A Comparison of Swing Kinematics in Male and Female Skilled Golfers

Sean A. Horan
BExSc MPhty

Griffith University
School of Physiotherapy and Exercise Science
Griffith Health
Griffith University

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Abstract

The full golf swing involves a complex pattern of trunk movement thought to be important in generating power. The three-dimensional kinematics of the trunk, however, have not been fully described. In particular, it is unknown whether gender differences exist in the dynamics and coordination of the thorax and the pelvis during the swings of skilled golfers. The aims of this project were to examine the movement patterns of the thorax and the pelvis during the full swing of male and female skilled golfers, as well as investigate the effects of an endurance based practice putting task on full swing kinematics.

New insights into the swing kinematics of skilled golfers

Linear displacement, angular displacement, and angular velocity magnitudes were significantly different between the thorax and pelvis segments of skilled golfers. However, despite the magnitude-based differences, profiles of three-dimensional displacement and velocity were similar amongst skilled golfers. The most notable difference between segments was the higher overall contribution of lateral tilt velocity to the motion of the thorax compared to that of the pelvis. Results from this project also revealed that skilled golfers were able to perform the motion of the golf swing with low levels of movement variability. Over repeated swings, variability of thorax and pelvis motion was low. Hand and club motion variability was also low, particularly at the point of ball contact. Lower levels of movement variability at ball contact compared to the preceding phases of the swing suggest that kinematic variability is influenced more by the accuracy demands in the final phases, rather than the initial phases where generating power is more of a priority.
New insights into gender differences in golf swing kinematics

While the general pattern of thorax and pelvis motion appeared similar for male and female skilled golfers, gender-related differences were revealed for the sagittal and frontal planes of motion. Females adopted a posture at ball contact where they exhibited less lateral tilt and anterior tilt of their thorax and pelvis compared to males, and were also in a position where their upper body was more rotated toward the target. In addition to differences in body position during the downswing, gender differences in the dynamics of segmental motion also emerged. Thorax and pelvis phase plane trajectories for the lateral and anterior-posterior directions were different, particularly during the latter half of the downswing. This suggests that males and females utilised different motor control strategies during the downswing, which ultimately lead to males achieving higher segment velocities at ball contact. Higher levels of thorax and pelvis variability, and lower consistency of thorax-pelvis coupling for females, further support gender-specific motor control strategies during the downswing. A particularly interesting finding was the absence of any gender differences for hand and clubhead variability. The similar levels of hand and clubhead variability in the presence of higher trunk variability indicate that the segments between the trunk and the club (i.e. the arms), may play an important regulatory role in ensuring consistent ball-club collisions. In response to an endurance based putting task, gender differences emerged in kinematics and coordination of the thorax and the pelvis. Interestingly, despite these observed differences at the level of the trunk following putting practice, both males and females were able to maintain similar clubhead velocities. The maintenance of an outcome related variable such as clubhead speed, even after prolonged putting, indicates that the role of the arms and hands may
have been altered during the swing to ensure the maintenance of high clubhead speeds.

Conclusion

While the general pattern of trunk motion was similar between genders, the results of this project demonstrated that males and females exhibited different dynamics and control of movement, particularly for frontal and sagittal plane motion of the trunk. The effect of a practice putting task on swing kinematics was gender specific, further supporting the notion that males and females exhibit differences in swing mechanics. The results also suggested a potentially important role of the upper limbs in the outcome of a shot, particularly in the latter part of the downswing.
Acknowledgements

There were many times throughout my PhD journey when I thought I would never arrive at this point. Now that I am here, and I reflect upon the past few years, I am certain I would have never of made it without the assistance and encouragement of a ‘select’ few.

Without doubt, it has been my three supervisors who have given me the greatest support along the way. To my principal supervisor, Dr Justin Kavanagh, you have by far and away exceeded my expectations of what a supervisor might offer their doctoral student in terms of assistance and guidance. Your door was always open and while you did not always give me the easy answer I was after, you did instil a sense of determination and resolve that allowed me to work through any problem. You have taught me what it takes to be a high quality researcher. Thankfully, we did not always talk shop. I enjoyed our frequent conversations on just about anything, but in particular rugby league. To my associate supervisor, Dr Kerrie Evans, I would not be the researcher and clinician I am today without your untiring support. You set an extremely high standard in all aspects of your professional work, which has inspired me to continually try to improve. While I might not have at the time, I thank you for frequently challenging me along the way which has without doubt contributed to my growth and development. To my other associate supervisor, Dr Norman Morris, thank you for convincing me to take on this project. If it wasn’t for you, I might still be searching for that passion I could never find in full-time clinical work. I particularly appreciate the advice and wisdom you offered me in those difficult times when I thought it was all too hard.
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Statement of originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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<th>Description</th>
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<tbody>
<tr>
<td>2D</td>
<td>2-Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3-Dimensional</td>
</tr>
<tr>
<td>ANCOVA</td>
<td>Analysis of covariance</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<tr>
<td>A-P</td>
<td>Anterior-posterior</td>
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<tr>
<td>ASIS</td>
<td>Anterior superior iliac spine</td>
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<tr>
<td>BC</td>
<td>Ball contact</td>
</tr>
<tr>
<td>C7</td>
<td>7th cervical vertebrae</td>
</tr>
<tr>
<td>CMD</td>
<td>Coefficient of multiple determination</td>
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<tr>
<td>CNS</td>
<td>Central nervous system</td>
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<tr>
<td>EMG</td>
<td>Electromyography</td>
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<td>EMTS</td>
<td>Electromagnetic tracking system</td>
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<td>ES</td>
<td>Effect size</td>
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<td>FPS</td>
<td>Frames per second</td>
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<td>GCS</td>
<td>Global coordinate system</td>
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<tr>
<td>HSD</td>
<td>Honestly significant difference</td>
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<td>LBP</td>
<td>Low back pain</td>
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<td>LCS</td>
<td>Local coordinate system</td>
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<td>MID</td>
<td>Mid-downswing phase</td>
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<tr>
<td>PSIS</td>
<td>Posterior superior iliac spine</td>
</tr>
<tr>
<td>R&amp;A</td>
<td>Royal &amp; Ancient Golf Club of St Andrews</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of motion</td>
</tr>
<tr>
<td>SAS</td>
<td>Statistical analysis software™</td>
</tr>
<tr>
<td>SSC</td>
<td>Stretch shorten cycle</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>SPSS</td>
<td>Statistical package for the social sciences™</td>
</tr>
<tr>
<td>T10</td>
<td>10\textsuperscript{th} thoracic vertebrae</td>
</tr>
<tr>
<td>TBS</td>
<td>Top of backswing</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>USA</td>
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Thesis organisation

Chapter 1 begins the thesis with a general introduction to the thesis, including a brief overview of the background and aims of the project.

Chapter 2 presents a review of the scientific literature regarding the swing kinematics of skilled golfers and methods used previously to examine golf swing kinematics.

Chapter 3 describes the development and refinement of the methods common to the experimental chapters in this project.

Chapter 4 presents a comprehensive 3-dimensional comparison of thorax and pelvis kinematics during the downswing of male and female skilled golfers.

Chapter 5 is an examination of discrete and continuous movement variability during the downswing of male and female skilled golfers.

Chapter 6 compares the effect of a 40 minute practice putting intervention on the swing kinematics of male and female skilled golfers.

Chapter 7 is a summary and synthesis of the experimental findings from the current project.

Appendix A contains a supporting experiment for this thesis, while Appendix B contains the warm-up routine employed in all experimental chapters.
List of publications

**Papers generated from this thesis:**


**Papers supporting this thesis:**


**Papers presented:**

Posters presented:

Chapter 1 - General introduction
1.1 Background

Golf is a popular sport enjoyed by both men and women of all ages [161]. Worldwide, an estimated 61 million individuals played golf in 2003 [181], but today this figure is approaching 100 million. This is in part due to the growth of the game in developing countries such as China and India [78]. In Australia, it is estimated that between 800,000 and 1.25 million individuals play golf every year [13, 61], which equates to participation rates of between 10% and 20% across all age groups [11, 14]. In 2005, golf was reported to be the third most popular sport or physical activity behind walking and whole body aerobic exercise for Australian men, and the eighth most popular activity for Australian women [12].

The game of golf is typically played over nine or eighteen holes and can take somewhere between two and six hours to complete [4]. During each game or round of golf, two fundamental actions are performed repeatedly: the full golf swing and the putting stroke. Both actions have a different set of physical and technical requirements, however the goal of each action is to propel the ball toward the hole. The full golf swing is a complex and technically demanding whole body movement that relatively few golfers ever truly master. Putting, on the other hand, involves considerably less body motion as the golfer maintains a relatively static posture during the task. Although some golfers may be more skilled at either the full swing or putting, being proficient at both actions is fundamental to successful performance [87]. While not exclusive to the full swing, a universal indicator of a golfer’s skill level is the golfer’s handicap, which represents a specific number of additional strokes allowed per round in order to achieve par [4]. Handicap is determined by previous
playing performances, with a lower number corresponding with a higher skill level [4]. Currently, average handicaps for Australian amateur men and women are reported to be 18 and 29 strokes respectively [14]. The fact that only 3% of males and 1% of females achieve a handicap lower than 4.5 strokes [14], further reinforces the notion that relatively few golfers achieve a high level of skill. For the purpose of this thesis a golfer with a handicap of less than four strokes will be considered a ‘skilled’ golfer.

