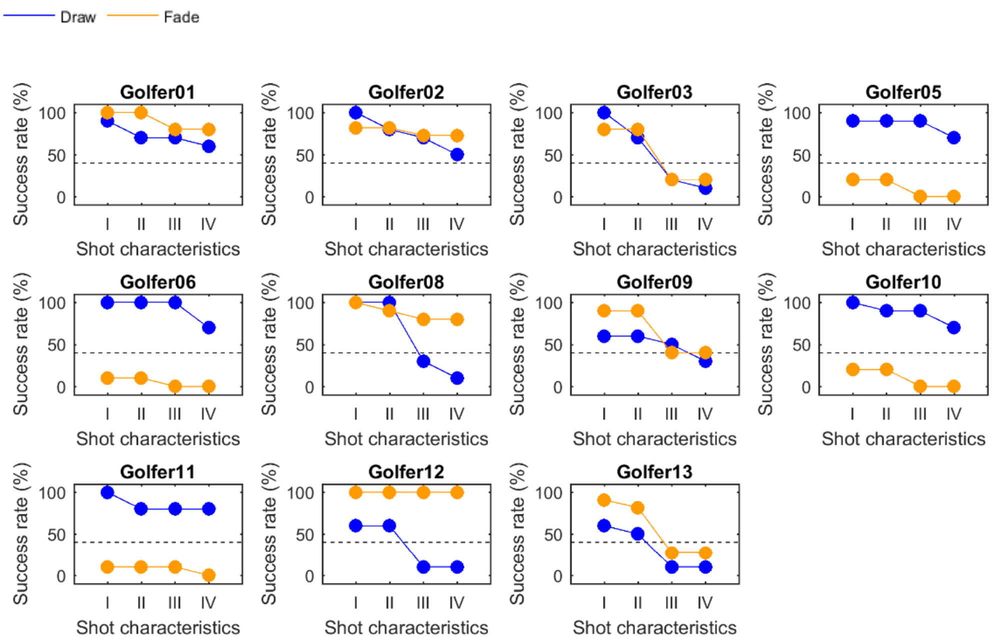


Figure 5-4: 5-Iron draw-fade success rates with the inclusion of each characteristic by golfer. The X-axis contains the shot characteristics, ordered by importance (I = spin axis, II = shot outcome, III = launch direction and IV = face-to-path angle).

Low-natural analysis

For the low-natural comparison lower launch angle, back-spin, and spin loft could be compared against the natural values. Launch angle was used, as opposed to peak height, due to the laboratory environment (see Section 5.3.4). Low launch angle, back-spin and spin loft were defined as less than the mean minus one standard deviation of the natural shot values. Again, the trajectory model shot outcome of each shot trajectory formed the final category. Launch angle was considered the most important characteristic of a low trajectory, forming the main definition by coaches. Of secondary importance was the trajectory model outcome, determining whether the shot was successful. The third important parameter was backspin, due to its association with peak ball height during flight, and finally, of least importance was spin loft, due to it being a club parameter. The percentage of successful shots, with the addition of each category was calculated (Figure 5-5). As a result, launch angle and trajectory model shot outcome formed the basis of the analysis, with backspin rate and spin loft being removed. The greater success rates following the inclusion of the trajectory model shot outcome allowed for the cut-off to be increased to 50% to facilitate the inclusion of more trials into the analysis and no golfers were removed from the analysis. The most extreme low trajectory shots were chosen for analysis versus the five median launch angle successful natural trajectory shots.

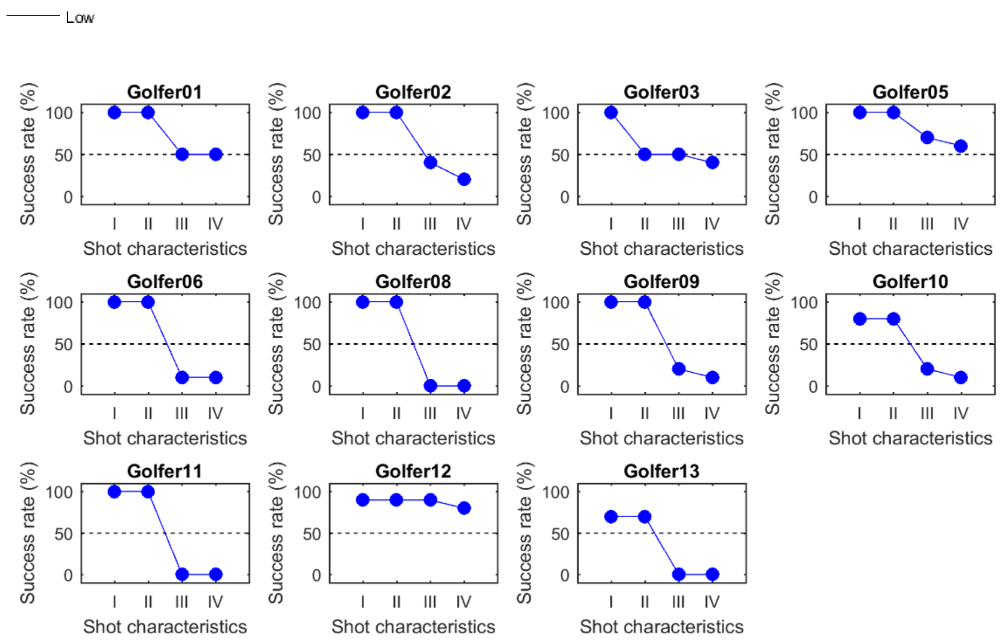


Figure 5-5: 5-Iron low-natural success rates with the inclusion of each characteristic by golfer. The X-axis contains the shot characteristics, ordered by importance (I = spin axis, II = shot outcome, III = backspin and IV = spin loft).

Impact location

To investigate whether the shot trajectories were due to differences in impact location rather than golfer biomechanics, the draw and fade as well as the low and natural trajectory impact locations of the shots identified above were compared statistically at a group and an individual-level using mixed model two-way analysis of variance with Bonferroni post-hoc tests ($\alpha = 0.05$).

Event analysis

The address variables were tested on a group-basis using the shots identified above, to identify biomechanical differences between shot trajectories. The data was initially tested for normality using Kolmogorov-Smirnov checks. For normally distributed data mixed model two-way analysis of variance (shot trajectory and golfer) with Bonferroni post-hoc tests were used to uncover significant shot and golfer interactions. Cohen's d effect sizes were then calculated; small, moderate and large were categorised as 0.2, 0.5 and 0.8 respectively (Cohen, 1969). For non-normally distributed data Friedman or Skillings-Mack with Wilcoxon signed rank post-hoc tests were conducted to determine differences between shots on a group basis. Effect sizes were again calculated (Rosenthal, 1994). The initial tests before multiple comparison correction were conducted with a significance level of $\alpha = 0.05$. The same process was then followed for the ball contact variables (Table 5-7).

Whole-swing analysis

The shot trajectories were investigated over the whole-swing, again using the shots selected above, to identify any swing changes golfers may have used when hitting the different trajectories. Firstly, the data curves were inspected visually to identify differences between shot trajectories. A data reduction technique, principal component analysis (Section 2.4), was then performed to more robustly identify key aspects of the swing for each shot trajectory. An advantage of the analysis is it can be used across the entire data curve and it has been applied to investigate different test conditions (see Section 2.4). The whole-swing is accounted for in terms of offset, magnitude, rate of change and timing differences.

For each shot comparison, the subsequent procedure was followed. For each biomechanical variable, an $n \times p$ matrix ***X*** was produced, comprising the shots from each golfer identified above, where n rows were trials and p columns were normalised time points. The same number of trials from each golfer was used to avoid introducing bias into the analysis. Principal components analysis was then performed on the covariance matrix of ***X****.* The results were orthonormalised for comparison across golfers. The principal components analysis had two main outputs. The first output was a $p \times n$ eigenvector matrix ***U***, the columns of which represented the coefficients for each principal component and the rows of which represented the weighting at each time point. The matrix ***U*** was arranged such that the columns were structured in descending order of the amount of variance the principal components explained within the data set. The second output was an $n \times 1$ eigenvalue vector ***L*** which contained the relative contribution of each principal component to the total variation. Scree analysis was used to reduce the data by discarding the remaining principal components once 90% of the data was explained leaving a model containing ***k*** principal components; previous principal components analysis in golf has typically led to the retention of two to five principal components at this threshold (Lynn et al., 2012; Smith, 2013; Smith et al., 2016). A cut-off threshold of 90% allowed for reduction in the amount of data whilst the majority was retained.

An $n \times n$ matrix of principal component scores ***S*** was computed by standardising ***X***, via z-scores, and multiplying by the eigenvector matrix ***U*** (Equation 5-1).

$$S = XU \tag{5-1}$$

Matrix ***S*** was initially used for residual analysis to assess the quality of the principal component model. The original data matrix ***X*** was reconstructed using only the retained principal components ($n \times k$ matrix ***S*** and $p \times k$ matrix ***U***) creating an $n \times p$ matrix $\hat{\boldsymbol{X}}$ (Equation 5-2; Jackson, 1991; Wrigley et al., 2006; Smith, 2013).

$$\hat{X} = SU + \bar{X} \tag{5-2}$$

where $\bar{\boldsymbol{X}}$ is the overall data mean. The reconstructions were visually inspected to ensure the retained principal components represented the overall data set. Furthermore, for each trial of each analysis a Q-statistic representing the sum of the squares of the residuals when comparing the reconstructed and original data matrices was calculated (Equation C-1; Appendix C; Jackson, 1991).

A critical value by which Q was judged was then calculated (Equation C-2 to Equation C-6; Appendix C; Jackson, 1991). If a Q-statistic corresponding to a trial exceeded the critical threshold the ***k***-component model could be judged as not fitting the data for the particular trial. The percentage of trials which satisfied the critical threshold was calculated. Overall, the Q-statistic satisfied the critical value 97.3%, 95.9% and 96.5% of the time for the driver draw-fade, 5-iron draw-fade and 5-iron low-natural trajectory analyses respectively.

The principal component score matrix ***S*** was used for the interpretation of the principal components analysis and to identify differences between shot trajectories (Deluzio et al., 1997; Wrigley et al., 2005; Deluzio & Astephen, 2007; Muniz & Nadal, 2009; Kobayashi et al., 2014). To compare shot trajectories, for each biomechanical variable, the principal component scores for each shot trajectory were treated separately. Firstly, they were tested for normality using Kolmogorov-Smirnov tests. The scores of each shot trajectory were then compared through paired t-tests with Cohen's d effect sizes for the normally distributed scores. For non-normally distributed the scores were compared through Wilcoxon signed rank tests and effect size (Rosenthal, 1994) was again calculated. Tests were conducted at a significance level of $\alpha = 0.05$.

To interpret the principal components analysis the results were displayed graphically one variable at a time (Ramsay & Silverman, 2005; Wrigley et al., 2006; O'Connor & Bottum, 2009; Smith, 2013). First of all, the coefficients of the principal components that explained over 90% of the variance were plotted. Secondly, for each of the principal components the coefficients (the corresponding column of ***U***) multiplied by a constant were added to and subtracted from the mean data curve $\bar{\boldsymbol{X}}$. These mean plus and mean minus curves were then plotted on top of the $\bar{\boldsymbol{X}}$ (Figure 5-6). The method enabled offset, timing, magnitude and rate of change differences to be identified (Section 2.4). Finally, principal component scores (columns of $\boldsymbol{S}$) were plotted against one another. A specific marker represented a single shot by a golfer and shot trajectories were distinguished by representation with either a filled or a non-filled marker. A positive score for a shot for any given principal component corresponded to a pattern for the given biomechanical variable more like the principal component coefficients added to the mean curve (Figure 5-6; red crosses). Conversely, a negative score meant the opposite (Figure 5-6; green dashes). Similarly, for a given golfer, if the draw scores were less positive or more negative than the fade scores the biomechanical pattern could be interpreted as more like the mean minus the coefficients (Figure 5-6; green dashes). Contrariwise, if the draw scores were more positive or less negative they could be interpreted the opposite (Figure 5-6; red crosses).

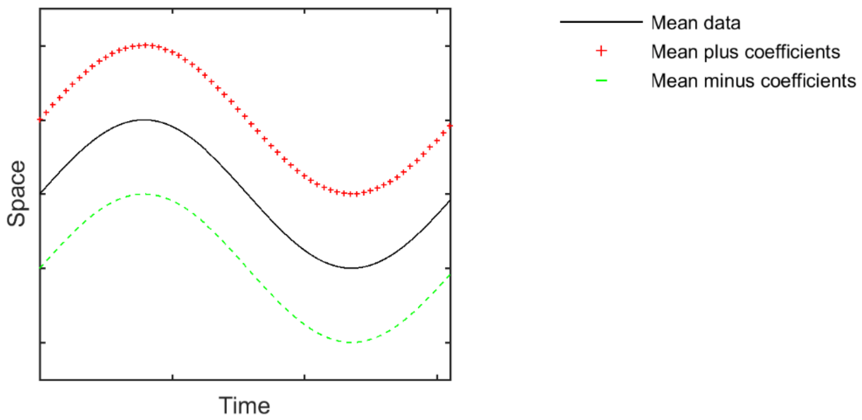


Figure 5-6: Example mean data curve plus and minus the principal component coefficients multiplied by a constant.

A final aspect involved the instantaneous swing planes. These were statistically analysed over the whole-swing using the same methods as for the other biomechanical variables. However, separate analyses were conducted for the backswing and downswing.

To investigate the swings on a more individual-level, for each golfer, the principal component scores of each trajectory were made relative to the natural shot. The scores of each golfer's opposing trajectories were then plotted against one another. For both clubs the fade scores were then subtracted from the draw scores to find the difference in scores between the shot trajectories. The same was done by taking the natural scores from the low scores for the 5-iron. These were then plotted, for all golfers, so similarities in swing patterns could be seen. T-tests then determined which golfers difference scores significantly differed from zero ($\alpha = 0.05$).

The final step of the analysis to identify individual golfers with similar swing patterns, multivariate correlation was performed containing all golfers' principal component difference scores to compare swing patterns of each golfer with that of all others.

5.7. Summary

Initially, the coaching literature regarding different trajectories was investigated through a literature search and face-to-face interviews with Professional Golf Association qualified coaches. This identified key coaching arguments and points related to each of the shot trajectories: draw, fade, high and low. Following the coach investigation high shots were excluded from the study; high shots were considered less important and less utilised than the other shot trajectories. For similar reasons, low trajectories for the driver session were excluded.

Biomechanical variables were identified from the coaching points and hypothesised differences formed regarding each variable. Draw trajectories were hypothesised to differ from fade at address through stance openness (more closed), pelvis rotation (more closed), thorax rotation (more closed), lead hand height (lower), thorax lateral flexion (rotated towards the lead) and centre of pressure (more towards the target). Over the whole-swing, the draw trajectories were hypothesised to differ via pelvis rotation, thorax rotation and X-factor (more rotated away), thorax lateral flexion (towards the lead), lumbar lateral flexion (towards the trail), lumbar forward flexion (more flexion), pelvis translation (greater translation towards the target), trail shoulder abduction (greater abduction), lead wrist supination (more supination), lead wrist deviation (less deviation) and centre of pressure (more towards the target). Finally, at ball contact, the same hypotheses were made as at address, for the relevant variables, with the addition of a more in-to-out and flatter swing plane in the draw trajectories.

Hypothesised differences at address for the low trajectories versus the natural included: ball position (away from the target), stance width (narrower), grip distance (smaller), lead hand forwardness (towards the target), thorax lateral flexion (towards the lead) and centre of pressure (towards the target). Over the whole-swing, the low trajectories were hypothesised to have slower pelvis, thorax and X-factor rotations, have a lumbar lateral flexion towards the trail and a thorax lateral flexion towards the lead, a lesser lead wrist deviation and a centre of pressure further towards the target. Finally, at ball contact, the same trajectories were hypothesised to have a lead hand forwardness further towards the target.

The main methodology was finalised in the final sections of the chapter. Golfer biomechanics were captured through motion analysis. The clubhead and ball were tracked using the GOM system (Section 3.2). Draw-fade and low-natural trajectory biomechanical analysis was conducted at address and ball contact using mixed model analysis of variance and over the whole-swing using principal components analysis and multivariate correlation.

CHAPTER SIX

THE ROLE OF BIOMECHANICS IN ACHIEVING DIFFERENT SHOT TRAJECTORIES WITH THE SAME CLUB – A GROUP-BASED FOCUS

6.1. Introduction

This chapter presents the results of the main biomechanical investigation at a group-based level. By doing this the chapter addresses the question "do measurable biomechanical differences exist when a golfer plays different types of shot trajectory with the same club? If so, what are the differences?" The comparisons of interest were the draw against the fade, low against natural trajectory and standardised club against golfers' normal clubs.

Based upon coaching points testable hypotheses were defined (Section 5.5.3):

> *Hypothesis:* A golfer will significantly alter their swing biomechanics to achieve different shot trajectories, as outlined in Table 5-9 and Table 5-10.

Golfers' swing biomechanics are evaluated in terms of the variables that coaches considered important to achieve the outcome of each shot trajectory and therefore were expected to differ between trajectories (Table 5-9 and Table 5-10) including address, ball contact and whole-swing analysis.

6.2. Use of standardised clubs

The results show a small number of differences between the standardised club and the golfers' own clubs for both the driver and 5-iron. However, the majority of these differences were of small magnitude and effect size. The exceptions, classified as moderate effect size, were lead hand forwardness at address (mean difference 15 ± 41 mm), trail shoulder abduction over the entire swing for the driver, (representing an offset between shot trajectories) and pelvis rotation at address for the 5-iron (mean difference of 1.2 ± 2.2º).

6.3. Driver draw versus fade

6.3.1. Magnitude of shot trajectories

The magnitude of fade and draw spin axes for all shots across all golfers are shown in Figure 6-1. On average the golfers achieved a more pronounced negative draw spin axis than positive fade spin axis, although the draw spin axis was more inconsistent.

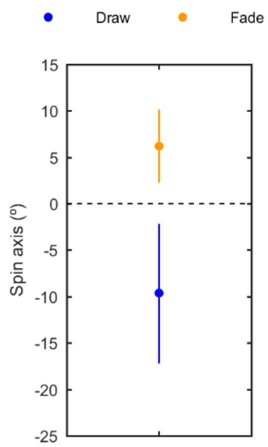


Figure 6-1: Mean spin axis (± 1 SD) for driver draw and fade trajectories across all golfers included in the analysis.

6.3.2. Impact location

Statistics related to the impact location on a group basis are shown in Table 6-1. The table shows that on a group-based level, there was a significant difference in impact location. This occurred for vertical impact location. However, in practical terms the difference is small (8 mm).

Table 6-1: Comparison of the overall golfer mean (& SD) impact locations relative to the geometric clubface centre for the draw and fade trajectories with the driver. Also shown are the upper and lower 95% confidence intervals.

Horizontal impact location (mm)					Vertical impact location (mm)				
Draw	Fade	p-value	Lower	Upper	Draw	Fade	p-value	Lower	Upper
-6 (7)	-6 (9)	0.1579	-6.4	0.9	-1 (13)	7 (13)	*0.0335*	-13.7	-0.5

6.3.3. Example variable results

Example driver draw-fade results are shown in Figure 6-2 and Figure 6-3, to illustrate some of the initial visual differences between draw and fade trajectories. For example, offsets are apparent in pelvis rotation (Figure 6-2d), pelvis translation (Figure 6-2j), lumbar lateral flexion (Figure 6-2e), thorax lateral flexion (Figure 6-2h) and horizontal swing plane (Figure 6-3a). Additionally, there appear to be magnitude differences in lumbar forward flexion (Figure 6-2b), trail shoulder abduction (Figure 6-2k) and centre of pressure (Figure 6-2i). Finally, another potential difference is a rate of change difference in vertical swing plane (Figure 6-3b).

The data in Figure 6-2 and Figure 6-3 provide an initial indication of variable patterns for each shot trajectory and differences between the shot conditions are visible. However, further analysis is required to explore the differences more objectively.

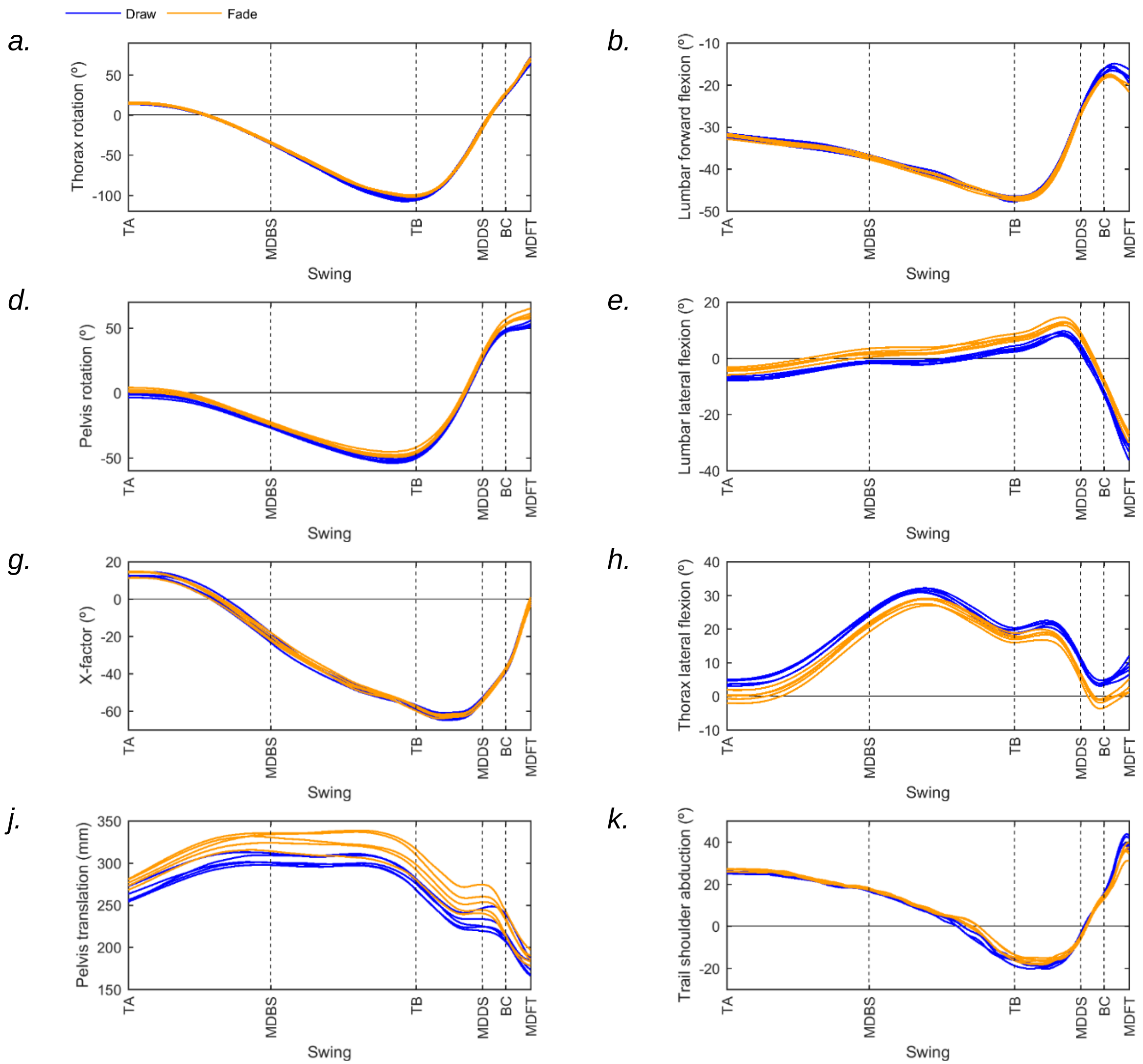


Figure 6-2: Example results (golfer eleven): a. thorax rotation; b. lumbar forward flexion; c. lead wrist deviation; d. pelvis rotation; e. lumbar lateral flexion; f. lead wrist supination; g. X-factor; h. thorax lateral flexion; i. centre of pressure; j. pelvis translation and k. trail shoulder rotation.

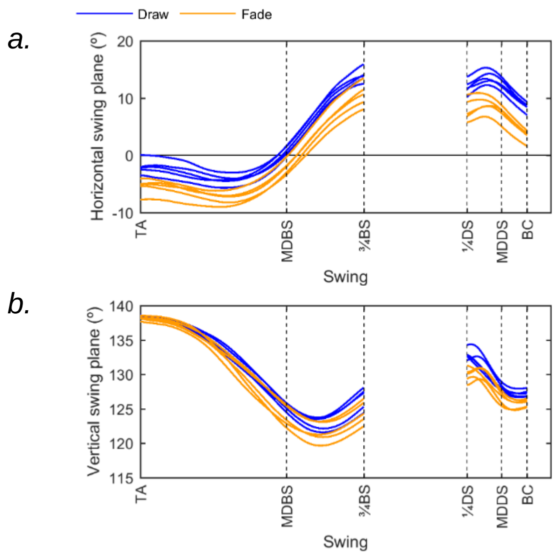


Figure 6-3: Example results (golfer eleven): a. horizontal swing plane and b. vertical swing plane.

6.3.4. Group event results

Address

Significant differences in mean address variables between the draw and fade were found (Table 6-2), constituting ball position, lead hand forwardness, thorax lateral flexion, pelvis rotation, thorax rotation and stance openness.

Table 6-2: Overall mean (& SD) driver draw-fade variable comparisons at address. The p-value, calculated from the z-value, represents the probability that there is a significant difference between the draw and the fade (MATLAB, 2017).

Variable	Significant	p-value	z-value	Effect size	Draw	Fade
Pelvis rotation (º)	*	*<0.0001*	4.00	0.63	2.7 (3.1)	4.4 (3.6)
Thorax rotation (º)	*	*<0.0001*	4.00	0.63	16.2 (3.5)	17.0 (4.4)
Stance openness (º)	*	*0.0002*	3.72	0.59	-2.7 (2.3)	1.6 (2.1)
Ball position (mm)	*	*<0.0001*	-4.93	-0.78	-72 (48)	-42 (53)
Stance width (mm)		0.5866	0.54	0.09	522 (66)	529 (64)
Grip distance (mm)		0.7718	-0.29	-0.05	149 (20)	147 (16)
Lead hand forwardness (mm)	*	*<0.0001*	-5.09	-0.80	44 (55)	80 (62)
Lead hand height (mm)		0.3496	-0.94	-0.15	732 (44)	731 (46)
Thorax lateral flexion (º)	*	*<0.0001*	6.24	0.99	-2.7 (5.3)	-5.2 (4.6)
Centre of pressure (%)		0.0565	1.91	0.30	54 (6)	52 (8)

Ball contact

The comparisons for the variables analysed at ball contact are shown in Table 6-3. The horizontal swing plane, lead hand forwardness, thorax lateral flexion and pelvis rotation were significantly different between the draw and fade trajectories.

Table 6-3: Overall mean (& SD) driver draw-fade variable comparisons at ball contact. The p-value, calculated from the z-value, represents the probability that there is a significant difference between the draw and the fade (MATLAB, 2017).

Variable	Significant	p-value	z-value	Effect size	Draw	Fade
Pelvis rotation (º)	*	*<0.0001*	-4.72	0.75	57.6 (30.8)	62.5 (29.5)
Thorax rotation (º)		0.3571	-0.92	-0.15	31.1 (5.6)	31.5 (5.1)
Lead hand forwardness (mm)	*	*0.0011*	-3.25	-0.51	-46 (65)	-30 (50)
Lead hand height (mm)		0.1090	1.60	0.25	844 (33)	852 (85)
Thorax lateral flexion (º)	*	*<0.0001*	5.34	0.84	3.7 (4.6)	-1.9 (4.7)
Centre of pressure (%)		0.1490	1.44	0.23	68 (32)	65 (32)
Swing plane vertical (º)		0.6746	0.42	0.07	131.9 (2.0)	131.0 (2.4)
Swing plane horizontal (º)	*	*<0.0001*	-4.67	-0.79	5.5 (4.0)	-0.9 (4.4)

6.3.5. Group swing results

Principal component analysis was conducted on the trials which successfully achieved the desired spin axis tilt and landed within the fairway for each golfer for draw-fade comparisons (Section 5.6.5). Across the analyses the number of principal components required to explain 90% of the variance in the data set for each model ranged from one to five, with the most common being two or three principal components.

Principal component analysis identified changes in the respective variable principal scores (Figure 6-4) between shot trajectories and between golfers. To biomechanically interpret the different principal components (Table 6-4) each variable's mean curve was plotted, to which the principal component coefficients multiplied by a constant were added and subtracted (Figure 6-5; Appendix D). For example, pelvis translation principal component one represented an offset whereby the mean plus curve showed a pelvis translation offset further away from the target and the negative further towards the target (Figure 6-5a). Principal component two showed a magnitude difference whereby, the mean plus curve showed a greater magnitude of translation towards the target (Figure 6-5b).

The analysis resulted in 18 significantly different principal components between the driver shot conditions across nine variables: centre of pressure, thorax lateral flexion, lumbar forward flexion, lumbar lateral flexion, pelvis rotation, pelvis translation, thorax rotation, X-factor and horizontal swing plane. Within Table 6-4 offsets refer to absolute differences between negative and positive principal component scores occurring over the whole-swing, whereas timing, magnitude and rate of change differences were relative differences.

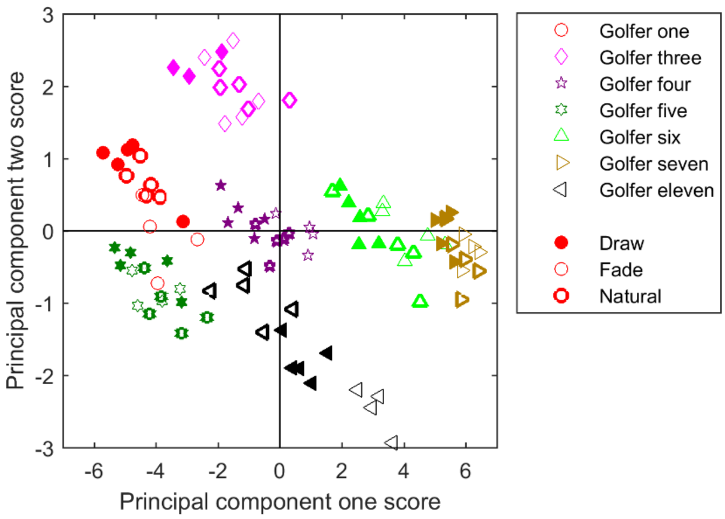


Figure 6-4: Example principal component score (driver pelvis translation) plot.

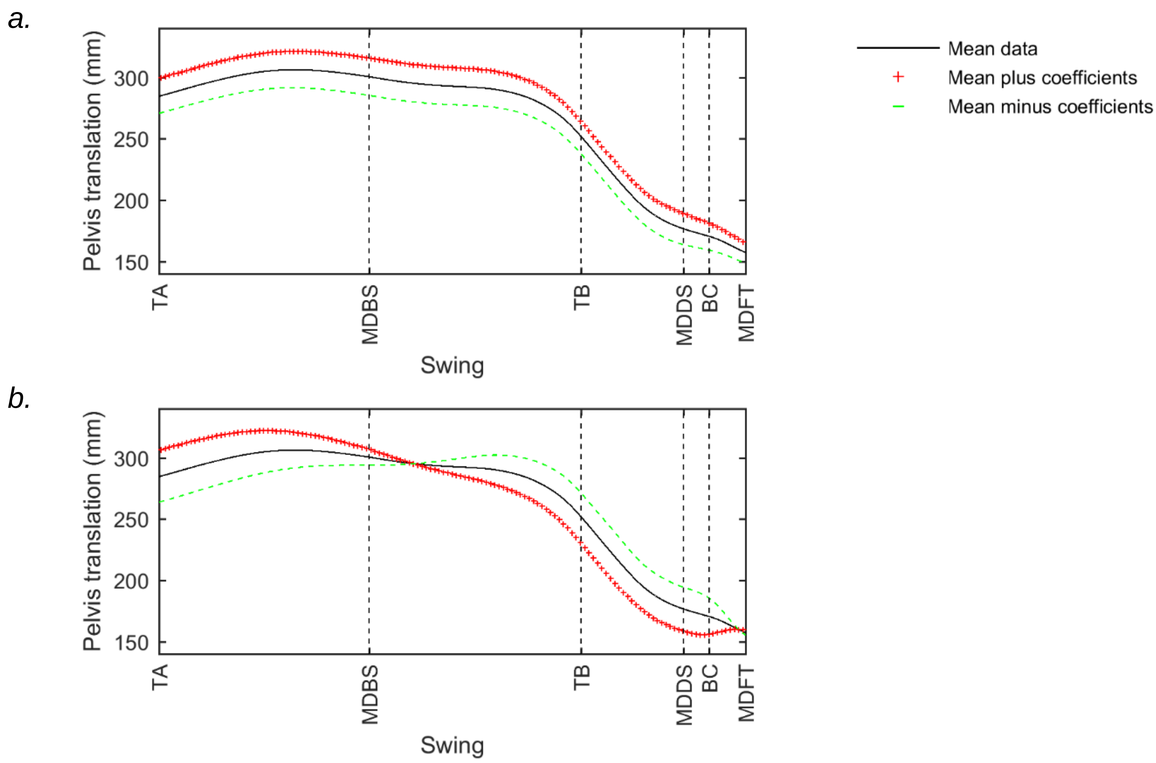


Figure 6-5: Example variable (driver pelvis translation) mean curve plus and minus the principal component coefficients multiplied by a constant, to aid biomechanical interpretation of the principal components: a. principal component one and b. principal component two.

Table 6-4: Principal component (PC) differences between the driver draw and fade trajectories. Italics indicates significantly different principal components. Also shown are the corresponding percentages of the variance each principal component explained and the biomechanical interpretation. Grey shading indicates findings associated with draw trajectories, white shows those associated with fade.

Variable	PC	Explained variance (%)	p-value	z-value	Effect size	Interpretation type	Positive difference between scores	Negative difference between scores
Pelvis rotation	1	77.4	*0.0109*	-2.55	0.43	Offset	Lesser rotation away from the target.	Greater rotation away from the target.
	2	12.4	*<0.0001*	-4.46	-0.44	Timing	Earlier rotation away from the target, followed by earlier rotation towards the target. Rotated more towards the target in the downswing.	Later rotation away from the target, followed by later rotation towards the target. Rotated less towards the target in the downswing.
Thorax rotation	1	68.1	0.1169	-1.57	-0.27	Magnitude Timing	Later, lesser rotation away, followed by a less rotated away from the target lag.	Earlier, greater rotation away, followed by a more rotated away from the target lag.
	2	13.6	*0.0143*	2.45	0.43	Magnitude	Greater rotation away from the target. Greater rotation towards.	Lesser rotation away from the target. Lesser rotation towards.
	3	10.4	0.2099	1.28	0.22	Magnitude Timing	Quicker rotation away. Earlier rotation towards, which halts around ball contact.	Slower rotation away. Later rotation towards, which continues through ball contact.
X-factor	1	51.6	0.9501	0.06	0.01	Magnitude	Lesser thorax rotation relative to the pelvis during the backswing and early downswing.	Greater thorax rotation relative to the pelvis during the backswing and early downswing.
	2	33.4	0.3391	0.96	0.16	Offset	Lesser thorax rotation away relative to the pelvis.	Greater thorax rotation away relative to the pelvis.
	3	7.9	*0.0463*	-1.99	-0.34	Timing	Immediate thorax rotation away relative to the pelvis. Halting of the rotation during the late backswing, followed by a continuation around top of the backswing. Later thorax rotation towards the pelvis in the downswing.	Later thorax rotation away relative to the pelvis. Earlier thorax rotation towards the pelvis in the downswing.
Lumbar forward flexion	1	52.2	0.0754	1.78	0.30	Magnitude	Greater flexing in the backswing. Greater extending in the downswing.	Lesser flexing in the backswing. Lesser extending in the downswing.
	2	34.6	*0.0155*	2.42	0.41	Magnitude Rate of change	Less flexed over the backswing. Slower extending in the downswing.	More flexed over the backswing. Quicker extending in the downswing.
	3	10.4	0.1405	1.47	0.25	Magnitude	Stable in the second half of the backswing, followed by extending in the downswing.	Flexing in the second half of the backswing, followed by to extending in the downswing.
Lumbar lateral flexion	1	75.1	*<0.0001*	-4.19	-0.71	Offset	Greater flexion towards the lead.	Greater flexion towards the trail.
	2	12.2	*0.0010*	-3.28	-0.55	Magnitude Timing	Flexed towards the lead initially. Flexing towards the trail around mid-backswing, followed by a reversal flexing towards the lead. More towards the lead in the downswing.	Flexed towards the trail initially. Flexing towards the lead in the mid-backswing. Earlier flexing towards the trail in the late backswing. More flexed towards the trail in the downswing.
	3	6.6	*0.0434*	-2.10	-0.03	Magnitude	Flexing towards the trail in the early backswing, followed by flexing towards the lead in the later backswing. Halt of the flexing towards the trail around mid-downswing.	Flexing towards the lead during the backswing. More prolonged flexing towards the trail in the downswing.
Thorax lateral flexion	1	72.2	*<0.0001*	4.12	0.70	Magnitude	Greater flexing towards the lead in the early backswing. More flexed towards the lead over the middle stages. Greater flexing towards the trail in the downswing.	Lesser flexing towards the lead in the early backswing. More flexed towards the trail over the middle stages. Lesser flexing towards the trail in the downswing.
	2	10.4	*0.0149*	2.57	0.20	Magnitude	More flexed towards the lead initially, followed by a greater reversal towards the trail and re-reversal towards the lead in the late backswing. More flexed towards the trail in the downswing.	More flexed towards the trail initially, followed by lesser reversal towards the lead and re-reversal towards the trail in the late backswing. More flexed towards the lead in the downswing.
	3	8.5	*0.0001*	3.89	0.66	Magnitude Timing	Greater flexing towards the lead in the backswing. Reversal towards the lead and re-reversal towards the trail in the late backswing. Continued flexing towards the trail in the downswing.	Lesser flexing towards the led in the backswing. Earlier flexing towards the trail in the late backswing into the downswing. Reversal of the flexing around ball contact.
Pelvis translation	1	88.2	*0.0005*	-3.90	-0.75	Offset	Greater translation away from the target.	Lesser translation away from the target.
	2	7.5	*0.0002*	3.69	0.62	Timing	Translated further away from target initially. Earlier forward translation.	Translated further towards the target initially. Later forward translation.
Trail shoulder abduction	1	87.8	0.2641	-1.12	-0.19	Offset	Greater adduction.	Greater abduction.
	2	5.5	0.8372	0.21	0.04	Magnitude	Greater abducting in the backswing and early downswing. Greater adducting in the downswing.	Lesser abducting in the backswing and early downswing. Lesser adducting in the downswing.
Lead wrist deviation	1	66.8	0.4684	-0.73	-0.12	Offset	Greater radial deviation.	Greater ulnar deviation.
	2	25.4	0.6951	-0.39	-0.07	Magnitude	Greater radial deviation in the backswing, greater ulnar deviation in the downswing.	Lesser radial deviation in the backswing, lesser ulnar deviation in the downswing.

Variable	PC	Explained variance (%)	p-value	z-value	Effect size	Interpretation type	Positive	Negative
Lead wrist supination	1	82.1	0.4405	-0.77	-0.13	Offset	Greater supination.	Greater pronation.
	2	10.3	0.6884	-0.40	-0.07	Magnitude	Greater pronating during the backswing and early downswing. Greater supinating in the downswing.	Lesser pronating during the backswing and early downswing. Lesser supinating in the downswing.
Centre of pressure	1	47.6	0.0913	1.69	0.29	Magnitude	Greater shift away from the target during the backswing. Greater shift towards during the downswing, followed by a reversal around mid-downswing.	Lesser shift away from the target during the backswing. Lesser shift towards the target during the downswing, followed by a reversal around mid-downswing.
	2	23.4	0.7818	-0.28	-0.05	Magnitude Rate of change	Lesser shift away, followed by a slower forward shift in the backswing, which quickens around top of the backswing.	Greater shift away. Halting of the forward shift in the downswing.
	3	11.3	*0.0075*	2.86	0.39	Timing	Later shift away, followed by earlier shift forward.	Earlier shift away, later shift forward.
	4	6.5	*<0.0001*	3.94	0.67	Magnitude Rate of change	Less towards the target initially. Marginally quicker forward shift.	Less away from the target initially. Marginally slower forward shift.
	5	6.2	*0.0276*	2.31	0.39	Magnitude Rate of change	More towards the target initially. Shift away, followed by a greater forward shift.	Less towards the target initially. Slowing of the forward shift in the mid-downswing.
Swing plane horizontal backswing	1	88.3	*0.0092*	2.60	0.47	Offset	Greater out-to-in plane.	Greater in-to-out plane.
	2	4.6	0.8454	-0.20	-0.03	Magnitude	Becomes an increasingly out-to-in plane initially, followed by a reversing and becoming an increasingly in-to-out plane.	Becomes an increasingly in-to-out plane initially, followed by a reversing and becoming an increasingly out-to-in plane.
Swing plane horizontal downswing	1	95.5	*<0.0001*	4.67	0.85	Offset	Greater in-to-out plane.	Greater out-to-in plane.
Swing plane vertical backswing	1	78.8	0.4015	0.85	0.14	Offset	Flatter plane.	Steeper plane.
	2	18.0	0.5124	0.66	0.11	Magnitude	Greater steepening around mid-backswing.	Lesser steepening around mid-backswing.
Swing plane vertical downswing	1	98.5	0.4611	0.74	0.13	Offset	Flatter plane.	Steeper plane.

6.3.6. Hypothesis outcomes

The outcome of the hypotheses presented in Section 5.5.3 are given in relation to the driver draw-fade outcomes in Table 6-5. The table also indicates whether differences between draw and fade trajectories emerged in addition to the specific hypotheses regarding each variable.

Table 6-5: Outcomes of the hypothesised changes, supported (✓), rejected (✗) or not applicable (N/A), in the biomechanical variables between the driver draw and fade trajectories at address, ball contact and over the whole-swing. Other outcomes refers to non-hypothesised differences between the trajectories.

Variable	Address	Ball contact	Whole-swing	Other outcomes
Pelvis rotation	✓	✓	✓	✓
Thorax rotation	✓	✗	✗	✓
X-factor	N/A	N/A	✗	✓
Stance openness	✓	N/A	N/A	✗
Ball position	N/A	N/A	N/A	✓
Lead hand forwardness	N/A	N/A	N/A	✓
Lead hand height	✗	✗	N/A	✗
Lumbar forward flexion	N/A	N/A	✗	✓
Lumbar lateral flexion	N/A	N/A	✓	✓
Thorax lateral flexion	✓	✓	✓	✓
Pelvis translation	N/A	N/A	✓	✓
Trail shoulder abduction	N/A	N/A	✗	✗
Lead wrist supination	N/A	N/A	✗	✗
Lead wrist deviation	N/A	N/A	✗	✗
Centre of pressure	✗	✗	✓	✓
Instantaneous swing plane horizontal	N/A	✓	✓	✗
Instantaneous swing plane vertical	N/A	✗	✗	✗

6.3.7. Group swing patterns

To achieve a draw or a fade trajectory golfers made biomechanical changes at address and regulated central body segments and kinetics relative to the opposite trajectory during the swing. Major changes occurred at address, in terms of ball position, lead hand forwardness, thorax lateral flexion, pelvis rotation, thorax rotation and stance openness (Figure 6-6). Ball position was on average 31 ± 32 mm further back, lead hand forwardness 34 ± 27 mm further forward and the thorax flexed laterally 2.5 ± 2.9º less towards the trail side for draw trajectories. Pelvis rotation, thorax rotation and stance openness were all closed for the draw and open for the fade trajectories. The differences between shot conditions were 1.7 ± 2.9º, 0.8 ± 1.5º and 4.3 ± 1.9º difference respectively.

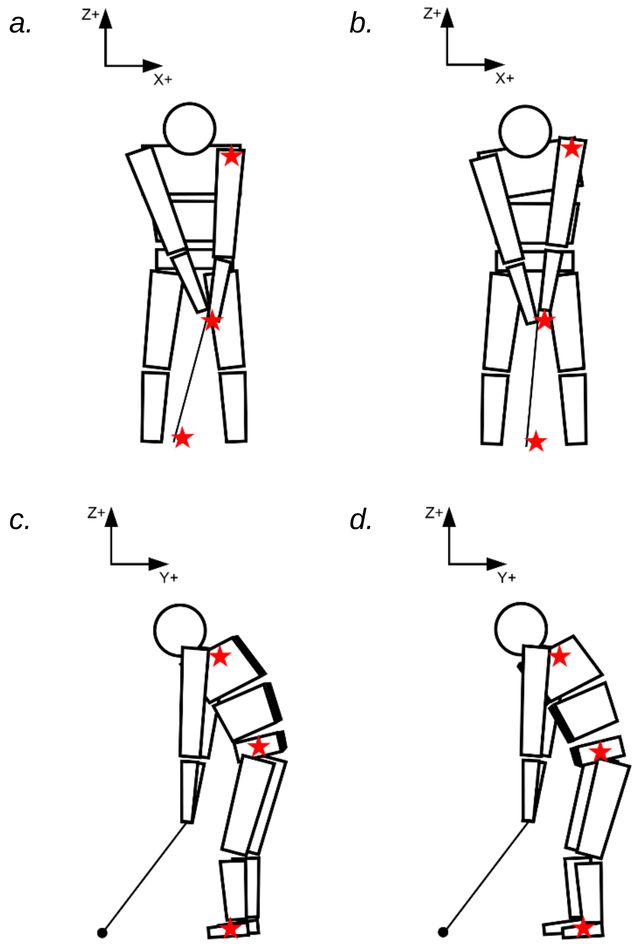


Figure 6-6: Driver draw-fade differences at address: a. draw front-on; b. fade front-on; c. draw side-on and d. fade side-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the central body segments.

Address differences may have caused differences over the whole-swing. For example, a difference in horizontal swing plane during the backswing of driver shots (Figure 6-3a) could have been a result of the more open or closed stance for each shot (Figure 6-6c and Figure 6-6d). On top of this there were also several other differences.

Firstly, there were absolute offset differences between the draw and the fade. For draw trajectories, the pelvis was positioned less away from the target (Figure 6-2j) and rotated further away from the target (Figure 6-2d), the latter likely due to the closed stance at address. Finally, lumbar lateral flexion showed more flexing towards the trail for draw trajectories (Figure 6-2e).

On top of the absolute differences between draw and fade trajectories, there was evidence of relative differences, in magnitude, rate of change and timing. The centre of pressure was positioned less away from the target and the thorax laterally flexed more neutral initially for draw trajectories (Table 6-4). From commencement of the swing there were thorax and pelvis rotations away from the target for both conditions and a gradual lumbar lateral flexing towards the lead in draw trajectories (Table 6-4). The thorax rotation away relative to the pelvis for draw trajectories was later (Table 6-4).

As the backswing progressed both trajectories showed a trail lumbar lateral flexing, which occurred earlier in the draw. Additionally, there was a greater, slower lateral flexing of the thorax towards the lead in these trajectories (Table 6-4). Draw trajectories also showed less lumbar forward flexion and greater thorax rotation away relative to the target (Table 6-4). There was evidence for centre of pressure shift away from the target in the later stages of the backswing. Interestingly, at mid-to-late backswing, the pelvis began to translate towards the target for both shot conditions, however, draw trajectories showed earlier forward translation (Table 6-4).

Towards the end of the backswing there was evidence for a reversal of the thorax lateral flexion, maybe of greater magnitude in the draw trajectories (Figure 6-2h).

Around the top of the backswing, characteristics of draw trajectories were a pelvis rotated further away from and translated less away from the target, thorax rotated more away from the target and maybe still rotating relative to the pelvis, a less forward flexed lumbar spine with more lateral flexion towards the trail and a centre of pressure positioned less away from the target. Near to the event of top of the backswing, a re-reversal of thorax lateral flexion, to begin once again flexing towards the lead, was apparent, continuing in the downswing (Figure 6-2h). Furthermore, evidence suggested a centre of pressure forward shift around top of the backswing, for both shot trajectories (Figure 6-2i), which may have been earlier for the draw.

With transition into downswing, the wrist deviation began to ulnar deviate for both shot trajectories. Over the initial stages, the thorax laterally flexed beginning towards the trail and the pelvis rotates back towards the target later for the draw trajectories (Table 6-4).

As the downswing progresses, the analysis uncovered evidence for slower lumbar extending in draw condition (Table 6-4). Furthermore, the thorax rotation towards the target was greater (Table 6-4) for draw trajectories, as was the centre of pressure forward shift (Table 6-4).

In the later stages of the downswing, the lumbar lateral flexion towards the trail is prolonged for draw trajectories, continuing right through into follow-through (Table 6-4). However, fade trajectories appeared to show a halting around mid-downswing. Finally, the thorax lateral flexion that commenced not long into the downswing showed a greater flexing towards the trail for draw trajectories, that was more prolonged through ball contact (Table 6-4).

The changes described above help achieve the body position at ball contact required for draw and fade trajectories (Figure 6-7). For example, for draw trajectories at ball contact a less open pelvis segment of on average 4.9 ± 3.8º was present. This, along with the openness of the feet at address could have contributed to the different horizontal swing planes immediately prior to ball contact; draw horizontal planes were in-to-out of the target line, whilst fade horizontal planes were out-to-in (Figure 6-7c and Figure 6-7d).

Further differences at ball contact were thorax lateral flexion 5.6 ± 3.2º relatively more flexed towards the lead and the hands further forward (16 ± 29 mm) for the draw trajectories (Figure 6-7a and Figure 6-7b).