Professional golfers are allocated a handicap of zero, however additional statistics are generally employed to describe different aspects of their performance.

The ability to produce consistent and accurate full swing shots may be influenced by a number of factors including equipment, physical proficiency and swing technique. With respect to equipment, much effort and funding has been devoted to the advancement of the golf club and golf ball. While significant improvements in performance have resulted, it is has been suggested that the game is nearing the limits that physical laws place on the performance of equipment [64]. A golfer may be more successful by focusing on improving factors such as physical skills through specific and validated, technical and physical training programs. Golf specific exercise programs have been demonstrated to have positive effects on the swings of both skilled and unskilled golfer [65, 115, 172]. But, just as in other human movement and sporting tasks, an improved understanding of the underlying physical requirements of the golf swing may help tailor individual exercise programs. To do this, analysing highly skilled performers is an essential endeavour [20, 38, 52, 95].

Despite the popularity of golf and the large financial rewards on offer for those who compete professionally, relatively few rigorous scientific investigations on the
mechanics of the golf swing exist. With a history dating back as far as 500 years, the evolution of the golf swing and golf equipment has largely revolved around trial-and-error methods rather than through the application of scientific principles. It was not until 1968 that the landmark golf swing study of Cochran and Stobbs [38] was undertaken. With funding from the Golf Society of Great Britain, these authors comprehensively investigated components of the golf swing, ball aerodynamics and equipment dynamics using high speed filming techniques. The major golf swing model to result from this investigation was that of the double pendulum model, which was the first of its kind to offer a theoretical explanation of swing kinematics. In this two lever model, the arms were represented by the upper lever, the club represented by the lower lever, and the wrists and hands between both levers were represented by a hinge. Although regarded as the foundation from which information about the modern golf swing emerged, a well recognised limitation of the double pendulum model is that it depicts the motion of the arms and club, but fails to recognise the importance of trunk and lower body motion to golf swing performance.

Over the past two decades, several studies have investigated the kinematics of the trunk and lower body during the golf swing [15, 28, 117, 118, 138, 182, 192]. While some of these studies have added to our understanding of swing mechanics, critical evaluation of the literature reveals a lack of consistency in the methodological approaches employed and consequently a lack of agreement in the descriptions of ‘optimal’ swing kinematics (See Chapter 2 - Literature Review). For example, most studies have reported axial rotation for the trunk at the top of backswing and ball contact, however these discrete variables only describe body position and do not provide insight into the control of movement. A clearer understanding of how skilled
golfers perform the golf swing can only be achieved if researchers make a concerted effort to fully describe the motion of the golf swing using current, gold-standard techniques such as 3-Dimensional (3D) motion analysis systems in conjunction with appropriate biomechanical modelling techniques. Knowing what constitutes a skilful golf swing will assist in identifying potential swing deficits, possible avenues for performance enhancement and factors that may underlie swing related injuries.

To date, research relating to the golf swing has focussed almost exclusively on the swing kinematics of male golfers with only two studies reporting the kinematics of skilled female golfers [56, 193]. Generalising the results of kinematic analyses of male golfers to females may not be appropriate, but without direct comparisons this remains unknown. The majority of known gender differences are based around golf performance outcomes, such as clubhead speed and driving distance. Data from the respective male and female professional tours in the USA, demonstrate that women achieve lower average driving distances and lower average clubhead velocities compared to men [98]. Although this in part may be explained by gender differences in strength, range of motion and anthropometrics; variations in swing kinematics may further explain these discrepancies. Interestingly, one gender comparison that has received some attention in the golf literature is that of injury frequency and injury location. In general, there has been an observable trend toward an increased incidence of lower back injuries in males, whereas, in females upper limb injuries predominate [21, 122, 123, 126, 171]. Comparing swing kinematics of male and female skilled golfers may therefore help explain the gender differences observed in injury profiles as well as in golf performance.
1.2 Statement of the problem

Despite the substantial role of the thorax and pelvis to the overall motion of the golf swing, relatively few studies have examined the 3D kinematics of both segments in detail. Consequently, the role that the trunk and more specifically the thorax and pelvis play during the full golf swing is still unclear. This issue is further compounded in that some investigations do not fully describe their methods, making interpretation of reported results difficult. Moreover, golf biomechanical studies have used a diverse range of participant skill levels, measurement techniques and outcome variables, meaning direct comparisons between studies is not always feasible.

Most investigations of the golf swing have restricted their analyses to measures of body position at the beginning or end of different phases. For instance, kinematic studies have frequently focussed on the orientation of the thorax and pelvis at the discrete time points of ball address, top of backswing (TBS), and ball contact (BC). Such analyses only provide ‘snapshots’ of information on how a segment is orientated at a single moment in time. From a motor control perspective, information about the interactions of individual body segments during the swing and in particular throughout the downswing will provide greater insight than orientation data alone.

Very little is known about gender differences in swing kinematics. Therefore, the primary focus of this project was to examine the swing kinematics of both males and females. Using discrete analyses in conjunction with continuous analyses from the motor control field, provides the capacity to determine potential factors underlying known gender differences in golfing performance and injury rates. Identifying gender-
based differences between the male and female golf swing is an important stepping stone in understanding why gender-based performance differences exist. Furthermore, if gender differences exist, it will be possible to better formulate physical and technical training programs aimed at addressing those differences.

1.3 General aims of the project

The aim of this project was to examine the movement patterns of the thorax and pelvis during the golf swing in a group of male and female skilled golfers. It was envisaged that this project would clarify how skilled male golfers move both their thorax and pelvis during the full golf swing and add new knowledge regarding the pattern of movement adopted by skilled female golfers. In this project, analyses capable of revealing the underlying dynamics of thorax and pelvis motion will be employed along with more traditional measures associated with golf biomechanics research. Such analyses will include velocity comparisons, phase planes, angle-angle plots and vector coding.

1.4 Specific aims of the project

The specific aims of the experiments comprising this thesis were to:

1. Use refined biomechanical techniques to examine the 3D kinematics of the thorax and pelvis during the downswing of skilled golfers, and determine if differences in kinematics exist between males and females.
2. Investigate movement variability of the thorax and the pelvis to determine how skilled golfers control segmental motion during the downswing, and determine if differences in movement variability exist between genders.

3. Examine the gender response to a physically challenging, golf-specific task, by investigating the effect of 40 minutes of putting practice on the swing kinematics of male and female skilled golfers.
Chapter 2 - Literature review
2.1 The full swing

The full golf swing accounts for more than half of the strokes made during a round of golf [149]. Furthermore, the full golf swing moves through the greatest range of motion of all swing types and has frequently been suggested to be the main cause of golf injuries [94, 166, 170]. The fundamental goal of the full swing is to propel the ball in the desired direction for an intended distance [4]. Relatively few golfers however, can achieve this on a consistent basis. Equipment, anthropometric, and environmental factors may all influence performance, but given that the full golf swing is a complex whole body movement, it is likely that variation in swing kinematics has the greatest influence.

In comparison to other whole body movements such as running, jumping, and throwing, less is known about the kinematics of the golf swing. Of the studies that have examined swing kinematics, differences in methodological techniques, variables analysed, and golfer characteristics, has meant it has not always been possible to compare findings. However, in general, consistency exists in the terminology used to describe phases of the golf swing. A common convention for describing the phases of the golf swing is presented in Figure 2.1 and is described below. Unless otherwise stated, descriptions throughout this thesis are based on a right-handed golfer. For most golfers the target is typically a distant point in the fairway such as a tree, or a point on the green such as the flag. ‘Away from the target’ refers to the right side of the golfer, while ‘toward the target’ refers to the left side of the golfer. It should also be noted that throughout this thesis, the term trunk represents the thorax and the pelvis.
Frontal plane view

Sagittal plane view

Figure 2.1 Frontal and sagittal plane views of the common phases used to describe the full golf swing; adapted from Kim et al. 2004 p.1325 [105]. The swing begins with the address phase and finishes with the follow-through phase. The entire swing is represented as a continuum, with the grey areas representing the four main phases and the black areas indicating the transitions between phases.

(a) Address

Often called set-up, address is the position adopted by the golfer while standing over the ball before the club begins to move. During address, the individual establishes proper alignment with the target, and is in a balanced and stable position in readiness to initiate the backswing. The trunk is flexed, while at the same time laterally tilted to the right [5].
(b) Backswing

The backswing involves the golfer moving their body and club into a position that allows for an efficient and powerful downswing. The initial part of the backswing, often referred to as ‘takeaway’ by golf coaches, involves movement from ball address to the point at which the club begins to move upward [44]. Following takeaway, the remainder of the backswing is largely characterised by thorax and pelvis axial rotation away from the target. At the end of the backswing, commonly referred to as TBS, the thorax will have generally moved through an axial rotation range about twice that of the pelvis [28].

(c) Downswing

The downswing describes movement from TBS to BC. The latter half of the downswing is sometimes referred to as ‘late acceleration’ but due to the difficulty in defining its start point, the term ‘downswing’ is most commonly used. The downswing phase incorporates the return of the clubhead on an appropriate trajectory, toward the golf ball. Historically, it was thought that the swing occurred about a single plane [30, 38], where swing plane is defined by the angle of the club shaft throughout the swing [185]. More recently however, investigations have revealed variations in swing plane exist, particularly during the downswing [41, 142, 143]. Throughout much of the downswing the lead wrist is often described as being ‘cocked’, with the amount of radial deviation and extension remaining relatively constant [134]. It is not until the last 40 milliseconds of the downswing phase where wrist uncocking occurs, resulting in rapid acceleration of the golf club just prior to BC [142]. In skilled golfers, the downswing is initiated by pelvis axial rotation toward the target, followed by axial rotation of the thorax and finally the hands and the club [28].
(d) Follow-through

The follow-through phase is characterised by the deceleration of body segments (and the club) from BC to the finish position. At the end of a typical follow-through phase, the thorax and pelvis are facing the target, with much of the golfer’s body weight over the target side leg [95].

2.2 Golf swing kinematics

2.2.1 Whole body sequencing

Despite the complexity of coordinating a whole body movement such as the golf swing, a consistent pattern of segmental movement has been observed in skilled golfers [28, 131, 157]. Typically it is suggested to involve a sequential pattern of proximal-to-distal motion. Many other multi-joint throwing and striking-type sports (e.g. baseball batting and pitching) share a similar pattern, whereby motion of the proximal segment precedes motion of the distal segment [6, 66, 153]. For the golf swing, the transfer of velocity from the proximal thorax and pelvis segments to the more distal hand and club segments is believed to be fundamental to producing high clubhead speeds, and therefore may provide an interesting avenue for investigating golfers of differing skill levels.

The downswing phase of the full swing is often referred to as a kinetic link system. Using this analogy, the body is represented as an open-linked chain consisting of rigid segments, where the end of the distal segment, that is the clubhead, moves freely in space [153]. Motion and velocity of the clubhead are not only dependent on muscle forces, but also interactive forces where momentum generated in one segment can be
transferred to the adjacent segment [60]. From a theoretical perspective, to generate large club head speeds and hence ball displacement, a golfer should aim to maximise velocity of the most proximal segment before sequentially maximising velocity of the distal segments [38, 134, 164, 174]. While many studies make reference to the summation of velocity principle during the golf swing [28, 134], only limited reports of actual segment velocity data are available. Of the limited data available, there is general support that the golf swing conforms to a kinetic link system where there is an increase in peak segment velocities from the proximal-to-distal segments (Figure 2.2) [72, 138, 140, 174, 192, 193].

![Angular Velocity (deg.s⁻¹) vs Time (s) diagram](image)

**Figure 2.2** A theoretical representation of a kinetic link system, and how the precise timing of segment velocities in a proximal to distal pattern can result in a summing of velocities and lead to higher velocities at the most distal segment. Figure adapted from Kreighbaum and Barthels 1996, p 343 [109].

In addition to an increase in the magnitudes of peak segment angular velocities proximally to distally, the timing of the peak velocities is also believed to play a key role in determining the end-point velocity of a kinetic link system [153]. Although
only a few studies have directly investigated timing of segmental velocity during the
golf swing, preliminary results suggest a precise and ordered timing of peak velocities
to be a common characteristic of highly skilled golfers [140, 174]. Both Tinmark
[174] and Neal [140] verified the existence of a proximal-to-distal relationship during
the full swing, with the pelvis achieving peak speed first, followed by the thorax, the
hands and finally the club. Interestingly, Tinmark [174] found that the timing
relationship between segments was maintained over a range of shots, from 40 metre
pitch shots to full driver shots, with the major difference being a lower magnitude of
peak speeds with the shorter shots. However, it is important to note that angular speed
was presented in these studies. This effectively means individual 3D angular
velocities of a segment were summed and presented as single values, which can
conceal important segmental differences (See Appendix A). Nevertheless, given the
consistent relationship of timing of peak angular speed during the swings of skilled
golfers, discrepancies in timing may emerge in lesser skilled golfers, golfers with
different physical attributes (such as females) or following a prolonged task such as a
round of golf. The implications may be important from a performance perspective,
and may assist in the development of more specific and guided training or coaching
programs.