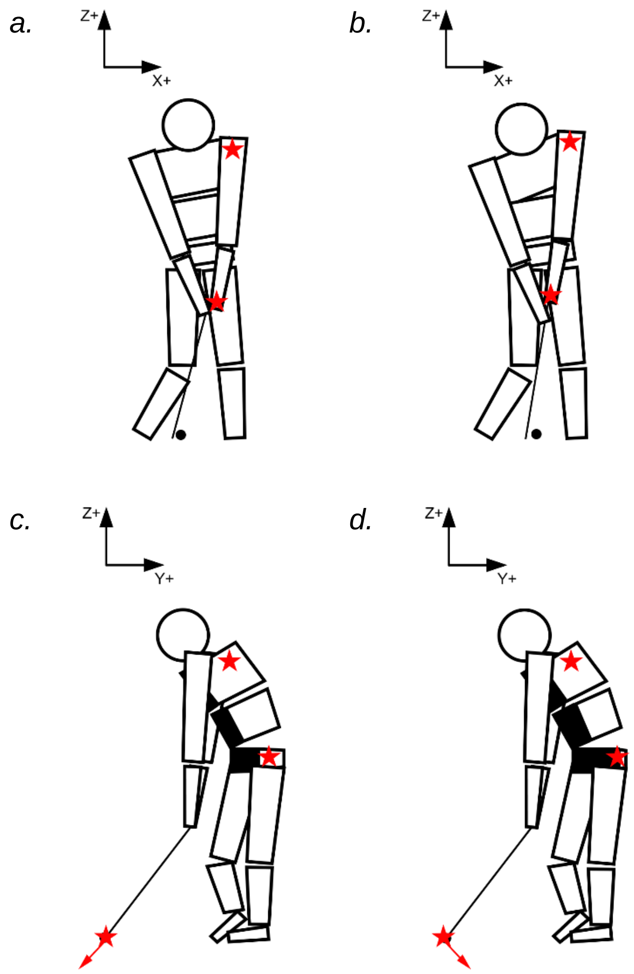


Figure 6-7: Driver draw-fade differences at ball contact: a. draw front-on; b. fade front-on; c. draw side-on and d. fade side-on. The stars represent where the differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the central body segments.

6.4. 5-Iron draw versus fade

6.4.1. Magnitude of shot trajectories

The magnitude of spin axes for both trajectories for all shots across all golfers are shown in Figure 6-8. Golfers achieved similar magnitudes of spin rates for both shot conditions.

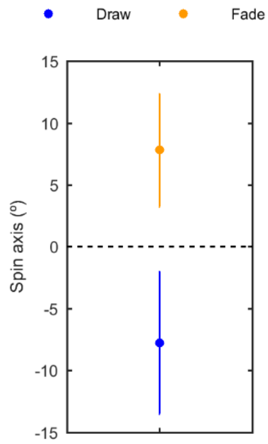


Figure 6-8: Mean spin axis (± 1 SD) for 5-iron draw and fade trajectories across all golfers included in the analysis.

6.4.2. Impact location

The impact location comparison results are shown in Table 6-6. Neither horizontal nor vertical impact location differed significantly between the draw and the fade.

Table 6-6: Comparison of the overall golfer mean (& SD) impact locations relative to the geometric clubface centre for the draw and fade trajectories with the 5-iron. Also shown are the upper and lower 95% confidence intervals.

Horizontal impact location (mm)					Vertical impact location (mm)				
Draw	Fade	p-value	Lower	Upper	Draw	Fade	p-value	Lower	Upper
-3 (13)	-1 (13)	0.9759	-7.4	5.5	-5 (5)	-6 (6)	0.9941	-2.8	3.4

6.4.3. Example variable results

As with the driver, example results from a golfer are shown to highlight some of the initial differences between shot trajectories with the 5-iron (Figure 6-9 and Figure 6-10). Offset differences are clear in pelvis translation (Figure 6-9j), lumbar lateral flexion (Figure 6-9e), thorax lateral flexion (Figure 6-9h), lead wrist deviation (Figure 6-9c), lead wrist supination (Figure 6-9f) and horizontal swing plane (Figure 6-10a). Magnitude differences may be apparent in trail shoulder abduction (Figure 6-9k) and centre of pressure (Figure 6-9i), with rate of change differences in thorax rotation (Figure 6-9a) and pelvis rotation (Figure 6-9d). Finally, thorax rotation may also see a timing difference (Figure 6-9a).

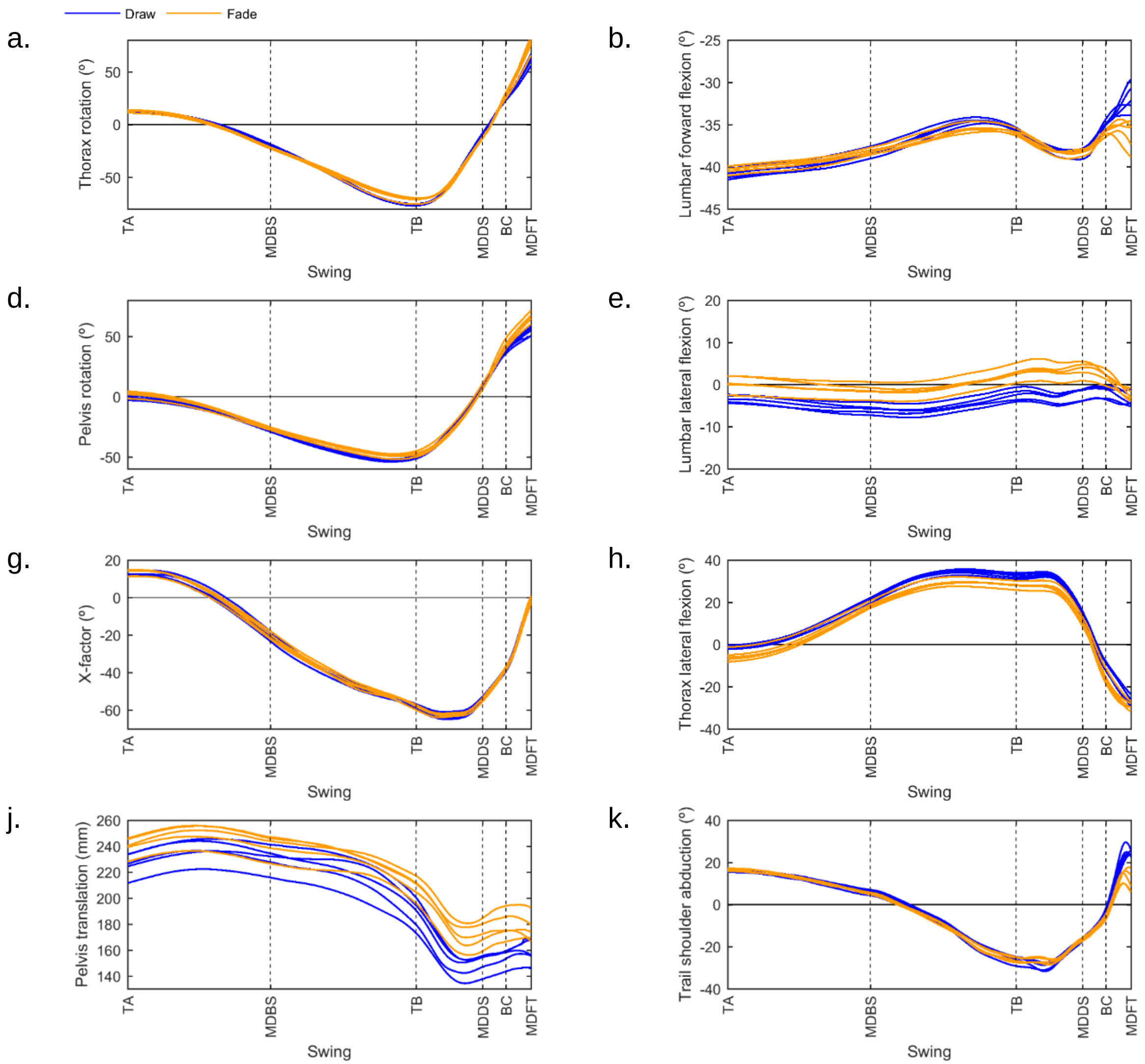


Figure 6-9: Example results (golfer eight): a. thorax rotation; b. lumbar forward flexion; c. lead wrist deviation; d. pelvis rotation; e. lumbar lateral flexion; f. lead wrist supination; g. X-factor; h. thorax lateral flexion; i. centre of pressure; j. pelvis translation and k. trail shoulder rotation.

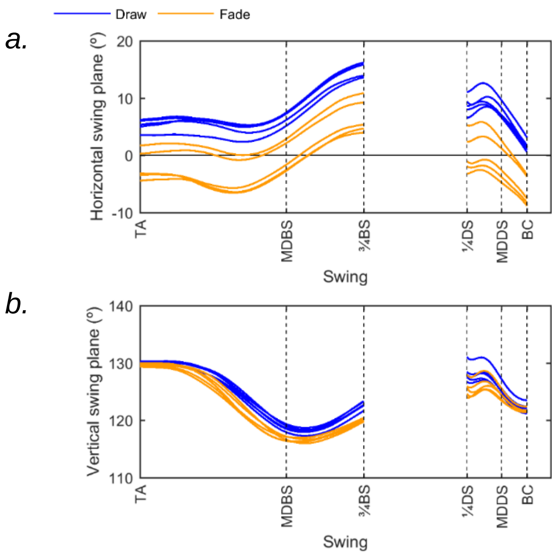


Figure 6-10: Example results (golfer eight): a. horizontal swing plane and b. vertical swing plane.

6.4.4. Group event results

Address

As with the driver, significant differences in mean address variables were found (Table 6-7). Ball position, lead hand forwardness, lead hand height, thorax lateral flexion, pelvis rotation, thorax rotation and stance openness were significantly different between draw and fade trajectories.

Table 6-7: Overall mean (& SD) 5-iron draw-fade variable comparisons at address. The p-value, calculated from the z-value, represents the probability that there is a significant difference between the draw and the fade (MATLAB, 2017)*.*

Variable	Significant	p-value	z-value	Effect size	Draw	Fade
Pelvis rotation (º)	*	*<0.0001*	-4.30	-0.73	5.2 (4.4)	6.9 (4.0)
Thorax rotation (º)	*	*<0.0001*	-4.68	-0.79	14.4 (2.0)	14.9 (2.1)
Stance openness (º)	*	*0.0078*	2.66	0.45	-1.1 (2.5)	1.8 (2.0)
Ball position (mm)	*	*<0.0001*	-4.57	-0.77	-143 (53)	-113 (43)
Stance width (mm)		0.0135	-2.47	-0.42	452 (51)	-449 (60)
Grip distance (mm)		0.0257	-2.23	0.38	142 (26)	148 (8)
Lead hand forwardness (mm)	*	*<0.0001*	-4.67	-0.79	-28 (33)	-4 (34)
Lead hand height (mm)	*	*0.0008*	-2.04	-0.34	713 (29)	717 (29)
Thorax lateral flexion (º)	*	*<0.0001*	4.68	0.79	-0.6 (4.5)	-2.8 (4.7)
Centre of pressure (%)		0.0619	1.87	0.32	57 (8)	55 (8)

Ball contact

Overall, five of the ball contact variables were significant between the draw and the fade trajectories with the 5-iron (Table 6-8). These constituted horizontal swing plane, lead hand forwardness, thorax lateral flexion, pelvis rotation and thorax rotation.

Table 6-8: Overall mean (& SD) 5-iron draw-fade variable comparisons at ball contact. The p-value, calculated from the z-value, represents the probability that there is a significant difference between the draw and the fade (MATLAB, 2017)*.*

Variable	Significant	p-value	z-value	Effect size	Draw	Fade
Pelvis rotation (º)	*	*<0.0001*	-4.21	-0.71	39.7 (8.6)	43.8 (5.4)
Thorax rotation (º)	*	*<0.0001*	4.37	0.74	24.6 (4.4)	26.3 (4.2)
Lead hand forwardness (mm)	*	*0.0052*	-2.80	-0.47	-95 (28)	-85 (25)
Lead hand height (mm)		0.2216	-1.22	-0.21	755 (23)	760 (19)
Thorax lateral flexion (º)	*	*<0.0001*	4.37	0.74	1.4 (7.3)	-2.4 (7.9)
Centre of pressure (%)		0.0288	2.19	0.37	80 (17)	77 (20)
Swing plane vertical (º)		0.5693	0.57	0.10	123.7 (1.8)	123.6 (2.9)
Swing plane horizontal (º)	*	*<0.0001*	-4.78	-0.87	2.3 (2.1)	-9.1 (2.9)

6.4.5. Group swing results

The principal component analysis procedure followed that of the driver. The most common number of principal components required to explain 90% of the variance in the data was two, with a maximum of four. The principal components were interpreted in the same way as for the driver (Table 6-9; Appendix E). Fourteen principal components significantly differed between the draw and the fade across nine variables: centre of pressure, thorax lateral flexion, lead wrist deviation, lumbar lateral flexion, pelvis rotation, pelvis translation, X-factor, horizontal swing plane and vertical swing plane.

Table 6-9: Principal component (PC) differences between the 5-iron draw and fade trajectories. Italics indicates significantly different principal components. Also shown are the corresponding percentages of the variance each principal component explained and the biomechanical interpretation. Grey shading indicates findings associated with draw trajectories, white shows those associated with fade.

Variable	PC	Explained variance (%)	p-value	z-value	Effect size	Interpretation type	Positive difference between scores	Negative difference between scores
Pelvis rotation	1	71.2	*0.0001*	-3.82	-0.66	Offset	Lesser rotation away from the target.	Greater rotation away from the target.
	2	16.7	*0.0438*	2.10	0.36	Magnitude	Rotated greater away from the target in the first half of the backswing. Lesser rotation away from the target in second half of the backswing.	Rotated lesser away from the target in the first half of the backswing. Greater rotation away from the target in second half of the backswing.
Thorax rotation	1	73.1	0.6106	-0.51	-0.09	Offset	Lesser rotation away from the target.	Greater rotation away from the target.
	2	15.2	0.1985	1.31	0.22	Magnitude Timing	Lesser, less prolonged rotation away from the target during the backswing. Earlier rotation towards the target in the downswing, that halts around mid-downswing.	Greater, more prolonged closing during the backswing. Later rotation towards the target in the downswing, that is prolonged through ball contact.
	3	7.5	0.2473	-1.18	0.20	Magnitude Timing	Lesser rotation away from the target in the mid-to-late backswing. Later rotation towards the target in the downswing, that is prolonged through ball contact.	Greater rotation away from the target in the mid-to-late backswing. Earlier rotation towards the target in the downswing, that reverses around mid-downswing.
X-factor	1	81.6	0.9184	-0.10	0.02	Offset	Lesser thorax rotation away from the pelvis.	Greater thorax rotation away from the pelvis.
	2	11.8	*0.0197*	-2.33	-0.**41**	Magnitude	Lesser thorax rotation away relative to the pelvis throughout the backswing and early downswing.	Greater thorax rotation away relative to the pelvis throughout the backswing and early downswing.
Lumbar forward flexion	1	78.9	0.2931	-1.05	-0.18	Offset	Less flexion.	Greater flexion.
	2	15.9	0.2556	-1.14	-0.19	Magnitude Timing	Lesser extending initially, followed by earlier, lesser flexing in the late backswing. Earlier extending in the downswing.	More extending initially, followed by later, greater flexing in the late backswing. Later extending in the downswing.
Lumbar lateral flexion	1	68.1	*0.0004*	-3.97	-0.56	Offset	Greater flexion towards the lead.	Greater flexion towards the trail.
	2	17.4	0.2416	-1.17	-0.20	Magnitude	Lesser flexing towards the lead in the backswing, lesser flexing towards the trail in the downswing.	Greater flexing towards the lead in the backswing, greater flexing towards the trail in the downswing.
	3	9.2	*0.0038*	2.90	0.50	Magnitude Rate of change Timing	Flexing towards the lead in the late backswing. Greater flexing towards the lead during the downswing.	More prolonged but lesser flexing towards the lead during the backswing. Earlier flexing towards the trail during the downswing.
Thorax lateral flexion	1	53.4	0.7126	-0.37	-0.06	Magnitude	Greater flexing towards the lead initially. More flexed towards the trail over the middle phase. Greater flexing towards the lead in the downswing.	Lesser flexing towards the lead initially. More flexed towards the lead over the middle phase. Greater flexing towards the trail in the downswing.
	2	22.7	*0.0026*	3.01	0.52	Magnitude	More flexed towards the lead initially, followed by a reversal towards the trail and re-reversal towards the lead around top of the backswing. More flexed towards the lead in the downswing.	More flexed towards the trail initially, followed by lesser reversal towards the trail and re-reversal towards the lead in the late backswing. More flexed towards the trail in the downswing.
	3	12.2	0.0948	1.67	0.28	Magnitude	Greater flexing towards the lead initially. Flexed towards the lead lag over the remainder of the swing.	Lesser flexing towards the lead initially. Flexed towards the trail lag over the remainder of the swing.
	4	9.6	*0.0046*	2.83	0.49	Rate of change Timing	Slower flexing towards the lead during the backswing and early downswing, with slight reversal towards the trail and re-reversal towards the lead around mid-backswing. Marginally earlier flexing towards the trail in the downswing, which slows around mid-downswing.	Quicker flexing towards the lead during the backswing, followed by a reversal towards the lead and re-reversal towards the trail in the second half of the backswing and early downswing. Marginally later flexing towards the trail in the downswing.
Pelvis translation	1	66.3	0.0640	-1.92	-0.32	Offset	Greater translation away from the target.	Lesser translation away from the target.
	2	25.9	*0.0257*	-2.23	-0.38	Timing	Translated less away from the target in the first half of the backswing. Translation away from the target around top of the backswing. Less translated towards the target in the downswing.	Translated further away from the target in the first half of the backswing. Earlier translation towards the target. Further translated towards the target in the downswing.
Trail shoulder abduction	1	86.6	0.2776	1.09	0.18	Offset	Greater adduction.	Greater abduction.
	2	7.0	0.5553	-0.59	0.10		Greater abducting in the backswing and early downswing. Greater adducting in the downswing.	Lesser abducting in the backswing and early downswing. Lesser adducting in the downswing.
Lead wrist deviation	1	63.1	0.1486	-1.44	-0.24	Offset	Greater radial deviation.	Greater ulnar deviation.
	2	29.6	*0.0257*	2.23	0.38	Magnitude	Greater radial deviation during the backswing. Greater ulnar deviation in the downswing.	Lesser radial deviation in the backswing, lesser ulnar deviation in the downswing.

Variable	PC	Explained variance (%)	p-value	z-value	Effect size	Interpretation type	Positive	Negative
Lead wrist supination	1	89.5	0.4069	0.84	0.14	Offset	Greater supination.	Greater pronation.
	2	7.2	0.1982	-1.29	-0.22	Magnitude	Lesser pronating in the backswing, lesser supinating in the downswing.	Greater pronating in the backswing, greater supinating in the downswing.
Centre of pressure	1	40.8	*0.0306*	2.16	0.37	Magnitude	More towards the target during the backswing. Forward shift.	Less towards the target during the backswing. Forward shift.
	2	26.3	0.7541	0.32	0.05	Rate of change Timing	Quicker shift away, followed by a marginally earlier forward shift.	Slower shift away, followed by a marginally later forward shift.
	3	21.6	0.5453	-0.61	-0.10	Magnitude	Less towards the target initially, with less prolonged shift away, followed by a lag shifted less away from the target during the downswing.	Less away from the target initially, with more prolonged shift away, followed by a lag shifted more away from the target during the downswing.
	4	5.3	*0.0364*	2.21	0.32	Magnitude Rate of change	More towards the target initially. Forward shift slows in the early downswing.	Less towards the target initially. Forward shift reverses around mid-downswing.
Swing plane horizontal backswing	1	88.3	*0.0483*	1.97	0.33	Offset	Greater out-to-in plane.	Greater in-to-out plane.
	2	8.2	0.1604	1.44	0.24	Magnitude	Becomes a lesser out-to-in plane initially, before reversing and becoming an increasingly out-to-in plane.	Becomes a lesser in-to-out plane initially, before reversing and becoming an increasingly in-to-out.
Swing plane horizontal downswing	1	92.3	*<0.0001*	4.58	0.84	Offset	Greater in-to-out plane.	Greater out-to-in plane.
Swing plane vertical backswing	1	98.3	0.0644	1.85	0.31	Offset	Flatter plane.	Steeper plane.
Swing plane vertical downswing	1	94.1	*0.0404*	2.05	0.37	Offset	Flatter plane.	Steeper plane.

6.4.6. Hypothesis outcomes

As for the driver, the outcome of the hypotheses outlined in Section 5.5.3 are displayed for the 5-iron draw-fade comparison, again with the addition of any further outcomes not initially hypothesised (Table 6-10).

Table 6-10: Outcomes of the hypothesised changes, supported (✓), rejected (✗) or not applicable (N/A), in the biomechanical variables between the 5-iron draw and fade trajectories at address, ball contact and over the whole-swing. Other outcomes refers to non-hypothesised differences between the trajectories.

Variable	Address	Ball contact	Whole-swing	Other outcomes
Pelvis rotation	✓	✓	✓	✓
Thorax rotation	✓	✓	✗	✗
X-factor	N/A	N/A	✗	✓
Stance openness	✓	N/A	N/A	✗
Ball position	N/A	N/A	N/A	✓
Lead hand forwardness	N/A	N/A	N/A	✓
Lead hand height	✓	✗	N/A	✗
Lumbar forward flexion	N/A	N/A	✗	✗
Lumbar lateral flexion	N/A	N/A	✓	✓
Thorax lateral flexion	✓	✓	✓	✓
Pelvis translation	N/A	N/A	✓	✓
Trail shoulder abduction	N/A	N/A	✗	✗
Lead wrist supination	N/A	N/A	✗	✗
Lead wrist deviation	N/A	N/A	✗	✓
Centre of pressure	✗	✗	✓	✗
Instantaneous swing plane horizontal	N/A	✓	✓	✗
Instantaneous swing plane vertical	N/A	✗	✓	✗

6.4.7. Group swing patterns

The majority of the address and whole-swing changes described for the driver draw-fade comparison in Section 6.3.7 are applicable to the 5-iron.

At address, ball position was on average 30 ± 28 mm further back, lead hand forwardness was 24 ± 22 mm further forward and the thorax laterally flexed 2.3 ± 2.0º more neutrally for the draw. Differences between the draw (closed) and fade (open) pelvis rotation, thorax rotation and stance openness were 1.7 ± 1.8º, 0.6 ± 1.1º and 2.3 ± 2.4º (Figure 6-6). In addition, lead hand height was 4 ± 15 mm lower for the draw. As with the driver, these address differences may have caused differences over the whole-swing.

Similar offsets were present over the whole-swing, including pelvis rotation (Figure 6-9d), lumbar lateral flexion (Figure 6-9e), and horizontal swing plane (Figure 6-10a). Also similar were the absolute differences over the whole-swing. However, there were occasional differences. For example, the pelvis rotated away initially with greater magnitude for the draw; however, no timing differences existed for thorax rotation (Table 6-9).

As the backswing progressed, the 5-iron showed no lumbar forward flexion differences and there was a distal difference in the wrists, with greater magnitude of radial deviation for the draw trajectories (Table 6-9). Furthermore, the thorax showed greater rotation away relative to the pelvis for these shots (Table 6-9). The pelvis rotation away from the target, which was greater initially in the draw, was of less magnitude in the second half of the backswing (Table 6-9).

With transition into downswing, the rotation of the thorax away relative to the pelvis continued for draw trajectories (Table 6-9). The vertical swing plane was flatter for these shots during the downswing (Table 6-9). Over the initial stages, the thorax laterally flexed towards the trail marginally earlier (Figure 6-9h). As the downswing progressed, the ulnar deviation was greater (Table 6-9). Finally, around mid-downswing, the 5-iron showed a slowing of the thorax lateral flexing for the draw shot condition (Table 6-9).

Like the rest of the swing, many of the differences at ball contact are similar to the driver (Figure 6-7). Specifically, draw trajectories had a less open pelvis segment of on average 4.0 ± 6.4º, a more laterally flexed thorax towards the lead of 3.8 ± 3.4º and a lead hand position 11 ± 33 mm further ahead. There was also a less open thorax of 1.6 ± 2.7º for draw trajectories, potentially aiding the swing plane differences at the event.

6.5. 5-Iron low versus natural

6.5.1. Magnitude of shot trajectories

The magnitude of launch angles for the low and natural trajectory shots of golfers are shown in Figure 6-11. Overall, on average, golfers reduced their launch angle by approximately 5º.

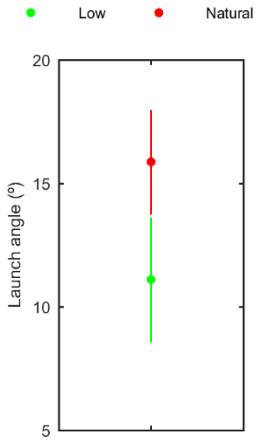


Figure 6-11: Mean launch angle (± 1 SD) for 5-iron low and natural trajectories across all golfers included in the analysis.

6.5.2. Impact location

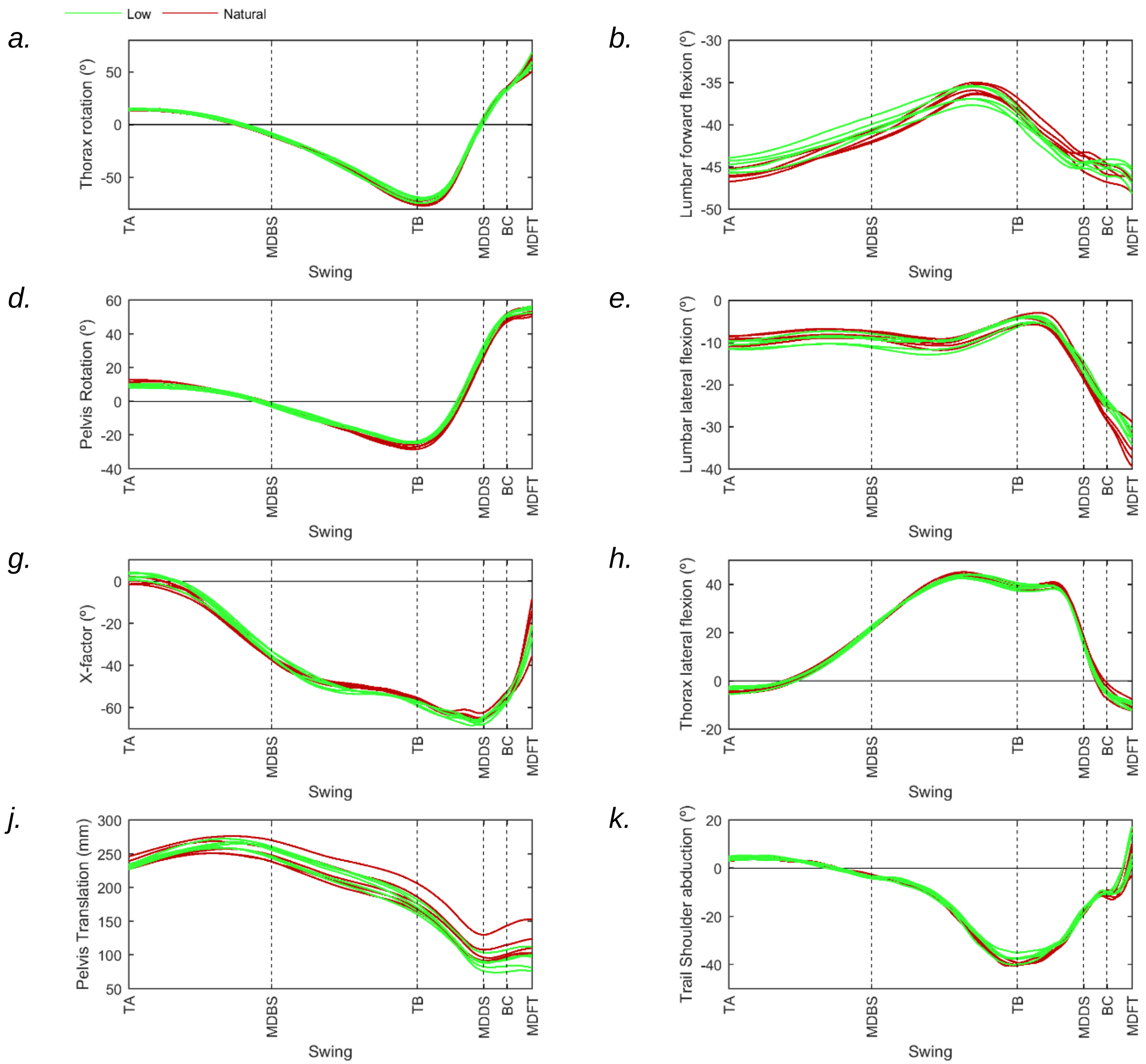
Impact location statistics are shown in Table 6-11. No significant differences were present.

Table 6-11: Comparison of the overall golfer mean (& SD) impact locations relative to the geometric clubface centre for the low and natural trajectories with the 5-iron. Also shown are the upper and lower 95% confidence intervals.

Horizontal impact location (mm)					Vertical impact location (mm)				
Low	Natural	p-value	Lower	Upper	Low	Natural	p-value	Lower	Upper
3 (16)	0 (13)	0.6700	-4.1	10.2	-5 (12)	-7 (5)	0.6068	-2.6	7.1

6.5.3. Example variable results

For the low-natural trajectory comparison, the example results appear to show fewer differences than the draw-fade comparison (Figure 6-12 and Figure 6-13). The golfer's data below shows few signs of offset differences, perhaps only occurring in the downswing horizontal swing plane (Figure 6-13a). Magnitude differences may occur in pelvis rotation (Figure 6-12d) and centre of pressure (Figure 6-12i). Lastly, rate of change differences could have occurred in pelvis translation (Figure 6-12j) and lumbar lateral flexion (Figure 6-12e).



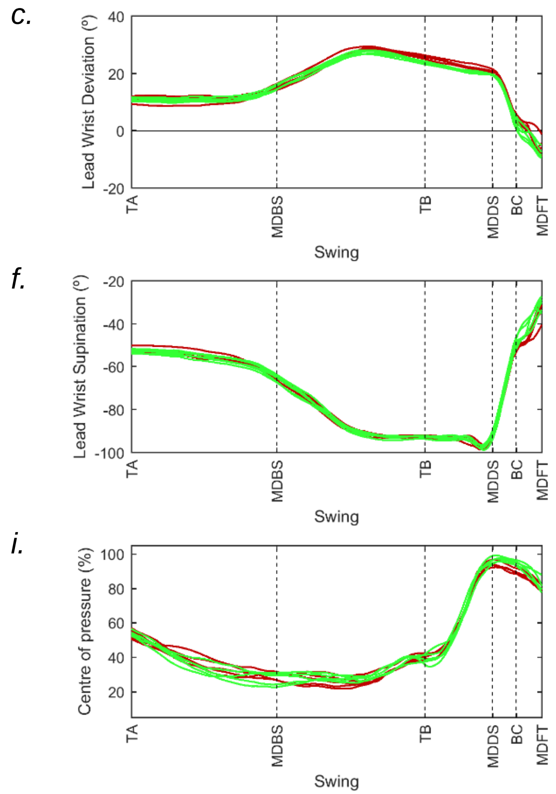


Figure 6-12: Example results (golfer three): a. thorax rotation; b. lumbar forward flexion; c. lead wrist deviation; d. pelvis rotation; e. lumbar lateral flexion; f. lead wrist supination; g. X-factor; h. thorax lateral flexion; i. centre of pressure; j. pelvis translation and k. trail shoulder rotation.

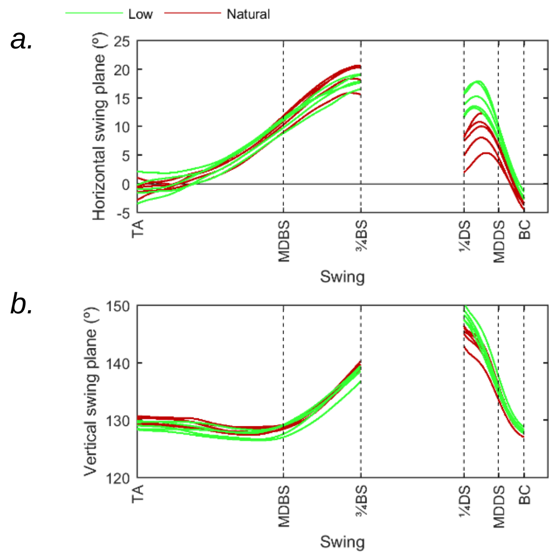


Figure 6-13: Example results (golfer three): a. horizontal swing plane and b. vertical swing plane.

6.5.4. Group event results

Address

The address analysis resulted in four significant differences across address variables (Table 6-12): ball position, lead hand forwardness, thorax lateral flexion and pelvis rotation.

Table 6-12: Overall mean (& SD) 5-iron low-natural trajectory variable comparisons at address. The p-value, calculated from the z-value, represents the probability that there is a significant difference between the low and the natural (MATLAB, 2017)*.*

Variable	Significant	p-value	z-value	Effect size	Low	Natural
Pelvis rotation (º)	*	*0.0042*	2.86	0.48	5.9 (4.7)	6.7 (4.8)
Thorax rotation (º)		0.0684	1.82	0.31	14.5 (2.6)	14.6 (2.2)
Stance openness (º)		0.0687	-1.82	-0.31	-0.7 (1.7)	-1.4 (2.4)
Ball position (mm)	*	*<0.0001*	3.92	0.66	-150 (49)	-121 (50)
Stance width (mm)		0.0472	-1.98	-0.33	442 (57)	441 (51)
Grip distance (mm)		0.3709	0.89	0.15	146 (6)	149 (13)
Lead hand forwardness (mm)	*	*<0.0001*	4.74	0.80	-45 (38)	-7 (37)
Lead hand height (mm)		0.0571	-1.90	-0.32	716 (30)	714 (25)
Thorax lateral flexion (º)	*	*0.0004*	-3.53	-0.60	-1.3 (4.9)	-3.0 (5.6)
Centre of pressure (%)		0.0975	1.66	0.28	56 (8)	56 (9)

Ball contact

Fewer differences were found at ball contact (Table 6-13), just two were significant: lead hand forwardness and centre of pressure.

Table 6-13: Overall mean (& SD) 5-iron low-natural trajectory variable comparisons at ball contact. The p-value, calculated from the z-value, represents the probability that there is a significant difference between the low and the natural (MATLAB, 2017).

Variable	Significant	p-value	z-value	Effect size	Low	Natural
Pelvis rotation (º)		0.6381	0.47	0.08	43.1 (6.5)	43.8 (6.3)
Thorax rotation (º)		0.5178	0.65	0.12	25.2 (4.2)	26.0 (4.7)
Lead hand forwardness (mm)	*	*<0.0001*	4.58	0.77	-139 (43)	-91 (26)
Lead hand height (mm)		0.0175	2.38	0.40	751 (18)	754 (20)
Thorax lateral flexion (º)		0.5178	0.65	0.11	-1.2 (8.9)	-1.7 (9.0)
Centre of pressure (%)	*	*0.0001*	-3.80	-0.64	91 (10)	80 (16)
Swing plane vertical (º)		0.2059	-1.27	-0.23	124.0 (1.4)	123.8 (2.0)
Swing plane horizontal (º)		0.7375	0.34	0.06	7.9 (3.2)	7.1 (4.6)

6.5.5. Group swing results

The process for the principal component analysis was fundamentally the same as for the draw-fade analysis; however, it was conducted on the low trajectories which successfully achieved a lower launch angle (less than the mean minus one standard deviation of the natural launch angle for each golfer) and landed within the fairway (Section 5.6.5). The five median natural shots in terms of launch angle were used as the comparison.

For this comparison, the number of principal components required to explain 90% of the variance in the data was typically two or three principal components. The interpretation of the principal components was conducted in the same was as previously (Table 6-14; Appendix F). However, fewer significant differences (six across five variables) between shot conditions emerged. These occurred in pelvis rotation, thorax rotation, pelvis translation, centre of pressure and horizontal swing plane.

Table 6-14: Principal component (PC) differences between the 5-iron low and natural trajectories. Italics indicates significantly different principal components. Also shown are the corresponding percentages of the variance each principal component explained and the biomechanical interpretation. Grey shading indicates findings associated with low trajectories, white shows those associated with natural.

Variable	PC	Explained variance (%)	p-value	z-value	Effect size	Interpretation type	Positive difference between scores	Negative difference between scores
Pelvis rotation	1	62.8	*0.0469*	1.99	0.27	Offset	Lesser rotation away from the target.	Greater rotation away from the target.
	2	25.8	0.1909	-1.30	0.18	Magnitude	Rotated more away from the target initially. Lesser rotation away from the target during the mid-to-late backswing. Lesser rotation towards the target lag in the downswing.	Rotated less away from the target initially. Greater rotation away from the target during the mid-to-late backswing. Greater rotation away from the target lag in the downswing.
	3	5.1	*0.0439*	2.02	0.28	Magnitude	Lesser rotation away from the target during the backswing, followed by a more prolonged rotation towards the target in the downswing.	Greater rotation away from the target during the backswing, followed by a rotation towards the target in the downswing that reverses around mid-downswing.
Thorax rotation	1	76.0	0.4840	0.70	0.09	Offset	Lesser rotation away from the target.	Greater rotation away from the target.
	2	13.0	*0.0366*	-2.09	-0.28	Timing	Earlier rotation away from the target during the backswing, earlier rotation towards the target during the downswing, reversing around mid-downswing.	Later rotation away from the target during the backswing, later rotation towards the target during the downswing, which prolongs through ball-contact.
	3	6.2	0.3174	1.01	0.14	Magnitude Rate of change Timing	Greater rotation away from the target during the backswing, followed by quicker rotation towards the target during the downswing. Reversal around mid-downswing.	Lesser rotation away from the target during the backswing, followed by slower rotation towards the target during the downswing.
X-factor	1	76.6	0.8431	-0.20	-0.03	Offset	Lesser thorax rotation away relative to the pelvis.	Greater thorax rotation away relative to the pelvis.
	2	15.4	0.5909	-0.54	-0.07	Magnitude	Greater thorax rotation away relative to the pelvis during the backswing.	Lesser thorax rotation away relative to the pelvis during the backswing.
Lumbar forward flexion	1	74.8	0.3277	0.99	0.13	Offset	Less flexion.	Greater flexion.
	2	14.9	0.9350	-0.08	-0.01	Magnitude	Greater flexing in the backswing. Greater extending in the downswing.	Extending initially, followed by flexing later in the backswing. Lesser extending in the downswing.
	3	8.5	0.8205	0.23	0.03	Timing	Extending before a later flexing in the late backswing.	Earlier flexing in the backswing.
Lumbar lateral flexion	1	62.7	0.8281	-0.22	0.03	Offset	Greater flexing towards the lead.	Greater flexing towards the trail.
	2	16.3	0.6191	-0.50	-0.07	Magnitude Timing	Stable during the backswing, followed by later, lesser flexing towards the trail in the downswing.	Flexing towards the lead during the backswing, followed by earlier, greater flexing towards the trail in the downswing.
	3	11.7	0.3520	0.94	0.13	Magnitude Rate of change	Flexing towards the lead in the late backswing, followed by quicker trail flexing in the downswing.	Stable during the backswing, followed by slower trail flexing in the downswing.
Thorax lateral flexion	1	54.1	0.4602	0.74	0.10	Magnitude	Greater flexing towards the lead initially. Flexed towards the lead over the middle phase. Greater flexing towards the trail in the downswing.	Lesser flexing towards the lead initially. Flexed towards the trail over the middle phase. Lesser flexing towards the trail in the downswing.
	2	20.9	0.7797	-0.28	-0.04	Magnitude	More flexed towards the lead initially, followed by a reversal towards the trail and re-reversal towards the lead around top of the backswing. More flexed towards the lead in the downswing.	More flexed towards the trail initially. More flexed towards the trail in the downswing.
	3	12.8	0.2527	-1.14	-0.15	Magnitude Timing	More flexed towards the trail initially, followed by a reversal towards the trail and re-reversal towards the lead around top of the backswing. More flexed towards the lead in the downswing.	More flexed towards the lead initially. Earlier lowering in the backswing. More flexed towards the trail in the downswing.
	4	7.7	0.5921	0.54	0.07	Magnitude	Greater flexing towards the lead initially, followed by a reversal towards the trail and re-reversal towards the lead in the late backswing. More prolonged flexing towards the trail in the downswing.	Lesser flexing towards the lead initially, followed by a reversal towards the trail and re-reversal towards the lead in the mid-backswing. Flexing towards the trail in the downswing halts around mid-downswing.
Pelvis translation	1	77.0	*0.0120*	-2.51	-0.35	Offset	Greater translation away from the target.	Lesser translation away from the target.
	2	17.9	0.3976	-0.86	-0.12	Magnitude Timing	Later, lesser translation towards the target.	Earlier, greater translation towards the target.
Trail shoulder abduction	1	88.9	0.4092	0.83	0.11	Offset	Greater adduction.	Greater abduction.
	2	8.5	0.9040	-0.12	-0.02	Magnitude	Greater abducting in the backswing, greater adducting in the downswing.	Lesser abducting in the backswing, lesser adducting in the downswing.

Variable	PC	Explained variance (%)	p-value	z-value	Effect size		Positive	Negative
Lead wrist deviation	1	70.5	0.7563	0.31	0.04	Offset	Greater radial deviation.	Greater ulnar deviation.
	2	18.8	0.2250	-1.21	-0.16	Magnitude	Greater radial deviation in the backswing, greater ulnar deviation in the downswing.	Lesser radial deviation in the backswing, lesser ulnar deviation in the downswing.
	3	5.5	0.3017	1.03	0.14	Rate of change Timing	Earlier radial deviating, followed by earlier, slower ulnar deviating.	Later radial deviating, followed by later, quicker radial deviating.
Lead wrist supination	1	85.2	0.6676	0.43	0.06	Offset	Greater supination.	Greater pronation.
	2	9.0	0.5163	-0.65	-0.09	Magnitude	Greater pronating in the backswing and early downswing, followed by greater supinating in the downswing.	Lesser pronating in the backswing and early downswing, followed by lesser supinating in the downswing.
Centre of pressure	1	43.0	0.7053	0.38	0.05	Magnitude Timing	Less away from the target in the backswing. Marginally later forward shift.	More away from the target over the backswing. Marginally earlier forward shift.
	2	23.3	*<0.0001*	3.37	0.49	Magnitude Rate of change	Quicker shift away initially, followed by a greater forward shift in the downswing.	Slower shift away initially, followed by a lesser forward shift in the downswing.
	3	15.5	0.2293	-1.20	-0.16	Magnitude	Less prolonged shift away, followed by a lag less away from the target.	More prolonged shift away, followed by a lag more away from the target.
	4	6.2	0.8144	-0.23	-0.03	Magnitude Timing	Shift away initially, followed by an earlier forward shift.	Less shift away over the backswing, followed by a later forward shift.
	5	5.2	0.3517	0.93	0.13	Magnitude Rate of change	More prolonged shift away, with a quicker forward shift in the downswing, followed by a reversal before mid-downswing.	Less prolonged shift away, with a slower forward shift in the late backswing. Reversal of the forward shift around mid-downswing.
Swing plane horizontal backswing	1	85.1	0.5561	-0.59	-0.08	Offset	Greater in-to-out plane.	Greater out-to-in plane.
	2	11.5	0.9471	0.07	0.01	Magnitude	Becomes a lesser out-to-in plane initially, before reversing and becoming a greater out-to-in.	Becomes a lesser in-to-out plane initially, before reversing and becoming a greater in-to-out plane.
Swing plane horizontal downswing	1	92.4	*0.0014*	-3.19	-0.46	Offset	Greater in-to-out plane.	Greater out-to-in plane.
Swing plane vertical backswing	1	96.0	0.0884	-1.70	-0.23	Offset	Flatter plane.	Steeper plane.
Swing plane vertical downswing	1	89.4	0.9765	-0.03	-0.00	Offset	Flatter plane.	Steeper plane.

6.5.6. Hypothesis outcome

The outcome of the hypotheses for the low-natural comparison are shown in Table 6-15.

Table 6-15: Outcomes of the hypothesised changes, supported (✓), rejected (×) or not applicable (N/A), in the biomechanical variables between the 5-iron low and natural trajectories at address, ball contact and over the whole-swing. Other outcomes refers to non-hypothesised differences between the trajectories.

Variable	Address	Ball contact	Whole-swing	Other outcomes
Pelvis rotation	N/A	N/A	✘	✓
Thorax rotation	N/A	N/A	✘	✓
X-factor	N/A	N/A	✘	✘
Ball position	✓	N/A	N/A	✘
Stance width	✘	N/A	N/A	✘
Grip distance	✘	N/A	N/A	✘
Lead hand forwardness	✓	✓	N/A	✘
Lumbar lateral flexion	N/A	N/A	✘	✘
Thorax lateral flexion	✓	✘	✘	✘
Lead wrist deviation	N/A	N/A	✘	✘
Centre of pressure	✘	✓	✘	✓

6.5.7. Group swing patterns

As with draw and fades, achieving a low shot involved a combination of address and whole-swing changes. At address, when setting up to hit low shots compared to their natural trajectory, golfers positioned the ball 29 ± 33 mm further back in the stance, the lead hand was 38 ± 26 mm further forward relative to the ball, the thorax was laterally flexed 1.6 ± 2.3º more neutrally and the pelvis was 0.8 ± 1.9º less open for the low shots (Figure 6-14).

Over the swing, there were absolute differences in the pelvis rotation and pelvis translation (Table 6-14). The pelvis rotation was offset less rotated away from the target for low trajectories, suggesting the finding of a less open pelvis rotation at address was coincidental. Furthermore, the pelvis was positioned less away from the target than for the natural trajectories (Table 6-14).

An additional magnitude of rotation difference at the pelvis could explain the discrepancy between the pelvis rotation event results and whole-swing results. As the backswing initiated, the pelvis segment rotated away from the target from early in the backswing for both shot conditions, but did so more for the natural trajectories (Figure 6-12d). The thorax rotated away from the target later for low trajectories (Table 6-14). Additionally, as the centre of pressure shifted away, it did so quicker for the low trajectories (Table 6-14). Therefore, at top of the backswing, for low trajectories, the pelvis was rotated relatively less and the centre of pressure shifted further away from the target.

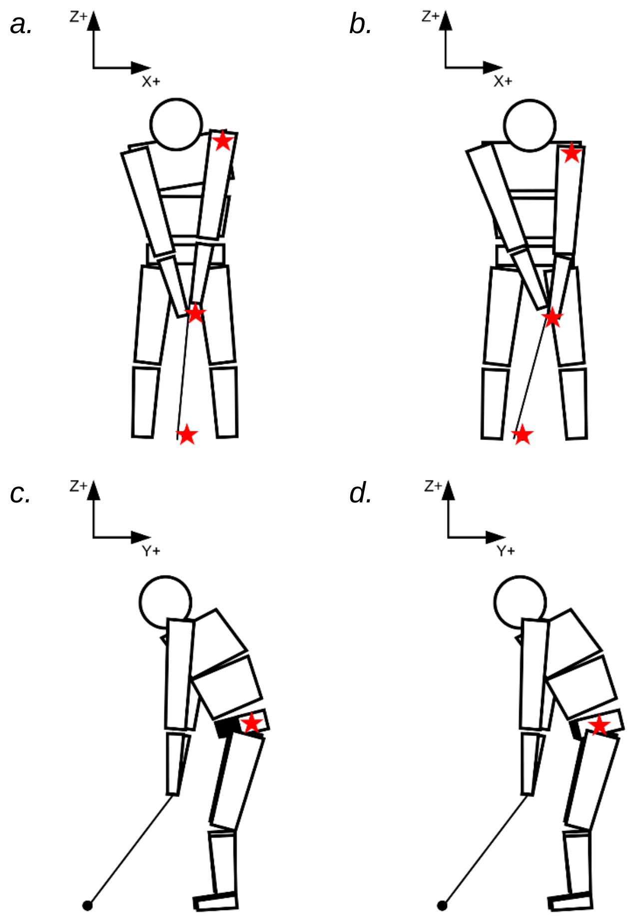


Figure 6-14: 5-Iron low-natural trajectory differences at address: a. natural front-on; b. low front-on; c. natural side-on and d. low side-on. The stars represent where the differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the pelvis.

With transition to the downswing, the centre of pressure shifted forward towards the target and the pelvis rotated back towards the target for both conditions. As the downswing progressed, the thorax rotation towards the target commenced later for the low trajectories (Table 6-14). The centre of pressure shift (Figure 6-12i) and the rotation of the pelvis towards the target were greater for the low condition (Table 6-14). Lastly, as ball contact approached the thorax rotation was more prolonged for the low shots (Table 6-14).

The less rotated away pelvis offset over the whole-swing could have contributed to differences in horizontal swing plane over the downswing, where there was an offset which saw low shots have a more out-to-in swing plane (Table 6-14).

At ball contact centre of pressure shift was located further forward towards the lead foot (10 ± 10% of the stance width) for low trajectories (Figure 6-15), probably due to the greater forward shift during the downswing. The other difference was in lead hand forwardness, where low shots had a lead hand further forward relative to the ball of 49 ± 32 mm (Figure 6-15).

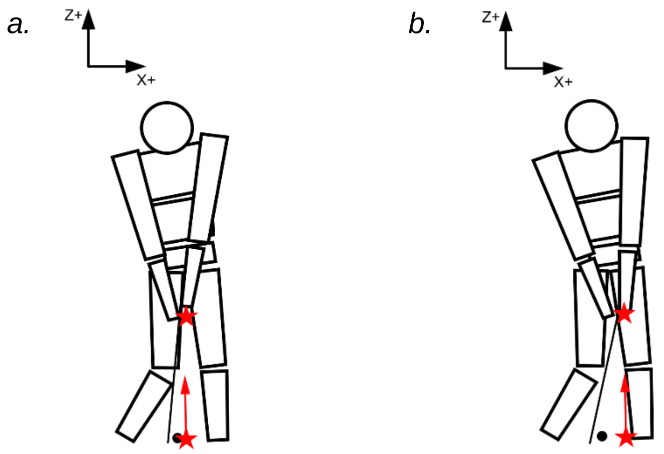


Figure 6-15: 5-Iron low-natural trajectory differences at ball contact: a. natural front-on and b. low front-on. The stars represent where the differences occurred. The figures are shown in plane for ease of representation.

6.6. Summary

This chapter has presented group-based results of the draw-fade and low-natural trajectory comparisons. Analysis at the key events of address position and ball contact and over the whole-swing found significant differences in key variables between shot trajectories.