2.2.2 Transitions between phases

The golf swing is frequently described using phases of the swing. This can be
complicated as there is often a lack of distinction between one phase and the next. For
example, during the transition between the backswing and the downswing, rotational
motion of individual body segments and the club are not always in the same direction.
In fact, when the club is approaching TBS, the pelvis has usually begun axially
rotating back towards the target [22, 71, 72]. This ambiguity has resulted in researchers using various methods to define the same point in the swing [28, 56, 138, 180, 192]. Similar problems exist for other transitional points during the full swing. While it should be acknowledged that examining segmental movement at the start and end of various phases is an important aspect of investigating golf swing kinematics, a more revealing approach may be to examine transitions between phases to ensure information before and after these important swing events is captured. This would have the benefit of revealing ‘how’ the body arrived at a particular position rather than ‘what’ position they achieved. Transitions afford an opportunity to do this, and importantly as they usually involve a change in direction are likely to provide added information with regard to the motor control of the task.
<table>
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<th>Author &amp; Year</th>
<th>Skill Level</th>
<th>Participants</th>
<th>Gender</th>
<th>Measurement System</th>
<th>Body Segments</th>
<th>Main Findings</th>
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<td>Neal and Wilson 1985</td>
<td>Professional &amp; elite amateur</td>
<td>6 (4 professional; 2 low handicap)</td>
<td>Male</td>
<td>2 high speed video cameras (294 Hz)</td>
<td>Wrist</td>
<td>- Wrist uncocking commenced between 0.1 s and 0.08 s prior to BC</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>- Peak clubhead velocity occurred just after BC</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Arm began accelerating 0.025 s prior to club</td>
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<tr>
<td>Sanders and Owens 1992</td>
<td>Elite &amp; novice</td>
<td>12 (6 elite; 6 novice)</td>
<td>Male</td>
<td>1 high speed video camera (200 Hz)</td>
<td>Upper body</td>
<td>- Elite demonstrated more consistent movement patterns of the hub (the point at which the clubhead rotates about) compared to novice</td>
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<td>- Radius of hub to clubhead peaked near BC in elite and after BC in novice</td>
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<td>- Novice group demonstrated a curvilinear clubhead path, which was thought to be a potential contributing factor to shot inconsistency</td>
</tr>
<tr>
<td>McTeigue et al. 1994</td>
<td>Professional &amp; amateurs</td>
<td>151 (51 professional, 46 senior professional, 34 amateur)</td>
<td>Male</td>
<td>Variation of a triaxial electrogoniometer (100 Hz)</td>
<td>Spine</td>
<td>- At address: forward bending angles in professionals = 28° and amateurs = 25°</td>
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<td>- Top of backswing: tour players rotated torso = 87° and hips = 55°; amateurs rotated torso = 87° and hips = 53°</td>
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<td>- Significant difference in side bending angle at top of the backswing; professionals = 3° and amateurs = 16°</td>
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<td>- Significant difference in side bending angle at BC: professionals = 31° and amateurs = 21°</td>
</tr>
<tr>
<td>Burden et al. 1998</td>
<td>Experienced</td>
<td>8 low handicap (mean 7±1 strokes)</td>
<td>Not defined</td>
<td>2 video cameras (50 Hz)</td>
<td>Thorax and pelvis</td>
<td>- Hip turn = 32° during backswing</td>
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<td>- Shoulder turn = 102° during backswing</td>
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<td>- At BC hips rotated 20° ‘open’ or towards target and shoulders rotated 10° towards target</td>
</tr>
<tr>
<td>Lindsay and Horton 2002</td>
<td>Professional</td>
<td>12 (6 with low back pain; 6 without low back pain)</td>
<td>Male</td>
<td>Triaxial electrogoniometer</td>
<td>Spine</td>
<td>- A non-significant difference in spinal flexion at address (using a driver) with no low back pain (NLBP) group = 25° and the low back pain (LBP) group = 37°</td>
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<td>- A significant difference in left side bending angle with LBP group = 7° and the NLBP group = 1°</td>
</tr>
<tr>
<td>Study: Lindsay et al. 2002 [118]</td>
<td>Category: Professionals</td>
<td>Sample Size: 44 professional</td>
<td>Sex: Male</td>
<td>Instrument: Triaxial electrogoniometer (60 Hz)</td>
<td>Spine:</td>
<td>Data:</td>
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<td>At address spinal flexion = 35° with 7-iron and 29° with a driver</td>
<td>Subjects setup in 7° of right side bend with both 7-iron and driver</td>
<td>Using a 7-iron maximum spinal ROM means for right rotation = 35°, left rotation = 40°, right side bend = 28°, left side bend = 10°</td>
</tr>
<tr>
<td>Study: Cheetham et al. 2001 [33]</td>
<td>Category: Skilled &amp; Novice</td>
<td>Sample Size: 19 (10 skilled; 9 novice)</td>
<td>Sex: Not defined</td>
<td>Instrument: 3 sensor Electromagnetic tracking system (30 Hz)</td>
<td>Thorax and pelvis</td>
<td>Data:</td>
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<td>Shoulder and hip turn differential (i.e. the ‘X-Factor’) = 48° in skilled and 44° in lesser skilled group (non-significant difference)</td>
<td>A significant difference in the percentage increase in X-Factor during early downswing (i.e. the ‘X-Factor Stretch’): skilled group = 19% and lesser skilled group = 13%</td>
<td></td>
</tr>
<tr>
<td>Study: Mitchell et al. 2003 [137]</td>
<td>Category: Groups based on age</td>
<td>Sample Size: 65 (19 mean hcp = 3; 24 mean hcp = 9; 22 mean hcp = 14)</td>
<td>Sex: Male</td>
<td>Instrument: 6 camera Motion Analysis Corp. (180 Hz)</td>
<td>Shoulder and thorax</td>
<td>Data:</td>
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<td>External rotation of right shoulder peaked at top of backswing: college = 86°, middle aged = 71° and seniors = 48°</td>
<td>Shoulder turn in college, middle aged and seniors peaked just after top of the backswing at 106°, 100° and 85° respectively</td>
<td></td>
</tr>
<tr>
<td>Study: Egret et al. 2006 [56]</td>
<td>Category: Experienced</td>
<td>Sample Size: 12 (7 males; 5 females)</td>
<td>Sex: Male &amp; Female</td>
<td>Instrument: 5 camera VICON system (50Hz)</td>
<td>Thorax, pelvis, knee, shoulder and elbow</td>
<td>Data:</td>
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<td>Shoulder turn at top of backswing: males = 84° and females = 109°</td>
<td>Hip turn at top of backswing: males = 38° and females = 64°</td>
<td>Knee flexion at top of backswing: males = 35°, females = 17°</td>
</tr>
<tr>
<td>Study: Wheat et al. 2007 [180]</td>
<td>Category: Variable</td>
<td>Sample Size: 10 (hcp range 1-17)</td>
<td>Sex: Male</td>
<td>Instrument: 8 camera Motion Analysis Corp. (300 Hz)</td>
<td>Thorax</td>
<td>Data:</td>
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<td>Thorax rotation at top of the backswing using the thorax vector (line perpendicular to plane formed by C7, sternal notch and midpoint between T8 &amp; xiphoid) = 84° while at BC thorax rotation = 13° ‘open’ or toward the target</td>
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<tr>
<td>Study: Myers et al. 2008 [138]</td>
<td>Category: Experienced</td>
<td>Sample Size: 100 (mean hcp = 8)</td>
<td>Sex: Not defined</td>
<td>Instrument: 8 camera Peak Motus system. (200 Hz)</td>
<td>Thorax and pelvis</td>
<td>Data:</td>
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<td>Moderate relationships exist between increased ball velocity and increased torso – pelvic separation at top of the swing; maximum torso – pelvic separation; and maximum upper torso rotation velocity</td>
<td>Increased upper torso rotation velocity and torso – pelvic separation velocity potentially contribute to increased ball velocity</td>
<td></td>
</tr>
<tr>
<td>Author &amp; Year</td>
<td>Skill Level*</td>
<td>Participants</td>
<td>Gender</td>
<td>Measurement System</td>
<td>Body Segments</td>
<td>Main Findings</td>
</tr>
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<tr>
<td>Evans et al. 2008 [63]</td>
<td>Professionals</td>
<td>29 (trainee professionals)</td>
<td>Male</td>
<td>4 sensor Electromagnetic tracking system (240 Hz)</td>
<td>Head, thorax, pelvis, hand</td>
<td>• 40 mins of putting practice led to lumbar extensor fatigue which in turn led to changes in swing kinematics when using a 5-iron • Post putting reductions in: thorax rotation in backswing, thorax and pelvis rotation in downswing, x-factor stretch, thorax speed, pelvis speed and hand speed</td>
</tr>
<tr>
<td>Neal et al. 2008 [140]</td>
<td>Elite amateurs</td>
<td>25 (13 males; 12 females)</td>
<td>Male &amp; Female</td>
<td>4 sensor Electromagnetic tracking system (240 Hz)</td>
<td>Thorax, pelvis, arm, hand</td>
<td>• Peak speeds occurred in a proximal-to-distal pattern. Average peak speeds across all subjects were: pelvis = 480 °/s, thorax = 660 °/s, hand = 960 °/s • There were no kinematic differences (peak speeds or timing of peak speeds) between self-reported ‘well-timed’ and ‘mis-timed’ shots</td>
</tr>
<tr>
<td>Zheng et al. 2008 [192]</td>
<td>Professionals &amp; amateurs</td>
<td>72 (18 hcp = 0; 18 hcp = 3; 18 hcp = 13; and 18 hcp = 21)</td>
<td>Male</td>
<td>6 camera Motion Analysis Corp. (240 Hz)</td>
<td>Thorax, pelvis, shoulder, elbow, wrist</td>
<td>• At top of backswing professionals exhibited the largest magnitudes of left shoulder horizontal adduction (125°), right shoulder external rotation (66°) and trunk (thorax-pelvis) rotation (60°) • During the downswing professionals exhibited largest angular velocities for club shaft (2410°/s), right elbow extension (850°/s), right wrist (1180°/s) and left wrist (1090°/s)</td>
</tr>
<tr>
<td>Zheng et al. 2008 [193]</td>
<td>Professionals</td>
<td>50 (25 male professionals; 25 female professionals)</td>
<td>Male &amp; Female</td>
<td>6 camera Motion Analysis Corp. (240 Hz)</td>
<td>Thorax, pelvis, shoulder, elbow, wrist</td>
<td>• At top of backswing significant differences were found for trunk flexion (F: 25° vs M: 31°) and pelvis axial rotation (F: 49° vs M: 42°) • At ball contact significant differences in pelvis axial rotation (F: -52° vs M: -42°) • Females exhibited significantly lower angular velocities for the club shaft (2050°/s), left wrist (820°/s), right wrist (860°/s) and right elbow extension (710°/s) compared to males</td>
</tr>
<tr>
<td>Cole &amp; Grimshaw 2009 [40]</td>
<td>Amateurs</td>
<td>15 (7 hcp = 7; 8 hcp = 14)</td>
<td>Male</td>
<td>3 video cameras (50 Hz)</td>
<td>Thorax and pelvis</td>
<td>• No statistically significant differences between low- and high-handicap groups for thorax or pelvis axial rotations or X-Factor &amp; X-Factor stretch • Magnitude of thorax and pelvis axial rotation in low handicap group at TBS and maximum, similar to other studies (thorax = 93°; pelvis = 30°)</td>
</tr>
<tr>
<td>Study</td>
<td>Level</td>
<td>Participants</td>
<td>System &amp; Rate</td>
<td>Marker Sites</td>
<td>Key Findings</td>
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<td>Chu et al. 2010 [36]</td>
<td>Experienced</td>
<td>308 (266 males; 42 females)</td>
<td>8 camera Peak Motus system (240 Hz)</td>
<td>Thorax, pelvis, hip, knee, shoulder, elbow, wrist</td>
<td>- Regression analyses revealed that thorax–pelvis separation angle (i.e. X-Factor), delayed release of the arms and wrists, trunk forward and lateral tilt, and weight-shifting were significantly related to ball velocity</td>
<td></td>
</tr>
<tr>
<td>Tinmark et al. 2010</td>
<td>Professional &amp; elite amateur</td>
<td>45 (11 male professionals; 21 male elite amateurs; 13 female elite amateurs)</td>
<td>3 sensor Electromagnetic tracking system (240 Hz)</td>
<td>Thorax, pelvis, hand</td>
<td>- Significant proximal-to-distal temporal relationship and a concomitant successive increase in peak segment angular speeds for every shot condition (40m, 55m, 70m, 5-I, Dr) for both genders and all levels of expertise</td>
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<td>- For shorter shots proximal-to-distal pattern still observed however timing of all segment peak speeds occurred later in downswing</td>
<td></td>
</tr>
<tr>
<td>Healy et al. 2011 [85]</td>
<td>Skilled</td>
<td>30 (15 high ball velocity, hcp = 4; 15 low ball velocity, hcp = 11)</td>
<td>12 camera VICON system (250Hz)</td>
<td>Thorax, pelvis, hip, knee, shoulder, elbow</td>
<td>- On average ball impact position on the clubface was significantly closer to centre of the face for HBV(^b) group compared to LBV(^b) group</td>
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<td>- HBV group had greater left elbow extension and greater shoulder extension angular velocity early in the downswing</td>
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<td>- HBV group had a greater X Factor angle during the downswing</td>
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<td>- HBV group had greater left shoulder adduction angular velocity at ball contact</td>
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<tr>
<td>Brown et al. 2011 [26]</td>
<td>Skilled</td>
<td>16 (hcp &lt; 5)</td>
<td>12 camera Qualisys system (240Hz)</td>
<td>Thorax and Pelvis</td>
<td>- Analysis of covariance revealed three determinants of variance in clubhead speed (adjusted (R^2 = 0.97)): (i) increased thorax-pelvis separation at TBS, (ii) increased pelvis translation during backswing, (iii) decreased backswing time</td>
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<td></td>
<td>- A significant correlation was found between clubhead speed and left hand grip strength ((R^2 = 0.54)); and clubhead speed and handicap ((R^2 = -0.61))</td>
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</tbody>
</table>