For the draw-fade comparisons, the hypothesis of a more closed address position relative to target (pelvis rotation, thorax rotation and stance openness) for the draw was supported, for both the driver and the 5-iron, as was regulation of the ball position, away from the target, and lead hand position towards the target. Over the swing, the pelvis rotation offset was maintained supporting the initial hypothesis. However, further timing differences between shot trajectories were uncovered. Also supported was the hypothesis of pelvis and centre of pressure translation further towards the target for draw trajectories. Finally, the hypotheses of flexing of the thorax (towards the lead for the draw) and the lumbar (towards the trail for the draw) were supported. At ball contact, similarly to address, the lead hand forwardness, thorax lateral flexion, and pelvis rotation hypotheses were supported. Ultimately, the movements over the swing helped to create a more in-to-out swing plane for the draw trajectories.

Fewer differences were found between the low and natural trajectory trajectories. The hypotheses of a ball position further away from the target and a lead hand forwardness further towards the target for the low trajectories were supported at address. As was a more flexed thorax towards the lead. None of the initial hypotheses were supported over the whole-swing; however, those related to lead hand forwardness and centre of pressure, both towards the target for the low, were supported at ball contact.

CHAPTER SEVEN

THE ROLE OF BIOMECHANICS IN ACHIEVING DIFFERENT SHOT TRAJECTORIES WITH THE SAME CLUB – AN INDIVIDUAL FOCUS

7.1. Introduction

The previous chapter presented results for the investigation of biomechanical variables across shot trajectory comparisons on a group-basis. However, there is a need within biomechanics to investigate movement patterns on a more individual basis, primarily because individual movement characteristics are often masked by grouping the participants. This may have been the case for the analysis of movement patterns described for each shot trajectory in Chapter 6

Therefore, this chapter delves deeper into the data to determine whether individual golfers or sub-groups of golfers utilised different biomechanical approaches to achieve the desired shot outcome. To do this, the principal component analysis results were explored further and multivariate correlation techniques introduced. The same testable hypothesis as defined in Chapter 5 provided the basis:

> *Hypothesis:* A golfer will significantly alter their swing biomechanics to achieve different shot trajectories, as outlined in Table 5-9 and Table 5-10.

7.2. Driver draw versus fade

7.2.1. Magnitude of shot trajectories

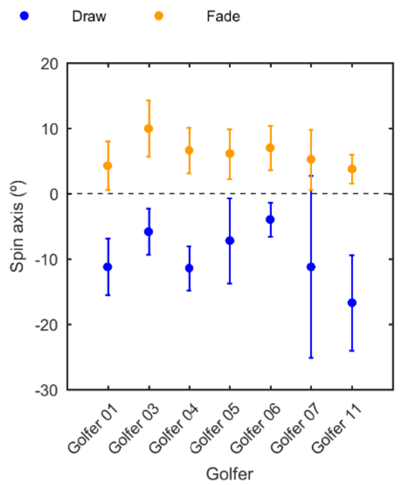


Figure 7-1: Mean spin axis (± 1 SD) for draw and fade trajectories by each golfer with the driver.

The magnitude of draw and fade achieved by each golfer is reflected in the spin axis (Figure 7-1). The individual golfer magnitudes help put some perspective on the golfer patterns which follow in the succeeding sections. Golfer seven showed a much wider distribution of draw trajectory spin axes (i.e. less consistency) compared to the fade.

7.2.2. Impact location

Impact location across shot trajectories is shown in Table 7-1. Draw or fade trajectories could have arisen from off-centre impact locations due to the gear effect (Jorgensen, 1999). Therefore, it is important to discount impact location as a possible mediator of the results. No significant differences were found for the driver draw-fade comparison across golfers, although there were small differences; for example, the 15 mm difference in vertical impact location of golfer three.

Table 7-1: Comparison of mean (& SD) horizontal and vertical impact location for both draw and fade trajectories by each golfer with the driver. Data is missing for golfer seven who was the left-handed golfer.

Golfer	Horizontal impact location			Golfer	Vertical impact location		
	Draw (mm)	Fade (mm)	p-value		Draw (mm)	Fade (mm)	p-value
One	2 (8)	8 (6)	0.1087	One	-4 (12)	1 (14)	0.6873
Three	-9 (6)	-5 (4)	0.4236	Three	-4 (14)	11 (4)	0.1715
Four	-4 (3)	0 (5)	0.2595	Four	-4 (5)	4 (9)	0.8048
Five	-14 (6)	-17 (5)	0.7204	Five	-11 (13)	-11 (17)	0.9841
Six	-10 (2)	-15 (4)	0.2167	Six	15 (2)	21 (5)	0.0833
Seven	-	-	-	Seven	-	-	-
Eleven	-4 (5)	-3 (6)	0.9749	Eleven	2 (9)	9 (5)	0.4704

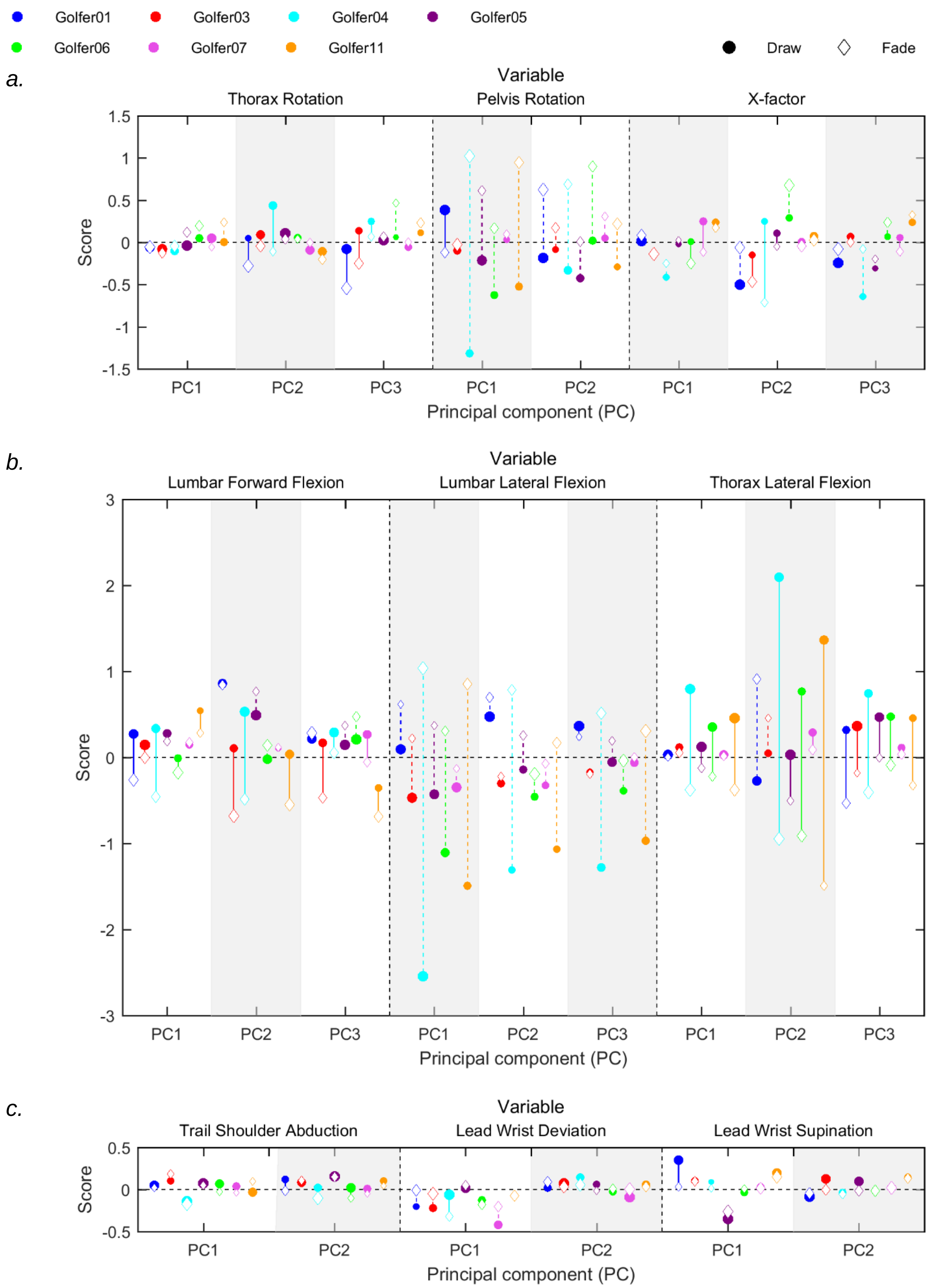
7.2.3. Individual event results

Individual golfer values for each of the address and ball contact variables are shown for the driver draw-fade comparison in Table G-1 and Table G-2 (Appendix G).

7.2.4. Individual swing results

Relative (to the natural trajectories) draw and fade principal component scores for the golfers included in the driver draw-fade analysis are shown in Figure 7-2. The figure gives a visual indication of the principal components which differed between the shot trajectory types. For each parameter, the number of principal components explaining over 90% of the variance in the data are included.

The graphs suggest there were common differences exhibited by multiple golfers across principal components (i.e. the golfers' draw scores were greater than their fade scores or vice versa). These were present in pelvis rotation principal components one and two (Figure 7-2a), lumbar lateral flexion principal components one, two and three (Figure 7-2b), thorax lateral flexion principal components one, two and three (Figure 7-2b), pelvis translation principal component one (Figure 7-2d) and centre of pressure principal components four and five (Figure 7-2d).


Golfer01
Golfer03
Golfer04
Golfer05
Golfer06
Golfer07
Golfer11
Draw
Fade
a.
Variable
Thorax Rotation
Pelvis Rotation
X-factor
Score
PC1
PC2
PC3
Principal component (PC)
b.
Variable
Lumbar Forward Flexion
Lumbar Lateral Flexion
Thorax Lateral Flexion
Score
Principal component (PC)
c.
Variable
Trail Shoulder Abduction
Lead Wrist Deviation
Lead Wrist Supination
Score
Principal component (PC)

d.

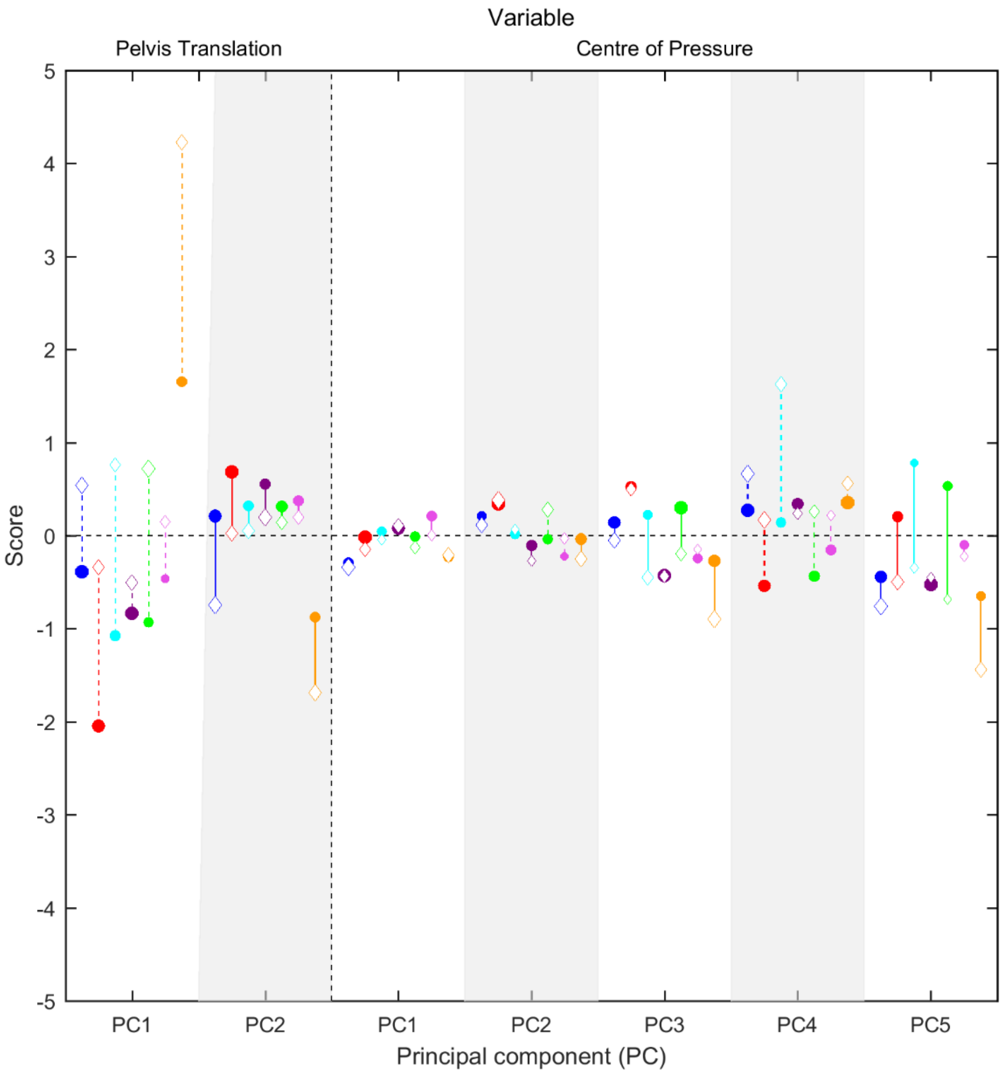


Figure 7-2: Mean scores for each principal component for each golfer in the driver draw-fade analysis: a. thorax rotation, pelvis rotation and X-factor; b. lumbar forward flexion, lumbar lateral flexion and thorax lateral flexion; c. trail shoulder abduction, lead wrist deviation and lead wrist supination and d. pelvis translation and centre of pressure. The draw and fade scores for each golfer are connected by lines. A solid line represents when the draw score is more positive, a dotted line when the fade is more positive. The size of marker indicates the size of the variance in principal components scores. All shots are expressed relative to the natural shot score.

The differences in principal component scores between the draw and fade conditions (draw minus fade) for each variable are illustrated in Figure 7-3. Patterns become more evident between golfers, for example, between golfer four and golfer eleven. Therefore, there is initial evidence for clusters of golfers who make similar biomechanical changes between draw and fade trajectories.

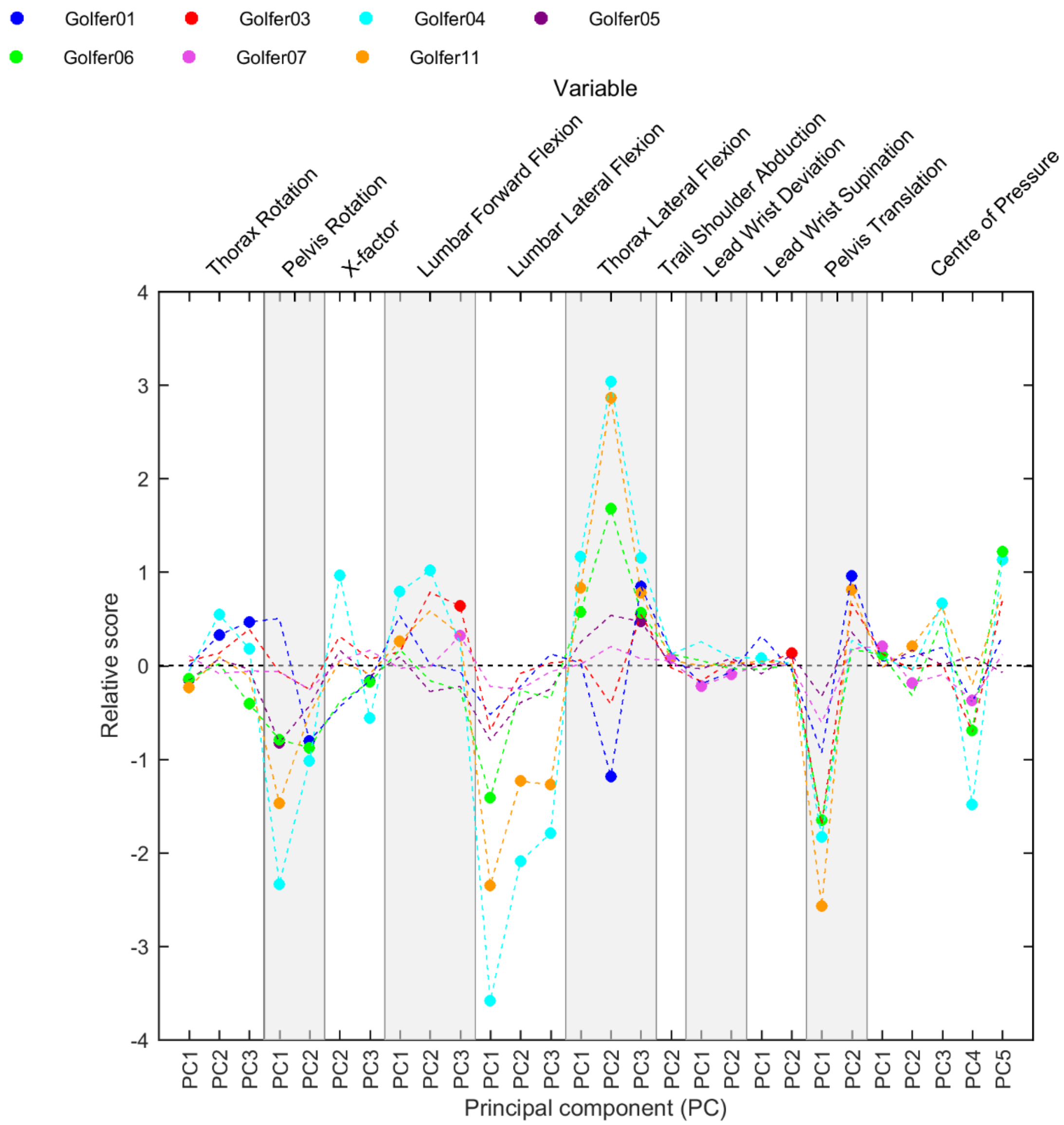


Figure 7-3: Difference in driver principal component scores (draw minus fade) for each golfer by variable. Those principal components where no golfer displayed significant differences have been removed. Markers represent significant differences.

To better identify these clusters, multivariate correlation, which correlated all principal component scores of every golfer to those of all other golfers, was performed (Figure 7-4). Scatter plots for all relationships are shown in Appendix H. The multivariate correlation produced numerous moderate-to-strong relationships and a cluster of golfers all of whom correlated strongly or very strongly with each other emerged (*Cluster I*). This included four of the seven golfers: golfers four, five, six and eleven.

Golfer	1	3	4	5	6	7	11
1	1.00						
3	0.43	1.00					
4	0.37	0.68	1.00				
5	0.20	0.19	0.73	1.00			
6	0.49	0.54	0.74	0.53	1.00		
7	0.24	0.58	0.40	0.10	0.46	1.00	
11	0.32	0.57	0.94	0.76	0.74	0.31	1.00

Positive
Very weak
Weak
Moderate
Strong
Very Strong
Perfect

(Evans, 1996)

Figure 7-4: Multivariate correlation r-values comparing each golfer's driver draw-fade principal components scores to all other golfers.

7.2.5. Hypothesis outcomes

The outcome of the hypotheses outlined in Section 5.5.3 in relation to *Cluster I* are presented in Table 7-2. The table also shows where outcomes not hypothesised initially emerged.

Table 7-2: Outcomes of the hypothesised changes, supported (✓), rejected (×) or not applicable (N/A), in Cluster I golfers' biomechanical variables between the driver draw and fade trajectories at address, ball contact and over the whole-swing. Other outcomes refers to non-hypothesised differences between the trajectories.

Variable	Address	Ball contact	Whole-swing	Other outcomes
Pelvis rotation	✓	✓	✓	✓
Thorax rotation	✓	✓	×	✓
X-factor	N/A	N/A	×	✓
Stance openness	✓	N/A	N/A	×
Ball position	N/A	N/A	N/A	✓
Lead hand forwardness	N/A	N/A	N/A	✓
Lead hand height	×	×	N/A	×
Lumbar forward flexion	N/A	N/A	×	✓
Lumbar lateral flexion	N/A	N/A	✓	✓
Thorax lateral flexion	✓	✓	×	✓
Pelvis translation	N/A	N/A	✓	✓
Trail shoulder abduction	N/A	N/A	×	×
Lead wrist supination	N/A	N/A	×	×
Lead wrist deviation	N/A	N/A	×	×
Centre of pressure	×	×	×	✓
Instantaneous swing plane horizontal	N/A	✓	✓	×
Instantaneous swing plane vertical	N/A	×	×	×

7.2.6. Cluster I swing pattern

At address golfers set up similarly; for example, all golfers positioned the ball further back, away from the target, relative to the lead foot for the draw. Stance width may have been a mechanism by which golfers achieved this, but there was no clear pattern across golfers. For the draw, *Cluster I* showed a more neutrally lateral flexed thorax compared to the fade (Figure 7-5). This could have aided the lead hand forwardness positioned further towards the target relative to the lead foot for draw trajectories.

In terms of alignment to target, *Cluster I* golfers' stances differed with pelvis and thorax rotation, being closed for draw trajectories and open for fade. This was also true for stance openness.

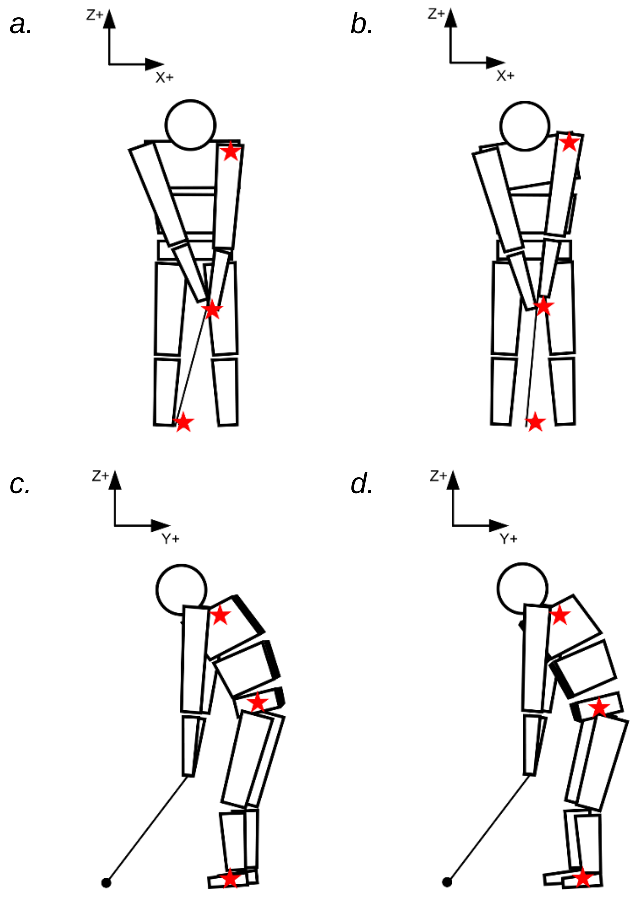


Figure 7-5: Differences in address position between draw and fade trajectories in Cluster I: a. draw front-on; b. fade front-on; c. draw side-on and d. fade side-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the central body segments.

Over the swing, *Cluster I* showed absolute offset differences between shot trajectories, firstly at the pelvis (rotated more away from the target for the draw), at the lumbar (flexion towards the trail for the draw) and lastly, pelvis translation (translated less away from the target for the draw). All other golfers shared the tendency for the lumbar lateral flexion offset. Golfer four showed a more pronounced offset in X-factor (the thorax rotated less away relative to the pelvis for the draw trajectories).

As the backswing commenced, across golfers the thorax was flexed neutrally and the lumbar spine began to forward flex, in both trajectories. For *Cluster I* draw trajectories, the centre of pressure was positioned further towards the target, compared to the fade, early in the backswing. As the backswing progressed, there was a later centre of pressure shift away from the target and the magnitude of lumbar forward flexion was greater in *Cluster I* for the draw. Additionally, the thorax flexed towards the lead to a greater magnitude for the same shots. The pelvis and thorax segments showed relative timing differences, with earlier rotation of the thorax and later rotation of the pelvis away from the target and of the thorax relative to the pelvis, again for the draw trajectories. The later pelvis rotation was in fact true for all golfers.

Over the middle and later phase of the backswing, the lumbar lateral flexion pattern was more complex than simply an offset with lead and trail flexion movements. Finally, as top of the backswing approached there was a reversal of the flexing of the thorax towards the trail, followed by a re-reversal and continuation of the flexing towards the lead in draw trajectories.

In transitioning into the downswing, there was a thorax and pelvis rotation back towards the target regardless of the shot condition, although the thorax rotation appeared later in golfer six for the draw. For *Cluster I*, the lumbar spine forward extended, the thorax flexed towards the trail and the centre of pressure shifted towards the target. The centre of pressure and pelvis translation shifts commenced earlier and quicker in draw trajectories; the latter of these true for all golfers. As the downswing progressed there was a greater magnitude of thorax rotation back towards the target and a greater magnitude of lumbar forward extending in draw trajectories, although not as evident for golfer six.

Into the later downswing, the rate of centre of pressure shift remained quicker for the draw condition and the magnitude of the shift was greater. However, the individual nature of centre of pressure meant at ball contact there was no clear pattern even within *Cluster I*. In this late phase, the lumbar lateral flexion towards the trail was prolonged for the draw trajectories through ball contact, and this was similar for thorax lateral flexion which saw continued flexing towards the trail. The flexing of the thorax towards the trail, along with initial ball position, could have helped promote a lead hand forwardness well ahead of the ball, towards the target, at ball contact; the lead hand was ahead to a greater extent for draw trajectories. However, the thorax itself tended to be less flexed towards the trail for these trajectories, potentially due to the greater flexing towards the lead in the backswing phase.

The movements over the late downswing helped promote swing plane differences (Figure 7-6). In terms of horizontal swing plane, draw trajectories showed an in-to-out plane, whilst fade showed an out-to-in. Also, at ball contact, pelvis rotation for all golfers showed a more open pelvis for the fade trajectories. Finally, the thorax was open more so for the fade for the golfers in *Cluster I*.

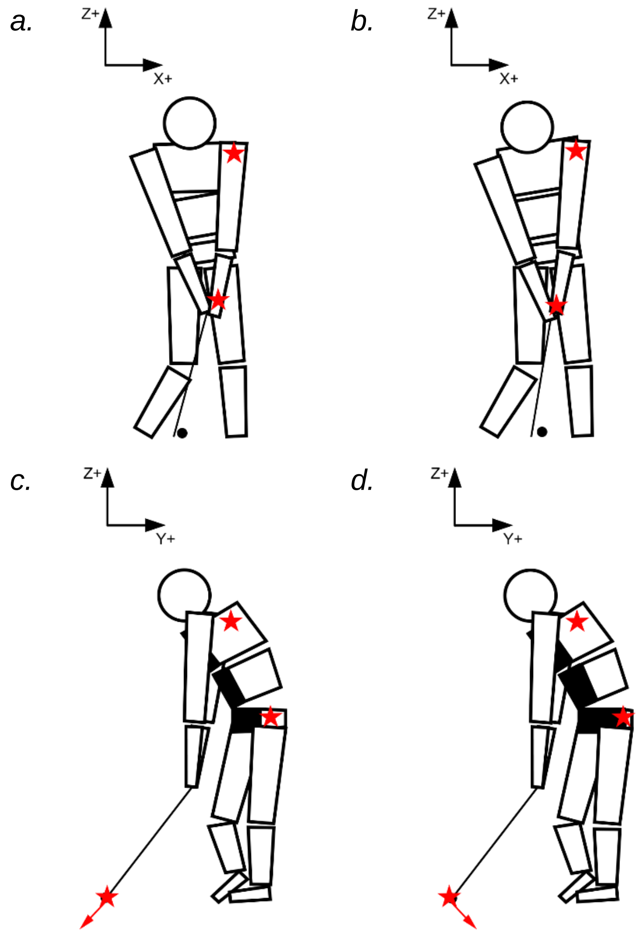


Figure 7-6: Differences in ball contact position between draw and fade trajectories in Cluster I: a. draw front-on; b. fade front-on; c. draw side-on and d. fade side-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the central body segments.

7.2.7. Golfer one swing pattern

Golfer one appeared to have a more unique swing pattern when compared to golfers in *Cluster I* (Figure 7-4). Whilst there were similarities at address, namely in, stance openness, ball position, lead hand forwardness and thorax lateral flexion, the golfer aligned their pelvis and shoulder rotation relative to the target line in an opposite manner to the cluster.

These differences may have transferred through to the whole-swing where the golfer appeared to show the opposite pelvis rotation offset over the whole-swing, rotated more away from the target for the fade trajectories (pelvis rotation principal component one; Figure 7-2a). Golfer one also differed from *Cluster I* around top of the backswing, where the golfer showed continued flexing of the thorax towards the lead. Furthermore, during the downswing, the golfer showed less thorax flexing towards the trail in the draw trajectories compared to the fade, the opposite to *Cluster I.*

Despite the differences at address and during the swing, golfer one still achieved the same horizontal swing plane difference between draw and fade trajectories at ball contact.

7.3. 5-Iron draw versus fade

7.3.1. Magnitude of shot trajectories

As for the driver, the magnitude of draw and fade spin axes are displayed for the 5-iron (Figure 7-7). Some golfers, for example golfer twelve, appeared more consistent than others, such as golfer one.

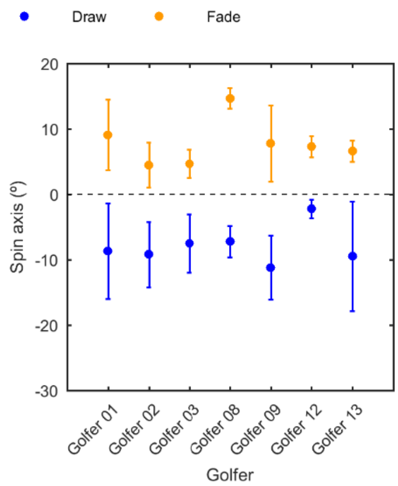


Figure 7-7: Mean spin axis (± 1 SD) for draw and fade trajectories by each golfer with the 5-iron.

7.3.2. Impact location

The 5-iron draw and fade impact locations are shown in Table 7-3. As with the driver, no significant differences were found across golfers.

Table 7-3: Comparison of mean (& SD) horizontal and vertical impact location for both draw and fade trajectories by each golfer with the 5-iron.

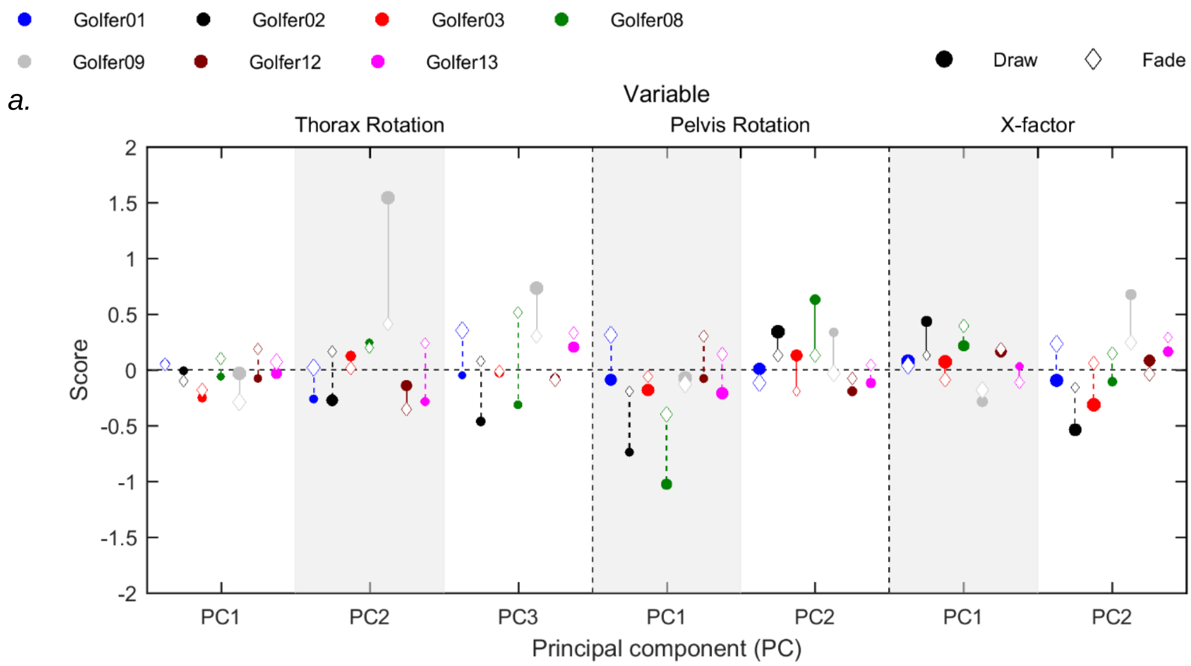
Golfer	Horizontal impact location			Golfer	Vertical impact location		
	Draw (mm)	Fade (mm)	p-value		Draw (mm)	Fade (mm)	p-value
One	-8 (8)	-5 (6)	0.9999	One	-0 (4)	-5 (3)	0.4938
Two	-1 (7)	2 (8)	0.8938	Two	-5 (4)	-9 (9)	0.8304
Three	2 (5)	6 (6)	0.2464	Three	-5 (6)	-9 (3)	0.8279
Eight	-3 (4)	-10 (9)	0.6872	Eight	-7 (9)	-5 (3)	0.6477
Nine	-19 (9)	-16 (11)	0.9880	Nine	-5 (5)	-7 (6)	0.9432
Twelve	-6 (6)	3 (4)	0.1279	Twelve	-3 (4)	-6 (2)	0.9987
Thirteen	-11 (8)	-7 (3)	0.2251	Thirteen	-6 (4)	-5 (6)	0.9887

7.3.3. Individual event results

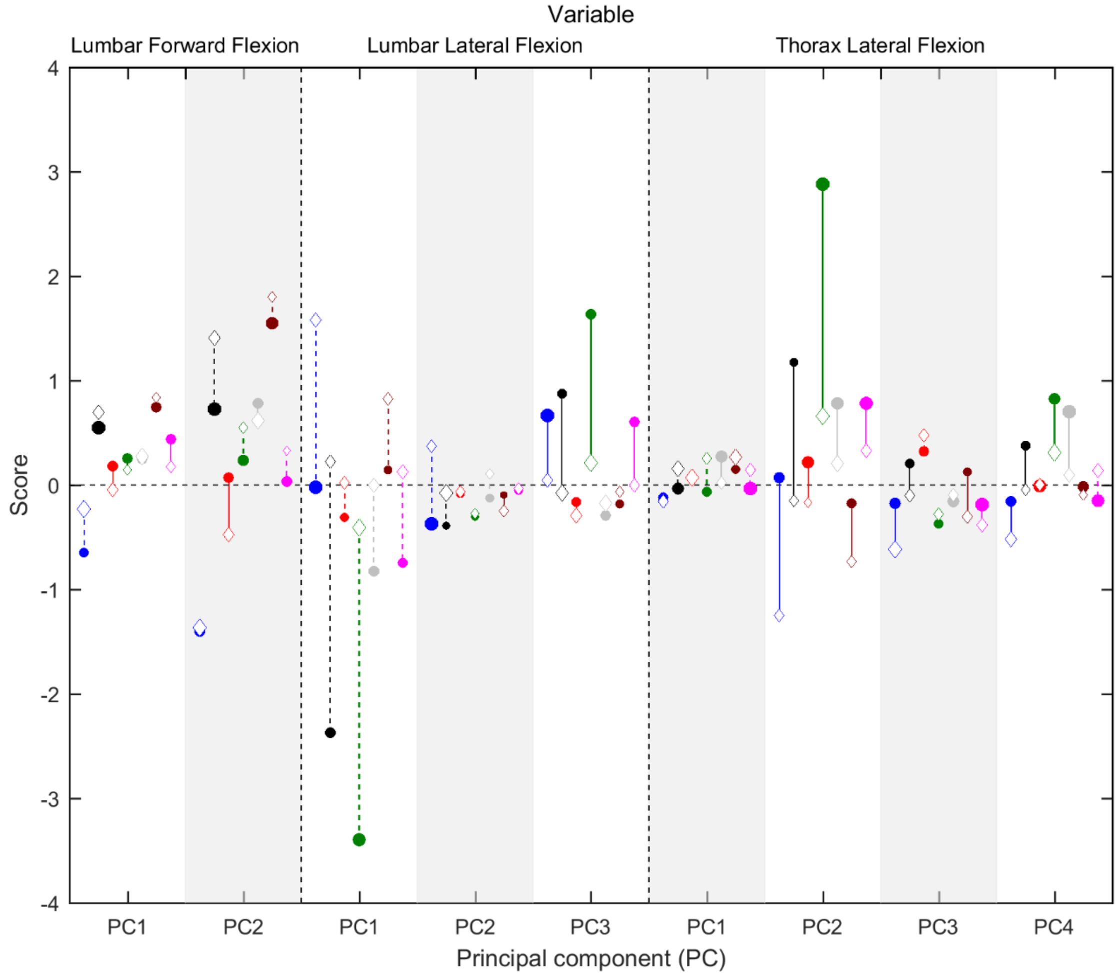
The 5-iron draw-fade address and ball contact variables are shown in Table G-3 and Table G-4 (Appendix G).

7.3.4. Individual swing results

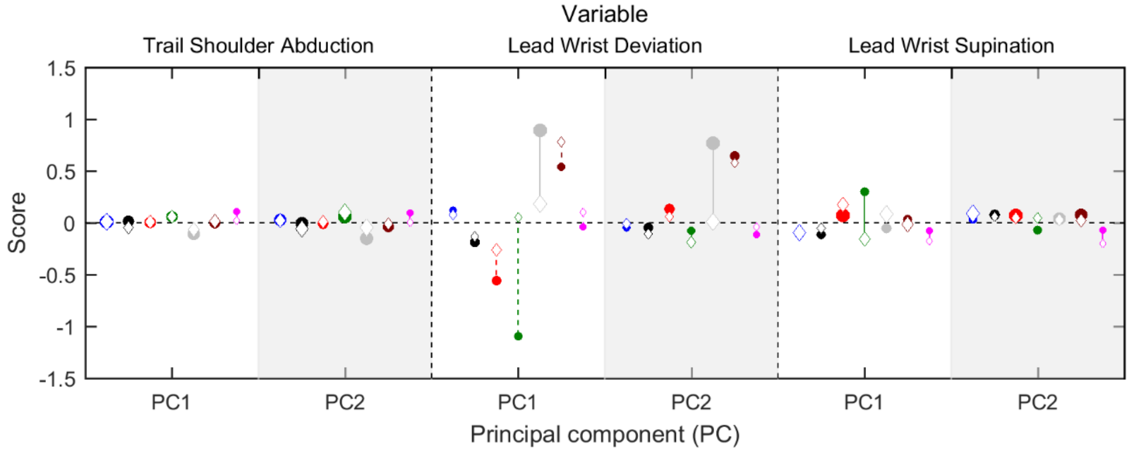
The same plots as for the driver comparison are shown, displaying all golfers' principal component scores across each variable (Figure 7-8). Again, there appears to be principal components for which common differences across multiple golfers occur. These can be seen in pelvis rotation principal component one (Figure 7-8a), lumbar lateral flexion principal component one (Figure 7-8b), thorax lateral flexion principal component two (Figure 7-8b) and pelvis translation principal component two (Figure 7-8d).



b.


Variable
Lumbar Forward Flexion
Lumbar Lateral Flexion
Thorax Lateral Flexion
Score
4
3
2
1
0
-1
-2
-3
-4
PC1
PC2
PC1
PC2
PC3
PC1
PC2
PC3
PC4
Principal component (PC)

c.


Variable
Trail Shoulder Abduction
Lead Wrist Deviation
Lead Wrist Supination
Score
1.5
1
0.5
0
-0.5
-1
-1.5
PC1
PC2
PC1
PC2
PC1
PC2
Principal component (PC)

d.

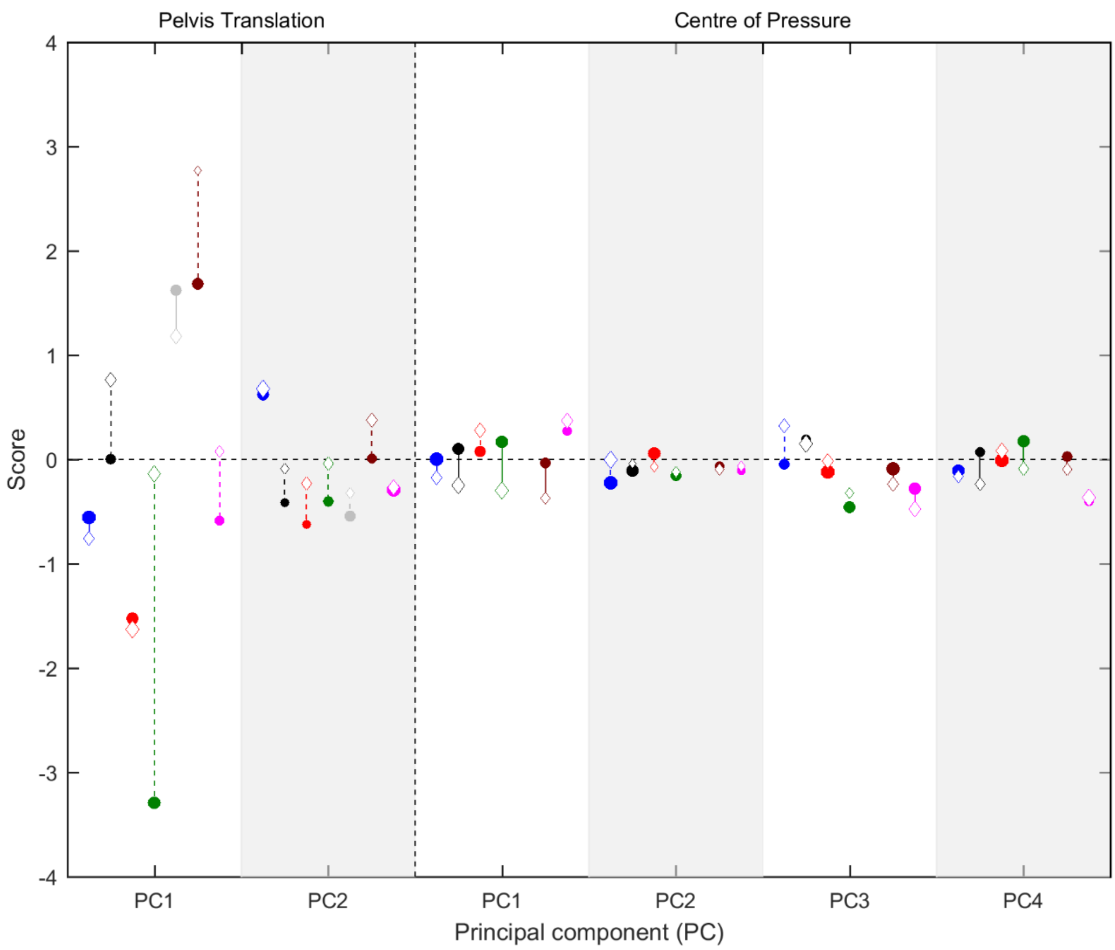


Figure 7-8: Mean scores for each principal component for each golfer in the 5-iron draw-fade analysis: a. thorax rotation, pelvis rotation and X-factor; b. lumbar forward flexion, lumbar lateral flexion and thorax lateral flexion; c. trail shoulder abduction, lead wrist deviation and lead wrist supination and d. pelvis translation and centre of pressure. The draw and fade scores for each golfer are connected by lines. A solid line represents when the draw score is more positive, a dotted line when the fade is more positive. The size of marker indicates the size of the variance in principal components scores. All shots are expressed relative to the natural shot score.

As for the driver, the difference in principal component scores for each variable (draw minus fade) is shown for the 5-iron, so that the patterns between golfers, such as golfers two and eight, can more easily be observed (Figure 7-9).

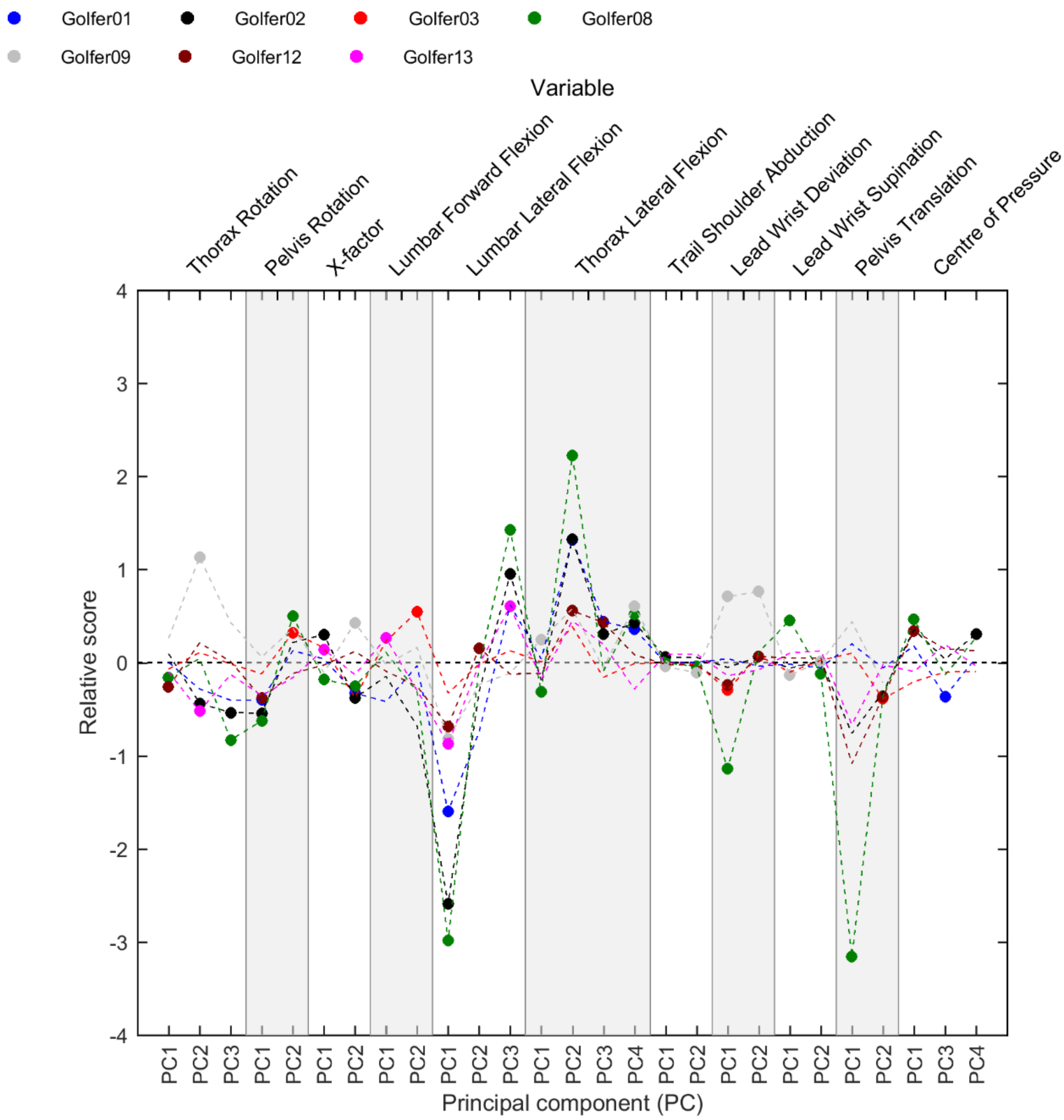


Figure 7-9: Difference in 5-iron principal component scores (draw minus fade) for each golfer by variable. Those principal components where no golfer displayed significant differences have been removed. Markers represent significant differences.

The multiple correlation showed a number of strong and very strong relationships (Figure 7-10; Appendix I). There appeared to be a cluster of golfers (*Cluster II*) which were all strongly correlated with each other, including five of the seven golfers, golfers one, two, eight, twelve and thirteen.

Golfer	1	2	3	8	9	12	13
1	1.00						
2	0.88	1.00					
3	0.46	0.40	1.00				
8	0.66	0.86	0.39	1.00			
9	0.45	0.38	0.35	0.31	1.00		
12	0.41	0.62	0.17	0.79	0.31	1.00	
13	0.62	0.82	0.25	0.80	-0.08	0.61	1.00

Negative	Positive	
		Very weak
		Weak
		Moderate
		Strong
		Very Strong
		Perfect

(Evans, 1996)

Figure 7-10: Multivariate correlation r-values comparing each golfer's 5-iron draw-fade principal components scores to all other golfers.

7.3.5. Hypothesis outcomes

As with the driver, the hypotheses outcomes outlined in relation to *Cluster II* are presented in Table 7-4. The table also displays outcomes which were not hypothesised initial but emerged as a result of the analysis.

Table 7-4: Outcomes of the hypothesised changes, supported (✓), rejected (✗) or not applicable (N/A), in Cluster II golfers' biomechanical variables between the 5-iron draw and fade trajectories at address, ball contact and over the whole-swing. Other outcomes refers to non-hypothesised differences between the trajectories.

Variable	Address	Ball contact	Whole-swing	Other outcomes
Pelvis rotation	✓	✓	✓	✓
Thorax rotation	✗	✓	✗	✓
X-factor	N/A	N/A	✗	✓
Stance openness	✓	N/A	N/A	✗
Ball position	N/A	N/A	N/A	✓
Lead hand forwardness	N/A	N/A	N/A	✓
Lead hand height	✗	✗	N/A	✗
Lumbar forward flexion	N/A	N/A	✓	✗
Lumbar lateral flexion	N/A	N/A	✓	✓
Thorax lateral flexion	✓	✓	✗	✓
Pelvis translation	N/A	N/A	✓	✓
Trail shoulder abduction	N/A	N/A	✗	✗
Lead wrist supination	N/A	N/A	✗	✗
Lead wrist deviation	N/A	N/A	✗	✗
Centre of pressure	✗	✓	✗	✓
Instantaneous swing plane horizontal	N/A	✓	✓	✗
Instantaneous swing plane vertical	N/A	✗	✗	✗

7.3.6. Cluster II swing pattern

At address, as with the driver, there were commonalities in set-up (Figure 7-11). All golfers except for golfer thirteen, positioned the ball back further away from the target, relative to the lead foot for the draw, which may have resulted from altered stance widths, but these were more individual. All golfers also addressed the ball with the lead hand further towards the target, relative to the ball, for the draw trajectories, maybe because the ball was further away from the target. However, it could also have been related to the thorax which for *Cluster II*, was flexed more neutrally in the draw.

In terms of the stance relative to target line, *Cluster II* showed a closed pelvis and stance openness for the draw and open for the fade, except for golfer thirteen.

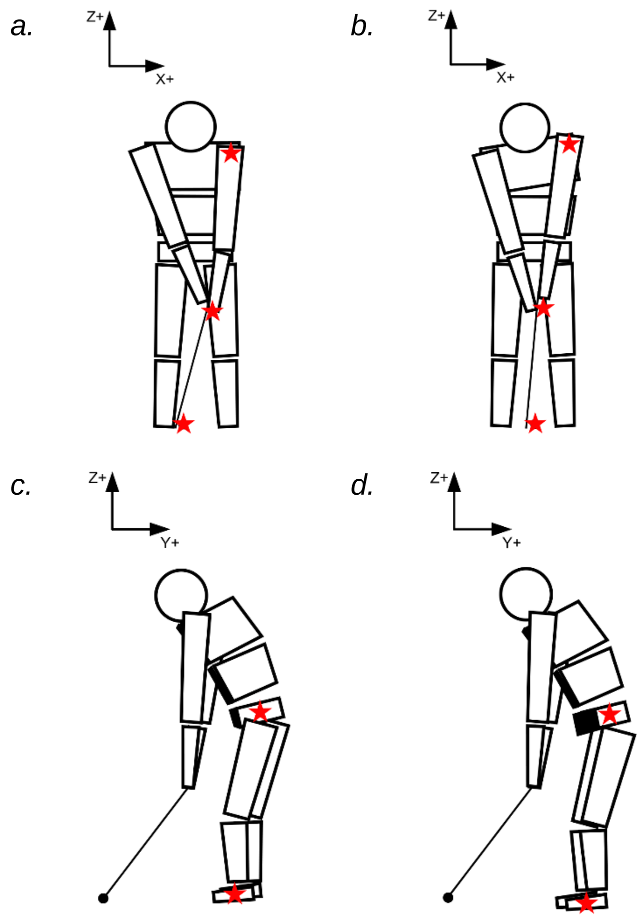


Figure 7-11: Differences in address position between the draw and fade trajectories in Cluster II: a. draw front-on; b. fade front-on; c. draw side-on and d. fade side-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the central body segments.

There were absolute offset differences between the draw and fade swings of *Cluster II*. The pelvis rotation was rotated more away from the target and the thorax less rotated away relative to the pelvis throughout for draw trajectories. For the same trajectories, in terms of the lumbar spine, there was a greater lumbar forward flexion and lumbar lateral flexion towards the trail side offsets. The second of these was true across all golfers; however, golfer eight showed the opposite X-factor and lumbar forward flexion offsets. Finally, pelvis translation was also offset positioned less away from the target for the draw trajectories.

As the backswing began, *Cluster II* demonstrated rotations of the thorax and pelvis away from the target, a lumbar lateral flexion towards the lead and a flexing of the thorax towards the lead. The last of these being at a slower rate for the draw. As the phase progressed the thorax rotation away from the target was less prolonged and the lumbar lateral flexion towards the lead of less magnitude in the draw trajectories. Additionally, *Cluster II* showed greater closing of the thorax relative to the pelvis in the later stages.

As the swing transitioned to the downswing, *Cluster II* showed earlier thorax rotation, pelvis translation and centre of pressure shift towards the target for draw trajectories. Pelvis translation was a feature of all golfers. A marginally earlier thorax lateral flexing towards the trail also occurred early in the phase for the same condition, barring golfer thirteen. As the downswing progressed, *Cluster II* showed less lumbar lateral flexion for the draw. Around mid-downswing, for the draw trajectories, the flexing of the thorax towards the trail and the centre of pressure shift slowed and even reversed in the latter case. Centre of pressure patterns were individual during the late downswing, however, most *Cluster II* golfers had a position further towards the target for the draw. Through the final stages of the downswing, the slowing of the thorax lateral flexing aided a position whereby the thorax was more neutral for the draw condition through ball contact. This could have aided a lead hand forwardness further towards the target for the draw trajectories. Finally, through ball contact the thorax rotation towards the target slowed for the draw condition.

At ball contact, all *Cluster II* had a more open pelvis rotation for the fade trajectories (Figure 7-12), a probable result of the pelvis offset, brought about by the change at address. It could have aided differences in horizontal swing plane, where all golfers had a more in-to-out swing plane for the draw.

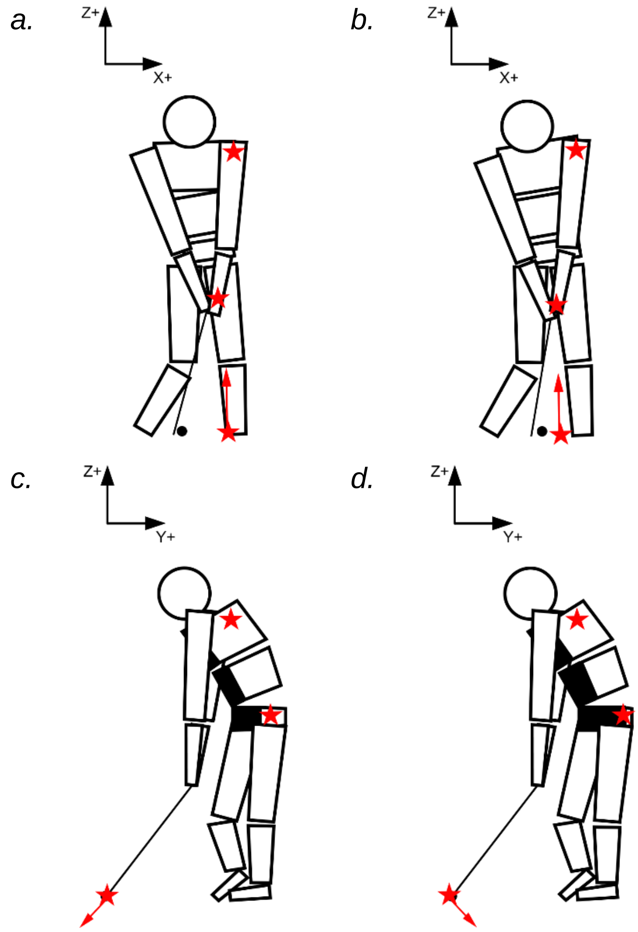


Figure 7-12: Differences in ball contact position between the draw and fade trajectories in Cluster II: a. draw front-on; b. fade front-on; c. draw side-on and d. fade side-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the central body segments.

7.3.7. Golfer nine swing pattern

Like golfer one for the driver, golfer nine displayed a swing pattern less strongly correlated to *Cluster II.*

The golfer displayed similar address and ball contact positions to *Cluster II* for the draw and fade trajectories, however, utilised some unique whole-swing changes between shot conditions. For example, prominent offset differences lay at the lead wrist segment (Figure 7-8c). The golfer showed more ulnar deviation for draw trajectories. Furthermore, there was also a magnitude difference during the swing, where draw trajectories showed greater radial deviation during the backswing and greater ulnar deviation during the downswing. Finally, golfer nine differed from *Cluster II*, in terms of X-factor, with less thorax rotation relative to the pelvis in the later backswing for draw trajectories, however, the thorax rotation alone was more prolonged through ball contact for these shots.

7.4. 5-Iron low versus natural

7.4.1. Magnitude of shot trajectories

The magnitude of low and natural trajectory launch angles achieved by each golfer is shown in Figure 7-13. Typically, low trajectory launch angles were less than 12º across golfers. However, the low trajectories for golfers ten and thirteen had launch angles higher than some golfers' natural values. In addition, some golfers decreased the launch angle by a greater magnitude than others compared to the natural. For example, golfer one effectively halved the launch angle for the low trajectories (8.3 ± 1.1º compared to 16.7 ± 0.9º for the natural trajectories), whereas golfer thirteen only reduced it by approximately 15% (16.1 ± 0.2º for the low compared to 19.2 ± 1.1º for the natural).

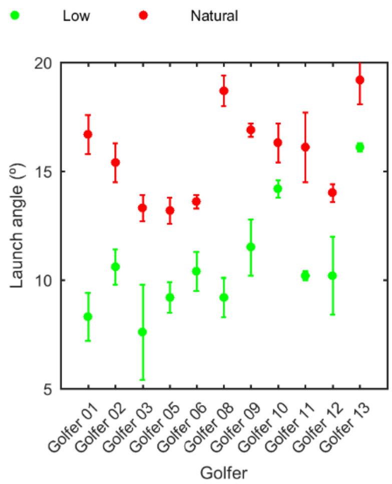


Figure 7-13: Mean launch angle (± 1 SD) for low and natural trajectories by each golfer with the 5-iron.

7.4.2. Impact location

Impact locations by golfer are shown in Table 7-5. There was one significant difference; the vertical impact location of golfer five. The difference showed the impact location of the natural trajectories tended to be lower than that of the low.

Table 7-5: Comparison of mean (& SD) horizontal and vertical impact location for both low and natural trajectories by each golfer with the 5-iron.

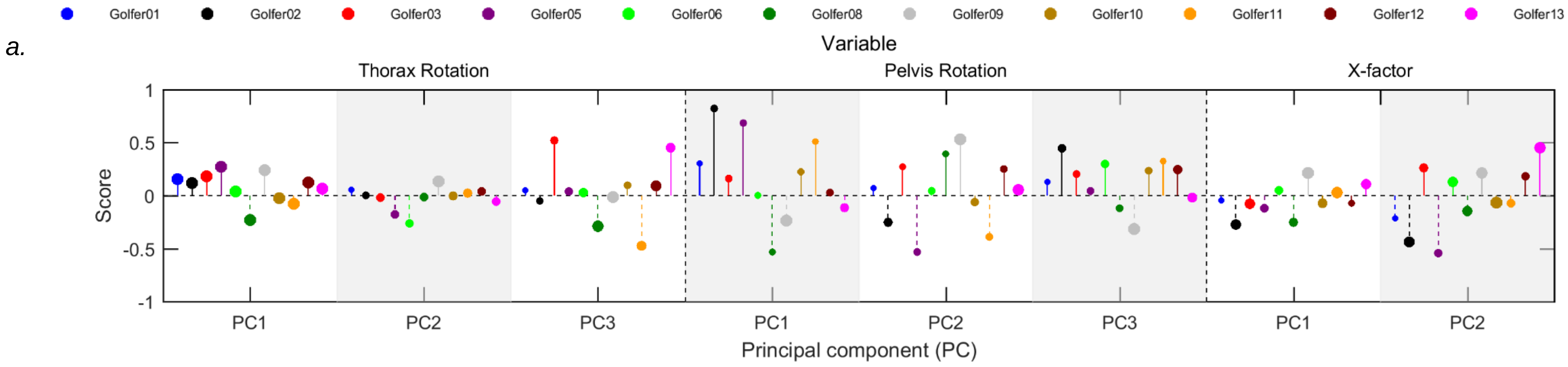
Golfer	Horizontal impact location			Golfer	Vertical impact location		
	Low (mm)	Natural (mm)	p-value		Low (mm)	Natural (mm)	p-value
One	1 (7)	-5 (5)	0.7078	One	-6 (3)	0 (4)	0.1905
Two	8 (5)	-2 (7)	0.1371	Two	-7 (2)	-7 (3)	0.9997
Three	5 (13)	12 (4)	0.5761	Three	-10 (11)	-10 (9)	0.9992
Five	-7 (4)	-2 (3)	0.1317	Five	-4 (6)	-10 (5)	*0.0048*
Six	5 (8)	4 (2)	0.9543	Six	-10 (10)	-9 (2)	0.6897
Eight	-5 (6)	5 (8)	0.4727	Eight	-8 (6)	-8 (4)	0.9798
Nine	-12 (6)	-13 (11)	0.9895	Nine	-11 (5)	-9 (5)	0.9727
Ten	0 (7)	0 (7)	0.9696	Ten	-10 (4)	-9 (6)	0.9676
Eleven	4 (6)	-4 (3)	0.0522	Eleven	0 (7)	-1 (3)	0.9676
Twelve	3 (7)	-1 (8)	0.7394	Twelve	-3 (6)	-4 (5)	0.9299
Thirteen	0 (5)	-11 (8)	0.7394	Thirteen	-4 (5)	-6 (4)	0.9301

7.4.3. Individual event results

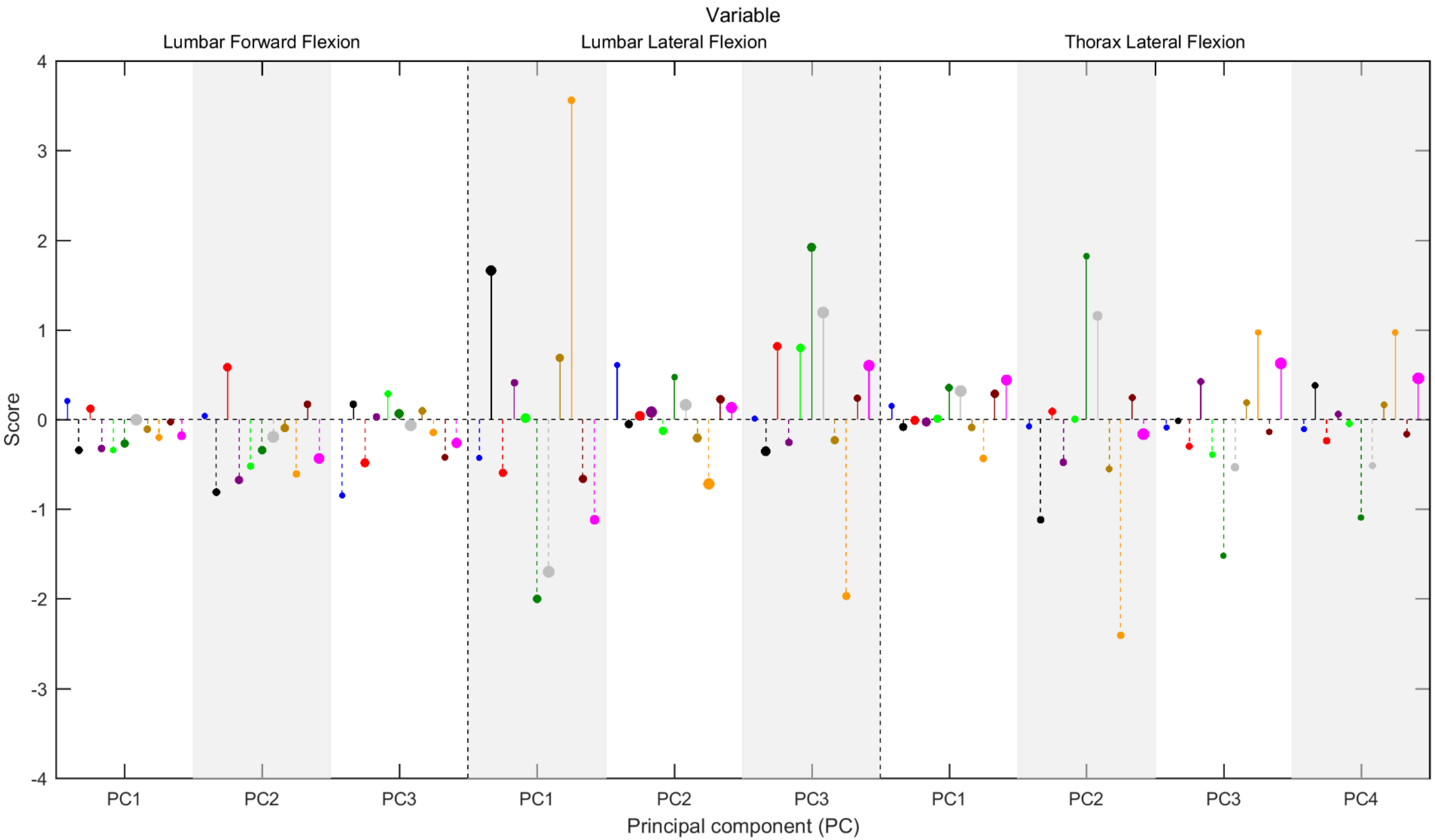
The 5-iron low-natural event results are shown in Table G-5 and Table G-6 (Appendix G).

7.4.4. Individual swing results

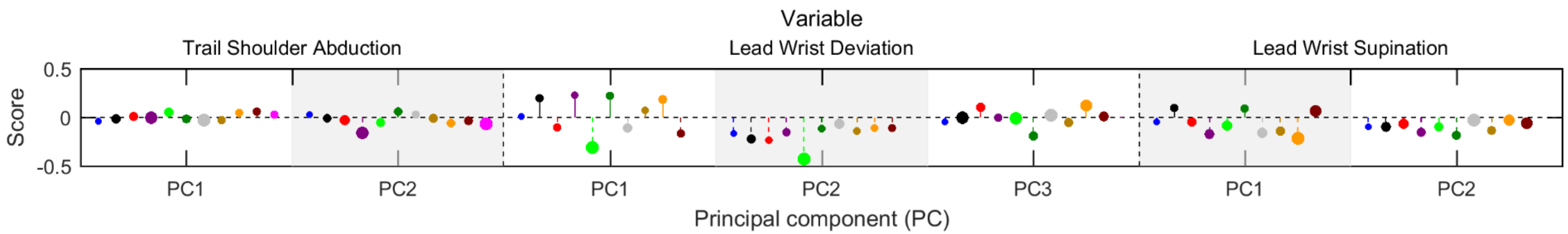
The principal component scores for low trajectories relative to natural are shown for each variable and golfer in Figure 7-14. Most variables show a spread of scores above and below the zero line, indicating that movements between golfers were different relative to the natural trajectory. However, for lumbar forward flexion principal components one and two (Figure 7-14b), pelvis translation principal components one and two (Figure 7-14d) and centre of pressure principal components one and two (Figure 7-14d) most, if not all, golfers show the same pattern.


Golfer01
Golfer02
Golfer03
Golfer05
Golfer06
Golfer08
Golfer09
Golfer10
Golfer11
Golfer12
Golfer13
a.
Variable
Thorax Rotation
Pelvis Rotation
X-factor
Score
1
0.5
0
-0.5
-1
PC1
PC2
PC3
PC1
PC2
PC3
PC1
PC2
Principal component (PC)

b.


Variable
Lumbar Forward Flexion
Lumbar Lateral Flexion
Thorax Lateral Flexion
Score
4
3
2
1
0
-1
-2
-3
-4
PC1
PC2
PC3
PC1
PC2
PC3
PC1
PC2
PC3
PC4
Principal component (PC)

c.


Variable
Trail Shoulder Abduction
Lead Wrist Deviation
Lead Wrist Supination
Score
0.5
0
-0.5
PC1
PC2
PC1
PC2
PC3
PC1
PC2
Principal component (PC)

d.

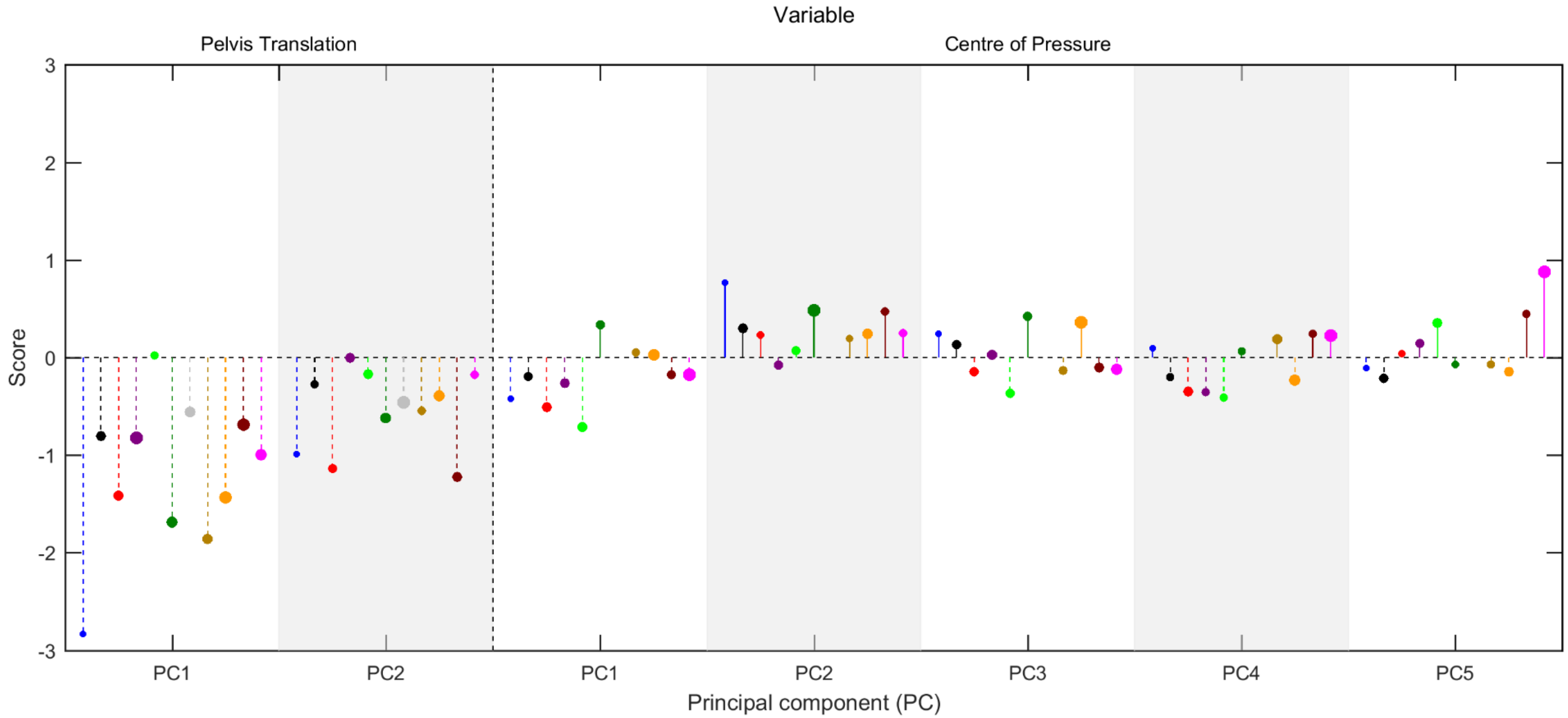


Figure 7-14: Mean scores for each principal component for each golfer in the 5-iron low-natural analysis: a. thorax rotation, pelvis rotation and X-factor; b. lumbar forward flexion, lumbar lateral flexion and thorax lateral flexion; c. trail shoulder abduction, lead wrist deviation and lead wrist supination and d. pelvis translation and centre of pressure. The low scores for each golfer are connected by lines. A solid line represents when the low score is positive, a dotted line when the low score is negative. The size of marker indicates the size of the variance in principal components scores. All shots are expressed relative to the natural shot score.

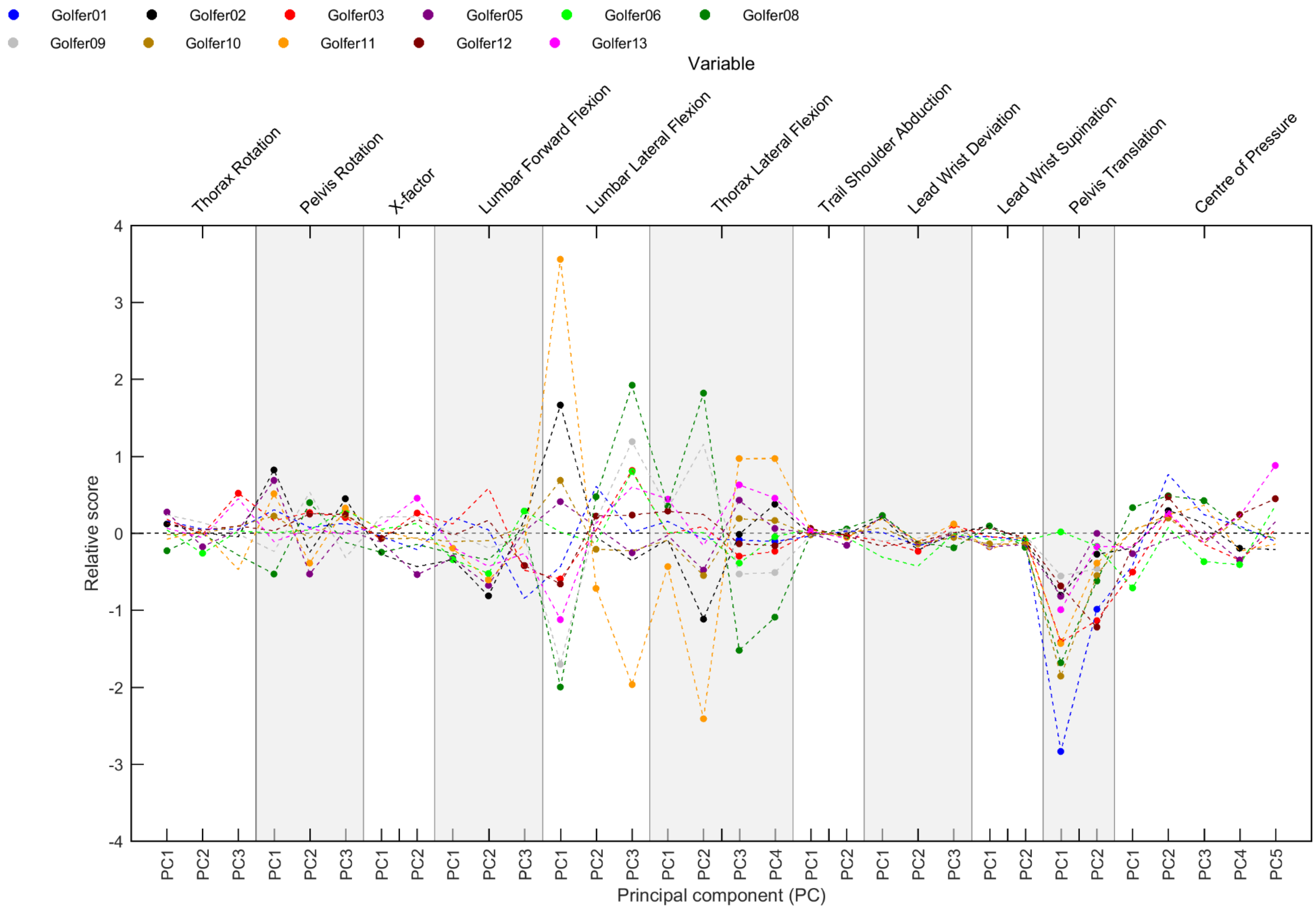


Figure 7-15: Difference in 5-iron principal component scores (low minus natural) for each golfer by variable. Those principal components where no golfer displayed significant differences have been removed. Markers represent significant differences.

When plotted on the same graph (Figure 7-15), very few common trends across all golfers can be seen initially. Therefore, further statistical analysis is necessary to provide more clarity.

The multivariate correlation suggested golfers were clustered based on their swing patterns (Figure 7-16; Appendix J). Two clusters appeared to emerge, containing nine of the eleven golfers. Golfers two, five, ten and eleven shared strong or very strong relationships with one another (*Cluster III*). The second cluster (*Cluster IV*) was formed by golfers one, three, eight, nine and twelve who had strong or very strong relationships. *Cluster IV* golfers were consistently, negatively correlated with the golfers forming *Cluster III*, suggesting the two clusters' movement patterns were different.

Golfer	1	2	3	5	6	8	9	10	11	12	13
1	1.00										
2	0.21	1.00									
3	0.79	-0.10	1.00								
5	0.38	0.79	-0.02	1.00							
6	-0.07	0.12	0.20	0.02	1.00						
8	0.43	-0.47	0.60	-0.29	0.45	1.00					
9	0.33	-0.64	0.57	-0.39	0.37	0.92	1.00				
10	0.74	0.69	0.47	0.64	-0.01	-0.05	-0.22	1.00			
11	0.12	0.86	-0.22	0.61	-0.23	-0.72	-0.82	0.67	1.00		
12	0.70	-0.20	0.87	-0.11	0.14	0.59	0.63	0.28	-0.30	1.00	
13	0.55	-0.17	0.55	0.17	0.20	0.42	0.52	0.28	-0.23	0.53	1.00

Figure 7-16: Multivariate correlation r-values comparing each golfer's 5-iron low-natural principal components scores to all other golfers.

Negative	Positive	
		Very weak
		Weak
		Moderate
		Strong
		Very Strong
		Perfect

(Evans, 1996)

7.4.5. Hypothesis outcomes

The outcomes of the hypotheses regarding the 5-iron low-natural comparison are outlined in Table 7-6. The table also shows findings which emerged but were not initially hypothesised. The benefit of the individual-approach to the analysis is highlighted; differences between *Cluster III* and *IV* can be seen, such as for lumbar lateral flexion.

Table 7-6: Outcomes of the hypothesised changes, supported (✓), rejected (×) or not applicable (N/A), in Clusters III and IV golfers' biomechanical variables between the 5-iron low and natural trajectories at address, ball contact and over the whole-swing. Other outcomes refers to non-hypothesised differences between the trajectories.

Variable	Address		Ball contact		Whole-swing		Other outcomes	
	Cluster III	*Cluster IV*	*Cluster III*	*Cluster IV*	*Cluster III*	*Cluster IV*	*Cluster III*	*Cluster IV*
Pelvis rotation	N/A	N/A	N/A	N/A	✗	✗	✓	✓
Thorax rotation	N/A	N/A	N/A	N/A	✗	✗	✗	✗
X-factor	N/A	N/A	N/A	N/A	✗	✗	✗	✗
Ball position	✓	✓	N/A	N/A	N/A	N/A	✗	✗
Stance width	✗	✓	N/A	N/A	N/A	N/A	✗	✗
Grip distance	✗	✗	N/A	N/A	N/A	N/A	✗	✗
Lead hand forwardness	✓	✓	✓	✓	N/A	N/A	✗	✗
Lumbar forward flexion	N/A	N/A	N/A	N/A	N/A	N/A	✓	✓
Lumbar lateral flexion	N/A	N/A	N/A	N/A	✓	✗	✗	✓
Thorax lateral flexion	✗	✓	✗	✓	✗	✗	✓	✓
Pelvis translation	N/A	N/A	N/A	N/A	N/A	N/A	✓	✓
Lead wrist deviation	N/A	N/A	N/A	N/A	✗	✗	✗	✗
Centre of pressure	✗	✗	✓	✓	✗	✗	✓	✓
Instantaneous swing plane horizontal	N/A	N/A	N/A	N/A	N/A	N/A	✓	✗

7.4.6. Cluster III versus Cluster IV swing patterns

At address, there were similarities across golfers (Figure 7-17 and Figure 7-18). For example, all golfers positioned the ball away from the target further, relative to the lead foot, in the low regardless of cluster. This could be related to the stance width, which appeared to be reduced for *Cluster IV*. Additionally, all golfers positioned their lead hand further towards the target relative to the ball for the low regardless of cluster, possibly helped by a change in thorax lateral flexion, particularly for *Cluster IV* whose golfers showed a more flexed thorax towards the lead for the low.

In terms of alignment to the target line, there were few patterns across either cluster. Similarly, neither showed differences in centre of pressure between the shot conditions, all golfers distributing their centre of pressure centrally for both shot conditions.

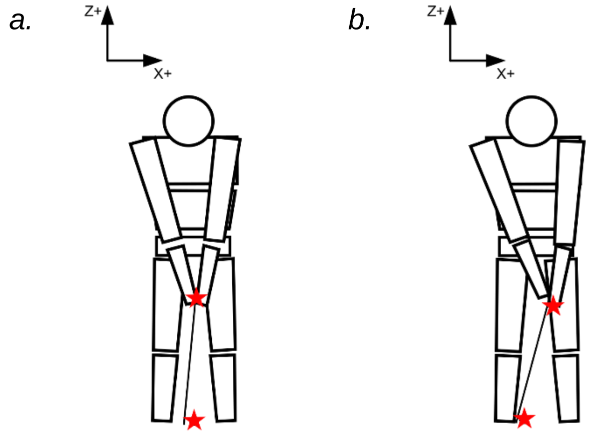


Figure 7-17: Differences in address position between low and natural trajectories in Cluster III: a. natural front-on and b. low front-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation.

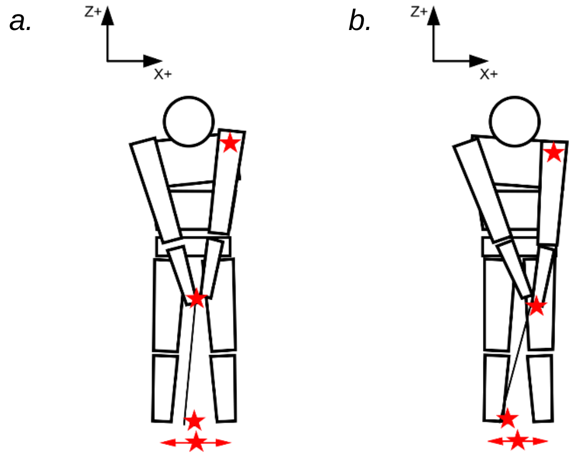


Figure 7-18: Differences in address position between low and natural trajectories in Cluster IV: a. natural front-on and b. low front-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation.

Over the whole-swing, for *Cluster III*, there were absolute offset differences between the low and natural trajectories. The lumbar spine had more lateral flexion towards the lead side for low trajectories and pelvis translation positioned less away from the target. In fact, the pelvis translation offset was common across nearly all golfers. *Cluster IV* showed a lumbar lateral flexion towards the trail.

As the backswing started, all golfer's centre of pressure was positioned more away from the target for low trajectories. Regardless of cluster, there were pelvis and thorax rotations away from the target for both conditions and the lumbar spine and thorax began to laterally flex towards the lead. *Cluster III* showed a forward extending of the lumbar spine over the earlier phases of the backswing in the low, whilst *Cluster IV* showed the opposite. For golfers in *Clusters III* and *IV*, in the early backswing, the centre of pressure shifted away from the target more quickly in the low.

Into the later backswing, the forward flexing of the lumbar spine was greater for *Cluster IV*, continuing through to top of the backswing for the low. The same cluster showed a greater magnitude of thorax flexing towards the lead in the later backswing for the low. In the late backswing, *Cluster III* showed greater rotation of the pelvis away from the target, whilst golfers eight and nine of *Cluster IV* showed the opposite. Around top of the backswing, for *Cluster IV*, there was a lumbar lateral flexion towards the lead.

During the downswing, for all golfers the thorax and pelvis rotated back towards the target. *Cluster IV* had an earlier centre of pressure forward shift for low trajectories. Furthermore, both *Cluster III* and *IV* showed an earlier pelvis translation towards the target in the low trajectories around this time in the swing.

As the downswing progressed, the thorax lateral flexion was flexed more towards the trail in *Cluster IV* for the low trajectories. In addition, for golfers eight and nine of *Cluster IV*, the lumbar spine was more forward flexed over the phase and the golfers saw greater lumbar forward extending for these trajectories over the period. This differed from *Cluster III* whose golfers showed less extending. Both clusters showed pelvis translation that was a later, lesser forward shift in the low. As with previous comparisons, the nature of centre of pressure shift in this phase was more individual. However, by ball contact golfers in both clusters appeared to have a centre of pressure positioned further towards the target for the low (Figure 7-19 and Figure 7-20). Lastly, *Cluster III* saw greater pelvis rotation back towards the target for the low.

During the later stages of the downswing phase there was greater lumbar forward extending for *Cluster IV* in the low, but was perhaps most prominent in golfer three. The same cluster displayed a slowing and halting of the thorax lateral flexing towards the trail as ball contact approached in the low trajectories, in opposition to *Cluster III* whose golfers showed prolonged thorax lateral flexing towards the trail right through the later stages of the downswing into ball contact. By ball contact lead hand forwardness was further ahead relative to the ball for the low in all golfers (Figure 7-19 and Figure 7-20), possibly aided by the flexing of the thorax.

The movements over the late downswing may have influenced golfers' swing planes (Figure 7-19). Those golfers in *Cluster IV*, achieved large negative horizontal swing planes for the low trajectories, however, there was no common difference pattern between low and natural trajectories. *Cluster III* golfers showed less pronounced negative swing planes than *Cluster IV* for the low, however, appeared to show a clear difference between low and natural trajectories, with a negative swing plane for the former trajectories and positive for the latter.

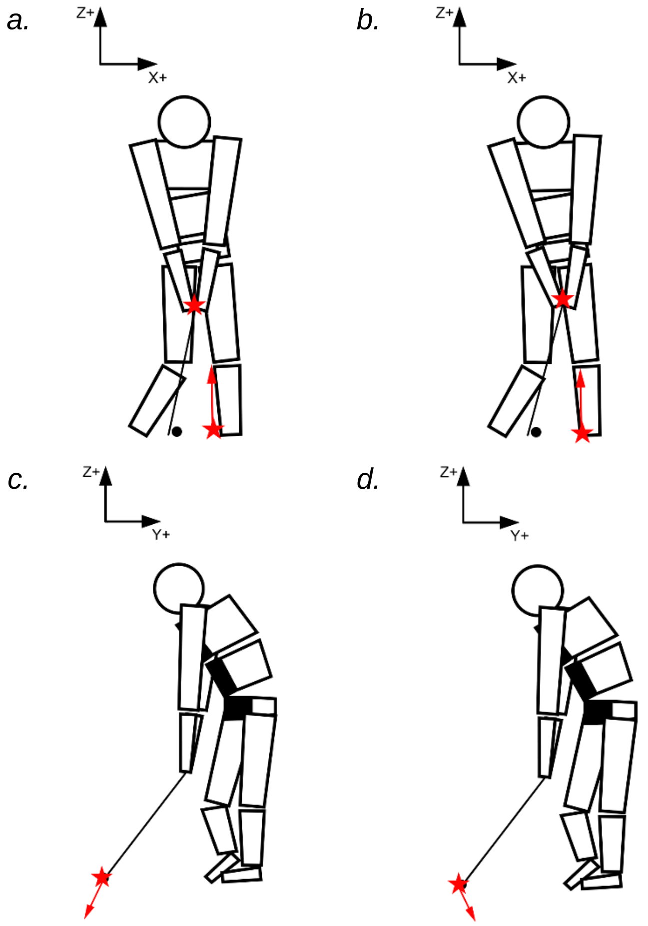


Figure 7-19: Differences in ball contact position between low and natural trajectories in Cluster III: a. natural front-on; b. low front-on; c. natural side-on and d. low side-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation. Dark shading emphasises the axial rotation of the central body segments.

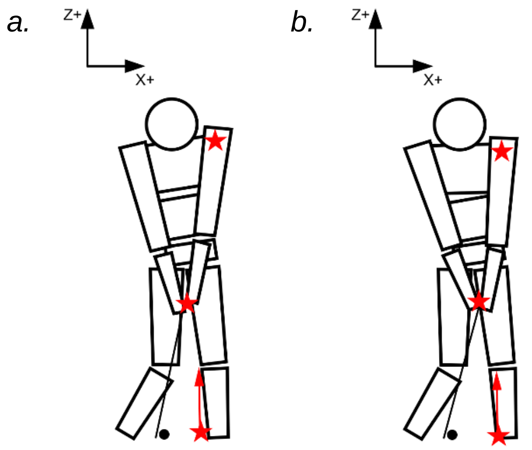


Figure 7-20: Differences in ball contact position between low and natural trajectories in Cluster IV: a. natural front-on and b. low front-on. The stars represent where differences occurred. The figures are shown in plane for ease of representation.

7.5. Summary

Chapter 7 has provided the results of trajectory comparisons with a more individual golfer focus. The benefits of the individual focus are evident, where differences between shot trajectories were masked at a group-level, but evident at a cluster-level.

When playing draw and fade trajectories with the driver, four of the seven golfers utilised very similar movement patterns (*Cluster I*). In general, *Cluster I* produced the same hypothesis outcomes as the whole-group analysis in Chapter 6. However, there were three differences. Firstly, both thorax lateral flexion and centre of pressure patterns of *Cluster I* over the whole-swing did not support the initial hypotheses. In the opposite manner, at ball contact, the thorax rotation, whilst not supportive of the initial hypothesis at a group-level was for the cluster, showing a more open rotation relative to the target line for fade trajectories.

For the 5-iron draw-fade trajectories, five of the seven golfers shared similar swing patterns (*Cluster II*). This cluster showed a number of differences from the whole-group hypothesis outcomes reported in Chapter 6. Firstly, no lead hand height differences were found between the draw and fade trajectories for *Cluster II*. Over the whole-swing, the initial lumbar forward flexion hypothesis was supported (more lumbar forward flexion in the draw), unlike thorax lateral flexion. Finally, centre of pressure whole-swing patterns did not support the hypothesis; however, it did so at the instant of ball contact (shifted further towards the target for the draw) trajectories), as did thorax rotation (more open relative to the target line for the fade trajectories).

For the 5-iron low-natural trajectories there appeared to be two swing patterns, one containing four of the eleven golfers (*Cluster III)*, the other contain five of the eleven (*Cluster IV)*. Overall, these two clusters supported many of the hypothesis outcomes for the whole-group analysis. However, there were differences. For example, *Cluster IV* supported the stance width hypothesis at address (narrower stance width for low) and the thorax lateral flexion hypothesis at ball contact (flexion towards the lead in the low), whereas *Cluster III* did not. Furthermore, *Cluster III* supported the thorax lateral flexion hypothesis at address and whole-swing lumbar lateral flexion hypothesis (flexion towards the lead in the low), whilst *Cluster IV* did not.

CHAPTER EIGHT

DISCUSSION OF THE ROLE OF BIOMECHANICS IN ACHIEVING DIFFERENT SHOT TRAJECTORIES WITH THE SAME CLUB

8.1. Introduction

Controlling shot trajectory is important for performance in sports such as tennis and golf. Better skilled players are able to manipulate trajectories to their advantage to overcome an opponent or to improve their score. As outlined in Chapter 2, the biomechanics of different shot trajectories have been investigated widely in tennis, however little has been done in golf. Chapters 5, 6 and 7 detailed the methods and results of a novel investigation into the biomechanics of achieving different shot trajectories in golf, with a focus on draw versus fade and low versus natural trajectories. This chapter provides discussion and context to the results presented in the previous two chapters.

8.2. Hypothesised differences: draw versus fade

8.2.1. Driver

Draw and fade trajectories with the driver were successfully investigated through a biomechanical comparison of address, ball contact and over the whole-swing (Chapters 6 and 7). It was hypothesised that altering the trajectory of the shot being played would cause significant biomechanical changes to golfers' swings to achieve the desired trajectory. Specifically, hypothesised changes in each biomechanical variable were investigated (Section 5.5.3). These specific hypotheses are replicated in Table 8-1, which includes the outcomes on whether or not the results support the hypothesised differences.

Numerous event and whole-swing differences were found. The hypotheses of four address and three ball contact variables were supported. At address, pelvis rotation, thorax rotation, stance openness and thorax lateral flexion were all supported at a group-level. At ball contact, pelvis rotation, thorax lateral flexion and horizontal swing plane were supported at the group-level, whilst thorax rotation was supported by *Cluster I.* Across the whole-swing six variable hypotheses were supported, all at a group-level: pelvis rotation, lumbar lateral flexion, thorax lateral flexion, pelvis translation, centre of pressure and horizontal swing plane. Further differences also emerged that did not arise as coaching points and consequently were not initially hypothesised, which are detailed in (Table 8-2).

Table 8-1: Hypothesised changes, supported (✓), rejected (×) or not applicable (N/A), in the biomechanical variables between the driver draw and fade trajectory shots. The outcomes of the hypothesis are given in terms of whether they were supported at the group and cluster-level. Hypotheses are given by referring to the draw relative to the fade.

Variable	Hypothesis	Outcome		
		Address	Ball contact	Whole-swing
Pelvis rotation	A more negative, less positive pelvis rotation in draw trajectories	✓ Group	✓ Group	✓ Group
Thorax rotation	A more negative, less positive thorax rotation in draw trajectories	✓ Group	✓ Cluster I	×
X-factor	A more negative, less positive X-factor in draw trajectories	N/A	N/A	×
Stance openness	A negative stance openness in draw trajectories, a positive stance openness in fade trajectories	✓ Group	N/A	N/A
Lead hand height	Smaller lead hand height distance for draw trajectories	×	×	N/A
Lumbar forward flexion	More lumbar forward flexion in draw trajectories	N/A	N/A	×
Lumbar lateral flexion	More flexing away from the target, towards the trail side in draw trajectories	N/A	N/A	✓ Group
Thorax lateral flexion	Lesser flexing of the thorax, so it's flexed towards the lead in draw trajectories	✓ Group	✓ Group	✓ Group
Pelvis translation	Greater pelvis translation towards the target in draw trajectories	N/A	N/A	✓ Group
Trail shoulder abduction	Greater trail shoulder abduction in draw trajectories	N/A	N/A	×
Lead wrist supination	A more supinated wrist in draw trajectories	N/A	N/A	×
Lead wrist deviation	Lesser wrist deviation angles in draw trajectories	N/A	N/A	×
Centre of pressure	Distributed further towards the target in draw trajectories	×	×	✓ Group
Instantaneous horizontal swing plane	A more in-to-out horizontal swing plane in the downswing in draw trajectories	N/A	✓ Group	✓ Group
Instantaneous vertical swing plane	A flatter vertical swing plane in the downswing in the draw trajectories	N/A	×	×

Table 8-2: Driver draw-fade differences that emerged at address and over the whole-swing, but were not initially hypothesised. Differences are described by referring to the draw relative to the fade.

Variable	Draw pattern	
	Group	Cluster I
Address		
Ball position	Translated further back parallel to the target line, away from the lead foot and target.	-
Lead hand forwardness	Positioned further forward towards the target parallel to the target line, relative to the ball.	-
Whole-swing		
Pelvis rotation	Later axial rotation of the pelvis away from the target during the backswing, followed by a later axial rotation of the pelvis towards the target during the downswing.	-
Thorax rotation	Greater axial rotation of the thorax away from the target during the backswing.	Earlier axial rotation of the thorax away from the target during the backswing, followed by greater axial rotation of the thorax towards the target in the downswing.
Lumbar forward flexion	Slower lumbar forward extending in the downswing	Greater lumbar forward flexion in the backswing
Lumbar lateral flexion	Earlier lateral lumbar flexing towards the trail around top of the backswing, followed by prolonged trail flexing through ball contact.	-
Thorax lateral flexion	Greater, slower thorax flexing towards the lead in the backswing, with a reversal towards the trail and re-reversal back towards the lead around top of the backswing. A prolonged trail flexing through ball contact.	-
Pelvis translation	Translated less away from the target relative to the lead foot, parallel to the target line, throughout the swing, with an earlier forward shift in late backswing.	-
Centre of pressure	Earlier forward shift towards the target in early downswing.	Quicker rate of forward shift towards the target in the downswing.

8.2.2. 5-Iron

The equivalent draw-fade hypotheses as for the driver are shown in Table 8-3 and the outcomes that emerged but were not initial coaching points and were not initially hypothesised are shown in Table 8-4. The same four address variable hypotheses were supported at a group-level for the 5-iron as for the driver: pelvis rotation, thorax rotation, stance openness and thorax lateral flexion. The hypotheses of four variables at ball contact were also supported at the group-level: pelvis rotation, thorax rotation, thorax lateral flexion and horizontal swing plane. Finally, over the whole-swing, the hypotheses of seven variables were supported at the group-level: pelvis rotation, lumbar lateral flexion, thorax lateral flexion, pelvis translation, centre of pressure, horizontal swing plane and vertical swing plane. Additionally, lumbar forward flexion was supported by *Cluster II.*

Table 8-3: Hypothesised changes, supported (✓), rejected (×) or not applicable (N/A), in the biomechanical variables between the 5-iron draw and fade trajectory shots. The outcomes of the hypothesis are given in terms of whether they were supported at the group and cluster-level. Hypotheses are given by referring to the draw relative to the fade.

Variable	Hypothesis	Outcome		
		Address	Ball contact	Whole-swing
Pelvis rotation	A more negative, less positive pelvis rotation in draw trajectories	✓ Group	✓ Group	✓ Group
Thorax rotation	A more negative, less positive thorax rotation in draw trajectories	✓ Group	✓ Group	×
X-factor	A more negative, less positive X-factor in draw trajectories	N/A	N/A	×
Stance openness	A negative stance openness in draw trajectories, a positive stance openness in fade trajectories	✓ Group	N/A	N/A
Lead hand height	Smaller lead hand height distance for draw trajectories	×	×	N/A
Lumbar forward flexion	More lumbar forward flexion in draw trajectories	N/A	N/A	✓ Cluster II
Lumbar lateral flexion	More flexing away from the target, towards the trail side in draw trajectories	N/A	N/A	✓ Group
Thorax lateral flexion	Lesser flexing of the thorax, so it's flexed towards the lead in draw trajectories	✓ Group	✓ Group	✓ Group
Pelvis translation	Greater pelvis translation towards the target in draw trajectories	N/A	N/A	✓ Group
Trail shoulder abduction	Greater trail shoulder abduction in draw trajectories	N/A	N/A	×
Lead wrist supination	A more supinated wrist in draw trajectories	N/A	N/A	×
Lead wrist deviation	Lesser wrist deviation angles in draw trajectories	N/A	N/A	×
Centre of pressure	Distributed further towards the target in draw trajectories	×	×	✓ Group
Instantaneous horizontal swing plane	A more in-to-out horizontal swing plane in the downswing in draw trajectories	N/A	✓ Group	✓ Group
Instantaneous vertical swing plane	A flatter vertical swing plane in the downswing in the draw trajectories	N/A	×	✓ Group

Table 8-4: 5-Iron draw-fade differences that emerged at address and over the whole-swing, but were not initially hypothesised. Differences are described by referring to the draw relative to the fade.