\(^a\) Skill level descriptions are based on terminology used in each particular study and as a result can vary depending upon an author’s definition

\(^b\) HBV = high ball velocity group; LBV = low ball velocity group
2.2.3 Kinematics of the trunk

In general, a number of key parameters have been employed to describe the kinematics of the thorax and pelvis during the golf swing. These include thorax flexion or thorax anterior-posterior tilt, thorax lateral flexion or thorax lateral tilt, thorax axial rotation, and pelvis axial rotation. As the term flexion is generally used to describe the sagittal plane angle of a joint or between two adjacent segments, and given this project mostly reports segmental movement, the terms anterior-posterior tilt and lateral tilt will be adopted throughout this thesis when referring to segmental movement of the thorax or pelvis.

Backswing

From address to TBS, skilled golfers rotate their thorax from a slightly open position to an angle somewhere between 84 - 106° [28, 40, 56, 131, 137, 138]. In the same manner as the thorax, the pelvis also axially rotates from an open position at address to an angle of somewhere between 30 - 55° at TBS [28, 40, 56, 63, 118, 132, 138]. The relatively large variation in reported thorax and pelvis axial rotation angles is most likely due to a combination of factors, including differences in the skill level of the golfers examined, differences in the instrumentation employed [20], and differences in the biomechanical modelling procedures adopted [180]. Further detail on these issues is provided in Chapter 3 of this thesis.

Limited reports of thorax anterior-posterior tilt angles during the backswing exist. Anecdotally, coaches emphasise the importance of maintaining a consistent thorax anterior tilt angle during the backswing, however McTeigue and colleagues [132] reported trunk flexion angle (sagittal plane angle between thorax and pelvis) to
decrease from 28° at address to 16° at TBS. Although Chu [36] did not report trunk inclination angle at address, a similar value of 22° at TBS was reported for male golfers. Although the golfers in the investigation of Chu had a higher handicap than those in McTeigue’s study, the results support the findings of McTeigue [132] and suggest that an element of trunk extension is common in the latter part of the backswing in skilled male golfers. A similar pattern also seems to exist for trunk motion in the frontal plane, where lateral tilt away (+6° to +13°) from the target at address occurs, but by TBS lateral tilt towards (-3° to -9°) has occurred [132, 193]. This upper body motion is complicated however, as the pelvis is axially rotated at TBS, and the trunk is in fact laterally tilted toward the ball at TBS.

Although not experimentally examined, Geisler [72] and Adlington [5] both propose that excessive thorax lateral tilt toward the target side (or more correctly toward the ball) at TBS often results in a compensatory lateral translation of the pelvis toward the target during the downswing. Normal translation values for both the thorax and the pelvis, however, are rarely reported in the literature. Evans and colleagues [63] are one of the only known groups to report upper body segment translations during the backswing and have found that in skilled male golfers, the thorax translates 8 cm to the right, the pelvis 6 cm to the right and 5 cm posteriorly. This combined translational movement would seemingly position the pelvis and thorax behind the ball or on to the right side at TBS, thus placing the golfer in an important preparatory position to start the downswing where rapid weight transfer toward the target side occurs.
Downswing

During the downswing phase, the trunk flexes between 0 and 6° [36, 132], while at the same time laterally tilting to the right. The range of right lateral tilt motion is between 34 - 40° [132], while actual peak values, which coincide with or occur soon after BC, have been reported to be 26 - 31° [117, 118, 132, 192]. Even though the downswing involves multi-planar thorax motion, the axial rotation component is generally considered to be the primary motion and as a result is most commonly reported in the literature. The considerable range of motion that the thorax rotates through from TBS to BC, is reported to be in the order of 75 - 113° for skilled male golfers [28, 40, 54, 132, 138].

As well as 3D angular rotations, the motion of the ‘hub’ during the downswing has been described by Sanders and Owens [157]. The ‘hub’ is described as the focal point of the clubhead path, and draws similarities with linear displacement of the upper body. The hub position could be likened to a theoretical point about which the golfers club rotates during the downswing. Early investigations of skilled and unskilled golfer’s revealed a consistent pattern of hub motion during the downswing and a higher position at BC for skilled golfers. This indicates skilled golfers swing with a flatter clubhead trajectory near BC [157]. It has been hypothesised that this is likely a result of greater lateral displacement of the upper body during the downswing, which would flatten the arc of the clubhead and improve consistency of BC. Surprisingly, reports of actual linear displacement indicate that the thorax only translates about 1 cm toward the target from TBS to BC [63], however this is likely due to the thorax laterally tilting away from the target near BC which would effectively decrease lateral translation toward the target. It is also likely that the majority of thorax translation
occurs following BC, which would further explain the relatively small downswing values for thorax translation.

Pelvis motion during the downswing has not been extensively investigated. Anterior-posterior tilt, lateral tilt and linear displacement of the pelvis have seldom been examined formally. Examinations to date have almost exclusively detailed axial rotation of the pelvis. Of the numerous studies to investigate pelvis axial rotation, reported ranges of motion from TBS to BC have been between 52 - 87° [28, 40, 63, 132, 138]. While some variation in skill level or performance between studies is inevitable, the values referred to are largely representative of highly skilled males. For pelvis translation, Evans et al [63] found that young male trainee professionals translated their pelvis posteriorly 3 cm and toward the target 4 cm during the downswing phase when using a driver. The findings of Evans and colleagues suggest that during the downswing, pelvis motion parallels and precedes thorax motion. That is, both segments undergo rapid axial rotation to the left and translation toward the target.

Surprisingly, velocity of upper body motion during the golf swing has only recently been a focus of examination [36, 63, 138, 174]. Like 3D angular displacement of the trunk, angular velocity has mostly been reported for the axial rotation direction. Maximal downswing thorax axial rotation velocities for skilled golfers have been reported to be 610 - 770°/s [36, 138], while slightly lower values (520°/s) have been observed at BC [138]. For the pelvis, maximal axial rotation values of 390 - 430°/s have been reported [36, 138]. More recently, the overall speed of upper body motion, which is typically calculated as the sum of the three angular velocity vectors of a
segment, has been presented. The major limitation of presenting speed is that it is a scalar measurement, and describes the rate of change in motion but fails to account for the orientation of a segment. Consequently, important velocity differences between directions and segments may be masked (see Appendix A for a more detailed comparison of segment speed and segment angular velocity). Despite these limitations, authors have reported segment speeds during the five-iron swings of male professional golfers, with the thorax and pelvis achieving peak speeds of 430 - 700 and 310 - 480°/s, respectively [63, 174]. As would be expected in the more powerful driver swing, higher maximal thorax and pelvis speeds of 760 and 500°/s respectively, have been reported [174]. Although it is apparent that higher speeds and velocities are evident during the downswing of shots where the ball is propelled further, and that higher upper body speeds are potentially related to higher clubhead speeds, it is likely there is a concomitant increase in the stress on the golfer’s body. Ultimately, the performance benefits of high body segment speeds needs to be weighed against the relative risk of injury.

**Ball contact**

In terms of distance and accuracy, BC is the most critical point of the golf swing. Although there is little a player can do to correct any errors at BC, information about body position may assist in understanding differences between good and poor swings and factors that contribute to common injuries. In regard to upper body position, at BC the pelvis is axially rotated 20 - 32° to the left, and thorax 10 - 26° to the left, indicating both segments have ‘cleared’ by the time of contact between the ball and the club [28, 132]. For the other planes of motion, the trunk is flexed 16 - 22°, while at the same time laterally tilted to the right 15 - 31° [36, 118, 132, 192]. This
combined trunk position results in high compressive and shear loads at or around BC during each swing an individual performs [93].