Variable	Draw pattern	
	Group	Cluster II
Address		
Ball position	Translated further back parallel to the target line, away from the lead foot and target.	-
Lead hand forwardness	Positioned further forward towards the target parallel to the target line, relative to the ball.	-
Whole-swing		
Pelvis rotation	Later axial rotation of the pelvis away from the target during the backswing, followed by a later axial rotation of the pelvis towards the target during the downswing.	-
Thorax rotation	-	Less axial rotation of the thorax away from the target during the backswing, followed by earlier axial rotation of the thorax towards the target during the downswing, which slowed as ball contact approached.
X-factor	-	Greater axial rotation of the thorax relative to the pelvis away from the target during the late backswing.
Lumbar lateral flexion	-	Less flexing towards the lead during the backswing, followed by less flexing towards the trail in the downswing.
Thorax lateral flexion	Earlier flexing towards the trail in the early downswing, followed by a slowing of the flexing towards the trail in the late downswing.	Slower thorax flexing towards the lead in the backswing.
Pelvis translation	Earlier forward shift, parallel to the target line, in late backswing.	-
Lead wrist deviation	Greater radial deviation during the backswing, followed by greater ulnar deviation during the downswing.	-
Centre of pressure	-	Earlier forward shift towards the target, parallel to the target line, in early downswing, followed by a slowing of the shift around mid-downswing.

8.3. Creating draw & fade trajectories

The majority of biomechanical changes between draw and fade trajectories were common across clubs. Therefore, the discussion for both clubs has been grouped.

8.3.1. Address

Group differences

Perhaps the simplest changes occurred at address. Variables at address are uninfluenced by the swing itself and expected to be characteristic of the intended trajectory, regardless of the outcome. However, for consistency, address event analysis included the same shots as those included in the whole-swing principal component analysis. Address position is an event which has been found to be a consistent position for golfers (Langdown et al., 2013). In this study, the event differences that emerged could be considered common across most, if not all, of the golfers.

Draw trajectories saw golfers position the ball back further away from the lead foot (and target) when compared to fade trajectory. To strike the ball centrally a change in biomechanics is required by moving the ball position. Indeed, ball position has been linked to altered swing mechanics by coaches (Smith, 2013; Smith et al., 2015b); however, the exact biomechanical changes due to ball position have not been a direct focus of an investigation, even within this study, therefore more work is necessary.

In addition to ball position, although not initially hypothesised, golfers positioned their lead hand towards the target relative to the ball, for the draw trajectories, a finding which was also true for ball contact. This could have been a result of the ball position further away from the target or consciously moving the lead hand towards the target or both. It could also have been aided by thorax lateral flexion, a flexion of which towards the lead may help lower the lead shoulder enabling the golfer to push their hands forward ahead of the ball. Indeed, all golfers showed a thorax lateral flexion more towards the lead for the draw.

Similarities could be drawn with tennis. When creating a kick or a slice trajectory, racket head trajectory at impact with the ball has been shown to differ relative to the shoulder position, facilitated by position of the hitting hand; for example, a more medial and posterior position for the kick serve compared to the flat (Sheets et al., 2011).

When aligning to target, golfers had a pelvis rotation, thorax rotation and stance openness orientated more closed for the draw trajectories. This stance is advocated by coaches (e.g. Palmer, 1991; Adams & Tomasi, 2001; PGA, 2010; Haney, 2012; Harmon, 2012). Stance openness may aid golfers to achieve the desired club direction in the late downswing. Coaches sometimes allude to creating a club direction or swing plane parallel to the vector between feet centres to help achieve the desired trajectory (e.g. Flick, 2012; BBC, 2017a; BBC, 2017b).

Lastly, it was hypothesised that the lead hand height would be reduced for draw trajectories versus fade. However, this was not the case across golfers. The idea of a lower lead hand height for draw trajectories could emerge from the path of the hands during the downswing. The position of the clubhead relative to the path of the lead hand has been shown to link to clubface squaring at ball contact (Mackenzie, 2012). Therefore, it is possible that a path that leads to a reduced height at ball contact may aid shot trajectories. However, in this study it did not appear to be the case. Future investigation could look into the path of the hands during the downswing in relation to shot trajectories, rather than just at address and ball contact.

8.3.2. Whole-swing

Group differences

Whole-swing differences were evident, on a group and a cluster-level, some of which were likely influenced by the initial address position. These manifested in between-trajectory absolute offset differences and relative magnitude, rate of change and timing differences.

The first difference related to pelvis rotation, which comprised firstly, a more rotated away from the target offset for the draw trajectories. This is likely partly related to the closed pelvis rotation at address and aided the less open pelvis at ball contact for the draw trajectories across all golfers. The rotation of the pelvis is slightly more complex, with timing differences also seemingly fundamental; a later rotation away from the target in the backswing and later back towards in the downswing for draw trajectories.

At the group-level, the offset in pelvis rotation was a major contributor for both the driver and 5-iron (explaining over 70% of the variance in this variable). Coaches advocate the more rotated away from target pelvis for draw trajectories and conversely less so for the fade (e.g. Palmer, 1991; Adams & Tomasi, 2001; PGA, 2010; Haney, 2012; Harmon, 2012). This is also the case for thorax rotation, however, this study suggests that it is the offset in the pelvis over the whole-swing that is the crucial aspect to achieving a draw or a fade. Thorax rotation was a more individual variable; indeed, intra-individual analysis has uncovered differences in this variable between shot trajectories in tennis (Vorobiev et al., 1993). For golfers of less ability, thorax rotation may be more difficult to align than pelvis rotation at address (Langdown et al., 2013). However, the golfers in this study were of high ability so the more individual nature of thorax rotation may be down to aiming at a target in the alien environment of the laboratory, discussed further in Section 8.6.

The pelvis rotation mechanics differed from findings in other hitting sports. For example, kick serves in tennis were shown to have a lesser magnitude of pelvis rotation than flat serves (Vorobiev et al., 1993; Reid & Elliott, 2002; Lo et al., 2004; Abrams et al., 2011). However, this may be because the kick and flat serves are not directly opposite shot trajectories, like that of the draw and fade. Furthermore, tennis players may be less likely to make changes at address to avoid providing visual clues to their opponent as to what trajectory of serve they are about the hit. Comparison between an elite tennis player's flat first serve and kick second serve showed that the former had greater pelvis rotation velocity (Vorobiev et al., 1993). However, rate of rotation differences were not fundamental to achieving draw and fade trajectories, possibly because both were hit for maximum distance; pelvis rotation is important for golf clubhead and ball speed (Cheetham et al., 2001; Myers et al., 2008; Chu et al., 2010).

A second fundamental movement for the draw-fade comparison appears to be the offset in lumbar lateral flexion, with more flexion towards the trail side for the draw trajectories. The flexing movement toward the trail was prolonged through ball contact. This draw-fade fundamental suggested in coaching literature (e.g. Foley, 2012) could have promoted the in-to-out swing plane and club direction necessary for the trajectory type. A greater magnitude of flexing is seen in kick trajectories in tennis (Abrams et al., 2011) and it could be that the greater flexing towards the trail in draw trajectories was aided by the pelvis translation.

Another fundamental whole-swing difference was the centre of pressure position over the initial stages of the swing, with a shift away from the target in the backswing and an earlier, quicker, greater forward shift in the downswing of draw trajectories. This aided differences in centre of pressure at ball contact. "Weight transfer" forward during the swing is a coaching point for draw trajectories (e.g. Miller, 2008).

There was also an individual nature of centre of pressure forward shift as ball contact approached. This agrees with previous work into centre of pressure in golf (Ball & Best, 2007a; Ball & Best, 2007b; Ball & Best, 2012; Smith et al., 2016). In the two centre of pressure cluster styles (front foot and reverse) identified by Ball & Best, (2007a), the centre of pressure follows the shift away, shift towards pattern described above, regardless of whether the golfer utilises the front foot or reverse style. It is the latter stages where differences really emerge between the two styles. This is in temporal agreement with the individual nature of centre of pressure observed in this investigation, however, graphical evidence did not necessarily suggest the golfers fall into either of the two styles.

There were two further group differences between draw and fade trajectories, relating to thorax lateral flexion and pelvis translation. The former, showed a greater, slower flexing towards the lead during the backswing, with greater, more prolonged flexing towards the trail in the downswing for the draw. The latter showed a pelvis translated further towards the target throughout, with an earlier forward translation during the backswing for the draw.

Key coaching points and scientific literature often states the importance of the pelvis for a successful swing in general (Brown et al., 2011; Beak et al., 2013); furthermore, coaches have related its kinematics to the trajectory of the shot (e.g. Palmer, 1991; Foley, 2012). In contrast, in the scientific literature, pelvis translation has not been related to shot trajectories. As mentioned above, a pelvis translated further towards the target may aid lumbar lateral flexion towards the trail side in draw trajectories, encouraging an in-to-out swing plane and club direction.

As with pelvis translation, the rotation of the thorax towards the trail could have promoted the out-to-in swing plane and club direction associated with the fade (e.g. Leadbetter, 2010; Smeltz & Villegas, 2009). Movement of the lead and trail shoulders has been described as a rotation like a Ferris wheel, so that the lead shoulder is higher for the fade, and a merry-go-round, so the lead shoulder is lower for a the draw (Leadbetter, 2010). Leadbetter, (2010) links this thorax lateral flexion to the closing of the clubface at ball contact, stating that the fade movement will encourage an open face, and the draw will encourage squaring. Future biomechanical work could potentially link the magnitude of this variable to the rate of clubface closing, measured at 2900 º/s by (Ellis et al., 2010).

Thorax lateral flexion has been linked to shot trajectories in other hitting sports. It was shown to be lower in flat serves compared to kick serves in tennis (Abrams et al., 2011). This could have contributed to the greater vertical velocity of the racket at ball contact in the kick serve trajectory. Therefore, in golf, it may be a mechanism to regulate the club direction, allowing the club to come more out-to-in for the fade trajectory.

A final aspect relates to lumbar forward flexion, where, despite not being hypothesised the group showed slower lumbar extending in the downswing for the draw. One coach spoke about natural faders seeming to lose posture during this swing, partly because of lumbar extension, which is considered an important part of "golfer posture" by coaches (Section 5.3; Smith et al., 2012). Therefore, golfers may maintain their central body posture for longer in the downswing, in order to successfully draw the golf ball.

Over the whole-swing, despite predicting differences across trajectory comparisons at the wrist, few golfers showed any difference between shot conditions. Key coaching points have at times recommended wrist changes to achieve different trajectories. For example, less deviation for lower trajectories (Weaver, 2012; Quinton, 2017b). Additionally, "rolling the hands", equivalent to lead wrist supination has been recommended for draw trajectories, whilst limiting the movement has been recommended for fade (e.g. Miller, 2008; Adler & Watson, 2012). In tennis, supination was associated with achieving different trajectories during backhand strokes (Elliott & Christmass, 1995). Furthermore, greater wrist velocities were associated with topspin strokes compared to backspin, and backspin stroke wrist angles were constant when compared to those of topspin (Elliott & Marsh, 1989). This makes the findings of this study perhaps somewhat surprising. The wrist is one of the last steps in the kinematic chain, before the club and has been shown to be an important aspect of a successful golf swing in terms of clubhead and ball speed (Budney & Bellow, 1982; Milburn, 1982; McLaughlin & Best, 1994; Sprigings & Neal, 2000; Sprigings & Mackenzie, 2002; Lindsay et al., 2008). Sprigings & Mackenzie, (2002), however, comment on the complexity that wrist movements introduce to the swing and thus they may not be worth the gains in performance; other mechanisms can produce the desired trajectory. Alternatively, movements such as the "rolling of the hands" for draw trajectories may initiate from the upper arm, in an external rotation movement.

Cluster differences

For both the driver and 5-iron, the multivariate correlation suggested a smaller cluster of golfers existed with similar swing patterns (*Clusters I* and *II*). These two clusters displayed differences between the draw and the fade trajectories which were not apparent over the entire group.

Firstly, the thorax rotation back towards the target of *Clusters I* and *II* was greater and earlier in draw trajectories during the downswing. However, *Cluster II* showed evidence for a slowing of the rotation in the draw trajectories around ball contact. Differences in thorax rotation between tennis shot trajectories have been found (Vorobiev et al., 1993; Reid & Elliott, 2002; Lo et al., 2004; Abrams et al., 2011), being greater for flat serves. It may be that some golfers utilise the segment to manipulate the swing plane between draw and fade trajectories.

A further noteworthy cluster difference related to lumbar forward flexion. *Cluster II* supported the initial hypothesis of more forward flexion for the draw and *Cluster I* showed the tendency during the backswing. The advantage of maintaining posture for draw trajectories is discussed above. Lumbar forward flexion has been shown to be influenced by the club, whether it be a driver or an iron, maybe due to club length (Egret et al., 2003; Joyce et al., 2013a). Reid & Elliott, (2002) found that topspin shots in tennis had a greater extension of the lumbar spine, producing a backwards lean. Therefore, it may be an important factor in golf in achieving the desired club swing plane.

8.3.3. Swing plane

Draw and fade trajectories were highlighted as a potential factor influencing instantaneous swing plane in the study by Coleman & Anderson, (2007). The overall horizontal and vertical swing plane patterns seen in this study were comparable to those of previous investigations (Coleman & Anderson, 2007; MacKenzie, 2012). At ball contact, the swing planes tended to support coaches; draw trajectories had a more in-to-out plane and fade trajectories had a more out-to-in swing plane. This may aid the clubhead path and orientation necessary to achieve each shot trajectory; for example, through the D-plane theory (Jorgensen, 1999).

The swing plane whole-swing analysis was divided into the first three quarters of the backswing and the latter three quarters of the downswing, to remove the period of the swing around top of the backswing; the limited frame-to-frame movement of the club shaft around this event makes the plane inconsistent (Coleman & Anderson, 2007). Main differences were offsets between the draw and fade analysis, with draw trajectories showing greater in-to-out horizontal planes in the downswing, possibly due to the differing address positions; however, as outlined above, biomechanical changes over the swing help to promote different swing plane movements. Therefore, absolute offset and the other relative differences may have been present regardless of the address position. This is consistent with the findings of Collinson et al., (2012), who despite defining a swing plane based on a larger, later part of the downswing, rather than instantaneously, found differences between the draw and fade trajectories present when address was accounted for. Unfortunately, no specific details of the differences were provided by the authors.

8.3.4. Impact location

Impact location has been discussed as potentially creating the impression of intentionally different trajectories through the gear effect (Section 2.2.2). This can particularly be the case in wood (metal) clubs, such as the driver, due to the bulge of the clubface and deeper location of the clubhead centre of gravity. No significant differences between horizontal impact location, were found at either a group or individual-level, a result which is evidence against draw and fade trajectories resulting from gear effect rather than changes in golfer biomechanics.

The only significant difference between shot conditions was the vertical impact location for the driver draw-fade at a group-level (Figure 8-1). The difference had a magnitude of 8 ± 12 mm, the exact influence of which is unknown, but may have influenced the final ball trajectory, creating a higher launch angle for fade trajectories. Impact locations in this study may contradict previous work which has shown more consistent impact location striking across the same standard of golfers, defined by handicap (Betzler et al., 2012b). The contradiction may be methodological in nature, with the study of Betzler et al., (2012b) utilising motion analysis to track the clubhead and ball.

Off-centre impacts could also have implications for the golfer. An impact away from the geometric centre could cause changes in clubhead mechanics during impact and therefore in the biomechanics of the golfer, a feature which has been noted in tennis, specifically in wrist kinematics (King et al., 2016). This could be the case for golf impacts and may have implications for injury, however, this is currently an unexplored topic.

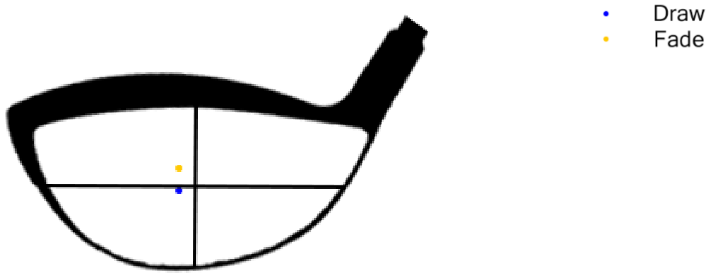


Figure 8-1: Group-level significant difference in vertical impact location for driver draw versus fade trajectories.

8.4. Hypothesised differences: low versus natural

Hypotheses were generated for the low-natural comparison in the same way as for the draw-fade comparisons. Similarly, event and whole-swing differences were uncovered, some of which were hypothesised initially (Table 8-5) and others emerged as a result of the analysis, but were not initially hypothesised from coaching points (Table 8-6). At address, three hypotheses were supported at a group-level: ball position, lead hand forwardness, and thorax lateral flexion. Furthermore, stance width was supported by *Cluster IV.* At ball contact, lead hand forwardness and centre of pressure were supported at the group-level, with thorax lateral flexion supported by *Cluster IV.* Finally, over the whole-swing, no hypotheses were supported at the group-level, however, *Cluster III*, supported lumbar lateral flexion.

Table 8-5: Hypothesised changes, supported (✓), rejected (✗) or not applicable (N/A), in the biomechanical variables between the 5-iron low and natural trajectory shots. The outcomes of the hypothesis are given in terms of whether they were supported at the group and cluster-level. Hypotheses are given by referring to the low relative to the natural.

Variable	Hypothesis	Outcome		
		Address	Ball contact	Whole-swing
Pelvis rotation	Slower rotation in low trajectories	N/A	N/A	✗
Thorax rotation	Slower rotation in low trajectories	N/A	N/A	✗
X-factor	Slower rotation in low trajectories	N/A	N/A	✗
Ball position	Ball further back in the stance for low trajectories	✓ Group	N/A	N/A
Stance width	Narrower distance in low trajectories	✓ Cluster IV	N/A	N/A
Grip distance	Grip down the club for low trajectories	✗	N/A	N/A
Lead hand forwardness	Hands further in front of the ball at address and ball contact for the low trajectories	✓ Group	✓ Group	N/A
Lumbar lateral flexion	Less flexing away from the target, towards the trail side in low trajectories	N/A	N/A	✓ Cluster III
Thorax lateral flexion	Lesser flexion of the thorax, so it's flexed towards the lead in low trajectories	✓ Group	✓ Cluster IV	✗
Lead wrist deviation	Lesser wrist deviation angles in low trajectories	N/A	N/A	✗
Centre of pressure	Distributed further towards the target in low trajectories	✗	✓ Group	✗

Table 8-6: 5-Iron low-natural differences that emerged over the whole-swing, but were not initially hypothesised. Differences are described by referring to the low relative to the natural.

Variable	Interpretation		
	Group	Cluster III	Cluster IV
Whole-swing			
Pelvis rotation	Less axially rotated away from the target throughout, with less axial pelvis rotation away from the target during the backswing and greater axial pelvis rotation towards the target during the downswing.	Greater axial pelvis rotation away from the target in the late backswing, followed by greater axial pelvis rotation towards the target in the downswing.	-
Thorax rotation	Later axial thorax rotation away from the target during the backswing, followed by later axial thorax rotation towards the target in the downswing, which was prolonged through ball contact.	-	-
Lumbar forward flexion	-	Lumbar forward extending over the initial backswing.	Lumbar forward flexing over the backswing, followed by greater forward extending in the downswing.
Lumbar lateral flexion	-	-	Lumbar lateral flexing towards the lead around top of the backswing.
Thorax lateral flexion	-	Prolonged thorax lateral flexing towards the trail through ball contact.	Greater thorax lateral flexing towards the lead in the late backswing, through top of the backswing. Slowing and halting of the thorax lateral flexing towards the trail as ball contact approached.
Pelvis translation	Less translated away from the target, parallel to the target line, throughout. Earlier, lesser pelvis translation towards the target in the downswing.	-	-
Centre of pressure	Quicker shift away from the target, parallel to the target line in the backswing, followed by greater shift towards the target in the downswing.	-	Earlier forward shift towards the target, parallel to the target line, in the downswing.

8.5. Creating low trajectories with a 5-iron

8.5.1. Address

Group differences

For this comparison, like draw trajectories, all golfers positioned the ball back further away from the lead foot (and target) for the low when compared to the natural. This is understandable as launch angle has been correlated with ball position in the stance (r = -0.67); changes in excess of 3º were suggested for a change of approximately 6 mm (Zhang & Shan, 2013). The change has also been advocated by coaches (e.g. Palmer, 1991; Adams & Tomasi, 2001; Weaver, 2012; Langer, 2015; Quinton, 2017b). Additionally, all golfers positioned their lead hand further towards the target relative to the ball, for low trajectories, which was also true at ball contact. Positioning the ball away from the target and moving the lead hand forward could promote a lower dynamic loft at ball contact (e.g. Alliss & Trevillion, 1969; Palmer, 1991; Crawley, 2010; Weaver, 2012; Jacobs, 2014; Langer, 2015). The difference between dynamic loft and attack angle has been called spin loft and has been theorised as a factor in controlling trajectory (Tuxen, 2008).

In addition to the supported outcomes, it was hypothesised that grip distance would be reduced (sometimes termed “gripping” or “choking down”) for low trajectories. However, this hypothesis was not supported. The differences in grip distance between shot trajectories were of a small magnitude (less than 20 mm), considering the lengths of the rubber grip were just less than 30 cm. The effect of this adjustment is unknown.

Cluster differences

It was hypothesised that stance width would narrow for low trajectories, based on coaching points (e.g. Alliss & Trevillion, 1969; Palmer, 1991; Weaver, 2012; Tomasi, 2017). A reduction in stance width was supported in *Cluster IV* only. It has been linked to the translation and rotation movement of the pelvis during the downswing (e.g. Golf Loopy, 2017; Quinton, 2017a); a narrower stance promoting more rotational movements compared to a wider stance. Therefore, narrowing the stance for low trajectories may impede the fundamental pelvis translation movements necessary for the shot trajectory. It is thus, perhaps unsurprising to see this variable not support the hypothesis across all golfers.

8.5.2. Whole-swing

Group differences

The pelvis translation was a group-level whole-swing difference when it came to low-natural trajectories. Low trajectories had a pelvis translated less away from the target throughout the swing. There was also a later, lesser shift forward. Maintenance of the pelvis further towards the target for the low trajectories, could potentially enable the kinematics of the upper segments to also position in this manner as ball contact is approached; for example, allowing the hands to position well ahead of the ball at ball contact.

The shift in pelvis translation may have led to changes in centre of pressure, where all golfers showed a greater forward shift towards the target in the downswing for the low trajectories. The fact that the centre of pressure was not located more towards the target throughout was surprising. Coaching literature advocates a golfer's "weight" be positioned towards the lead foot (e.g. Adams & Tomasi, 2001; Weaver, 2012). However, it appears it is the shift in the downswing that is important for achieving a low trajectory.

It appears golfers emphasised these translational movements as opposed to rotational ones. The pelvis rotated less away from the target during the backswing and less towards the target in the downswing, for low trajectories. Interestingly, rate of rotation of the pelvis, shoulders and X-factor, not magnitude, have been highlighted as a coaching point for low trajectories (Section 5.3.4). However, none emerged as significant, supporting findings in tennis, where peak velocities or velocities of central segments at ball contact were not significantly different between serve trajectories (Sheets et al., 2011), however it could be methodological; rotational velocities were not treated as independent variables, but rather interpreted through rate of change within the principal components analysis. The findings in both golf and tennis may be expected. In golf the shots are being hit for the same distance and in tennis the racket head velocity has been shown to not change with trajectory (Chow et al., 2003; Reid, 2006).

Cluster differences

The multivariate correlation analysis appeared to produce two clusters of swing patterns for the low-natural comparison. Different ways of playing shot trajectories has been alluded to in coaching literature (e.g. Flick, 2012). However, individual outlying points (principal component scores) could have amplified these negative correlations. Therefore, an air of caution is necessary when interpreting their meaning.

The cluster differences in lumbar lateral flexion and lumbar forward flexion were evident for the low-natural comparison. For the former, *Cluster III* showed no differences between shot trajectories. However, *Cluster IV* supported the hypothesis with more lumbar flexion towards the lead throughout for the low. Furthermore, the cluster displayed a flexing towards the lead around top of the backswing. These differences could have aided the pelvis translation difference present in the downswing, discussed above and contributed to an earlier centre of pressure shift towards the target in the downswing.

The two clusters differed in lumbar forward flexion during the backswing for low trajectories. *Cluster III* extended over this period, whereas *Cluster IV* flexed. The latter of these clusters also showed greater extending during the downswing. This variable, along with other central segments which differed between low and natural trajectories, could have led to different swing planes amongst *Cluster III.* The low trajectories had a less out-to-in swing plane at ball contact.

8.5.3. Impact location

The sole difference between low and natural trajectories conditions was the vertical impact location of golfer five, with a magnitude of 6 ± 7 mm (Figure 8-2). This could have decreased the discrepancy between low and natural launch angles, by creating an artificially lower natural launch angle, not produced by the golfer's biomechanics, due to the gear effect described in Section 2.2.2 (Jorgensen, 1999). The launch angle magnitudes of the natural and low trajectories for the golfer were 9.2 ± 0.6º and 13.2 ± 0.6º, respectively.

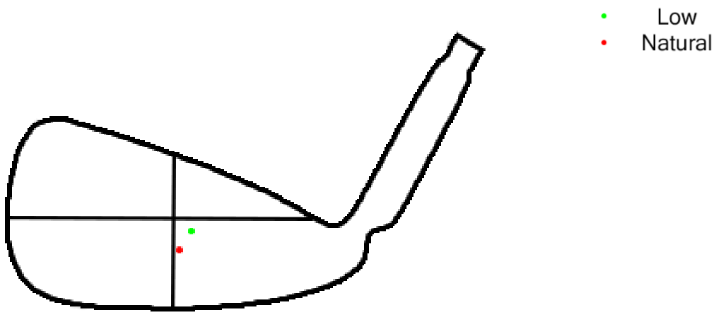


Figure 8-2: Significantly different vertical impact location of golfer five's low versus natural trajectories.

8.6. Methodological considerations

There were several methodical considerations associated with the biomechanical investigation in this thesis. They are discussed below.

8.6.1. Data collection environment

Firstly, due mainly to the nature of the equipment used in the study, testing took place in a laboratory environment. This allowed for control of conditions, desirable for the GOM and

VICON motion analysis systems. However, the decision introduced other factors such as the lack of entire ball flight. A trajectory model was applied to predict ball landing position on a predefined fairway. The model was based on that of Smits & Smith, (1994) and was arguably more applicable to the driver shots than the 5-iron, due to the greater spin rates for the latter club. However, to enhance the model it was adjusted based on similar trajectory models developed at Loughborough University relating to other sports and by matching to the TrackMan algorithm. The model fairway was arbitrarily defined to become progressively wider as shot carry distance increased; however, it was controlled at a width of 30 yards at a carry distance of 200 yards.

A further limitation of the indoor environment, was that the golfers were not able to aim at the target as they would on a course. A target line was defined, via a laser line positioned behind the net; however, this was only approximately six metres in front of the tee. This atypical method of alignment may have reduced success rates when it came to launch direction. It could also be reflected in biomechanical address position, such as thorax rotation and stance openness. It could be the reason, for example, that golfer one displayed, on average, a pelvis rotation opposite to the key coaching point (e.g. Haney, 2012; Harmon, 2012) and that several golfers appeared to display a stance openness opposite to the key coaching point for the 5-iron draw-fade comparison.

8.6.2. Selection of participants

The nature of the investigation meant that a high standard of golfer was required. However, how high a standard of golfer was needed to achieve the required shot trajectories on command remained uncertain. In the United States of America less than 2% of male golfers have a handicap of scratch or better and only just over 10% have a handicap of five or better (USGA, 2017). Investigation into coaching points, established that golfers at or as close as possible to scratch would be needed, which, presuming similar handicap percentages in the United Kingdom, would greatly reduce the target population from the 3.5 million adults who play golf (European Tour, 2017). Furthermore, of the golfing population who play full length courses, only 14% are female (European Tour, 2017), therefore, recruitment was limited to male golfers.

The results of this study suggest that there were golfers who could achieve the requested outcomes; however, other golfers were removed from the analysis because their success rates were too low, highlighting the difficult nature of the task. Overall, the subset of golfers who remained appear to have provided meaningful insights into the biomechanics of achieving the shot trajectories.

8.6.3. Use of standardised clubs

Two different standardised clubs were used during the investigation. It is generally considered that clubs built for longer hitting are easier to alter the draw-fade trajectory of than shorter clubs (e.g. PGA, 2010; BBC, 2017a). For this reason, the driver and 5-iron were selected for the investigation. The exact clubs were chosen mainly due to the requirements of the GOM data capture process (see Section 3.2.2).

Club standardisation is common in golf biomechanics, with the assumption that high standard golfers are capable of using any club. Set-up was as closely matched to golfers as possible. For example, stiff shafts were used to match all golfers' normal clubs; although, other club characteristic differences may have occurred, for example swingweight. Initial investigation into the effect of the standardised club (versus their own clubs) on swing biomechanics illustrated some differences, likely due to the difference in club properties. Furthermore, in terms of swing plane, club properties could have influenced the results; for example, deflection of the shaft (MacKenzie & Sprigings, 2009; Betzler et al., 2012a) could influence swing plane depending on where markers used to defined the swing plane are located on the shaft. To counteract the influence of shaft deflection, the plane was defined using the two markers on the upper shaft (OBJ1 and OBJ2; Figure 5-2), as opposed to the whole shaft.

Overall, it is acknowledged that use of the standardised clubs could prove a limitation of the study. However, it was a requirement of the methodology.

8.7. Future research & investigation

From the biomechanical investigation, several areas for future investigation emerge. Firstly, the principal component analysis method developed by Smith, (2013) and built on in this thesis can continue to be applied to understand the golf swing further. Future investigation could recruit a far larger sample of golfers to determine whether swing patterns lie on a continuum. Additionally, there were other areas identified during the literature review, that are associated with shot trajectories in other sports, which were not included in this investigation, mainly because the coaching investigation narrowed the focus of the thesis. These areas included, ground reaction forces, joint loading, lower body kinetics and kinematics, centre of gravity and segmental sequencing. Furthermore, segmental rotational velocities were not included as standalone variables; instead principal component analysis allowed interpretation of rate of change differences in the position variables. However, inclusion of segmental rotational velocities in the analysis as standalone variables may have produced further differences between shot trajectories. Areas such as these, and those that didn't emerge from the literature review, could provide further answers as to how golfers achieve different trajectories and could provide coaches with insight beyond traditional theory.

Another factor not fully considered was grip. This was investigated in relation to the distance the golfer gripped up or down the shaft for each trajectory. However, other grip adjustments may have been made for each trajectory. Two tennis grip styles were investigated by Elliott & Christmass, (1995). They found that the position of the ball-racket impact significantly differed between grip styles and for one shot type (hitting a high bouncing ball) the peak racket-shoulder speed significantly differed. Therefore, grip may well have an influence in hitting sports. Coaches sometimes recommend a change of grip to aid a draw or fade trajectory (e.g. Hill, 2017; BBC, 2017a; BBC, 2017b). However, the effect this has is unknown scientifically.

Furthermore, in this investigation there was no criteria placed on the amount of right-to-left or left-to-right curvature in the air for the draw and fade trajectories. The changes in the golfer biomechanics could, in future, be related to the amount of curvature achieved. This links to other shot trajectories, namely hook and slice shots which are more pronounced draw and fade trajectories and are considered errors (Section 2.2.2). Understanding of how these shots manifest would be useful for coaches and golfers in eradicating their sporadic appearance. This investigation assumed that the golfers played controlled draw and fade trajectories and that hooks and slices were not present during the data collection.

This study assumed that golfers have a natural or preference when it comes to draw or fade trajectories. It did not investigate whether golfers were more successful at their preferred trajectory or whether the magnitudes differed between their preferred or non-preferred shape. In future studies, shot trajectories could be investigated with more emphasis placed upon preferences to determine why some golfers appear more able to achieve one over the other. There could be some relation to physical characteristics, which were also not a focus of this thesis. Factors such as height, could alter the natural swing plane on which a golfer swings a club and thus make it easier to achieve a certain trajectory. More work is therefore needed.

A further future investigation could focus on differences between clubs when playing shot trajectories. Previous work has highlighted how golfers' swings differed when using different clubs, probably due to the club properties, such as shaft length. This study used a driver and a medium-long 5-iron, however, differences between them were not directly compared. Indeed, a lot of the findings were generalisable across the clubs, however, some findings emerged in one and not the other.

A final future investigation relates to other shot trajectories such as high, which were excluded from this study, for reasons detail in Section 5.3. However, there is a body of coaching literature which provides theory into how to achieve a higher trajectory with the same club.

CHAPTER NINE

CONCLUSIONS

A round of golf requires many types of golf shot to achieve a low score. Golfers are at a course management advantage if they are adept at achieving different outcomes with a given club. Quite how golfers achieve different trajectories is a subject of key coaching points but not scientific investigation.

The area of different shot trajectories with the same club was identified early in this thesis and the clear gap in scientific knowledge was highlighted. The area therefore became the focus of investigation. However, to determine the success of a shot trajectory accurate tracking of the clubhead and ball was required. Consequently, two research questions were outlined:

> *Research Question 1*: Do measurable biomechanical differences exist when a golfer plays different types of shot trajectory with the same club? If so, what are the differences?
>
> *Research Question 2:* How suitable are commercially available clubhead-ball impact measurement technologies for use in scientific biomechanical investigation to measure performance outcomes?

Research Question 2 was addressed in Chapters 3 and 4 with the main conclusion:

- Both the TrackMan Pro IIIe and Foresight GC2+HMT systems showed closer agreement to GOM for ball velocity and ball path than clubhead parameters. Furthermore, both systems showed close agreement to GOM for total spin rate. Foresight showed close agreement for backspin, however, spin axis for TrackMan and sidespin for Foresight showed poorer agreement. As a consequence of the poorer agreement across various parameters, the systems were deemed unsuitable for use in research in this thesis.

This is the first independent research into the accuracies of the commercial launch monitor systems, based on an accurate optical tracking method. The degree of agreement was determined using Bland-Altman statistics and by pre-defining grades of agreement, the research and coaching grades, following which the percentage of trials which met these grades could be identified. The research agreement between systems for ball velocity, launch angle, launch direction, total spin rate and backspin was good. However, to be included in this research, closer agreement at a research grade level for sidespin, spin axis, clubhead velocity, attack angle, club direction, face angle, and dynamic loft which were used to define draw, fade and low trajectories was required.

The conclusion is an important one for golf biomechanics research. Often, launch monitors are used in scientific work without any question regarding their accuracy. Although the main conclusion excluded the systems from the succeeding work in this thesis, the research shows the launch monitors are useful tools. The close agreement of certain parameters means that the launch monitors could be applied in other biomechanical research. For example, they could be used to track ball velocity as a measure of performance. Furthermore, agreement was much closer for the pre-defined coaching grade. Therefore, launch monitors are very useful outside of scientific research, a key finding for professionals, coaches and club-fitters.

In addition to the main research question, a further conclusion from the launch monitor investigation was drawn:

- The GOM system, typically used in aeronautical and automotive engineering can be applied to accurately track the golf clubhead and ball through impact.

By using the point tracking element of the GOM system, a method was developed for tracking clubhead and ball impact parameters (Chapter 3). The applicability of high speed video, limited only by the cameras maximum frame rate, to generate three-dimensional tracking data provided an ideal tool for the rapid clubhead-ball collision. The accuracy of each step of the chain from point tracking to calculation of spin rates was verified and its capability to act as a benchmark to validate other systems was demonstrated.

The method allows for a deeper experimental understanding of clubhead-ball impacts than has previously been reported. This has implications for experimental understanding of the clubhead-ball impact. For example, it would enable detailed investigation of impact location; the method could be used to test the effects of off-centre impacts on the rotation of the clubhead through impact and the resultant ball flight parameters. Such an investigation would have wider implications for those with a scientific interest in golf and for club manufacturers, who could more comprehensively understand the role of club properties, such as centre of gravity location and moment of inertia, allowing the design of higher performing clubheads.

Research Question 1 was addressed at a group and cluster-level with the following main conclusion:

- Biomechanical differences exist when golfers play a different shot trajectory with the same club, relating to variables at both address and over the whole-swing. Therefore, for most golfers achieving a different shot trajectory is more than simply changing address position and swinging “normally”.

Despite the importance of the entire swing, changes at address were simplest to make between shot trajectories and consequently did play an important role. Indeed, some of the whole-swing differences may have resulted from those at address. For the draw-fade comparison, golfers moved the ball away from the lead foot, along the target line towards the trail foot for draw trajectories. They also positioned their hands further towards the target for the same trajectories and closed the pelvis rotation, thorax rotation and stance openness relative to target line for draw trajectories. Finally, golfers laterally flexed their thorax less towards the trail side for the draw.

On top of these changes at address, whole-swing changes were also important. At a group-level, pelvis rotation was offset, rotated more away from the target, with later rotations away from and towards the target for draw trajectories. Lumbar forward flexion saw slower extending in the downswing for the draw. Lumbar lateral flexion saw a greater bending towards the trail side offset over the whole-swing, whilst thorax lateral flexion saw a greater flexing towards the lead in the backswing, with greater, more prolonged flexing towards the trail in the downswing for the same shots. Centre of pressure saw an earlier, quicker, greater forward shift in the downswing of the draw trajectories. Finally, the pelvis was translated less away from the target throughout, with an earlier forward translation for the draw. Findings such as the pelvis rotation and lumbar lateral flexion offsets may have been due to the changes at address, however others such as timing and magnitude differences were likely unrelated to this time point.

In addition to group differences there were others that were common across clusters of golfers, highlighting how few golfers' swings are the same. These related to the thorax rotation and the lumbar forward flexion. *Cluster I* for the driver (57% of golfers) and *Cluster II* for the 5-iron (71% of golfers) showed greater and earlier thorax rotation towards the target in the downswing for draw trajectories. However, this rotation slowed for *Cluster II* late in the downswing. Furthermore, both clusters showed a tendency for more lumbar forward flexion, *Cluster I* in the backswing and *Cluster II* over the whole-swing.

Several of the findings described in the previous two paragraphs support the coaching points identified in the coaching literature search (Section 5.2) and coach interviews (Section 5.3). For example, the pelvis rotation, thorax rotation and stance openness relative to the target line at address. However, other differences emerged in addition to the coaching points. At the group level, these included changes in ball position and lead hand forwardness at address as well as the magnitude differences in pelvis translation and thorax lateral flexion; the rate of change difference in lumbar forward flexion; and the timing differences in pelvis rotation, pelvis translation and centre of pressure over the whole-swing. At the cluster level, they included the magnitude differences in lumbar forward flexion and thorax rotation and the timing difference in thorax rotation over the whole-swing.

For the address position of low and natural trajectories, at the group-level, golfers altered their ball position and lead hand forwardness. These represented the same changes for the low as for the draw. Further to these group changes, *Cluster IV* (45% of golfers) narrowed their stance width and laterally flexed their thorax towards the lead, for low trajectories.

Over the whole-swing, at the group-level, fundamental differences concerned pelvis translation and centre of pressure. The former showed less translation away from the target throughout in the low, however, there was later, lesser forward shift than the natural. Centre of pressure showed a greater forward shift in the downswing for the low trajectories.

Across *Cluster III* (36% of golfers) and *Cluster IV*, lumbar forward flexion and lumbar lateral flexion differences were evident. For the former, *Cluster III* forward extended over the backswing, whereas *Cluster IV* flexed, and for the latter, *Cluster IV* showed more flexion towards the lead throughout.

Of the findings for the low-natural comparison, the timing difference in pelvis translation emerged in addition to the coaching points at the group level, as did the lumbar forward flexion differences at the cluster level.

The biomechanical findings have implications for biomechanists. The importance of controlling the shot trajectory being played must be recognised when conducting scientific golf research. Furthermore, the application of the methodological approaches used in this thesis have been shown to be suitable for golfer analysis at a group and an individual-level. For example, principal component analysis, enabled comparison of shot conditions firstly by group-average and then by isolation of each golfer's principal component scores. Furthermore, the study was designed to analyse subtle differences between shot trajectories. These are arguably more difficult to identify than differences between golfers of different ability. The methods used enabled subtle differences to be investigated.

For coaches, when teaching a golfer to play different shot trajectories, they should be aware of the group-level differences. These represent key coaching points for a golfer. However, coaches should also be aware of the cluster and individual nature of golf swings. Changes at address are easy for a coach (and golfer) to make. Coaches should ensure that offsets are maintained from address through the swing, for example, pelvis rotation for draw-fade trajectories. They should also aim to encourage "in-swing" differences, such as the timing of pelvis rotation, the magnitude of the centre of pressure shift and the rate of change of the lumbar forward flexion for draw-fade trajectories or the magnitude and timing of pelvis translation and centre of pressure movements for low-natural trajectories. However, these latter changes may prove more difficult for a golfer to master.

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APPENDICES

APPENDIX A

Kalibrierstelle der Deutschen Akkreditierungsstelle (DAkkS), Akkreditierungsnummer D-K-17127-01 für Länge und weitere geometrische Messgrößen. Akkreditiert nach DIN EN ISO/IEC 17025:2005.

Prüflabor zur Prüfmittelüberwachung gemäß DIN ISO 9000ff. und VDI/VDE-Richtlinien 2618ff.

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Kalibrierschein-Nr.
Calibration Certificate-No.

Werks-Kalibrierschein
Proprietary Calibration-Certificate

Gegenstand *Object*	**Calibration Panel Aluminium**
Hersteller *Manufacturer*	**GOM**
Typ *Type*	**Calibration Panel 250 CP 10 / MV 250x200 mm²**
Fabrikat/Serien-Nr. *Serial Number*	**CP10/250/D07445** Identifikations-Nr. *Identification-No.*
Prüfintervall *Inspection interval*	**12 Monate**
Auftraggeber *Customer*	**GOM Gesellschaft für opt. Messtechnik mbH Mittelweg 7-8 38106 Braunschweig**
Auftragsnummer *Work order No.*	**603845**
Anzahl der Seiten *Number of pages*	**2**
Datum der Kalibrierung *Date of calibration*	**25.03.2008**
Prüfer *Inspector*	**S. Lausen**
Prüfentscheid *Calibration result*	**Das Prüfmittel hält die Spezifikation ein**

Die Kalibrierung erfolgt durch Vergleich mit Bezugsnormalen bzw. Bezugsnormalmesseinrichtungen, die in einer innerhalb der International Laboratory Accreditation Cooperation (ILAC) akkreditierten Kalibrierstelle kalibriert wurden und damit rückgeführt sind auf die nationalen Normale, mit denen die Physikalisch-Technische Bundesanstalt (PTB) die physikalischen Einheiten in Überein-stimmung mit dem Internationalen Einheitensystem (SI) darstellt.

Für die Kalibrierung und deren Dokumentation trägt der Aussteller dieses Kalibrierscheines die alleinige Verantwortung.

The calibration is performed by comparison with reference standards or standard measuring equipment which are calibrated by a Calibration laboratory accredited within the International Laboratory Accreditation Cooperation (ILAC) and thus traceable to the national measurement standards maintained by the Physikalisch-Technische Bundesanstalt (PTB) for the realisation of the physical units according to the International system of Units (SI).

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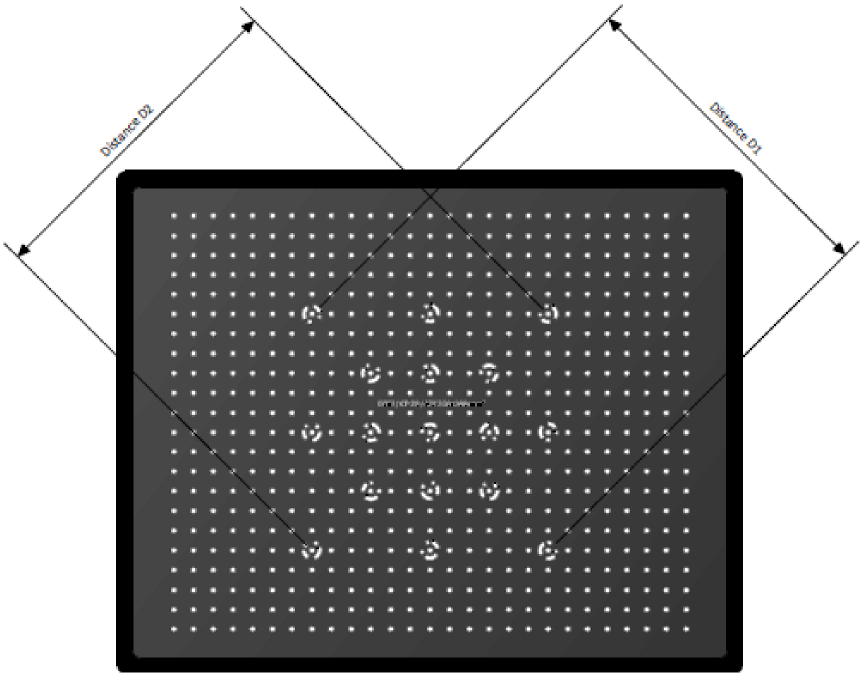
Decom Prüflabor Verwaltungs GmbH
Amtsgericht Kappeln HRB 272

Protokoll-Nr. Protocol N°	K080600.5	Decom Prüflabor GmbH & Co. KG	Seite Page	2 / 2

Gegenstand Object	Calibration Panel (Aluminium)	Serien-Nr. Serial-N°	CP10/250/D07445
Typ Type	CP 10 / MV 250x200 mm²	Material Material	Aluminium: 22.90 · 10^{-6} · K^{-1}
Prüfanweisung Test instructions	Decom / GOM Test Instructions according to VDI/VDE/DGQ 2618, Blatt 27 "Prüfanweisung für Sonderlehren und Prüfvorrichtungen"		



Measuring Results

Testing Feature	Measured Value [mm]	Measured Value [inch]
D1	244.354 mm	9.6202 in
D2	244.368 mm	9.6208 in

Ambient conditions

Temperature	Relative air humidity
(20 ± 1) °C	(50 ± 10) % rF

Remarks

Measurement standards

Nr	Measuring system	Traceability to national standards	exp. measurement uncertainty (P = 95%)
1)	OGP Smartscope Vantage 600 (2D x- and y-axis)	Gauge blocks 1054 DKD 01301	U = 1.50 µm + 4.00 · L · 10-6 µm, L = Length

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APPENDIX B

The definition of the Thorax_ab segment used as part of the calculation of the RT_SHOULDER and LT_SHOULDER landmarks is shown in Table B-1. The segment was solely used for this purpose.

Table B-1: The Thorax_ab segment definition required for the creation of the RT_SHOULDER and LT_SHOULDER landmarks.

	Proximal	Distal	Tracking	Origin
Thorax_ab	RT_ILLIAC / LT_ILLIAC	RAC / LAC	RT_ILLIAC / LT_ILLIAC / CLAV / STRN / T10 / T2 / T8	Mid-proximal

The coda pelvis was used to identify the RIGHT_HIP and LEFT_HIP landmark locations. The segment was defined based on the markers RASIS, LASIS, RPSIS and LPSIS (C-Motion, 2016). The origin was defined as the mid-point of the RASIS and LASIS markers. A plane (XY) was then fitted through the RASIS, LASIS and mid-point of the RPSIS and LPSIS markers. The positive segment coordinate system X-axis is then defined from the origin towards the RASIS marker, the positive Z-axis is vertically perpendicular to the XY plane and the positive Y-axis the cross-product of the X and Y-axes using the right-hand rule.

The final model is shown in Figure B-1.

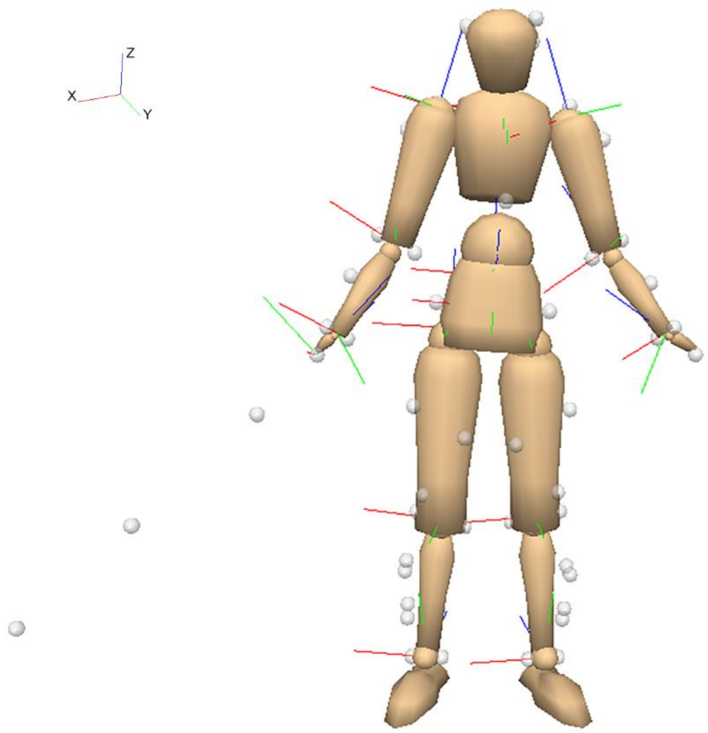


Figure B-1: Visualisation of the Visual3D model (Smith, 2013), showing the segment coordinate systems.

APPENDIX C

The equations for calculating and assessing the Q-statistic value used to assess the principal component reconstructions are shown (Equation C-1 to Equation C-6; Jackson, 1991). The Q-statistic was initially calculated using Equation 3:

$$Q = (X - \hat{X})'(X - \hat{X}) \tag{C-1}$$

where $\boldsymbol{X}$ is the original data matrix and $\hat{\boldsymbol{X}}$ is the retained principal components (those explaining 90% of the variance in the data). The critical by which the Q-statistic was then calculated using Equation B-2 to Equation B-6.

$$\theta_1 = \sum_{i=k+1}^{p} L_i \tag{C-2}$$

$$\theta_2 = \sum_{i=k+1}^{p} {L_i}^2 \tag{C-3}$$

$$\theta_3 = \sum_{i=k+1}^{p} {L_i}^3 \tag{C-4}$$

$$h_0 = 1 - \frac{2\theta_1\theta_3}{3{\theta_3}^2} \tag{C-5}$$

$$CV = \theta_1 \left[\frac{C_\alpha \sqrt{2\theta_2 {h_0}^2}}{\theta_1} + \frac{\theta_2 h_0 (h_0 - 1)}{{\theta_1}^2} + 1 \right]^{\frac{1}{h_0}} \tag{C-6}$$

where $\boldsymbol{L}$ is the eigenvalue vector, $\boldsymbol{k}$ is the number of retain principal components (explaining 90% of the variance in the data) and CV is the critical value. The term C_α is the alpha level from a t-distribution, in this case $\alpha = 0.05$.