2.2.4 Thorax-pelvis interactions

The relationship between thorax and pelvis motion has frequently been cited as an important factor in the development of speed and power during the golf swing [28, 33, 95, 128]. Many coaches emphasise the importance of creating a large differential angle between the ‘hips’ (pelvis) and ‘shoulders’ (thorax). This differential angle has been described using a variety of methods, but is most commonly referred to as the difference in the axial rotation angle for the thorax and the pelvis (Figure 2.3). Historically, a greater differential angle at TBS has been associated with longer driving distances [128]. Jim McLean [128], a prominent American golf coach was the first to describe this event known as ‘X-Factor’, after analysing a small group of tour professionals. Using a correlation analysis, McLean found a positive relationship between X-Factor and golf driving distance.
Figure 2.3 Thorax-pelvis differential, termed ‘X-Factor’. Lines are drawn through the hip and shoulder joint centres of rotation to visualise the X-Factor. The golfer on the right demonstrates a larger pelvis-trunk differential angle compared to the golfer on the left.

However, in contrast to the findings of McLean, McTeigue and colleagues [132] failed to identify any differences in X-Factor between tour professionals (32°), senior tour professionals (29°) and amateurs (34°) [132]. While McTeigue made note of higher clubhead speeds in the professional group which would theoretically correspond with longer driving distances, no empirical data was provided to support this statement. Given the conflicting findings of McLean and McTeigue, Cheetham et al [33] investigated the relationship between X-Factor and the increase in X-Factor early in the downswing phase, which they termed ‘X-Factor Stretch’. It was hypothesised that skilled players would increase the magnitude of X-Factor early in the downswing due to their increased propensity to commence the downswing with pelvis rotation prior to thorax rotation [28, 132]. Results indicated that skilled golfers
increased X-Factor Stretch early in the downswing significantly more than novice golfers (skilled = 19%; novice = 13%), however no difference in the magnitude of X-Factor was observed. It is also important to note that, like McTeigue, Cheetham did not report clubhead velocity data and as such it cannot be confirmed if differences existed between groups.

The top of the backswing and the early part of the downswing have been suggested to involve a stretch shorten cycle (SSC) [33, 40, 95, 100, 138]. Thorax-pelvis separation at TBS and early downswing supposedly causes stretching of the muscles of the hip, trunk, abdomen and shoulder, which theoretically leads to a more forceful and powerful downswing [100]. Although the exact mechanism behind the SSC remains contentious, it is frequently claimed that golfers utilise elastic energy stored during the backswing phase [33, 95, 100, 138, 141]. This appears tenuous, particularly given no direct examination of muscle-tendon unit properties has occurred during the golf swing. Moreover, the major muscles responsible for the motion of the downswing such as the gluteals and abdominals [125], have relatively short muscle-tendon units and the storage of elastic energy appears unlikely. Increased time for force production and changes in contractile mechanics seem more likely explanations, however further investigation is warranted. However, until appropriate methods are utilised to investigate muscle-tendon properties during the golf swing, it is speculative to assume a SSC exists.

While the examination of thorax-pelvis motion has largely revolved around analyses of X-Factor and X-Factor Stretch which are predominately discrete axial rotation measures, the relationship and or coordination between both segments is more
complex. As outlined in section 2.2.3, the thorax and pelvis move through large ranges of motion, at times in opposite directions. Such complex patterns of coordinated movement are unlikely to be fully understood with discrete measures. A deeper understanding is likely to be gained by examining kinematic time series data, using more complex analyses from the motor control field. Such analyses include angle-angle plots, phase-plane plots, cross correlations and vector coding. Although it is generally only qualitative information that is gathered, angle-angle plots can reveal information about the motion of one segment relative to another, while phase plane plots detail the range of motion with respect to the angular velocity of an individual segment [76, 179]. For cross-correlation and vector coding analyses, quantitative information about the coupling relationship and the variability of coupling between segments can be gained [50, 169, 179]. The major benefits of these analyses are that they not only provide insight into the complex 3D relationships between the thorax and the pelvis, but also the evolution of these relationships during the different phases of the swing.

2.3 Gender differences in the golf swing

Anatomical, hormonal and neuromuscular differences between males and females are well known to influence physical performance. With respect to anatomical factors, gender differences exist in various musculoskeletal parameters including bone density and geometry, tendon and ligament strength indices, total muscle mass, and muscle fibre type distribution [102, 135, 165]. Additionally, neuromuscular differences in absolute muscle strength, muscle endurance, and muscle activation patterns have been observed in men and women when performing a variety of tasks [88, 96, 120, 163].
The combined effect of these gender related differences on the biomechanics of a goal directed task such as the golf swing is unknown. Given that gender differences in outcome parameters (e.g. kinematics) during tasks such as running and jumping exist [49, 162, 163, 173], it is plausible that the mechanics of the golf swing might differ between male and female golfers.

2.3.1 Swing kinematics

Kinematic, kinetic and electromyographic analysis of the golf swing has almost exclusively focused on the male golfer. In fact, only two studies have compared the swing kinematics of male and female golfers [56, 193] and one study has detailed the kinematics of a skilled female cohort [26]. While differences in subject skill level, golf teaching and training background, and the kinematic analyses undertaken were evident, several similarities in findings were present. In the study of Egret and colleagues [56], swing kinematics in a small group of experienced male (n = 7, hcp = 6.6) and female (n = 5, hcp = 6.1) golfers were compared while using the driver club. Although only a few select kinematic variables were examined and the reporting of the methods used to calculate those variables was limited, marked differences between males and females were found at TBS. Specifically, female golfers rotated both their thorax and pelvis significantly more than males at TBS (Females: thorax = 110 ± 19°, pelvis = 64 ± 12°; Males: thorax = 84 ± 16°, pelvis = 38 ± 8°). Despite Zheng and colleagues [193] examining a more skilled group of golfers, a similar finding of greater thorax and pelvis rotation at TBS using a driver club was also observed for females (thorax = 109 ± 7°, pelvis = 49 ± 8°) compared to males (thorax = 100 ± 8°, pelvis = 42 ± 7°).
Interestingly, even though differences in X-Factor existed between the studies of Egret and Zheng [56, 193], males and females effectively created the same differential angle at TBS (Egret: females = 46°, males = 46°; Zheng: females = 60°, males = 58°). This finding conflicts with the conclusions drawn by Egret et al [56] that males achieve a lower magnitude of absolute rotation due to ‘poor muscular or articular suppleness’. Alternatively, greater absolute thorax and pelvis rotation observed in females may be due to factors such as discrepancies in hip joint and lower limb range of movement (ROM), weight shift differences, and an element of ‘over-swinging’ or over rotation in the females. Possible gender differences in lower limb ROM may also in part explain greater knee flexion angles at TBS in males [56], and a greater magnitude of pelvis rotation at BC in females [193].

Zheng and colleagues [193] extended the work of Egret et al [56], by reporting trunk and upper limb peak angular velocities as well as the timing of peak velocities for males and females. The main outcome of Zheng’s investigation was that females exhibited lower peak velocities for elbow and wrist angular motion, while timing of peak velocities were the same for both genders. Predictably, the lower angular velocities generated in the upper limbs coincided with females not achieving the same magnitude of clubhead velocity as males. This finding in conjunction with no differences in angular velocities of the thorax and pelvis for males and females is somewhat unexpected. If males have higher velocities at the more distal segments and end-points compared to females, then theoretically, they should also exhibit higher velocities at the more proximal segments. However, in the investigation of Zheng et al., male and female golfers demonstrated differences in clubhead velocity yet
generated the same thorax and pelvis rotation velocities. A similar relationship was also observed by Brown and colleagues [26], who investigated determinants of clubhead speed in a group of skilled female golfers. Not including increased thorax-pelvis separation at TBS, Brown and colleagues found that no downswing pelvis-thorax angular displacement or velocity variables explained variance in clubhead speed. It is obvious from these findings and those of Zheng and colleagues that the relationship between high clubhead velocity and optimal swing kinematics is complex, and that further investigation of the swings of both genders is required. Analyses that fully describe the 3D kinematics of the trunk and account for coordination or coupling between trunk segments are likely to provide further insight into how higher clubhead velocities are generated.

2.3.2 Injury characteristics

Although golf-related injuries are not the focus of this thesis, epidemiology data does support the importance of examining and comparing the swing characteristics of male and female golfers. It is important to note, however, that the epidemiological investigation of golf-related injuries has been uncommon over the past few decades. Of the handful of investigations undertaken (see Table 2.2), all but one has been conducted retrospectively and only 500 out of a total 4500 participants could be considered to be highly skilled. Other limitations include that the majority of reported injuries are based on self-reported survey data, the potential for selection bias due to very low response rates, and the limited delineation between actual golf related injuries and injuries due to activities of daily living or other physical tasks. Nonetheless, of the studies presented in Table 2.2, the majority have included data for
both male and female golfers and demonstrate agreement in the frequency and the type of injuries sustained.