APPENDIX D

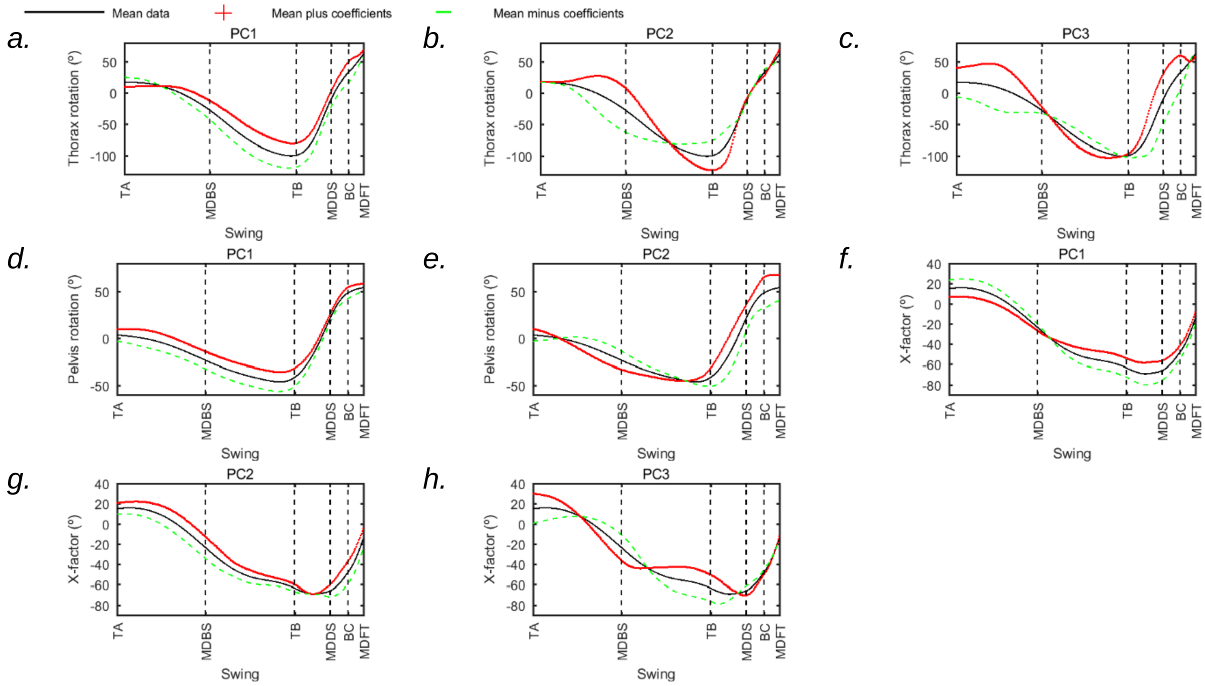


Figure D-1: Driver draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-c. thorax rotation; d-e. pelvis rotation and f-h. X-factor.

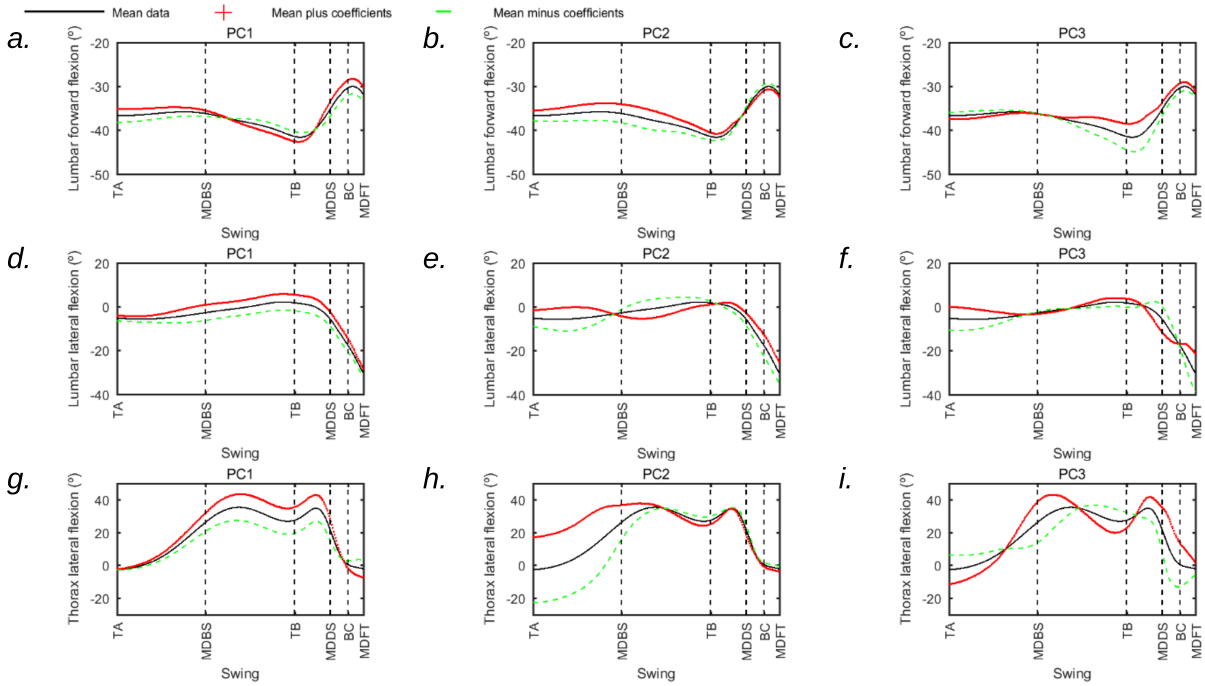


Figure D-2: Driver draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-c: lumbar forward flexion; d-f. lumbar lateral flexion and g-i. thorax lateral flexion.

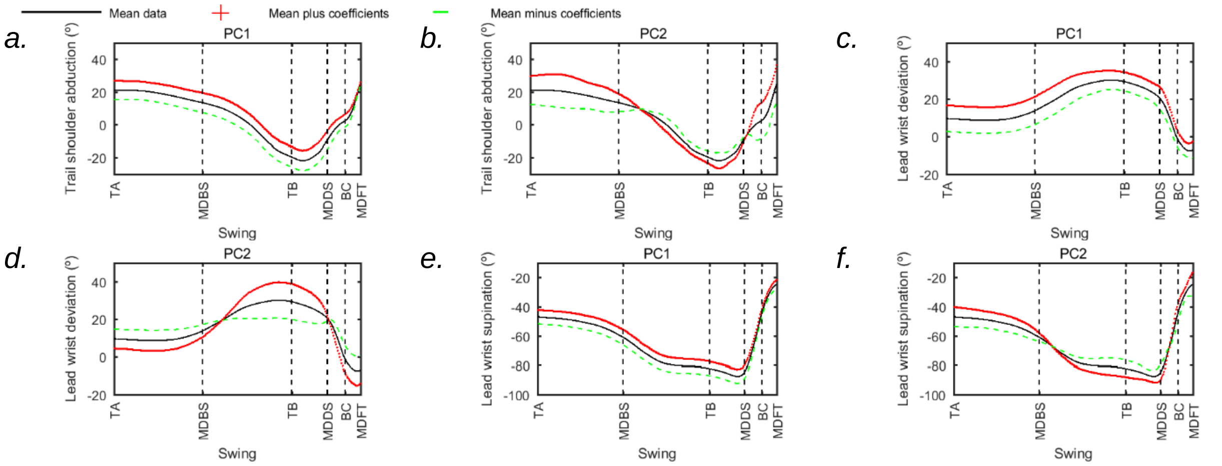


Figure D-3: Driver draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. trail shoulder abduction; c-d. lead wrist deviation and e-f. lead wrist supination.

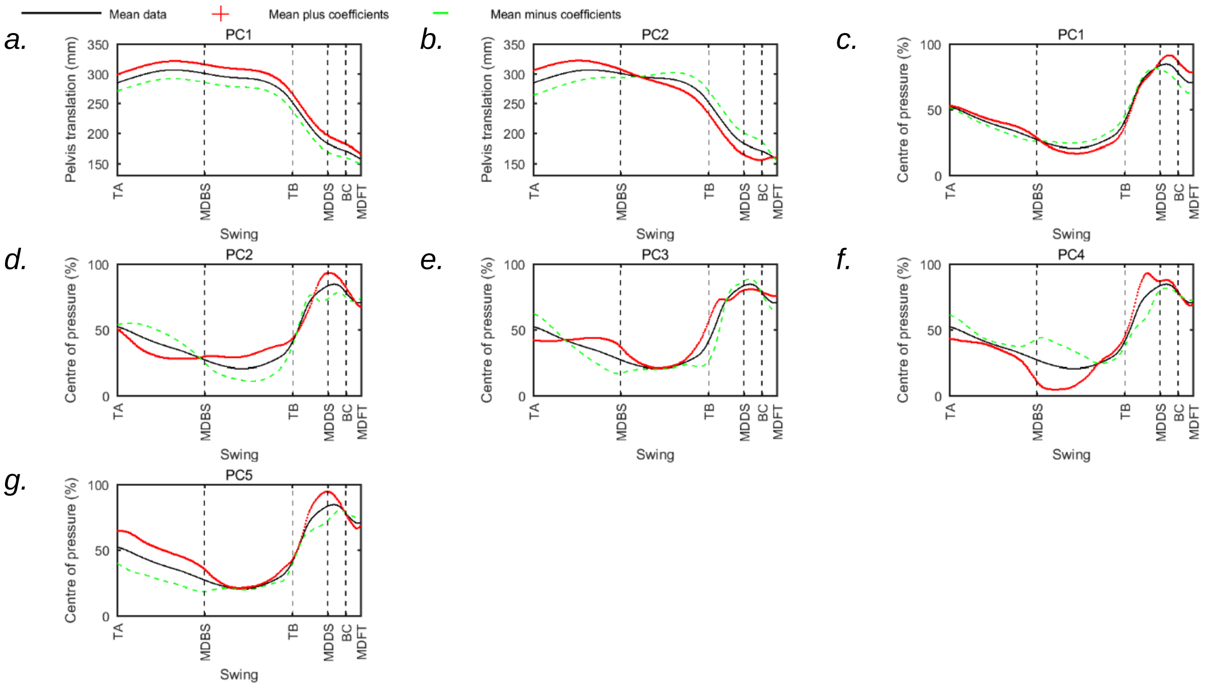


Figure D-4: Driver draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b pelvis translation and c-g. centre of pressure.

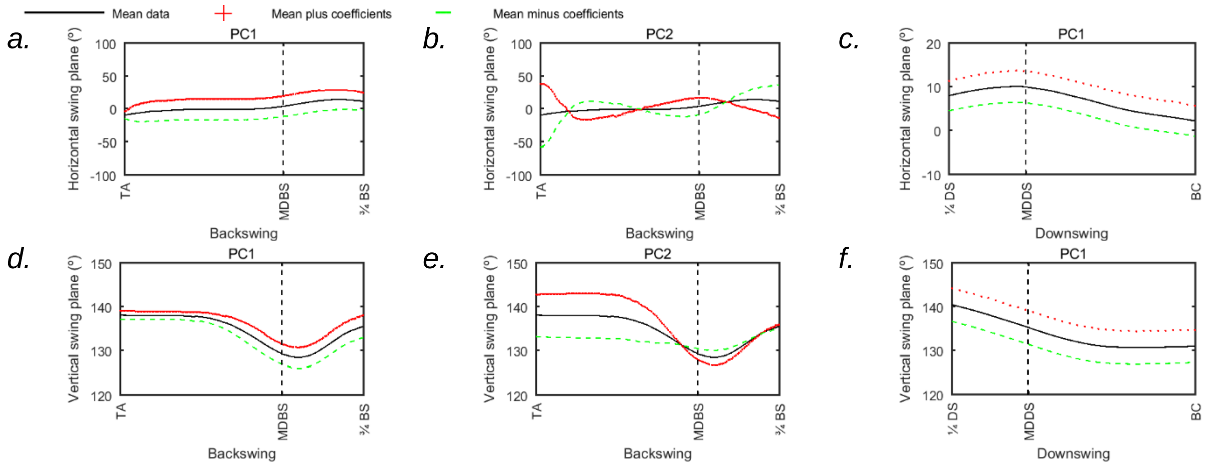


Figure D-5: Driver draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients plots: a-b. horizontal swing plane during the backswing; c. the horizontal swing plane during the downswing; d-e. the vertical plane during the backswing and f. the vertical plane during the downswing.

APPENDIX E

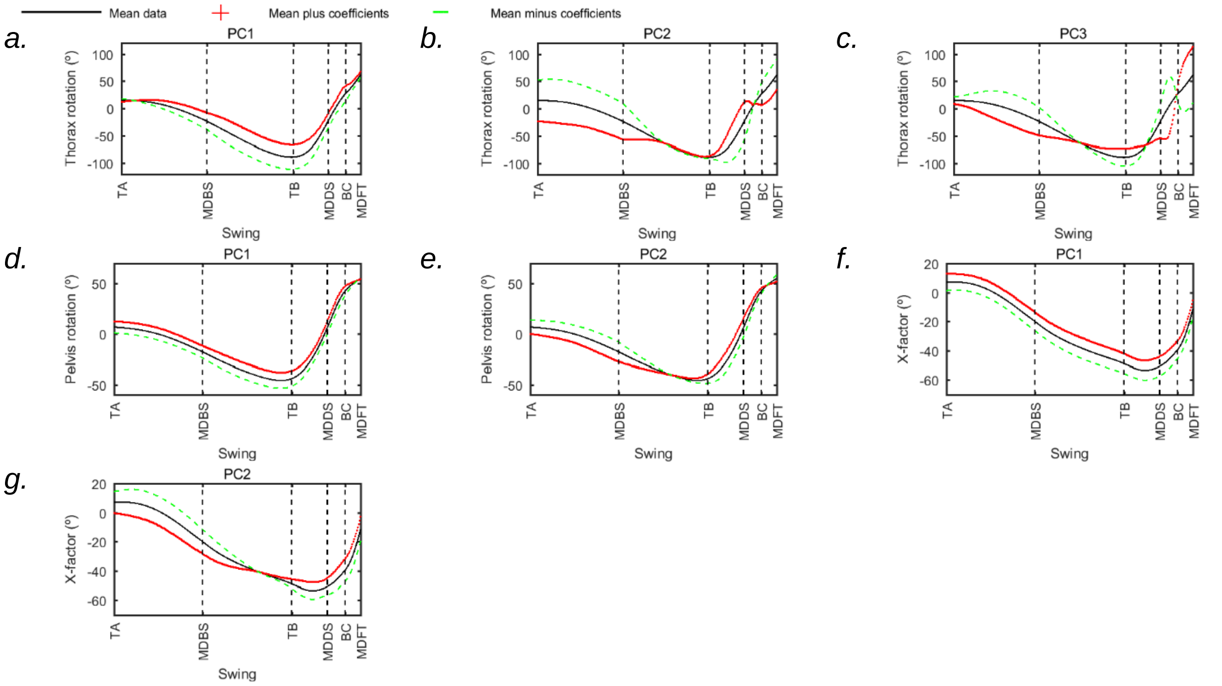


Figure E-1: 5-iron draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-c. thorax rotation; d-e. pelvis rotation and f-g X-factor.

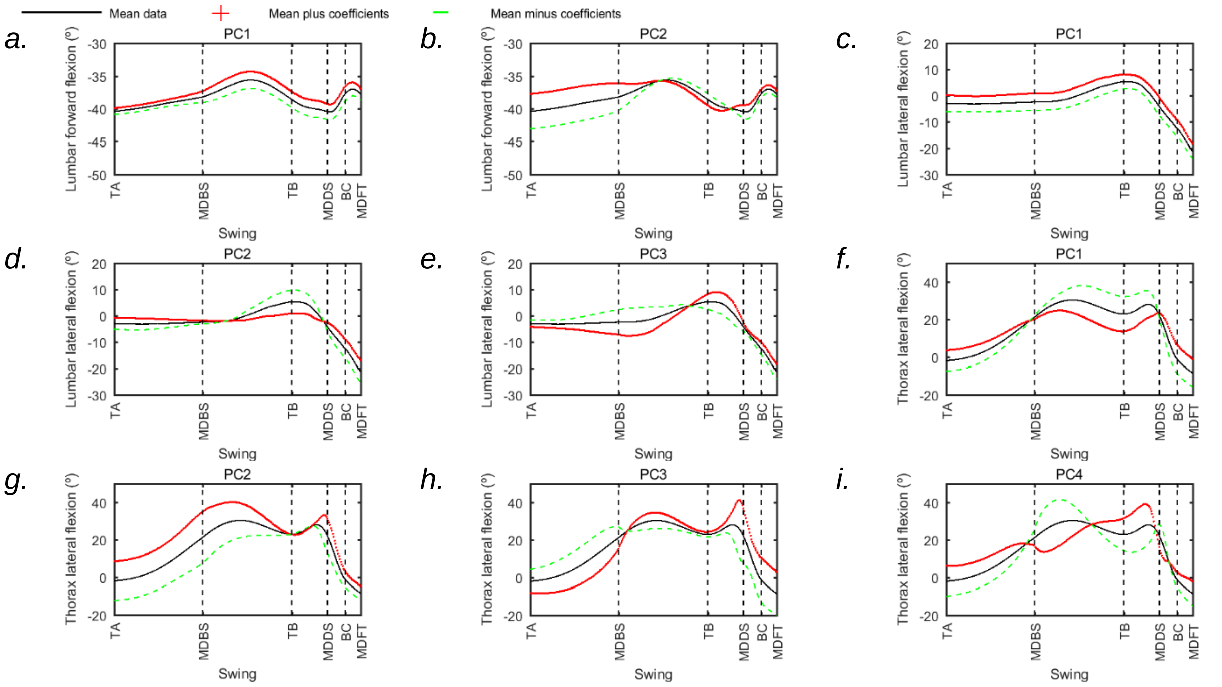


Figure E-2: 5-iron draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. lumbar forward flexion; c-e. lumbar lateral flexion and f-i thorax lateral flexion.

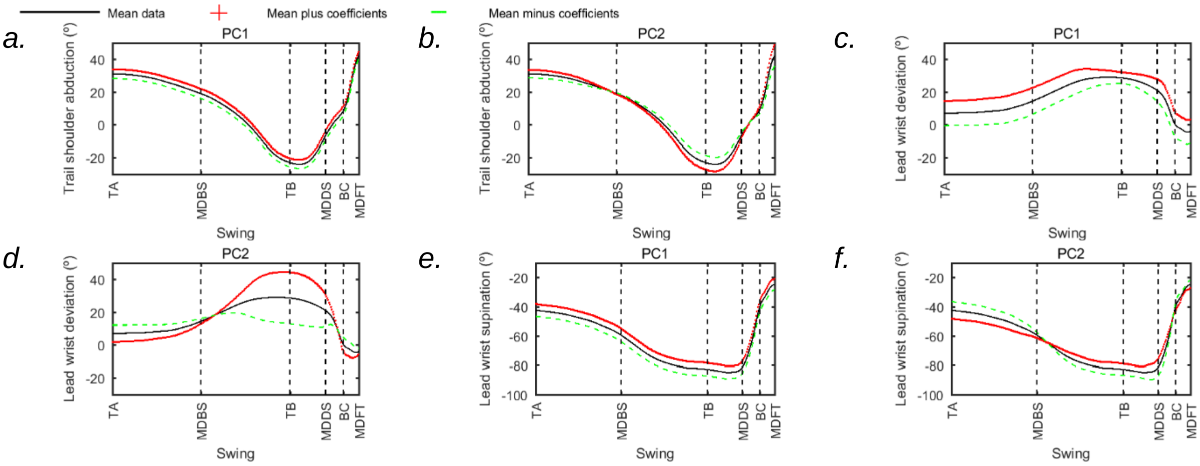


Figure E-3: 5-iron draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. trail shoulder abduction; c-d. lead wrist deviation and e-f. lead wrist supination.

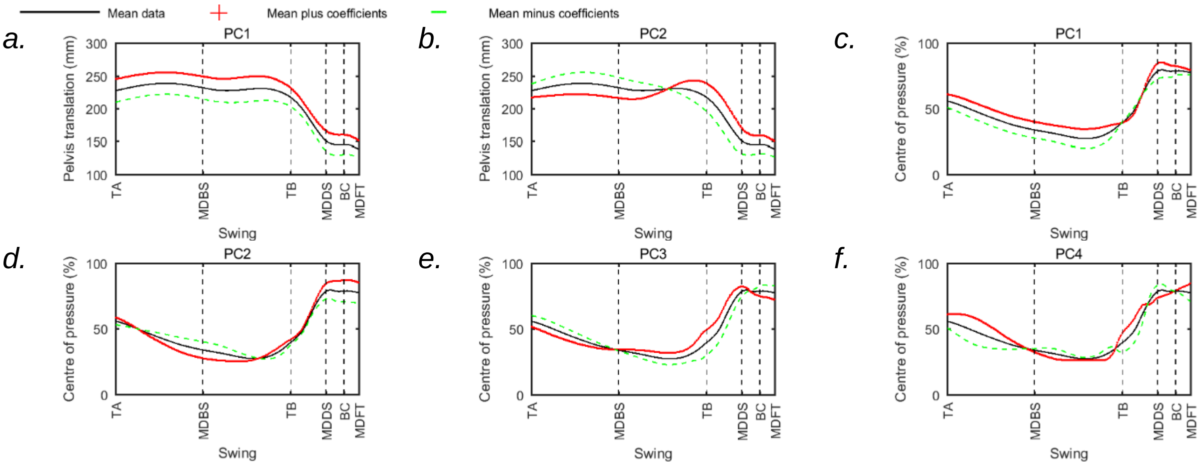


Figure E-4: 5-iron draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. pelvis translation and c-f. centre of pressure.

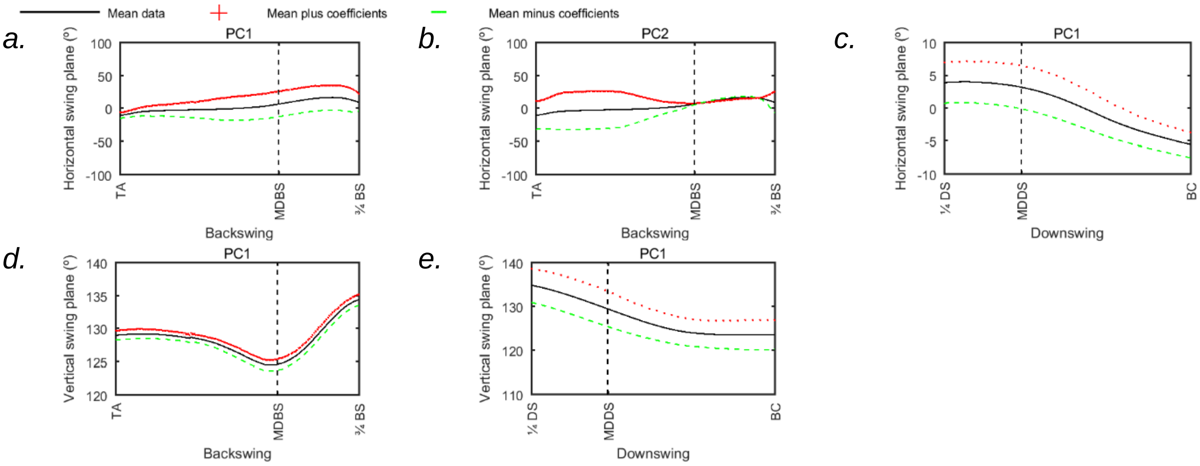


Figure E-5: Driver draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. the horizontal swing plane during the backswing; c. the horizontal swing plane during the downswing; d. the vertical plane during the backswing and e. the vertical plane during the downswing.

APPENDIX F

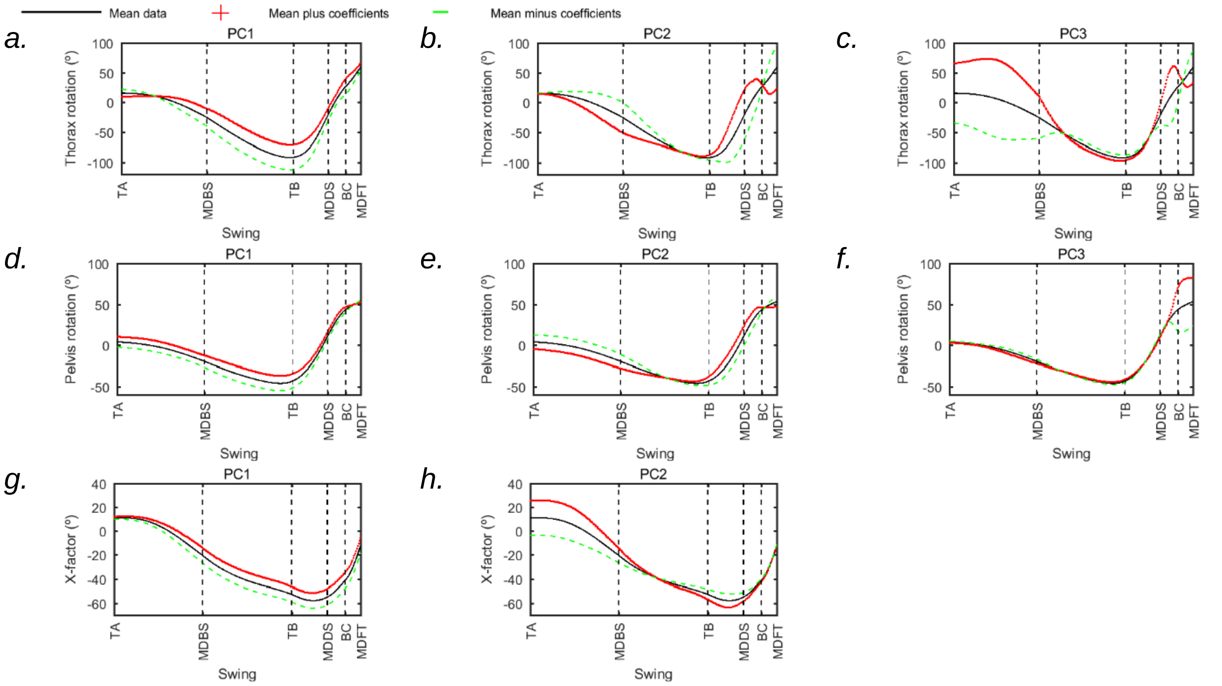
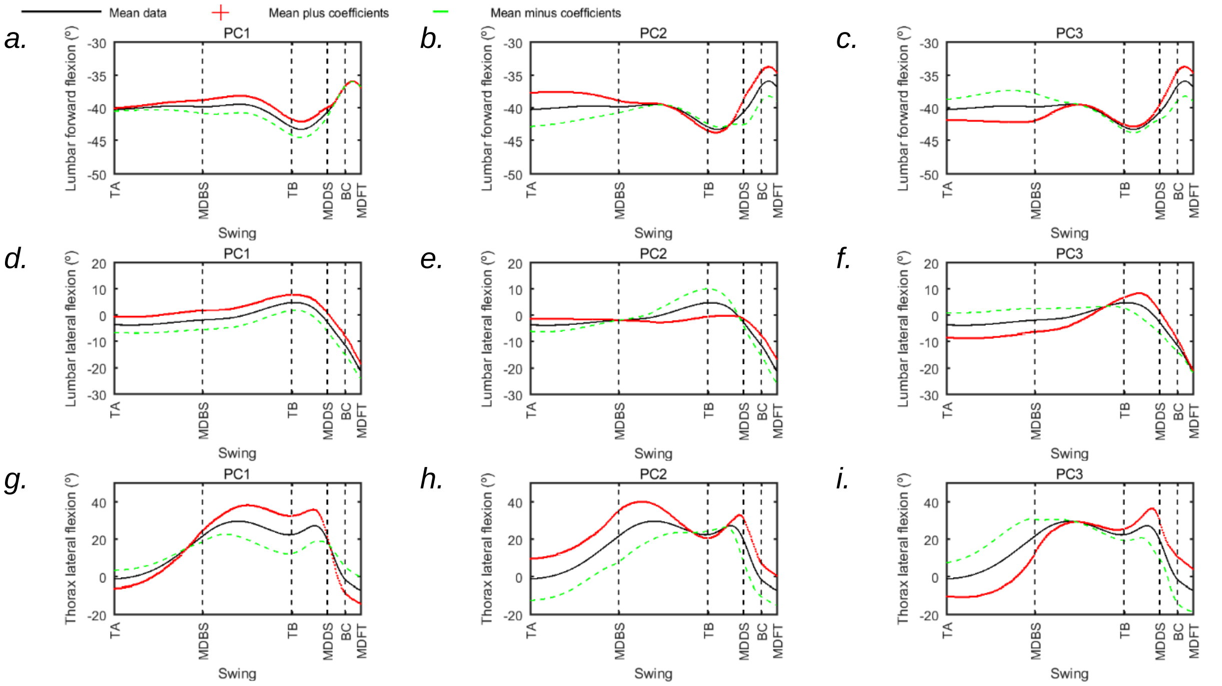


Figure F-1: 5-iron low-natural principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-c. thorax rotation; d-f. pelvis rotation and g-h. X-factor.



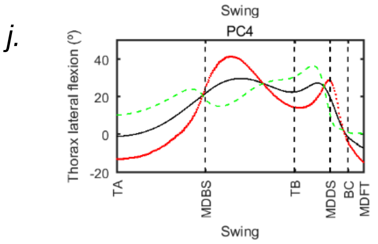


Figure F-2: 5-iron low-natural principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-c. lumbar forward flexion; d-f. lumbar lateral flexion and g-j. thorax lateral flexion.

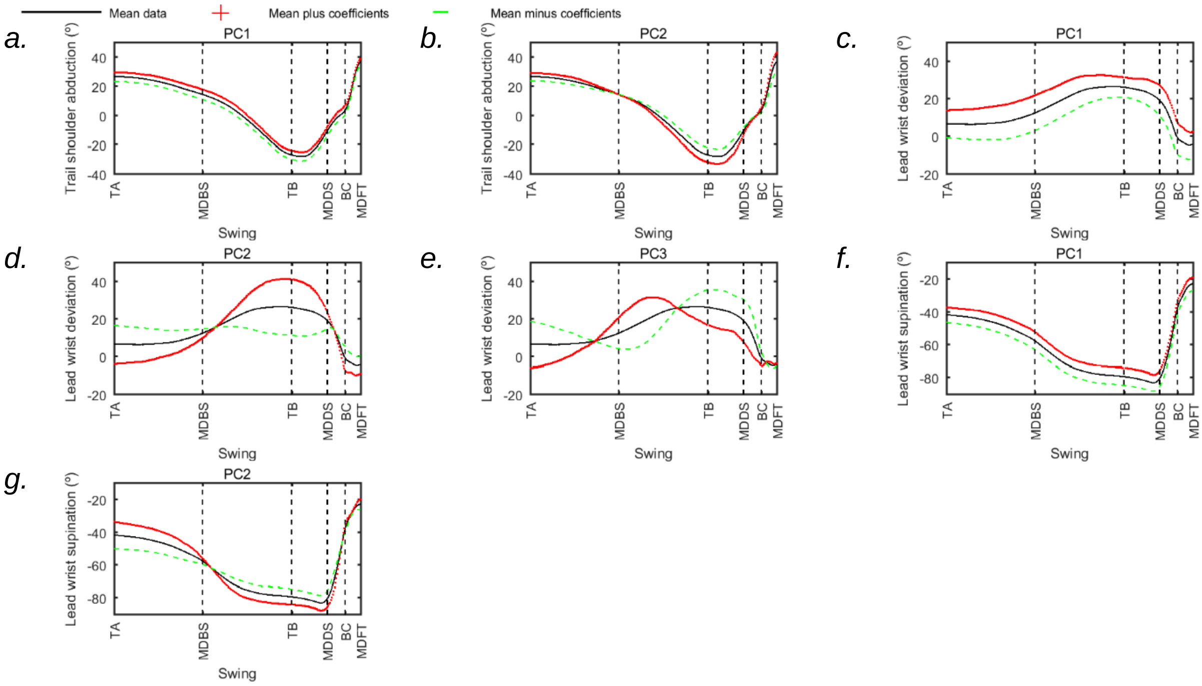


Figure F-3: 5-iron low-natural principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. trail shoulder abduction; c-e. lead wrist deviation and f-g. lead wrist supination.

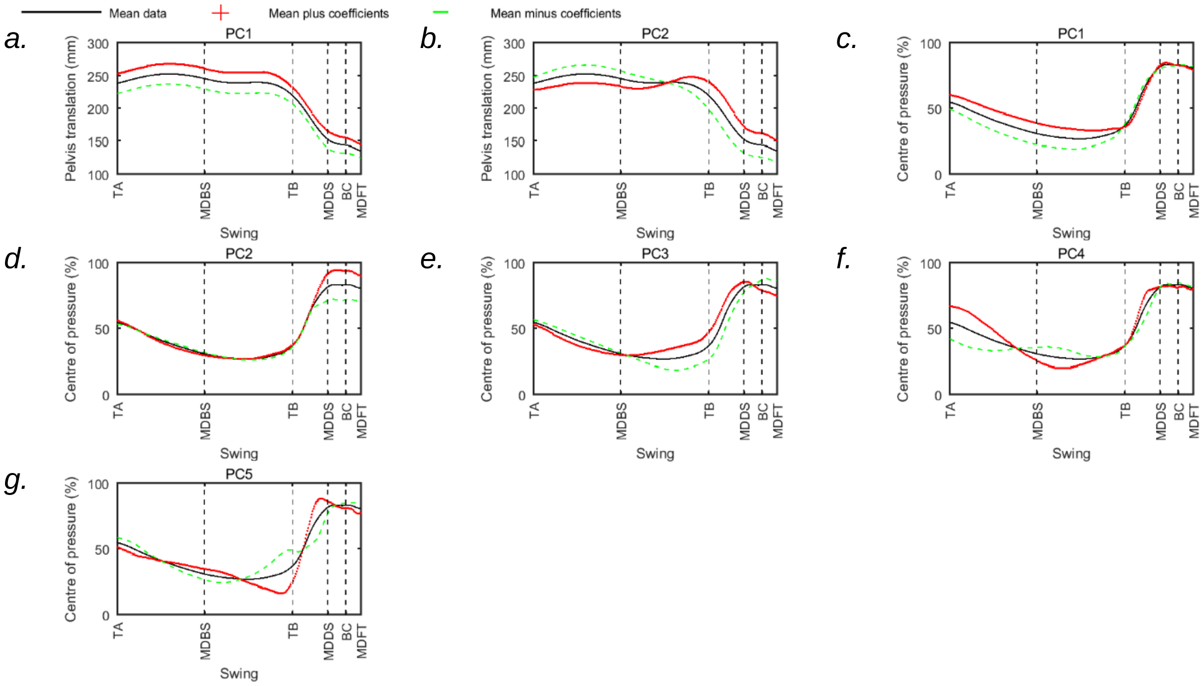


Figure F-4: 5-iron low-natural principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. pelvis translation and c-g. centre of pressure.

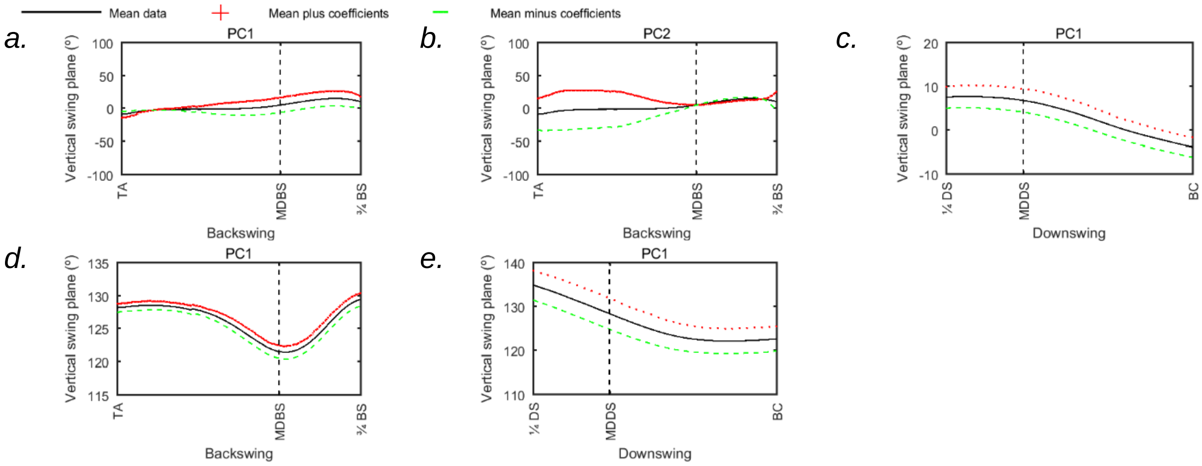


Figure F-5: Driver draw-fade principal component (PC) analysis plots, showing the mean data curve plus and minus the coefficients: a-b. the horizontal swing plane during the backswing; c. the horizontal swing plane during the downswing; d. the vertical plane during the backswing and e. the vertical plane during the downswing.

APPENDIX G

Table G-1: Mean (& SD) address variable values for each golfer for the draw and fade trajectories with the driver.

Golfer	Pelvis rotation (º)		Thorax rotation (º)		Stance openness (º)		Ball position (mm)		Stance width (mm)		Grip distance (mm)		Lead hand forwardness (mm)		Lead hand height (mm)		Thorax lateral flexion (º)		Centre of pressure (%)	
	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade
1	1.4 (1.2)	-1.6 (0.9)	15.6 (0.8)	14.6 (0.5)	-1.2 (0.5)	0.7 (0.4)	-58 (11)	-28 (3)	456 (7)	457 (4)	147 (2)	147 (2)	35 (9)	87 (13)	770 (4)	770 (3)	-3.5 (0.7)	-1.7 (0.2)	47 (2)	46 (4)
3	5.1 (0.9)	5.3 (1.3)	13.1 (0.1)	13.1 (0.7)	0.3 (0.7)	0.3 (0.6)	-89 (11)	-75 (4)	551 (19)	561 (9)	138 (1)	136 (2)	89 (9)	121 (10)	726 (5)	722 (4)	-4.0 (0.5)	-4.0 (1.7)	52 (4)	43 (9)
4	2.5 (0.9)	8.5 (1.7)	21.0 (0.6)	22.4 (0.7)	-5.6 (1.0)	2.6 (0.8)	-99 (16)	-1 (25)	568 (8)	554 (5)	151 (3)	132 (3)	10 (19)	91 (16)	740 (5)	755 (8)	6.1 (1.0)	0.0 (1.3)	55 (0)	54 (2)
5	7.5 (1.2)	8.5 (0.8)	12.6 (1.3)	13.2 (0.6)	-5.3 (0.7)	3.8 (0.9)	-5 (16)	25 (8)	446 (13)	444 (14)	161 (5)	163 (1)	78 (13)	102 (13)	806 (5)	812 (2)	-1.9 (1.1)	-2.9 (1.1)	58 (4)	59 (1)
6	-1.6 (0.6)	0.6 (1.2)	22.1 (0.2)	25.0 (0.9)	-1.9 (0.4)	-0.2 (0.8)	-52 (5)	-29 (19)	571 (5)	564 (14)	167 (1)	167 (2)	47 (5)	64 (14)	733 (3)	740 (4)	-5.5 (1.0)	-8.6 (0.6)	52 (1)	48 (2)
7	3.9 (0.7)	4.1 (0.7)	17.2 (0.4)	17.3 (1.0)	-3.7 (0.5)	4.5 (0.8)	-110 (5)	-111 (11)	633 (4)	640 (7)	158 (1)	161 (5)	-77 (5)	-76 (7)	645 (2)	643 (8)	-9.1 (0.6)	-9.9 (1.1)	55 (1)	54 (2)
11	-1.3 (1.2)	2.3 (1.8)	13.8 (0.7)	15.5 (1.1)	-1.5 (0.5)	-1.0 (1.7)	-151 (15)	-114 (20)	496 (11)	517 (18)	121 (2)	119 (5)	-30 (16)	21 (17)	722 (4)	721 (5)	4.4 (0.5)	-0.7 (1.6)	59 (2)	58 (2)
Mean	2.7 (3.1)	4.4 (3.6)	16.2 (3.5)	17.0 (4.4)	-2.7 (2.3)	1.6 (2.1)	-72 (48)	-42 (53)	522 (66)	529 (64)	149 (20)	147 (16)	26 (55)	60 (62)	732 (44)	731 (46)	-2.7 (5.3)	-5.2 (4.6)	54 (6)	52 (8)

Table G-2: Mean (& SD) ball contact variable values for each golfer for the draw and fade trajectories with the driver.

Golfer	Pelvis rotation (º)		Thorax rotation (º)		Lead hand forwardness (mm)		Lead hand height (mm)		Thorax lateral flexion (º)		Centre of pressure distribution (%)		Swing plane vertical (º)		Swing plane horizontal (º)	
	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade
1	41.6 (2.7)	46.4 (2.3)	28.4 (1.6)	28.8 (1.3)	-45 (6)	-33 (7)	862 (7)	845 (6)	-0.3 (0.9)	-7.8 (0.5)	34 (4)	29 (13)	130.9 (0.4)	132.1 (0.8)	7.2 (0.8)	-0.5 (1.8)
3	46.6 (1.4)	49.2 (1.6)	39.9 (0.9)	39.0 (2.3)	-133 (2)	-111 (10)	810 (5)	808 (9)	-2.2 (2.4)	-6.5 (1.5)	94 (2)	91 (1)	133.3 (0.4)	133.7 (0.5)	2.1 (1.3)	-2.3 (1.2)
4	52.0 (1.5)	60.4 (2.9)	35.9 (1.2)	36.5 (1.4)	-107 (30)	-56 (18)	825 (12)	819 (4)	8.7 (1.4)	-1.4 (2.8)	94 (2)	97 (2)	133.2 (0.3)	133.1 (0.1)	8.0 (1.0)	-5.6 (4.7)
5	50.0 (3.6)	52.5 (1.2)	34.5 (2.4)	35.1 (1.9)	-55 (17)	-38 (15)	894 (7)	892 (2)	-2.0 (2.2)	-5.6 (1.5)	92 (4)	90 (5)	129.1 (0.2)	129.2 (0.3)	-1.8 (1.5)	-5.7 (1.0)
6	48.5 (2.3)	52.6 (0.7)	29.9 (0.7)	30.6 (1.5)	-38 (9)	-36 (14)	854 (7)	844 (15)	5.6 (1.4)	-0.2 (2.0)	87 (5)	85 (5)	132.3 (0.3)	132.5 (0.5)	9.4 (1.1)	2.2 (2.4)
7	43.1 (1.2)	43.9 (0.9)	32.3 (1.3)	31.4 (1.3)	94 (7)	69 (16)	821 (4)	918 (5)	9.2 (1.0)	7.0 (1.9)	96 (2)	93 (2)	129.2 (0.2)	129.1 (0.2)	8.8 (0.9)	-5.4 (1.5)
11	47.2 (0.4)	54.7 (1.2)	21.7 (1.1)	25.6 (1.1)	-58 (14)	-28 (19)	886 (4)	886 (8)	4.0 (1.0)	-2.7 (1.2)	55 (7)	43 (11)	128.2 (0.5)	127.3 (0.6)	5.1 (1.9)	-1.0 (1.8)
Mean	3.7 (4.6)	-1.9 (4.7)	31.1 (5.6)	31.5 (5.1)	-46 (65)	-30 (50)	844 (33)	852 (85)	3.7 (4.6)	-1.9 (4.7)	68 (32)	65 (32)	131.9 (2.0)	131.0 (2.4)	5.5 (4.0)	-0.9 (4.4)

Table G-3: Mean (& SD) address variable values for each golfer for the draw and fade trajectories with the 5-iron.

Golfer	Pelvis rotation (º)		Thorax rotation (º)		Stance openness (º)		Ball position (mm)		Stance width (mm)		Grip distance (mm)		Lead hand forwardness (mm)		Lead hand height (mm)		Thorax lateral flexion (º)		Centre of pressure (%)	
	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade
1	0.5	4.1	12.9	13.8	-1.3	1.4	-143	-90	402	384	150	151	-28	5	750	750	3.6	0.3	44	44
	(1.3)	(2.1)	(0.5)	(0.5)	(0.5)	(0.6)	(2)	(16)	(7)	(11)	(2)	(5)	(9)	(19)	(1)	(3)	(0.8)	(1.0)	(1)	(2)
2	10.7	13.1	15.2	14.9	-2.0	-1.0	-58	-30	379	359	145	147	22	32	695	700	-8.5	-11.4	66	64
	(0.9)	(0.4)	(0.4)	(0.5)	(1.8)	(0.6)	(14)	(7)	(1)	(9)	(3)	(3)	(22)	(9)	(4)	(3)	(0.7)	(0.3)	(1)	(3)
3	9.9	11.5	14.1	14.0	-0.9	0.4	-131	-116	478	478	141	141	-11	11	720	719	-4.1	-4.6	54	54
	(0.6)	(0.9)	(0.5)	(0.6)	(0.5)	(1.0)	(18)	(4)	(11)	(15)	(1)	(2)	(16)	(6)	(5)	(3)	(0.5)	(0.3)	(2)	(2)
8	-0.4	2.6	12.4	13.2	2.7	3.4	-160	-119	423	414	144	145	-25	27	714	704	-1.3	-6.4	56	51
	(1.0)	(1.4)	(0.3)	(0.5)	(1.9)	(1.6)	(6)	(9)	(3)	(11)	(1)	(1)	(10)	(10)	(3)	(1)	(0.8)	(1.8)	(3)	(3)
9	3.6	4.3	16.0	18.1	-0.1	0.7	-239	-171	474	482	153	164	-66	-21	709	724	5.0	2.6	-	-
	(0.8)	(0.6)	(0.7)	(0.5)	(1.8)	(0.4)	(24)	(8)	(14)	(27)	(6)	(3)	(9)	(7)	(5)	(2)	(0.6)	(0.8)		
12	3.5	4.1	12.0	12.7	-2.3	2.9	-156	-147	510	513	152	153	-18	-12	747	753	1.5	1.2	56	55
	(0.8)	(0.5)	(0.4)	(0.6)	(0.3)	(0.5)	(8)	(12)	(8)	(5)	(1)	(1)	(6)	(7)	(1)	(2)	(0.4)	(0.6)	(1)	(2)
13	8.4	8.5	17.5	17.7	-3.8	4.5	-123	-120	515	511	112	138	-76	-69	661	666	-0.3	-1.3	63	66
	(0.7)	(0.9)	(0.5)	(0.4)	(0.9)	(0.8)	(9)	(13)	(7)	(4)	(2)	(2)	(6)	(8)	(3)	(2)	(1.1)	(1.2)	(1)	(2)
Mean	5.2	6.9	14.4	14.9	-1.1	1.8	-143	-113	452	-449	142	148	-28	-4	713	717	-0.6	-2.8	57	55
	(4.4)	(4.0)	(2.0)	(2.1)	(2.5)	(2.0)	(53)	(43)	(51)	(60)	(26)	(8)	(33)	(34)	(29)	(29)	(4.5)	(4.7)	(8)	(8)

Table G-4: Mean (& SD) ball contact variable values for each golfer for the draw and fade trajectories with the 5-iron.

Golfer	Pelvis rotation (º)		Thorax rotation (º)		Lead hand forwardness (mm)		Lead hand height (mm)		Thorax lateral flexion (º)		Centre of pressure distribution (%)		Swing plane vertical (º)		Swing plane horizontal (º)	
	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade	Draw	Fade
1	41.3	44.5	20.7	21.1	-112	-106	769	763	3.6	-3.0	56	49	122.6	122.8	-1.2	-11.4
	(2.6)	(3.4)	(1.2)	(1.2)	(28)	(19)	(7)	(6)	(1.6)	(2.4)	(10)	(16)	(0.8)	(0.7)	(1.9)	(1.7)
2	43.9	48.7	21.1	20.8	-95	-75	741	742	2.9	-3.2	97	88	124.5	124.2	-1.1	-7.2
	(2.4)	(0.8)	(1.3)	(0.5)	(16)	(8)	(3)	(3)	(2.0)	(1.0)	(3)	(5)	(0.3)	(0.3)	(0.5)	(0.3)
3	50.4	50.5	33.0	33.5	-99	-124	738	735	-3.7	-4.4	91	95	126.6	126.6	-4.4	-5.9
	(1.1)	(2.1)	(2.1)	(1.3)	(13)	(13)	(11)	(6)	(2.0)	(2.0)	(6)	(3)	(0.4)	(0.5)	(0.4)	(0.7)
8	37.5	41.1	22.5	25.6	-104	-70	750	743	-9.3	-14.3	66	55	123.6	122.9	-3.1	-13.5
	(2.6)	(1.9)	(1.2)	(1.3)	(17)	(12)	(4)	(3)	(1.8)	(1.4)	(4)	(5)	(0.8)	(0.4)	(1.5)	(1.5)
9	28.9	33.9	25.3	28.2	-63	-63	777	789	12.9	10.6	-	-	121.7	121.8	-0.1	-7.3
	(1.9)	(1.9)	(1.4)	(1.1)	(8)	(9)	(4)	(3)	(1.6)	(1.1)			(0.7)	(0.8)	(1.3)	(0.6)
12	43.0	45.0	26.6	27.1	-92	-94	761	765	-4.0	-7.3	93	88	123.2	123.6	-4.9	-9.3
	(0.8)	(1.8)	(0.9)	(1.3)	(10)	(12)	(4)	(5)	(0.3)	(1.7)	(2)	(2)	(0.2)	(0.3)	(0.7)	(1.0)
13	33.3	42.8	23.5	26.8	-96	-64	748	779	6.1	5.0	75	85	122.9	122.8	0.6	-3.1
	(3.0)	(1.0)	(1.1)	(0.6)	(20)	(9)	(51)	(5)	(4.3)	(1.8)	(10)	(13)	(0.2)	(0.4)	(0.8)	(1.4)
Mean	39.7	43.8	24.6	26.3	-95	-85	755	760	1.4	-2.4	80	77	123.7	123.6	2.3	-9.1
	(8.6)	(5.4)	(4.4)	(4.2)	(28)	(25)	(23)	(19)	(7.3)	(7.9)	(17)	(20)	(1.8)	(2.9)	(2.1)	(2.9)

Table G-5: Mean (& SD) address variable values for each golfer for the low and natural trajectories with the 5-iron.

Golfer	Pelvis rotation (º)		Thorax rotation (º)		Stance openness (º)		Ball position (mm)		Stance width (mm)		Grip distance (mm)		Lead hand forwardness (mm)		Lead hand height (mm)		Thorax lateral flexion (º)		Centre of pressure (%)	
	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural
1	2.8	1.5	12.6	13.4	-1.0	-0.6	-174	-153	389	415	151	151	-71	-39	750	753	2.5	3.2	44	44
	(1.1)	(0.8)	(0.2)	(0.9)	(0.6)	(0.5)	(10)	(9)	(9)	(10)	(1)	(2)	(10)	(9)	(2)	(2)	(1.1)	(0.4)	(4)	(2)
2	13.3	14.6	15.5	15.8	-0.4	-0.7	-60	-26	357	357	145	144	-27	1	690	689	-10.9	-11.9	65	68
	(1.6)	(0.9)	(0.6)	(0.9)	(1.5)	(1.2)	(9)	(12)	(12)	(8)	(3)	(1)	(9)	(6)	(5)	(4)	(1.5)	(1.0)	(3)	(2)
3	9.7	10.7	14.4	14.2	-1.8	-1.5	-127	-124	455	487	139	129	19	38	730	716	-2.9	-4.0	53	55
	(0.7)	(0.5)	(0.4)	(0.6)	(0.6)	(1.5)	(12)	(13)	(5)	(10)	(3)	(4)	(6)	(5)	(3)	(2)	(1.1)	(0.4)	(2)	(2)
5	5.3	2.6	16.0	15.7	-0.4	2.8	-144	-117	357	390	145	152	-59	-26	763	758	-2.6	-1.6	53	57
	(0.6)	(0.6)	(0.3)	(0.6)	(0.6)	(0.7)	(16)	(8)	(13)	(11)	(4)	(2)	(8)	(4)	(1)	(2)	(0.6)	(0.8)	(2)	(1)
6	-2.4	0.5	23.9	24.4	-0.7	-4.1	-185	-127	472	480	162	156	-73	-29	714	713	0.8	-2.8	40	43
	(0.9)	(0.8)	(0.5)	(0.8)	(0.5)	(1.0)	(12)	(6)	(13)	(10)	(10)	(1)	(6)	(7)	(3)	(5)	(0.6)	(0.8)	(3)	(1)
8	0.1	3.5	11.7	12.9	1.3	-3.6	-187	-106	426	426	146	147	-45	34	704	701	-2.7	-7.7	53	52
	(0.5)	(1.8)	(0.4)	(0.7)	(0.8)	(2.7)	(8)	(25)	(7)	(6)	(2)	(2)	(6)	(30)	(4)	(7)	(0.2)	(2.9)	(2)	(3)
9	3.8	5.3	17.1	18.2	1.7	-2.6	-200	-161	440	532	163	164	-55	-46	760	766	4.3	1.9	-	-
	(0.9)	(0.7)	(0.4)	(0.4)	(0.5)	(0.7)	(9)	(7)	(25)	(4)	(2)	(1)	(12)	(7)	(2)	(1)	(0.5)	(1.0)		
10	1.9	2.1	16.4	16.4	0.0	-0.3	-153	-134	513	470	129	125	-127	-68	690	694	-0.8	-0.9	57	56
	(0.5)	(0.7)	(0.2)	(0.2)	(0.7)	(0.2)	(14)	(3)	(4)	(24)	(1)	(3)	(16)	(9)	(1)	(4)	(0.4)	(0.7)	(2)	(1)
11	-1.6	-0.9	12.1	12.2	0.0	0.2	-244	-137	464	492	152	165	-39	-30	752	735	-2.1	-0.9	58	56
	(0.5)	(0.6)	(0.7)	(0.6)	(0.5)	(0.8)	(20)	(4)	(8)	(9)	(2)	(2)	(15)	(4)	(2)	(2)	(0.8)	(0.4)	(1)	(1)
12	2.5	3.1	11.6	11.8	-1.6	-1.9	-186	-105	516	520	139	137	-105	-61	668	668	2.4	1.4	55	56
	(0.3)	(1.7)	(0.4)	(1.1)	(0.4)	(0.5)	(25)	(10)	(8)	(4)	(2)	(4)	(27)	(2)	(11)	(3)	(0.7)	(0.7)	(1)	(0)
13	9.4	9.6	18.6	16.5	-5.2	-5.6	-115	-105	513	457	148	149	-57	-23	722	719	-1.8	-3.0	64	63
	(1.8)	(0.9)	(0.7)	(0.3)	(0.9)	(1.5)	(16)	(10)	(14)	(10)	(3)	(2)	(11)	(8)	(4)	(3)	(1.7)	(0.8)	(4)	(1)
Mean	4.0	4.5	15.5	15.6	-1.0	-1.4	-161	132	446	452	148	149	-57	-21	722	722	-1.3	-2.4	54	54
	(4.8)	(4.7)	(3.5)	(3.6)	(1.7)	(2.4)	(49)	(45)	(58)	(53)	(10)	(14)	(39)	(35)	(31)	(29)	(4.0)	(4.6)	(8)	(8)

Table G-6: Mean (& SD) ball contact variable values for each golfer for the low and natural trajectories with the 5-iron.

Golfer	Pelvis rotation (º)		Thorax rotation (º)		Lead hand forwardness (mm)		Lead hand height (mm)		Thorax lateral flexion (º)		Centre of pressure distribution (%)		Swing plane vertical (º)		Swing plane horizontal (º)	
	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural	Low	Natural
1	39.9 (1.4)	41.4 (1.3)	18.9 (0.9)	21.0 (0.5)	-191 (8)	-124 (16)	760 (5)	774 (9)	8.9 (0.3)	5.4 (1.7)	85 (6)	62 (6)	122.8 (0.6)	122.6 (0.7)	-11.1 (1.5)	-0.5 (1.2)
2	49.8 (2.0)	48.7 (2.3)	21.5 (1.5)	20.2 (0.8)	-112 (52)	-79 (11)	729 (5)	734 (3)	-7.7 (0.6)	-2.4 (1.4)	96 (5)	93 (6)	124.8 (0.6)	124.9 (0.4)	-6.1 (0.8)	-0.2 (0.9)
3	52.2 (1.2)	51.5 (2.1)	32.3 (1.1)	34.0 (1.5)	-171 (5)	-110 (10)	737 (11)	730 (11)	4.0 (1.2)	-6.5 (3.3)	101 (1)	91 (2)	126.3 (0.3)	126.4 (0.6)	-3.5 (0.7)	-5.9 (0.7)
5	37.3 (1.6)	41.1 (1.3)	29.9 (0.5)	32.4 (1.0)	-202 (17)	-143 (8)	793 (5)	800 (3)	12.8 (1.1)	-3.2 (0.5)	90 (3)	85 (2)	119.2 (0.3)	119.8 (0.3)	0.4 (0.7)	1.9 (1.1)
6	47.4 (1.5)	47.9 (1.8)	24.9 (1.9)	24.4 (1.7)	-133 (73)	-106 (9)	757 (10)	764 (5)	2.6 (1.0)	2.2 (1.0)	95 (3)	93 (2)	123.0 (0.4)	123.3 (0.2)	-2.4 (1.1)	0.6 (0.7)
8	42.7 (1.9)	47.1 (3.7)	23.8 (1.0)	26.8 (1.9)	-159 (23)	-71 (11)	736 (5)	750 (6)	-2.2 (0.8)	-16.5 (3.6)	74 (6)	63 (3)	123.0 (0.4)	122.9 (0.4)	-12.4 (0.9)	-13.5 (1.5)
9	31.7 (2.3)	33.7 (1.5)	27.2 (1.5)	28.2 (1.3)	-88 (21)	-75 (16)	770 (13)	775 (5)	-8.5 (1.5)	10.3 (1.0)	-	-	123.2 (1.0)	121.7 (0.8)	-7.4 (1.5)	-7.5 (0.7)
10	45.7 (0.9)	44.8 (1.4)	24.6 (0.4)	24.4 (1.0)	-123 (22)	-95 (9)	771 (5)	778 (2)	-5.9 (0.2)	0.0 (0.8)	62 (2)	57 (2)	122.4 (0.2)	122.5 (0.4)	-0.2 (1.1)	2.6 (0.9)
11	47.0 (2.2)	48.2 (1.5)	13.4 (1.4)	15.6 (0.9)	-161 (12)	-93 (11)	784 (5)	782 (6)	-8.3 (0.5)	-6.2 (0.9)	79 (1)	70 (5)	118.2 (0.6)	118.2 (0.6)	-2.5 (0.8)	4.9 (1.7)
12	44.1 (2.3)	40.3 (2.2)	26.2 (0.9)	25.6 (1.0)	-154 (13)	-108 (11)	752 (5)	746 (3)	2.9 (1.8)	-3.7 (0.7)	98 (2)	93 (3)	123.7 (0.4)	123.7 (0.2)	-6.9 (0.5)	-9.3 (1.0)
13	41.2 (2.2)	41.8 (1.8)	26.5 (0.9)	26.6 (0.1)	-100 (11)	-52 (13)	772 (7)	782 (11)	0.6 (0.4)	6.4 (0.1)	93 (5)	88 (11)	122.9 (0.5)	122.9 (0.7)	-2.5 (1.3)	-1.6 (2.0)
Mean	43.5 (5.8)	44.4 (5.4)	24.5 (5.1)	25.3 (5.4)	-145 (45)	-98 (26)	760 (21)	765 (22)	-1.2 (7.2)	-1.7 (7.3)	87 (12)	78 (15)	122.7 (2.3)	122.6 (2.2)	-5.1 (4.2)	-2.6 (5.6)

APPENDIX H

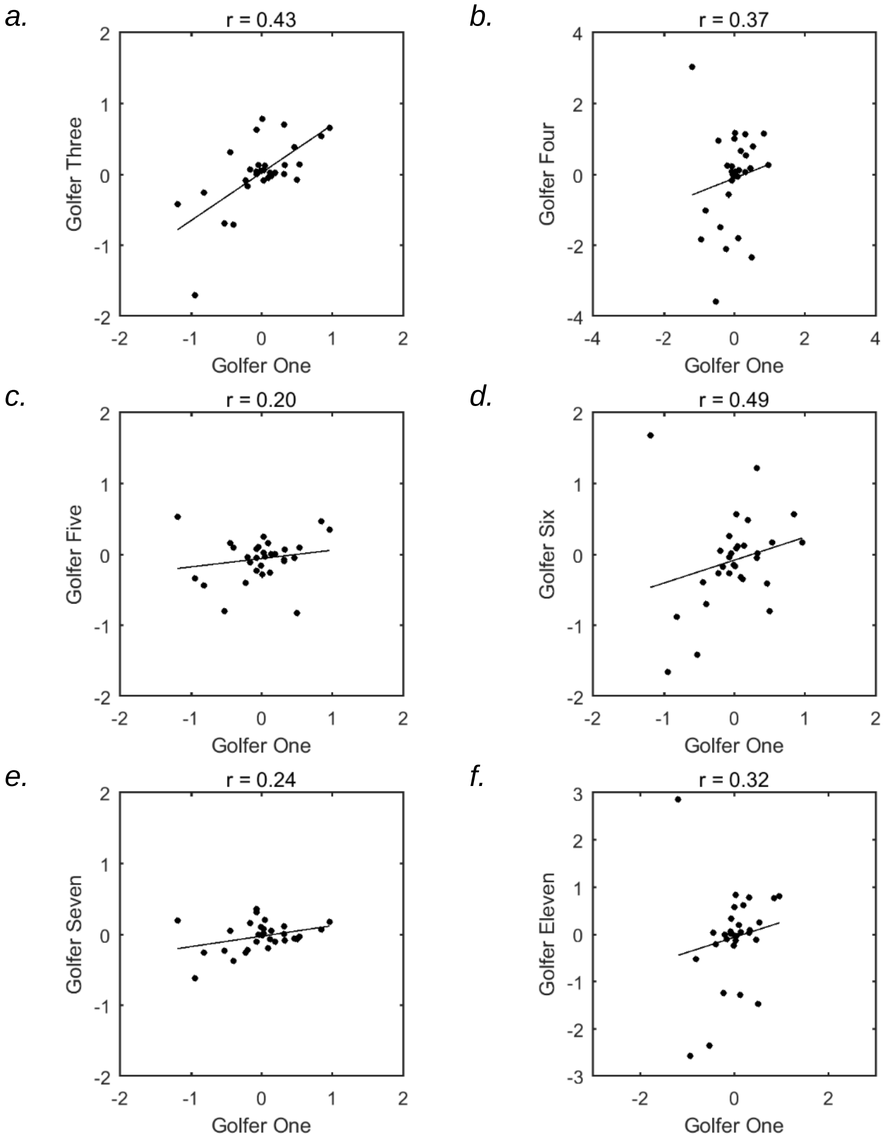


Figure H-6: Principal component score correlation plots of golfer one versus all other golfers: a. golfer three; b. golfer four; c. golfer five; d. golfer six; e. golfer seven and f. golfer eleven.

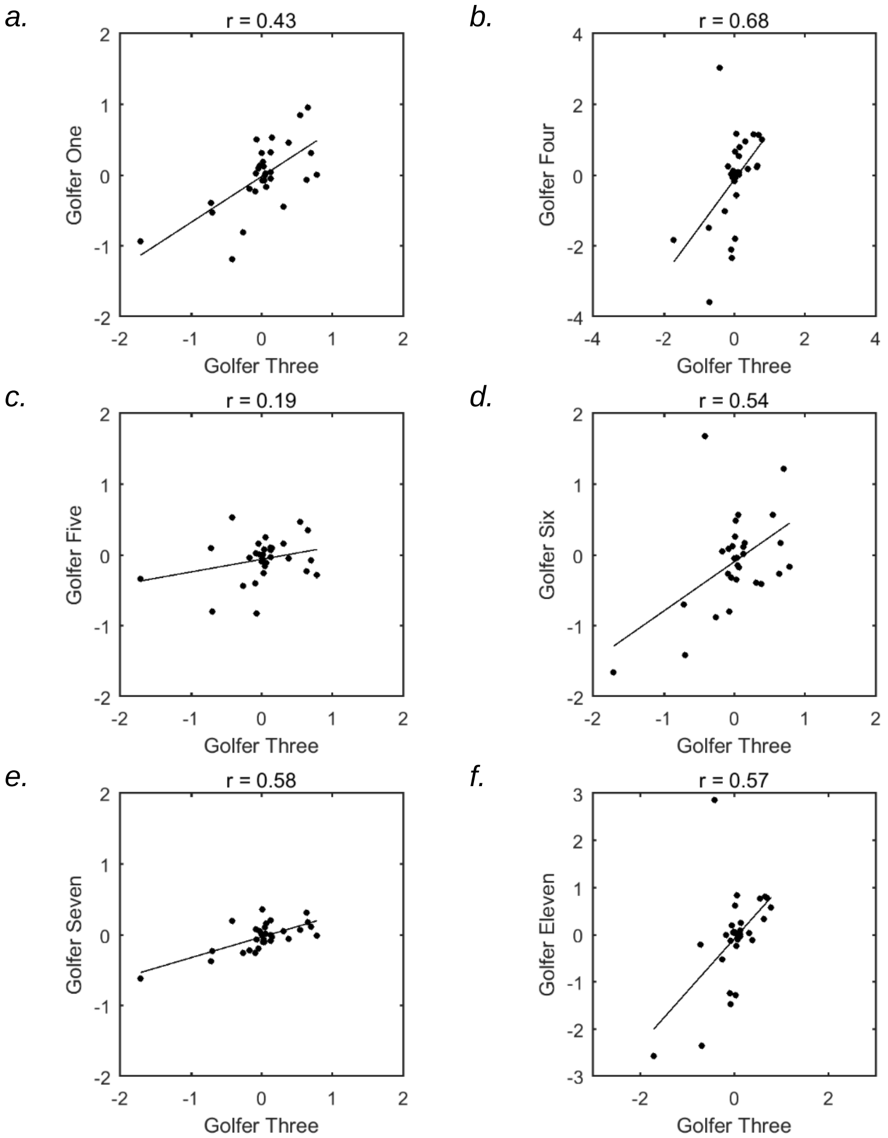


Figure H-7: Principal component score correlation plots of golfer three versus all other golfers: a. golfer one; b. golfer four; c. golfer five; d. golfer six; e. golfer seven and f. golfer eleven.

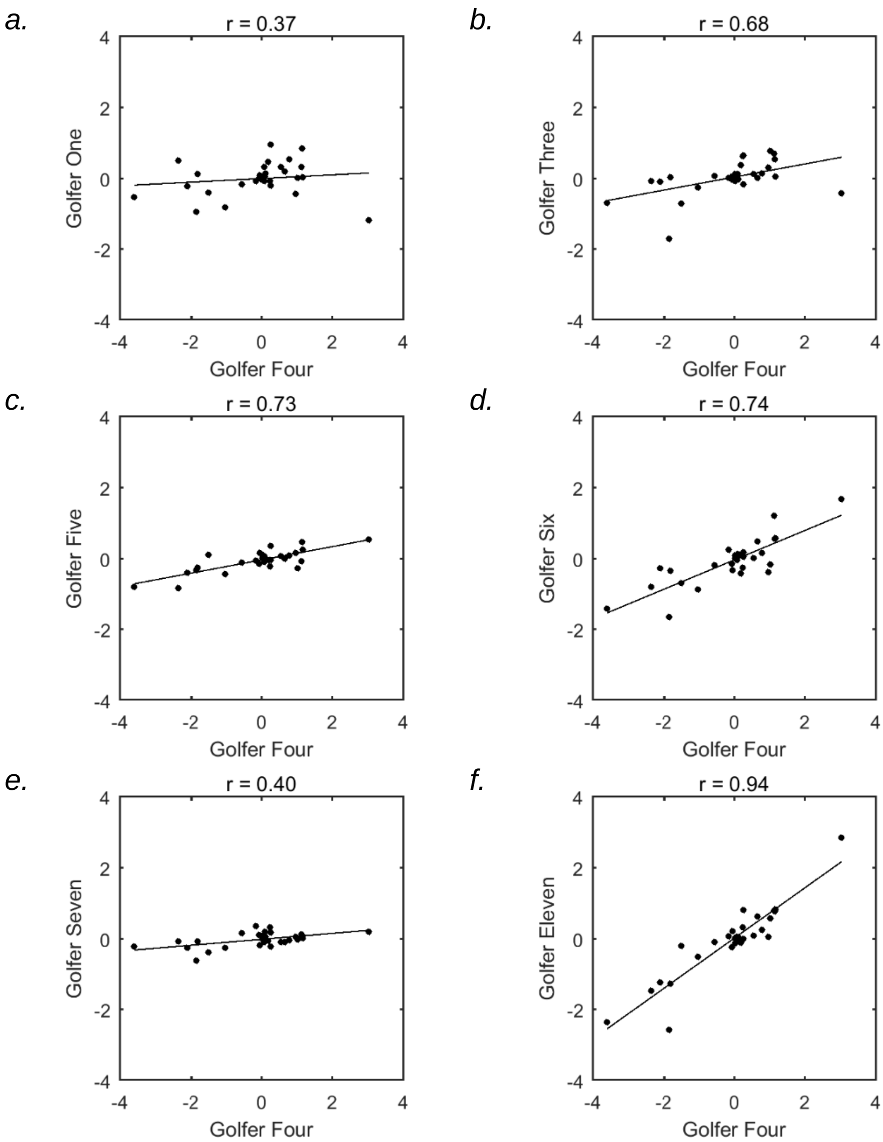


Figure H-8: Principal component score correlation plots of golfer four versus all other golfers: a. golfer one; b. golfer three; c. golfer five; d. golfer six; e. golfer seven and f. golfer eleven.

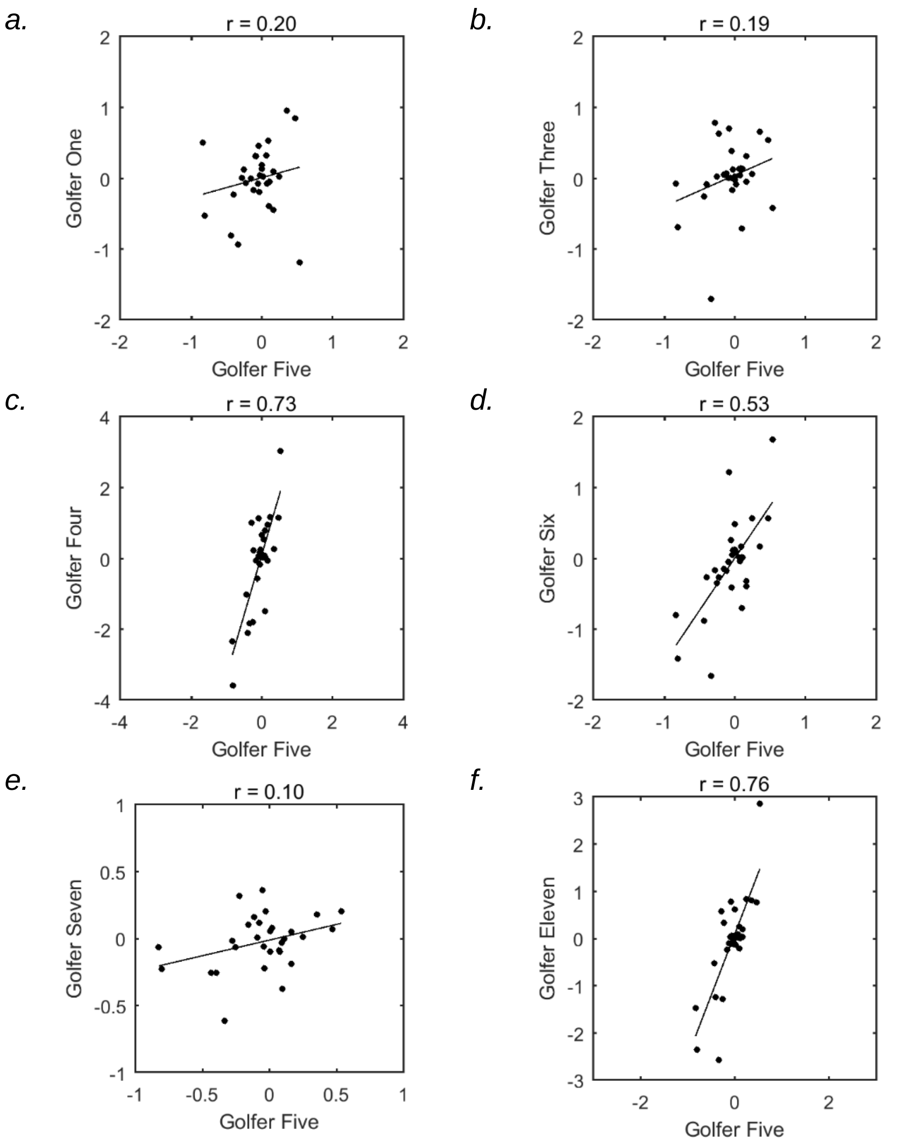


Figure H-9: Principal component score correlation plots of golfer five versus all other golfers: a. golfer one; b. golfer three; c. golfer four; d. golfer six; e. golfer seven and f. golfer eleven.

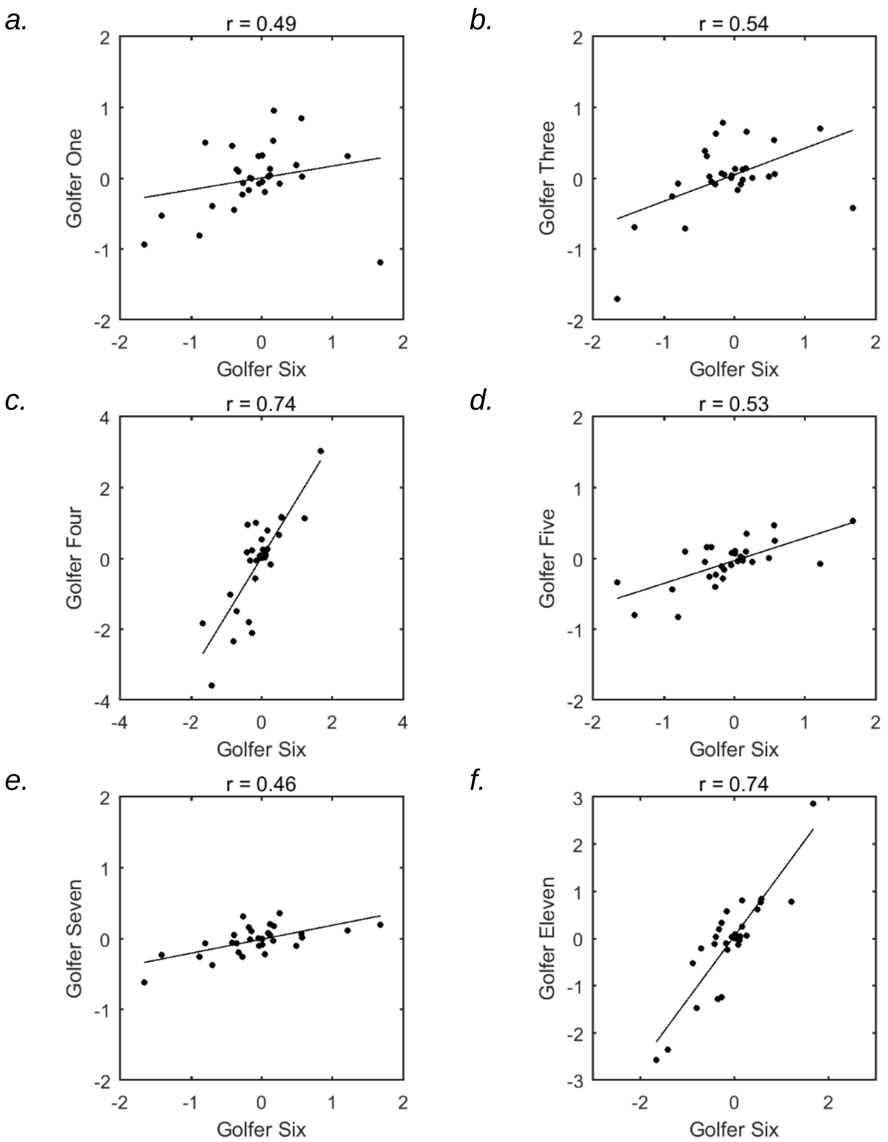


Figure H-10: Principal component score correlation plots of golfer six versus all other golfers: a. golfer one; b. golfer three; c. golfer four; d. golfer five; e. golfer seven and f. golfer eleven.

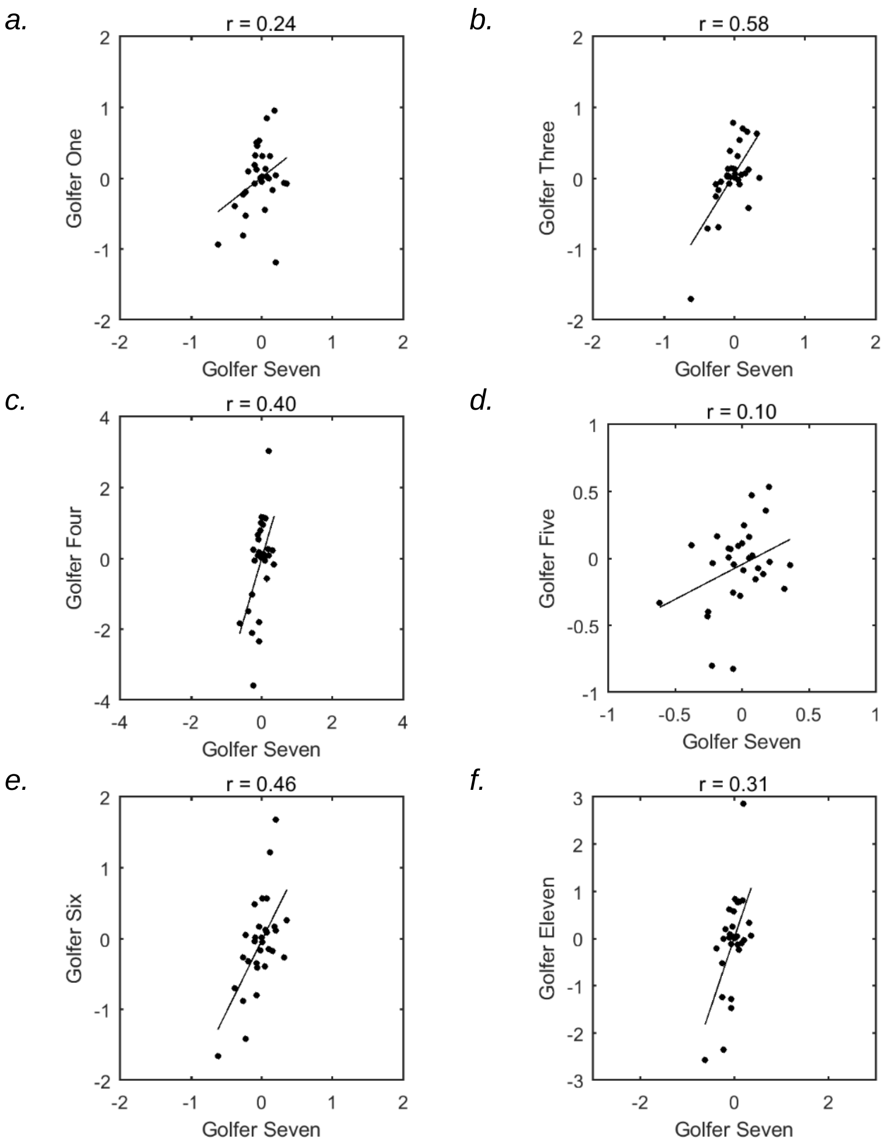


Figure H-11: Principal component score correlation plots of golfer seven versus all other golfers: a. golfer one; b. golfer three; c. golfer four; d. golfer five; e. golfer six and f. golfer eleven.

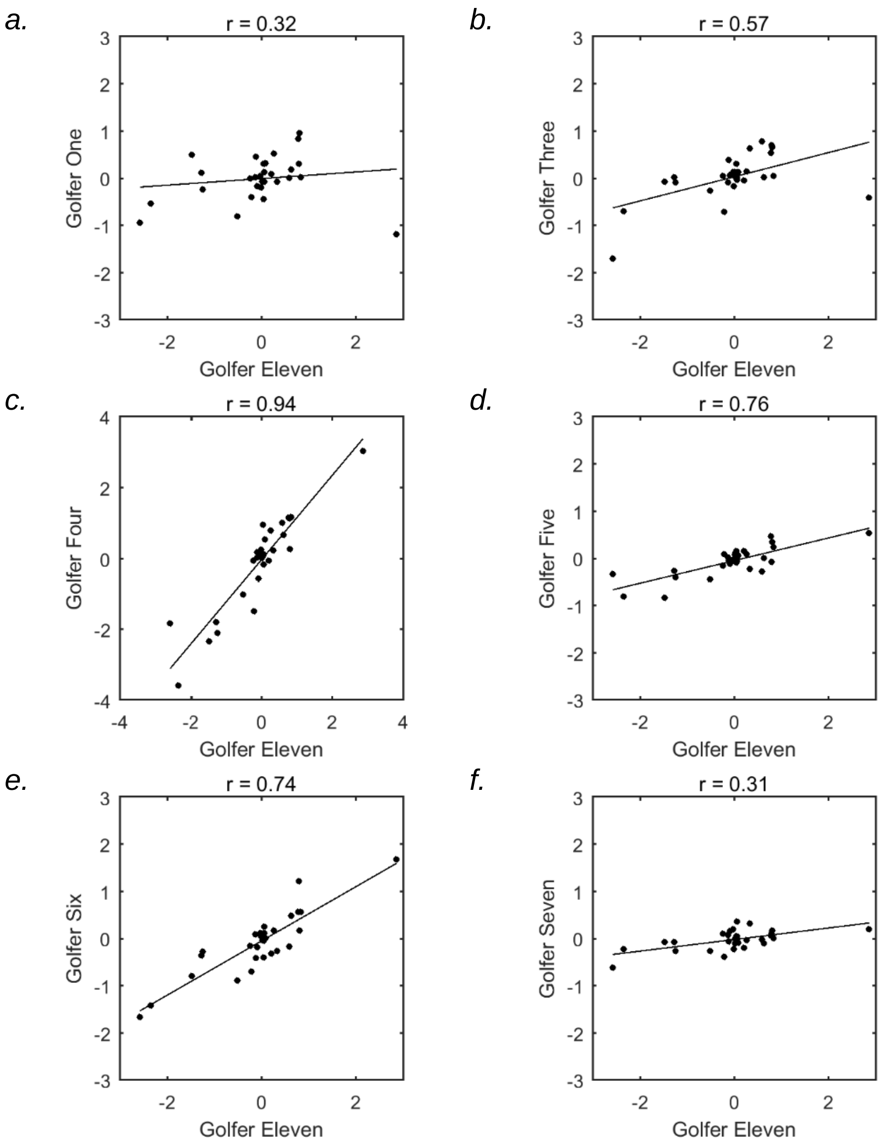


Figure H-12: Principal component score correlation plots of golfer eleven versus all other golfers: a. golfer one; b. golfer three; c. golfer four; d. golfer five; e. golfer six and f. golfer seven.

APPENDIX I

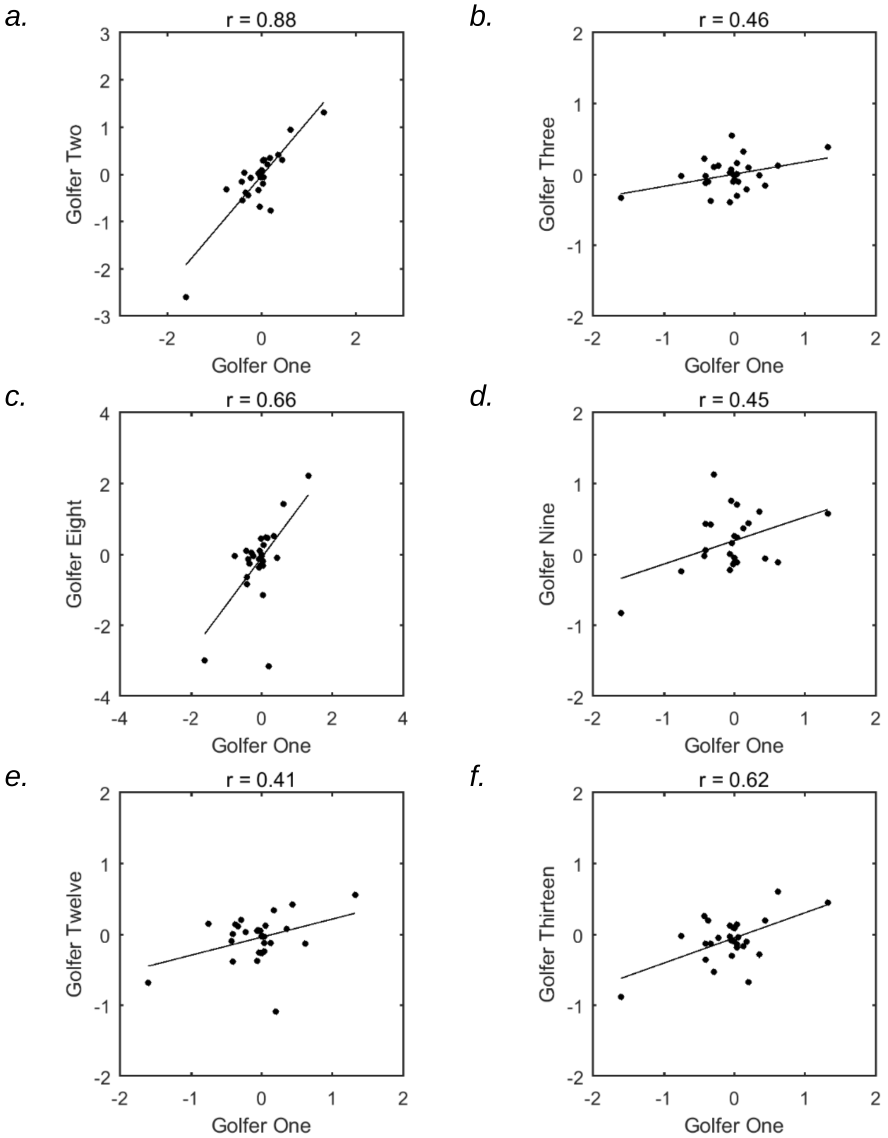


Figure I-1: Principal component score correlation plots of golfer one versus all other golfers: a. golfer two; b. golfer three; c. golfer eight; d. golfer nine; e. golfer twelve and f. golfer thirteen.

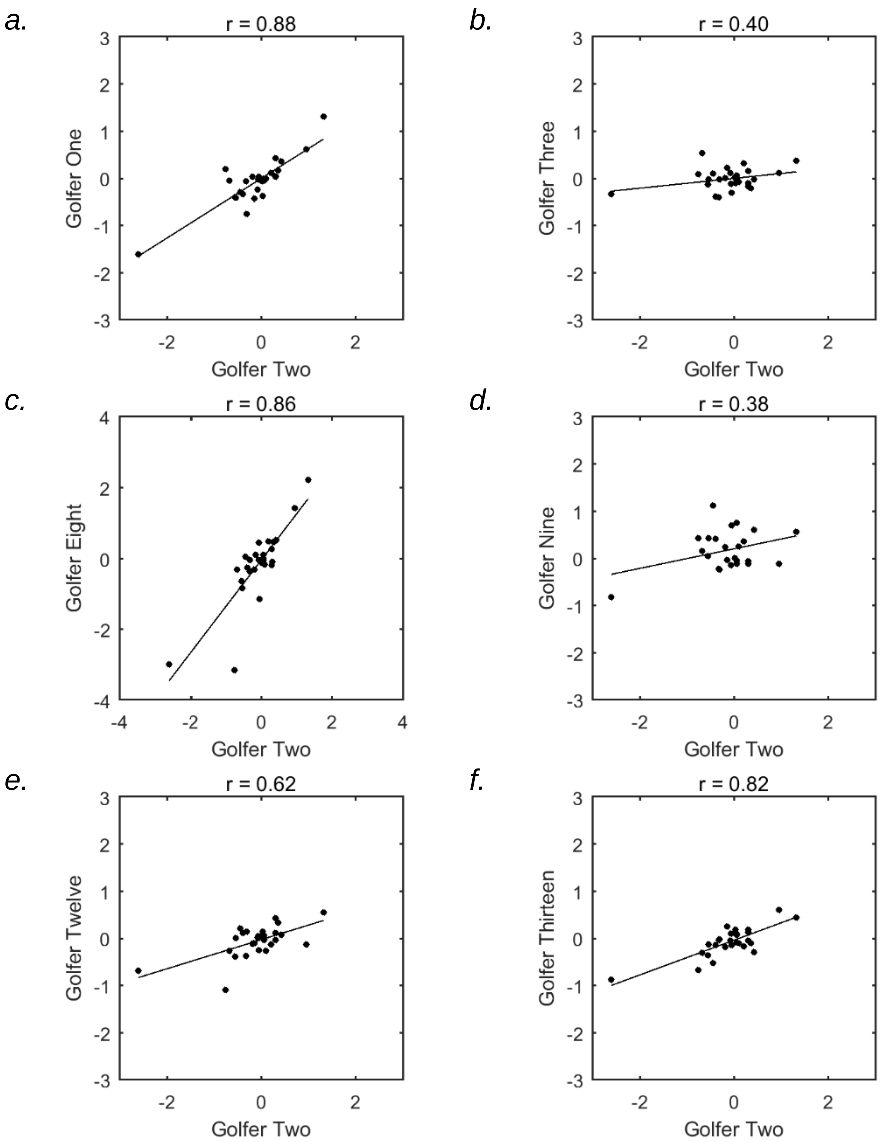


Figure I-2: Principal component score correlation plots of golfer two versus all other golfers: a. golfer one; b. golfer three; c. golfer eight; d. golfer nine; e. golfer twelve and f. golfer thirteen.

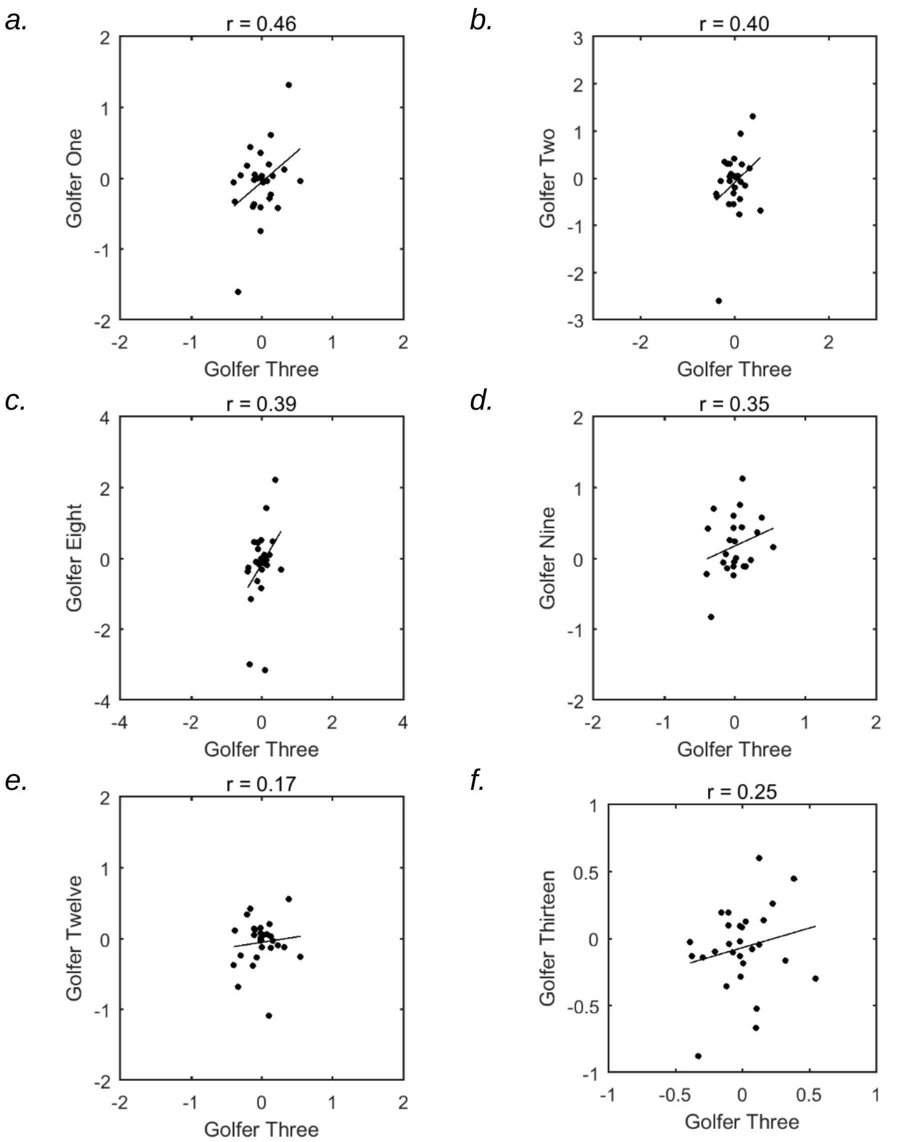


Figure I-3: Principal component score correlation plots of golfer three versus all other golfers: a. golfer one; b. golfer two; c. golfer eight; d. golfer nine; e. golfer twelve and f. golfer thirteen.

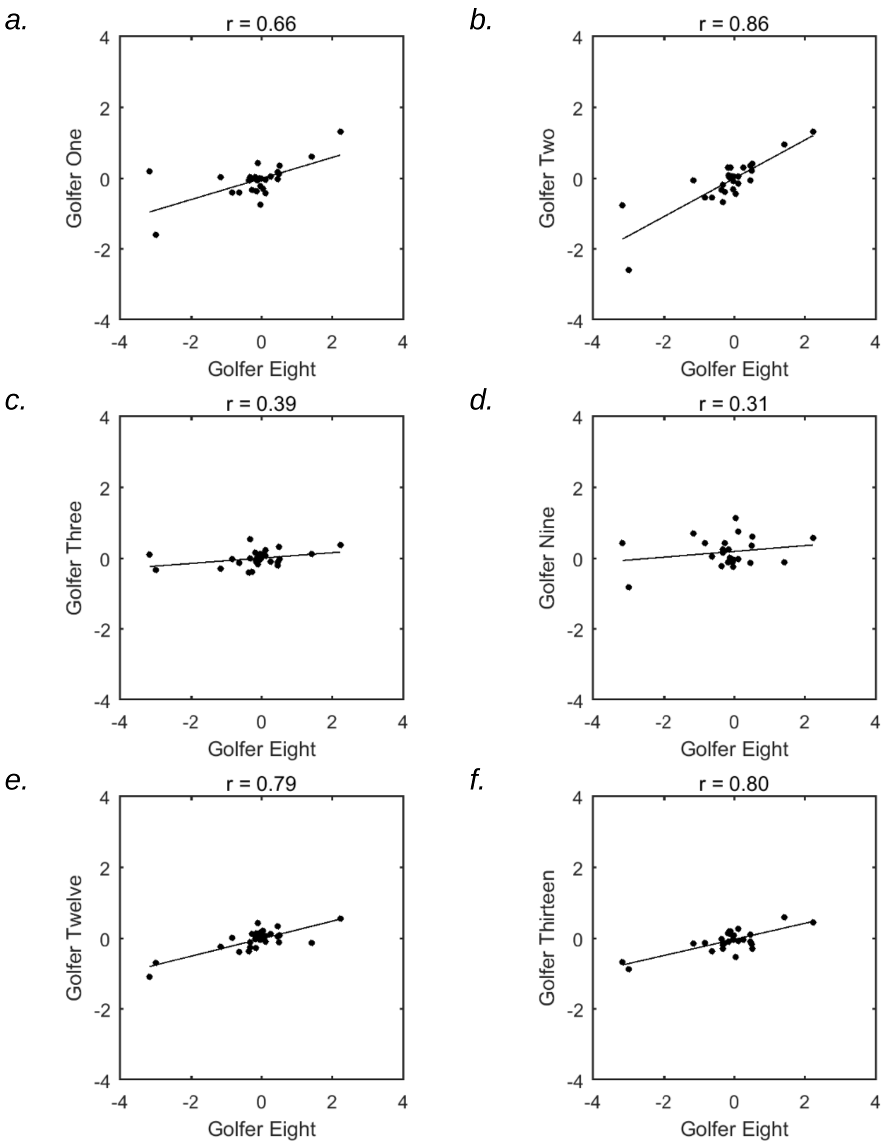


Figure I-4: Principal component score correlation plots of golfer eight versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer nine; e. golfer twelve and f. golfer thirteen.

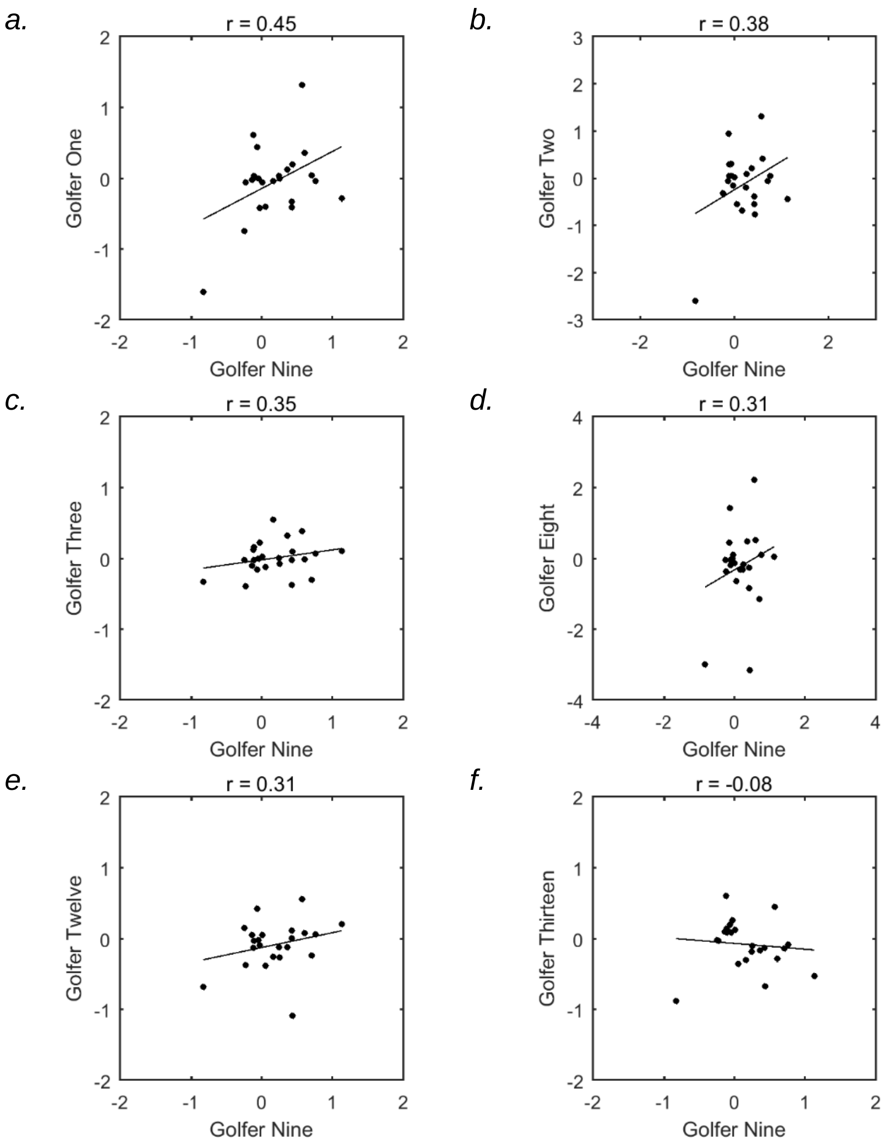


Figure I-5: Principal component score correlation plots of golfer nine versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer eight; e. golfer twelve and f. golfer thirteen.