With respect to frequency of injury, similar rates have been reported for male and female golfers even across differing skill levels [21, 79, 123]. Conversely, analyses of golf-related injuries based on anatomical location reveal notable differences between genders. In general, female golfers display a trend toward increased incidence of upper limb injuries (i.e. wrist, elbow and shoulder), whereas males experience a greater frequency of lower back injuries [21, 122, 123, 126, 171]. Some authors have attempted to explain this finding by suggesting that differences in downswing motion exist for males and females [170]. While this may be true for skilled golfers, it is unlikely that kinematic differences alone are responsible, as reported injury data is based on both skilled and unskilled golfers. Unskilled male and female golfers are likely to show similarly large variations in swing kinematics, hence physical differences in height, weight, upper body strength, and flexibility are all likely to contribute to the observed gender differences in injury location [170]. For at least skilled golfers, there is merit in examining swing kinematics of both genders as it may not only assist in understanding the mechanisms behind gender specific injuries, but also assist in guiding gender specific coaching and training programs.
<table>
<thead>
<tr>
<th>Study / Year</th>
<th>Gender</th>
<th>Skill Level a</th>
<th>Respondents</th>
<th>Injured Golfers</th>
<th>Total Injuries</th>
<th>Most Common Injuries</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCarroll and</td>
<td>Male &amp; Female</td>
<td>Professional</td>
<td>226</td>
<td>190</td>
<td>393</td>
<td>Males: 1.low back 2.left wrist 3.left shoulder&lt;br&gt;Females: 1.left wrist 2.low back 3.left hand</td>
<td>- Injury rate = 1.74 per golfer, 1.51 per male golfer, 2.03 per female golfer&lt;br&gt;- Most common cause of injury reported to be repetitive practice</td>
</tr>
<tr>
<td>Gioe 1982 [122]</td>
<td></td>
<td></td>
<td>(127 males)</td>
<td>(103 males)</td>
<td>(male = 192)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(99 females)</td>
<td>(87 females)</td>
<td>(female = 201)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McCarroll et al.</td>
<td>Male &amp; Female</td>
<td>Amateur</td>
<td>1,144</td>
<td>708</td>
<td>908</td>
<td>Males: 1.low back 2.elbow 3.wrist &amp; hand&lt;br&gt;Females: 1.elbow 2.low back 3.shoulder</td>
<td>- Injury rate = 0.79 per golfer, 0.80 per male golfer, 0.76 per female golfer&lt;br&gt;- Poor swing mechanics and excessive practice cited as most common cause</td>
</tr>
<tr>
<td>1990 [123]</td>
<td></td>
<td></td>
<td>(942 males)</td>
<td>(584 males)</td>
<td>(male = 754)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(202 females)</td>
<td>(124 women)</td>
<td>(female = 154)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batt 1992 [21]</td>
<td>Male &amp; Female</td>
<td>Varied</td>
<td>193</td>
<td>61</td>
<td>61</td>
<td>Males: 1.wrist 2.back&lt;br&gt;Females: 1.elbow 2.shoulder</td>
<td>- Injury rate = 0.37 per golfer, 0.32 per male golfer, 0.28 per female golfer&lt;br&gt;- Overuse and poor swing mechanics reported to be main cause for injuries&lt;br&gt;- Significant number of wrist injuries in young male golfers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(164 males; hcp = 14.2, range 2-24)&lt;br&gt;(29 females; hcp = 23.4, range 5-36)</td>
<td>(cumulative lifetime incidence)</td>
<td>(male = 53)&lt;br&gt;(female = 8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burdorff et al.</td>
<td>Male</td>
<td>Novice</td>
<td>221</td>
<td>124 (cumulative lifetime incidence)</td>
<td>Only reported on LBP</td>
<td>Only reported on lower back pain</td>
<td>- 28% reported having an episode of LBP in the previous month&lt;br&gt;- 48% reported having more than one episode of LBP</td>
</tr>
<tr>
<td>1996 [29]</td>
<td></td>
<td></td>
<td>(12 month follow-up; n = 96)</td>
<td>(12 months lifetime incidence)</td>
<td>(cumulative lifetime incidence)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theriault et al.</td>
<td>Male &amp; Female</td>
<td>Varied</td>
<td>528</td>
<td>Not specified</td>
<td>198</td>
<td>Males: spine / back&lt;br&gt;Females: upper limb</td>
<td>- Injury rate = 0.38 per golfer&lt;br&gt;- Increased frequency of upper limb injuries in females&lt;br&gt;- Most common causes reported by respondents: 1. technical error 2. overtorsion of trunk during swing 3. overuse</td>
</tr>
<tr>
<td>1996 [171]</td>
<td></td>
<td></td>
<td>(347 males)</td>
<td>(181 females)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Gender</td>
<td>Level</td>
<td>Participants</td>
<td>Injuries</td>
<td>Injuries</td>
<td>Mechanisms</td>
<td>Injury Rate</td>
</tr>
<tr>
<td>------------------------------</td>
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</tbody>
</table>
| Sugaya et al. 1999 [166]     | Male & Female | Professional | 282 (113 males; 55 seniors; 113 females) | Not specified | 458 (male = 203; seniors = 102; female = 153) | Males: 1. lower back 2. neck 3. elbow / shoulder / wrist  
Females: 1. low back 2. neck 3. wrist | Injury rate = 1.62 per golfer, 1.80 per male golfer, 1.35 per female golfer  
Players with LBP: 51% right sided, 28% left sided, and 21% central |
| Gosheger et al. 2003 [79]    | Male & Female | Professional and amateur | 703 (54 pro/males & 6 pro/females; 456 am/males & 187 am/females) | 291 (36 professionals; 255 amateurs) | 637 (pro = 110; amateur = 527) | Professionals: 1. lumbar spine 2. wrist 3. shoulder  
Amateurs: 1. elbow 2. shoulder 3. lumbar spine | Injury rate = 0.91 per golfer, 1.83 per professional golfer, 0.82 per amateur golfer  
82.6% of reported injuries due to overuse |
| Fradkin et al. 2005 [67]     | Female  | Varied    | 522 (522 females; median hcp = 17, range = 2-44) | Not specified | 184 | Female: 1. lower back 2. shoulder 3. elbow | Injury rate = 0.35 per golfer  
Strains reported as the most common type of injury (67.9%)  
Overuse followed by technical error most common self-reported cause of injury |
| McHardy et al. 2007 [127]    | Male & Female | Novice    | 588 (473 males; hcp = 17.8 ± 6.5; 115 females; hcp = 26.7 ± 9.2) | 78 (male = 78; female = 15) | 93 | Overall: 1. lower back 2. elbow / forearm 3. foot / ankle 4. shoulder | Injury rate = 0.16 per golfer, 0.17 per male golfer, 0.13 per female golfer  
The golf swing / swing mechanism was the most commonly reported cause (46.2%) followed by overuse (23.7%) |
| Fradkin et al. 2007 [69]     | Male & Female | Varied    | 304 (217 Males; 87 Females; Median hcp = 13) | Not specified | 111 | Overall: 1. lower back 2. shoulder 3. elbow | Injury rate = 0.37 per golfer  
Most common causes were: overuse (30%) & overexertion (26%)  
64% missed participation in golf  
39% missed 1-3 practice sessions while 47% missed 1-3 rounds of golf |

\* Skill level descriptions are based on terminology used in each particular study and as a result can vary depending upon an author’s definition  
\* Actual injuries = 72, although 11 were omitted as they were the result of a third party or a minor / incidental ailment. E.g. struck by ball, bee attack  
\* Injury rate per golfer is based upon total number of injuries divided by questionnaire respondents (injuries / respondents). Figures may vary in actual articles as some base injury rate on total injuries divided by number of injured players
2.4 Methods used to examine golf swing kinematics

Over the past two decades a wide variety of methodological approaches have been adopted in studies of swing kinematics, making comparisons between published results difficult. The intent of the following section is to provide a summary of the major biomechanical approaches used in golf research and outline some of the benefits and limitations of each approach.

2.4.1 Biomechanical techniques used to measure swing kinematics

The majority of devices used to examine golf swing kinematics to date, have been optical based systems which generally involve the use of one or more cameras often in conjunction with markers attached to the body of interest [28, 38, 40, 93, 134, 139, 142, 157]. Optical based systems afford a certain amount of flexibility, as different camera types can be used such as conventional high-speed film cameras, generic or standard video cameras, high-speed video cameras and cameras that sense electronic wave signals (i.e. infrared cameras). Besides optical devices, the two other major systems used to measure golf swing kinematics have been electrogoniometer devices and electromagnetic tracking systems [33, 117, 118, 132, 140]. Ultimately the aim of each system is similar in that accurate and repeatable measurement of golf swing kinematics is required.

2.4.2 Two-dimensional and three-dimensional video analysis

Quantitative two-dimensional (2D) video analysis is a simple, cost effective way of analysing common sporting tasks such as the golf swing. The basic concept of 2D
video analysis is a simple linear transformation from image to ‘movement-plane’
coordinates using a scaling object (e.g. 1 m rule) in the camera field of view [20]. A
particular task is recorded by a single video camera, and anatomical landmarks such
as joint centres are identified and digitized. Digitized points are subsequently used to
calculate linear and angular positions and displacements as a function of time.