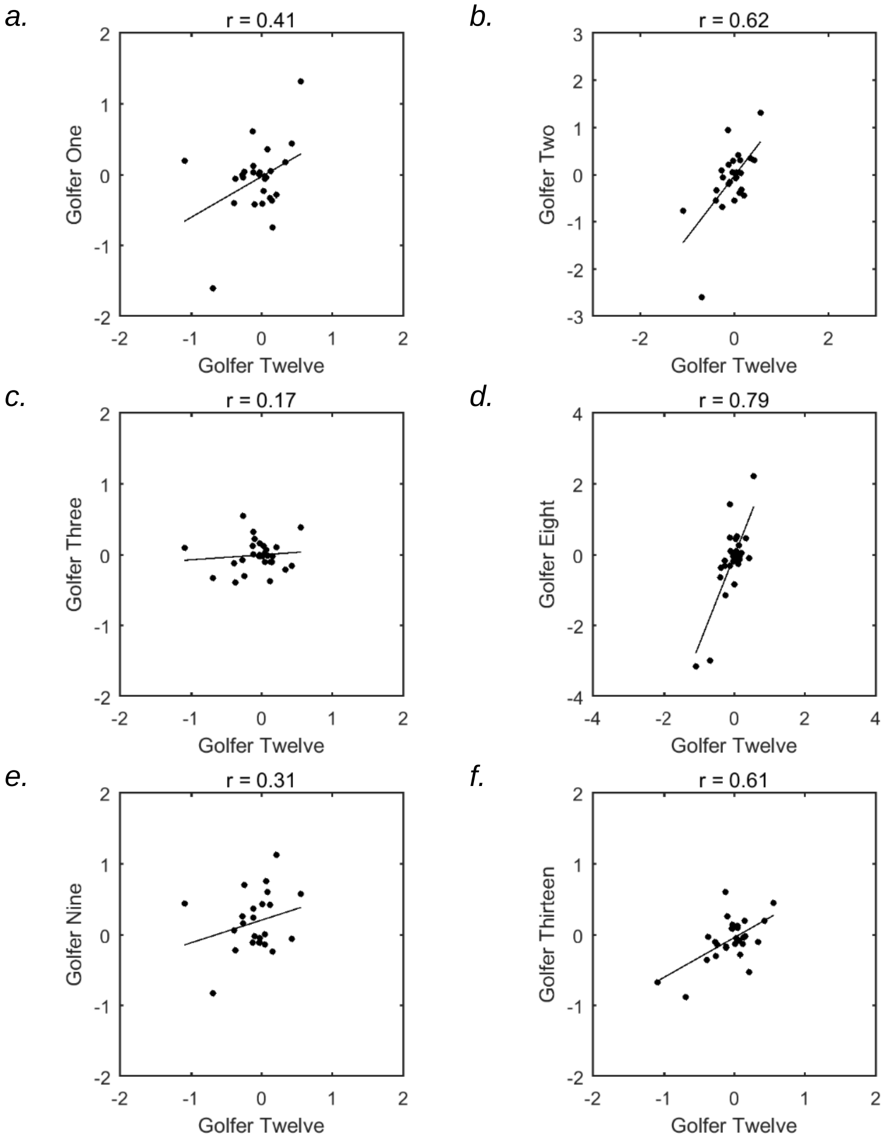


Figure I-6: Principal component score correlation plots of golfer twelve versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer eight; e. golfer nine and f. golfer thirteen.

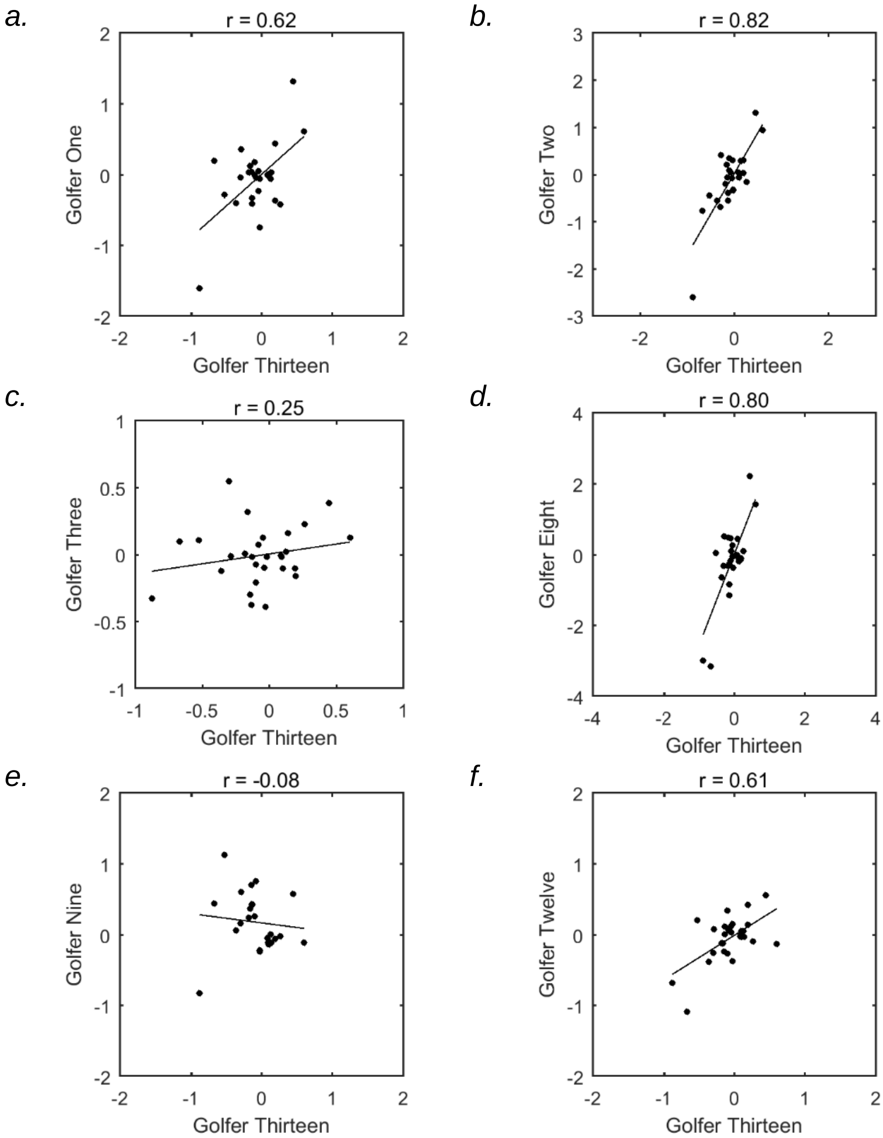


Figure I-7: Principal component score correlation plots of golfer thirteen versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer eight; e. golfer nine and f. golfer twelve.

APPENDIX J

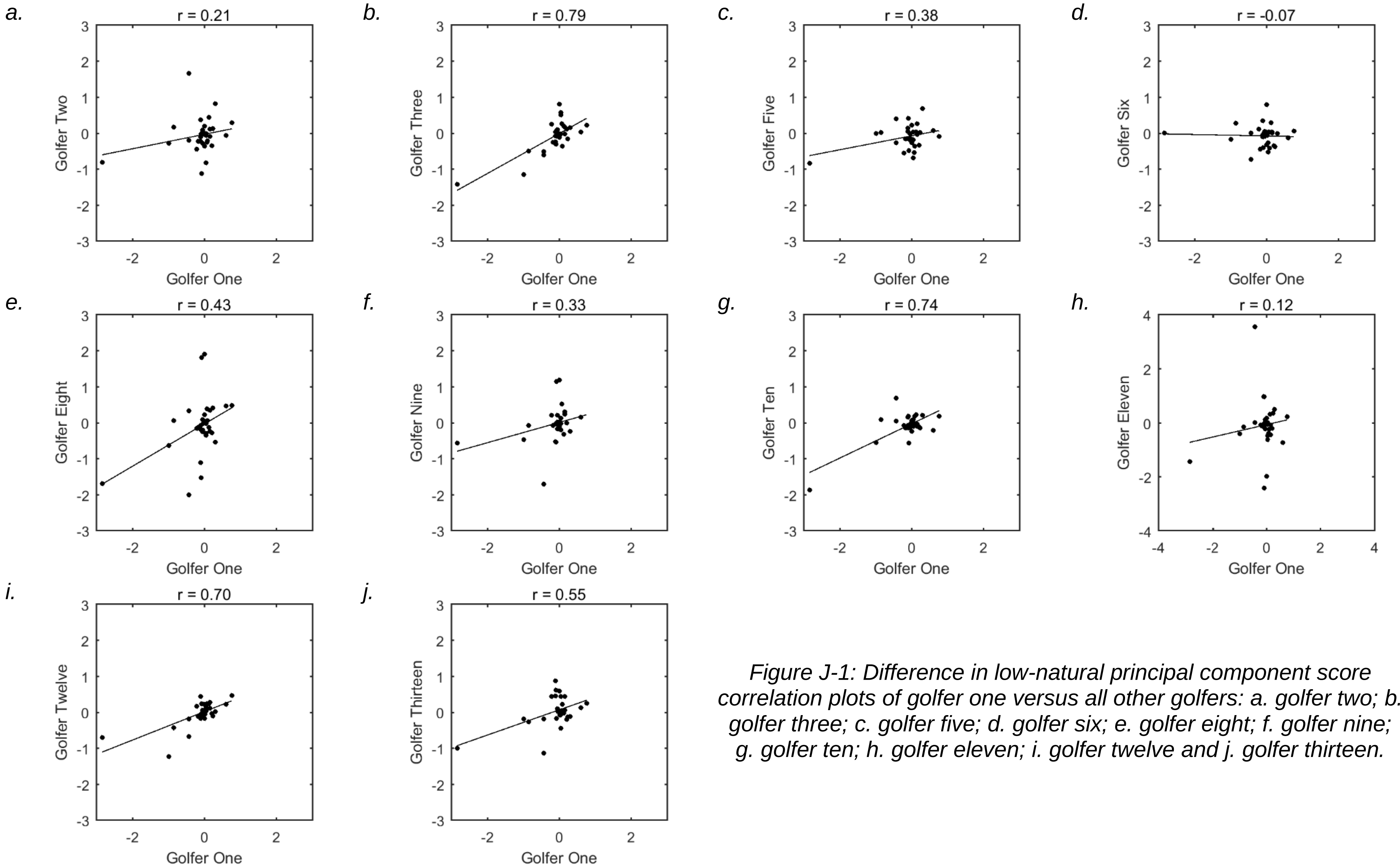


Figure J-1: Difference in low-natural principal component score correlation plots of golfer one versus all other golfers: a. golfer two; b. golfer three; c. golfer five; d. golfer six; e. golfer eight; f. golfer nine; g. golfer ten; h. golfer eleven; i. golfer twelve and j. golfer thirteen.

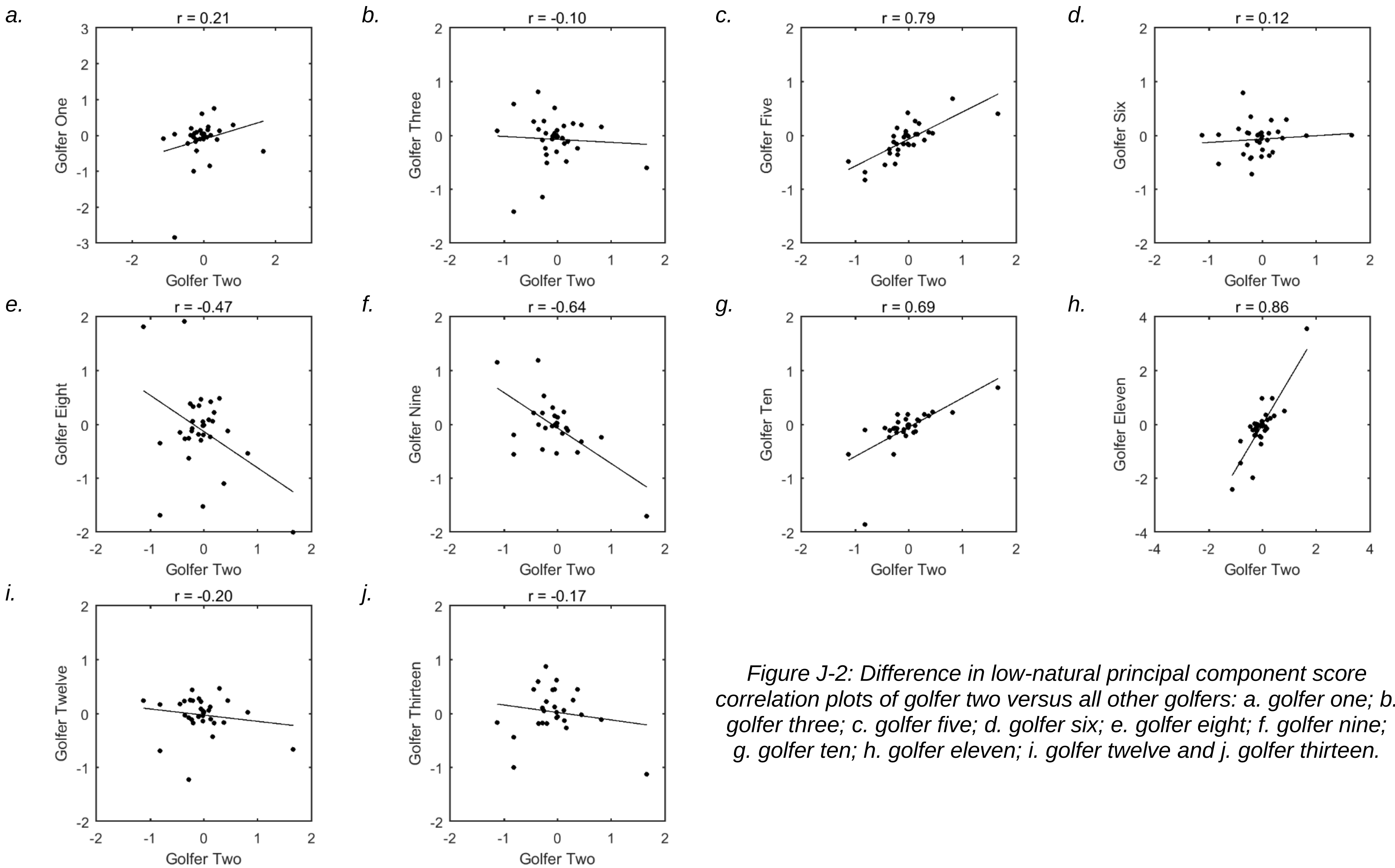


Figure J-2: Difference in low-natural principal component score correlation plots of golfer two versus all other golfers: a. golfer one; b. golfer three; c. golfer five; d. golfer six; e. golfer eight; f. golfer nine; g. golfer ten; h. golfer eleven; i. golfer twelve and j. golfer thirteen.

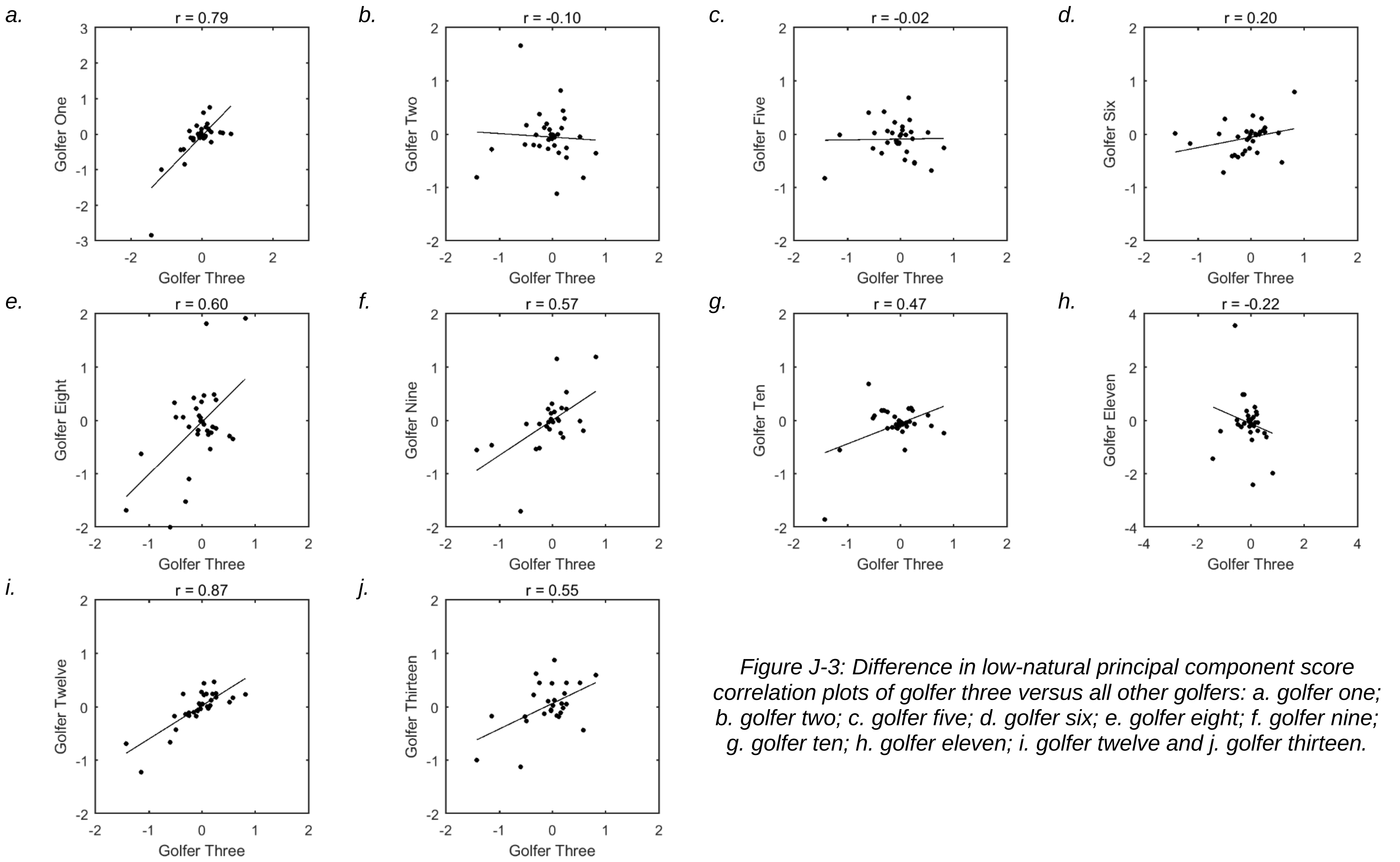
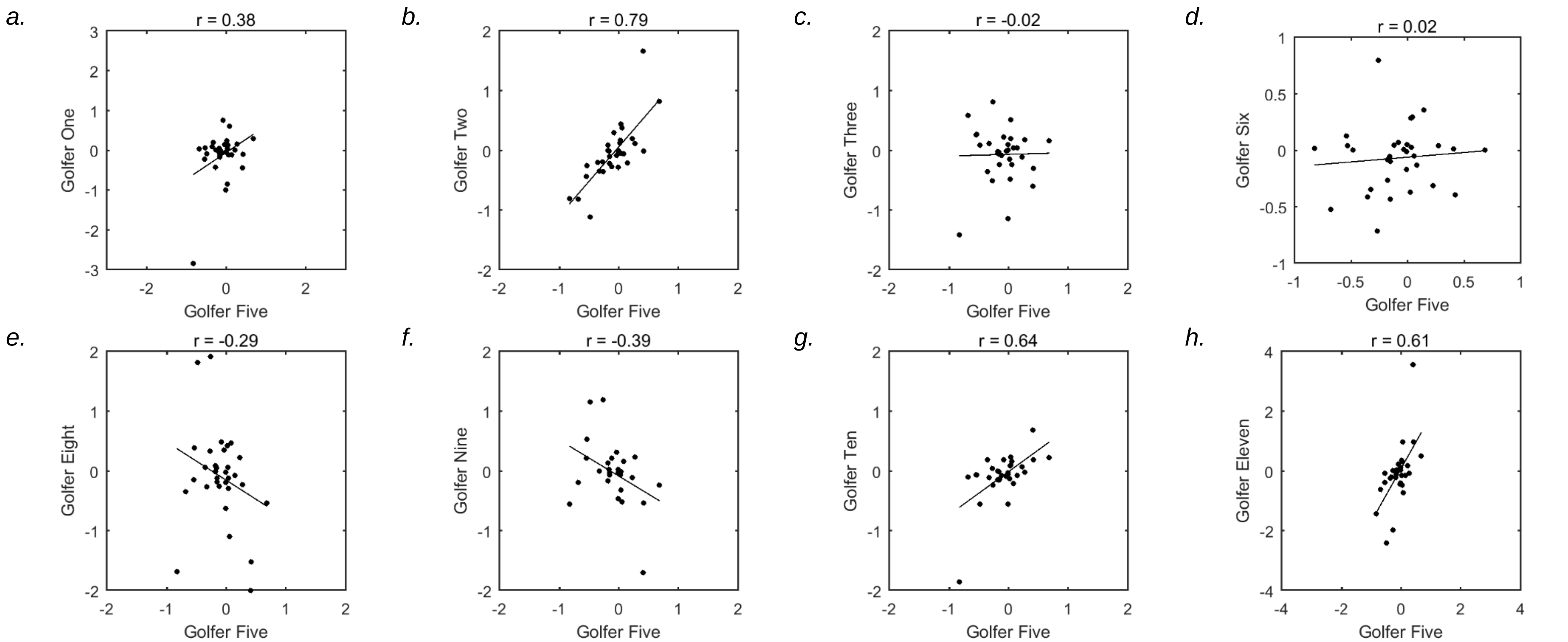


Figure J-3: Difference in low-natural principal component score correlation plots of golfer three versus all other golfers: a. golfer one; b. golfer two; c. golfer five; d. golfer six; e. golfer eight; f. golfer nine; g. golfer ten; h. golfer eleven; i. golfer twelve and j. golfer thirteen.



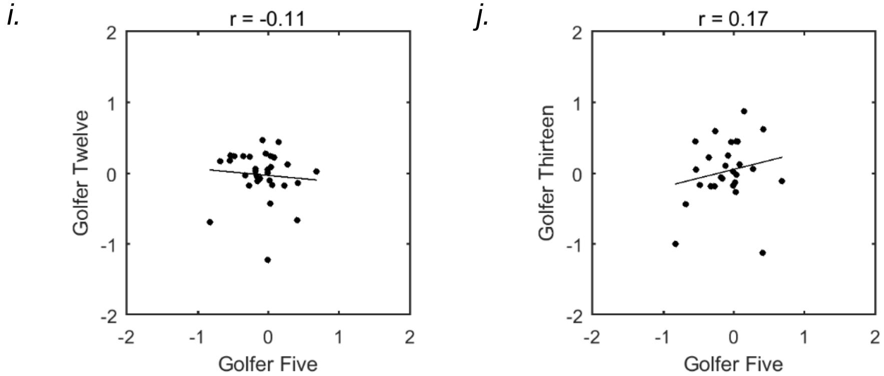


Figure J-4: Difference in low-natural principal component score correlation plots of golfer five versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer six; e. golfer eight; f. golfer nine; g. golfer ten; h. golfer eleven; i. golfer twelve and j. golfer thirteen.

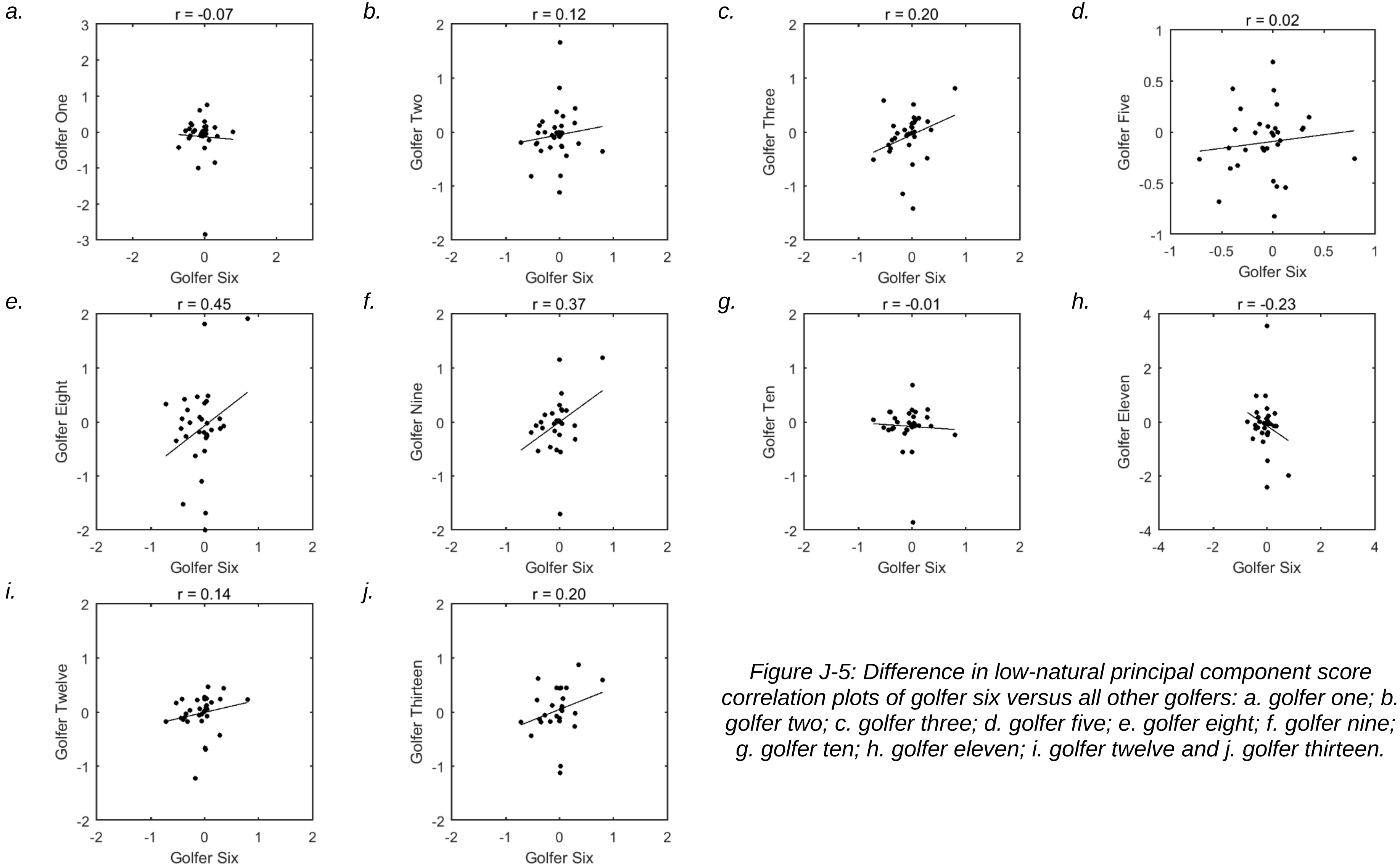


Figure J-5: Difference in low-natural principal component score correlation plots of golfer six versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer five; e. golfer eight; f. golfer nine; g. golfer ten; h. golfer eleven; i. golfer twelve and j. golfer thirteen.

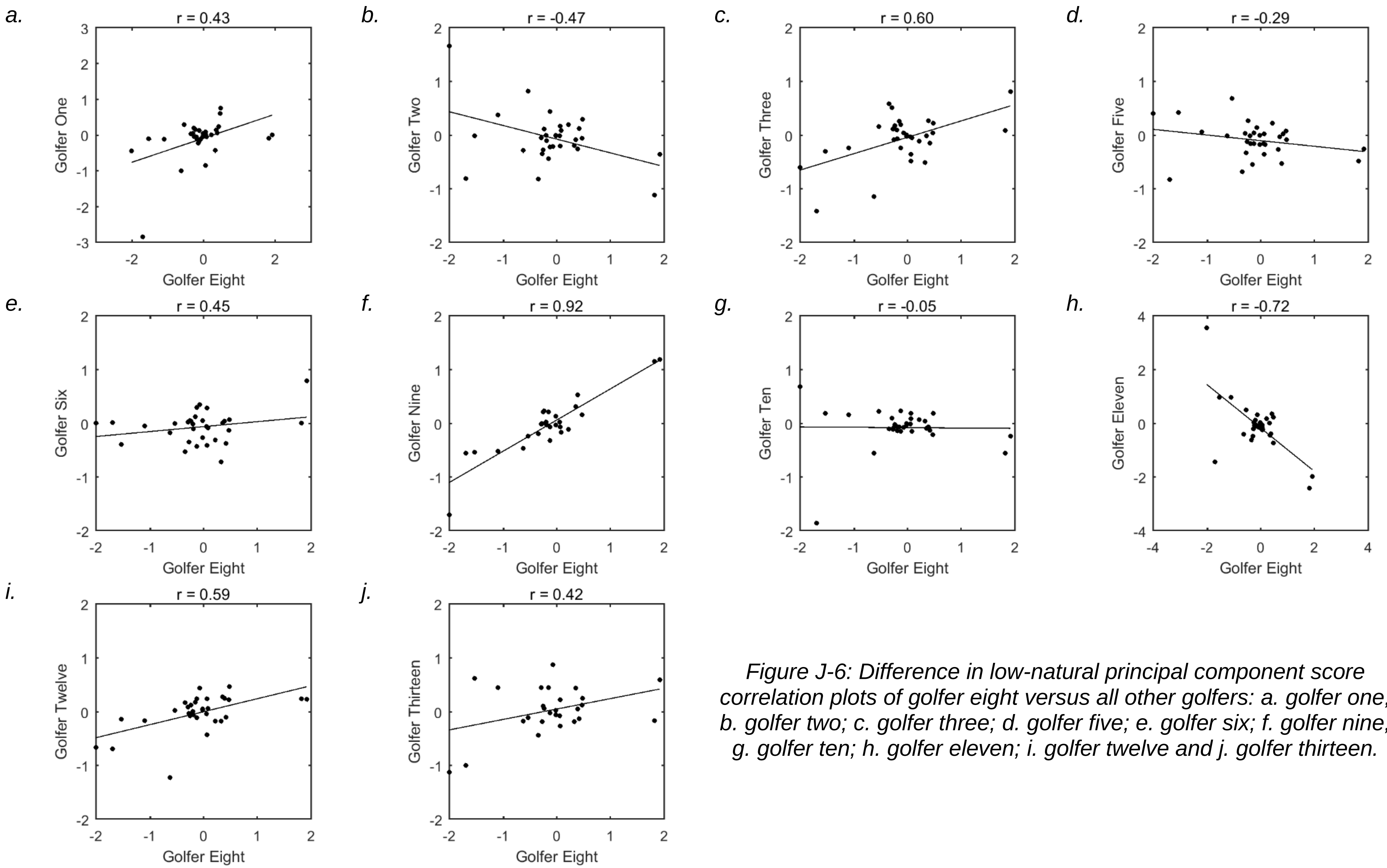
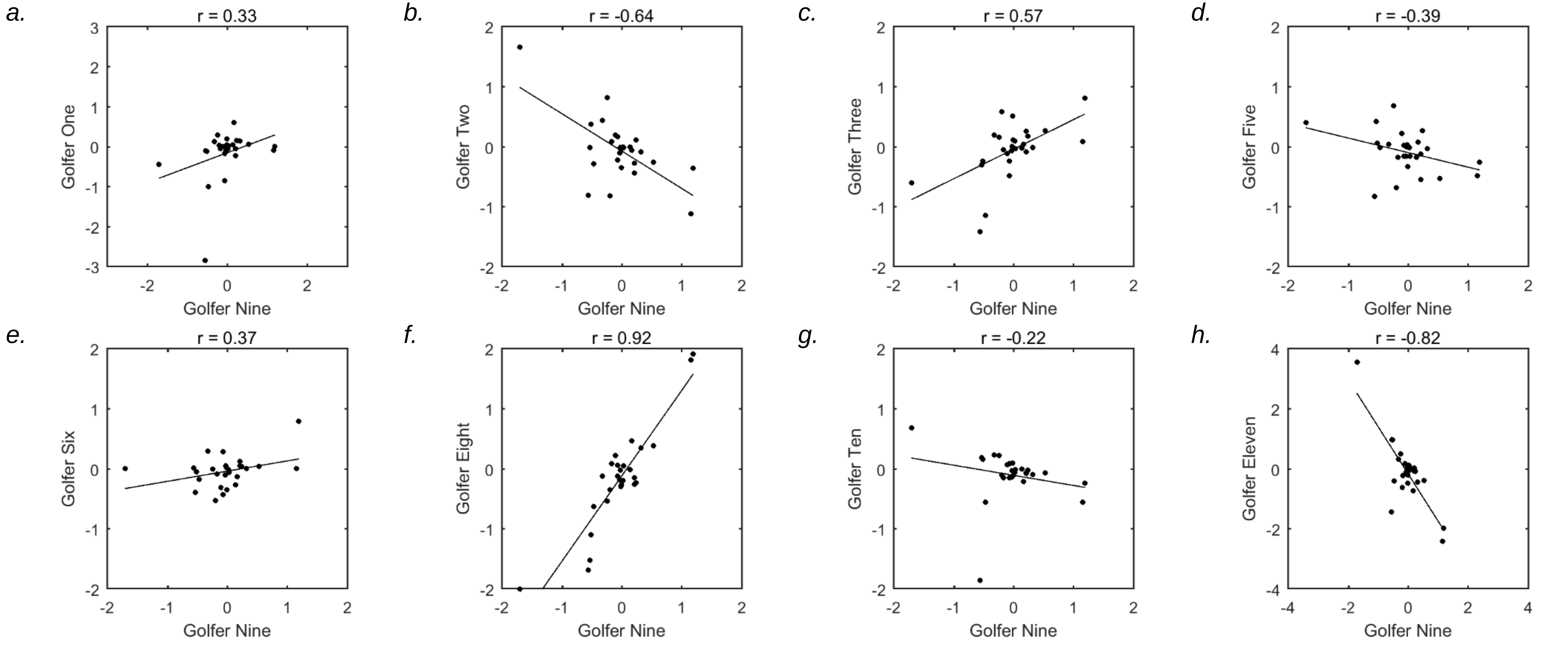


Figure J-6: Difference in low-natural principal component score correlation plots of golfer eight versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer five; e. golfer six; f. golfer nine; g. golfer ten; h. golfer eleven; i. golfer twelve and j. golfer thirteen.



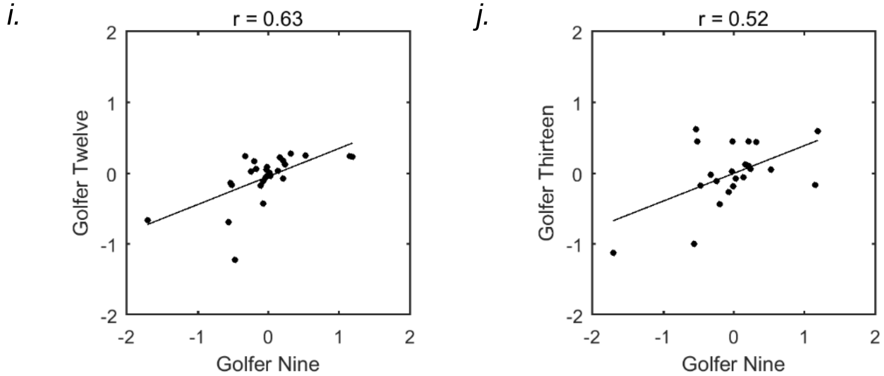


Figure J-7: Difference in low-natural principal component score correlation plots of golfer nine versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer five; e. golfer six; f. golfer eight; g. golfer ten; h. golfer eleven; i. golfer twelve and j. golfer thirteen.

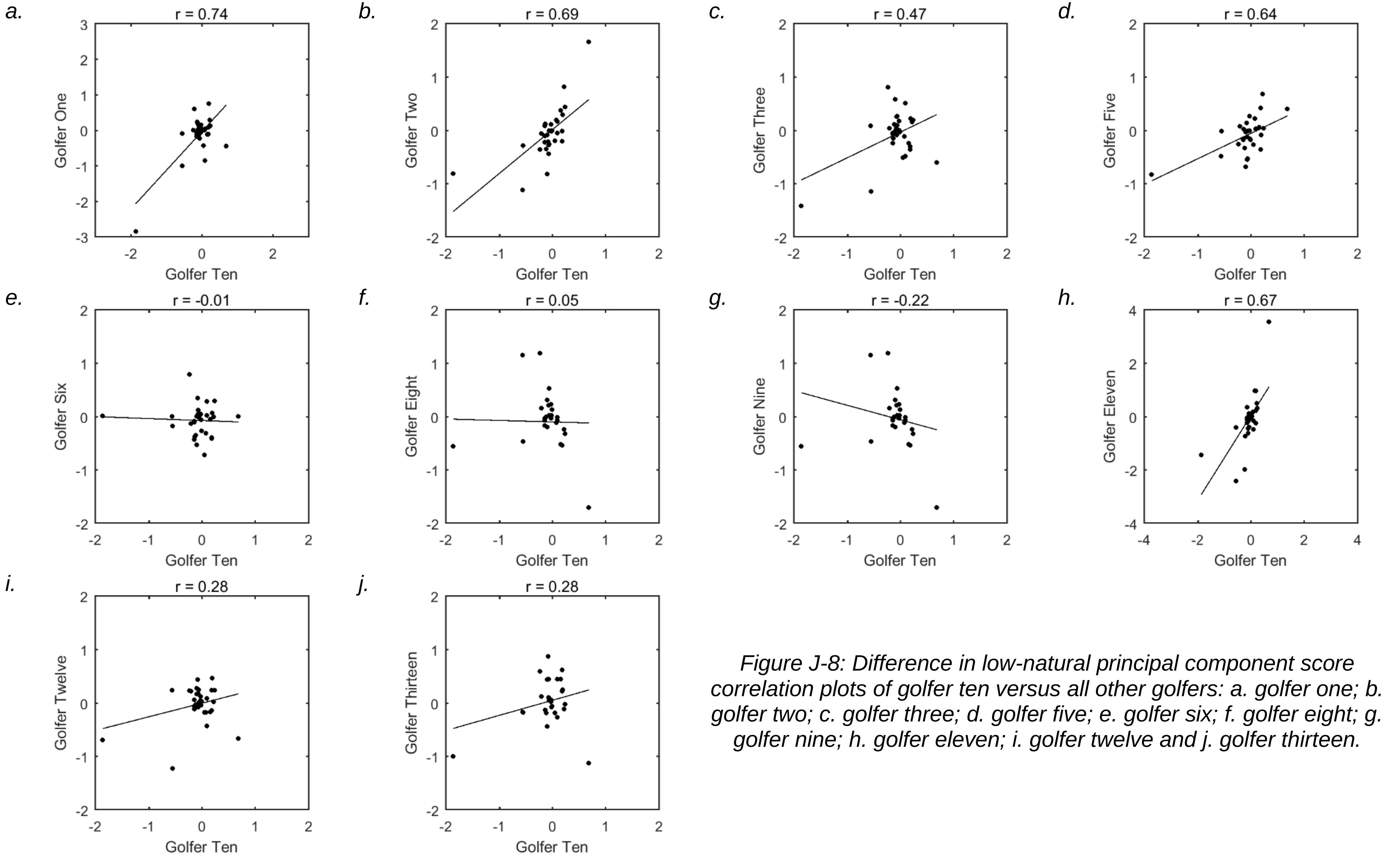


Figure J-8: Difference in low-natural principal component score correlation plots of golfer ten versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer five; e. golfer six; f. golfer eight; g. golfer nine; h. golfer eleven; i. golfer twelve and j. golfer thirteen.

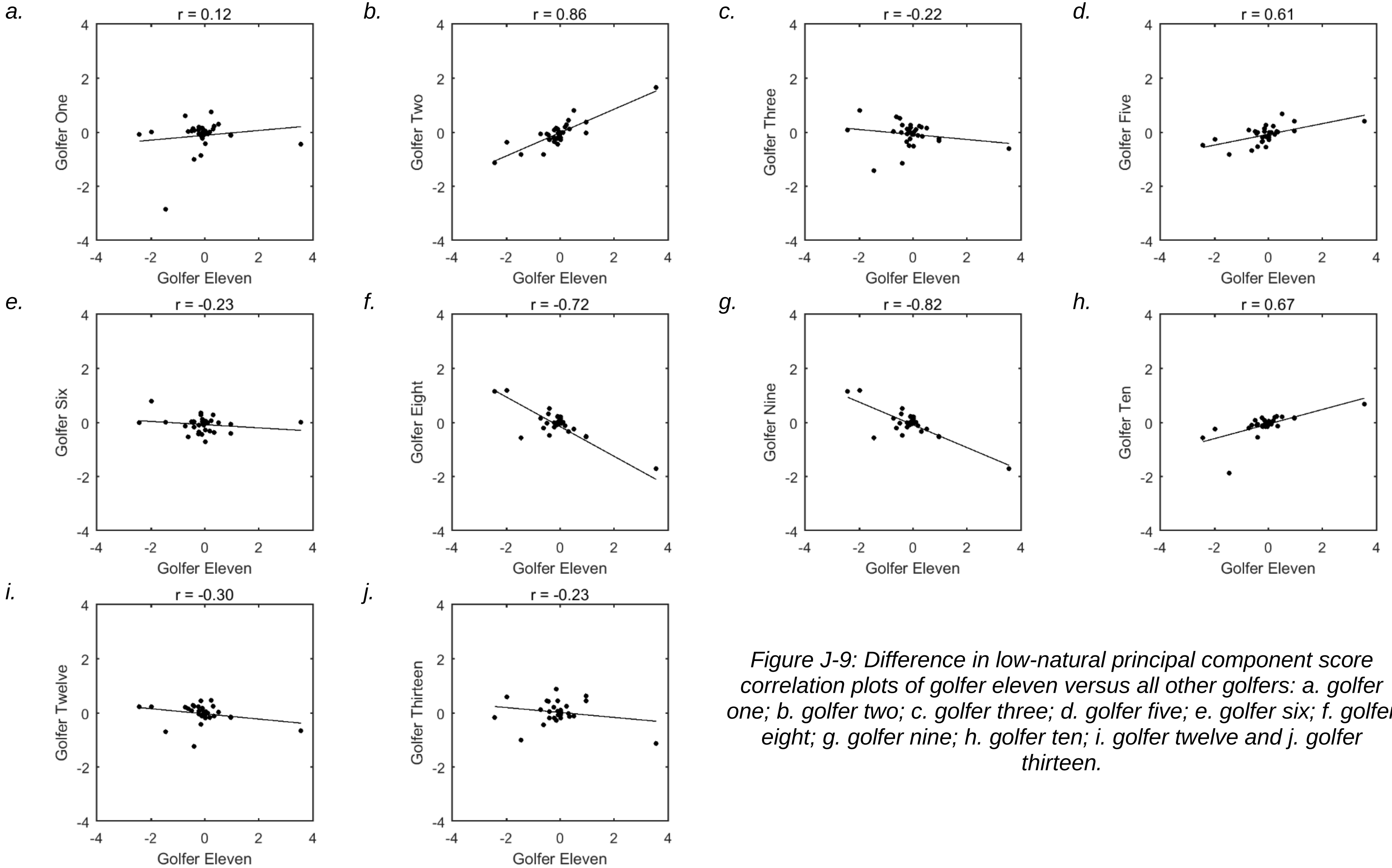


Figure J-9: Difference in low-natural principal component score correlation plots of golfer eleven versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer five; e. golfer six; f. golfer eight; g. golfer nine; h. golfer ten; i. golfer twelve and j. golfer thirteen.

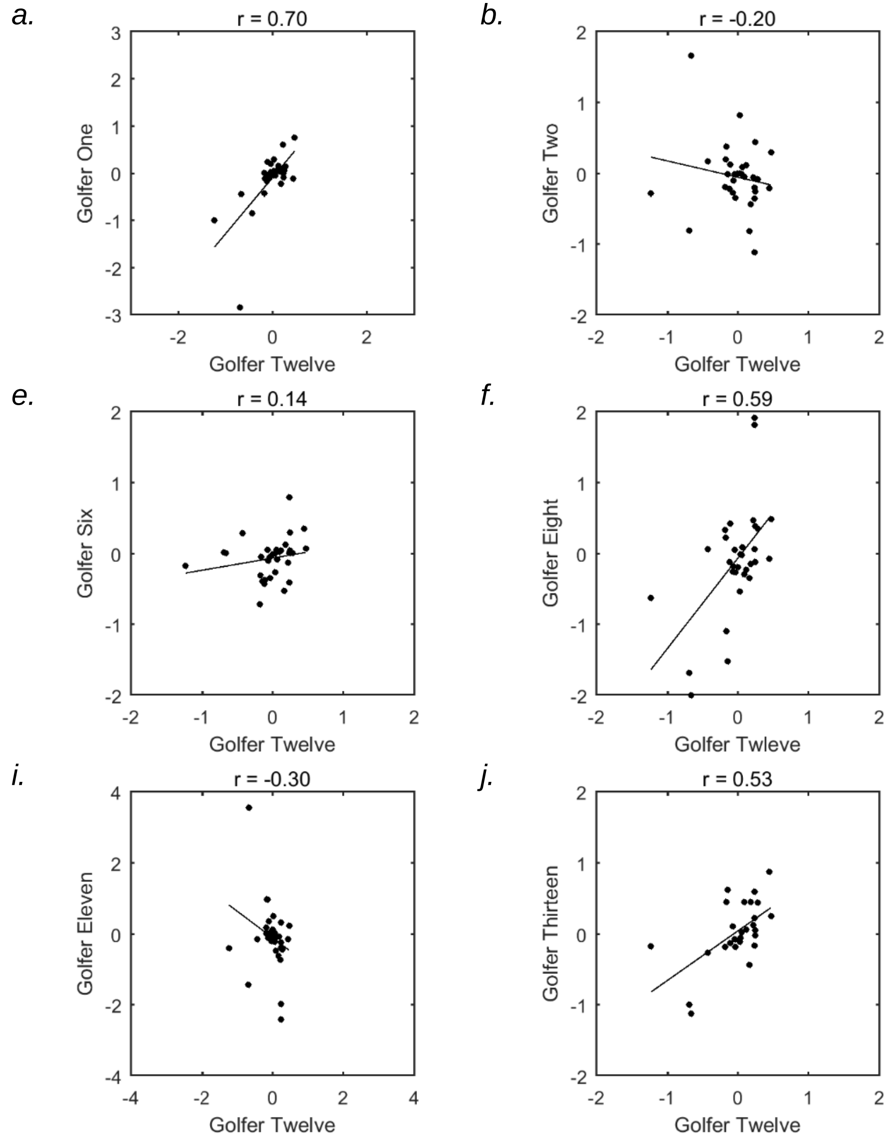


Figure J-10: Difference in low-natural principal component score correlation plots of golfer twelve versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer five; e. golfer six; f. golfer eight; g. golfer nine; h. golfer ten; i. golfer eleven and j. golfer thirteen.

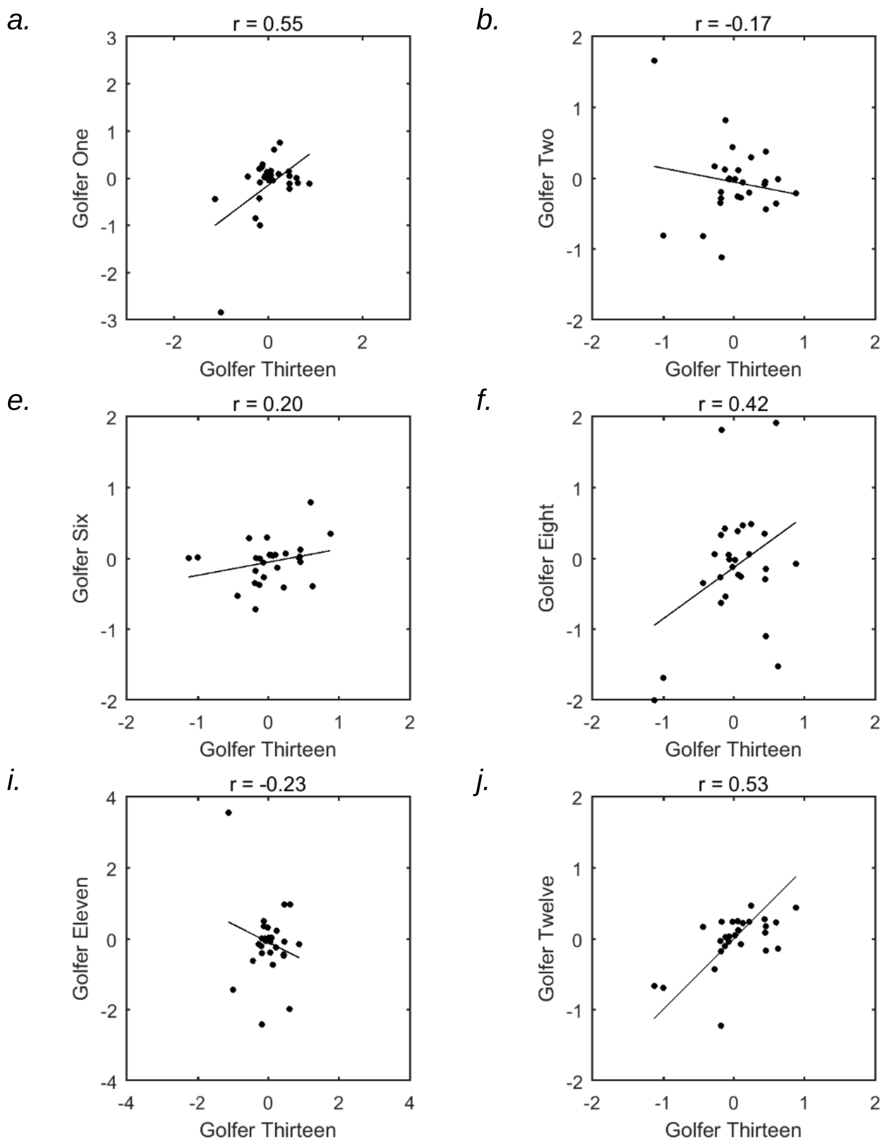


Figure J-11: Difference in low-natural principal component score correlation plots of golfer thirteen versus all other golfers: a. golfer one; b. golfer two; c. golfer three; d. golfer five; e. golfer six; f. golfer eight; g. golfer nine; h. golfer ten; i. golfer eleven and j. golfer twelve.