Considerable limitations exist in the use 2D analyses of the golf swing. A single video
camera can only reveal quantitative information in 2D and as the golf swing involves
the rapid movement of many body segments in all three planes of movement, the loss
of valuable information is inevitable. Furthermore, attempting to examine a 3D
movement using a 2D analysis technique results in problems such as perspective and
parallax error [147]. Other acknowledged limitations include the need to control
lighting and hence the environment the task is captured in, potential errors in manual
or automatic digitization procedures, and the difficulty in analysing rapid motions
with video based devices that have low sampling rates [7, 20, 81]. Of the studies that
have examined golf swing kinematics using 2D video or film, most have focused on
the upper limbs and club segments. While these early studies revealed details about
the importance of late wrist uncocking in generating high clubhead speeds [134, 142],
few have described the 3D motion of the larger more proximal segments during the
swing.

The obvious progression from 2D video analysis is to 3D analysis using two or more
video cameras. Technological advancement, ease of access and the desire for a more
accurate and thorough description of the complex motion of the golf swing has
contributed to the increased use of 3D analyses [7, 52]. Similar to 2D analyses,
‘scaled’ 3D positional data are required for the information collected to be of any real use. The derivation of 3D positional data is a somewhat more complicated task than simply placing a scaling object in the capture volume. Replacing the scaling object used in 2D analysis is a calibration object, which has at least six control points or coordinates. Some type of algorithm is then required to transform the ‘video image’ coordinates from the calibration trial to ‘movement-space’ coordinates, whereby independent transformation parameters are applied to each camera [20]. The most common method used is the Direct Linear Transformation algorithm first introduced by Abdel-Aziz and Karara [2]. Once the relevant camera calibration procedures have been undertaken, 3D video analysis requires that the captured data be digitised. Typically, marks on the skin or attached markers used to identify the underlying bone segments are manually digitized for each frame of the captured trial. Some of the more recent 3D systems can automatically track manually identified points, however, a major drawback of such systems are errors associated with auto-tracking particularly when markers are in close proximity. Moreover, many of the aforementioned limitations and assumptions associated with 2D video analyses also remain true for 3D video analyses. For further information, errors associated with the common assumptions of rigid body mechanics such as relative and absolute marker movement, and incorrect marker placement are discussed in Chapter 3.

### 2.4.3 Three-dimensional electro-magnetic tracking systems

Electromagnetic tracking systems (EMTS) are a relatively new biomechanical tool that researchers have used to examine the kinematics of the golf swing [33, 63, 140, 174]. EMTS utilise a source or transmitter in conjunction with one or more light weight sensors, tethered to the body segments of interest. Both the transmitter and the
sensors contain three orthogonal coils. By sequentially supplying a current to each of the coils in the transmitter, three magnetic fields are generated [7, 107]. In each orthogonal coil of the respective sensor, the measured magnetic fields will generate proportional currents that are used to calculate a set of three linearly independent vectors signifying the direction and strength of the magnetic fields. From these vectors, position \((x, y, z)\) and orientation \((\text{azimuth}, \text{elevation}, \text{and roll})\) of each sensor relative to the transmitter can be calculated. The accuracy of EMTS is generally high [84, 107], with rates of 0.25 mm for positional data and 0.1° for orientation data being reported [136]. This equates to error rates of ~ 2%.

In addition to good accuracy, other advantages of using an EMTS to analyse the golf swing are its ability to be used in a field-based setting and its ability to collect unobstructed data due to the golfer’s body being transparent to the magnetic fields. Cheetham and colleagues [33] were one of the first groups to take advantage of an EMTS to examine golf swing kinematics. While the methodological procedures used were not fully described, Cheetham et al., [33] did provide insight into the relationship between thorax and pelvis motion during the golf swing and prompted others to investigate similar kinematic measures [40, 138, 140, 192].

Like any measurement device, EMTS have several limitations when used to analyse golf swing kinematics. EMTS can suffer from electromagnetic interference from metallic objects that are in close proximity to the sensors [7, 107, 133, 136]. Meskers et al. [133] reported that the steel reinforced concrete floor in their calibration experiment lead to considerable inaccuracies in positional and orientation data. Metal is also the primary material used in the construction of most golf clubs, making it very
difficult to record information about the club during the swing. Club data is essential if critical points during the swing, such as BC, are to be defined. Another limitation that should be considered is the tethering of sensors to the golfer which could potentially affect their swing, particularly when multiple sensors are used. This is an important consideration for EMTS, as kinematics have been shown to be altered in golfers when tethered to electromyographic equipment [55].

2.4.4 Three-dimensional optoelectronic systems

Optoelectronic systems are considered to be the gold standard of motion analysis based devices [17], and have become increasingly popular among researchers investigating golf swing kinematics [41, 42, 54, 56, 83, 115, 137, 138, 180, 192, 193]. Multiple video-based cameras positioned around a capture volume emit infra-red light onto small reflective markers attached to the subject of interest. Reflected light from each visible marker is then optically detected by the infra-red light sensitive chip within each camera. This information is electronically converted to data containing the 2D location in space [81]. Data converting procedures occur quickly, enabling some systems to sample at rates as high as 2000 Hz. The passive reflective markers are small in size (5 - 30 mm diameter) and typically constructed from light weight plastic material. Unencumbered movement during the golf swing is an important feature, and makes optoelectronic systems particularly amenable to golf researchers. Residual errors as low as 1 mm for reconstructed data have been quoted in the literature [81, 84]. Following calibration, trajectories of specifically placed markers can be captured and reconstructed into 3D coordinates.
With regard to golf swing analyses, the use of optoelectronic systems have two main advantages over other video based systems and EMTS. Compared to video, processing times are dramatically reduced as there is no need for manual digitization of data points. Most optoelectronic cameras carry powerful onboard processors, allowing for not only reduced processing times but also high sampling rates. Secondly, the small light weight markers used by optoelectronic systems mean that markers can be placed on the golf club, allowing for the recording of important information about the golf club and the definition of critical events such as BC. High sampling rates also contribute to this process.

Despite the advantages associated with optoelectronic systems, some limitations do exist. Optoelectronic cameras detect reflections from markers, therefore if markers are obscured from view (usually by the subjects body), marker data cannot be captured. Additionally, each marker must be visible by at least two cameras for the reconstruction of data into 3D. Through the use of multiple astutely positioned cameras around the capture volume, the issue of marker obstruction can usually be minimised [7, 81]. A further drawback when using optoelectronic systems is the need to carefully control the capture environment. This usually involves capturing data in an indoor facility, where lighting can be easily controlled. For golf studies, this means creating a simulated environment where the golfers are most likely to hit from an artificial grass mat into a net. Some argue such environments are not ecologically valid, potentially affecting the way an individual performs the swing. Nevertheless, all currently available biomechanical measurement systems used to analyse golf swing kinematics exert some sort of constraint on the golfer or their environment and, until technology permits, minimisation of these constraints is the most feasible solution.
2.5 Summary

- The full golf swing is a complex full body movement that involves coordinating the motion of many body segments in an effort to consistently and accurately contact the ball with a high clubhead velocity.

- Of the four phases commonly used to describe the golf swing (address, backswing, downswing and follow-through), it is the downswing, where rapid coordinated motion of the trunk and arms occur, that is considered most critical for hitting the ball accurately.

- In skilled golfers, segmental movement of the upper body occurs in a consistent and sequential proximal-to-distal pattern, which is thought to assist in the development of high end-point speeds through the summation of speed principle.

- No uniform methodological approach for examining golf swing kinematics has been developed or adopted, meaning that direct comparisons between most studies are not possible.

- Investigations of upper body swing kinematics in skilled golfers have largely revolved around measures of thorax and pelvis axial rotation at discrete swing events, with very few reports of other directions or of the coordination between segments throughout the swing.
Little is known about the swing kinematics of skilled female golfers, with only two preliminary investigations reporting selected lower and upper body kinematic variables at address, TBS and BC.

Gender disparities in the anatomical location of injury lend support to the importance of examining and comparing the swing kinematics of male and female skilled golfers.

While a variety of methods have been used to examine golf swing kinematics, the use of 3D optoelectronic systems offer such advantages as high accuracy, high sampling rates and being relatively unobtrusive in nature.

A combination of analyses including velocity comparisons, phase planes, angle-angle plots and vector coding has the capacity to provide a greater understanding of the dynamics and coordination of the trunk during the golf swing than discrete orientation measures alone.
Chapter 3 - Development and refinement of methods
3.1 Introduction

Although the biomechanics of the golf swing has been investigated for a number of decades, there has been limited consistency in methods of data collection, data analysis, and in the reporting of results. A lack of detailed reporting of the biomechanical modelling procedures adopted by investigators has also further complicated this issue. This often makes it difficult for the reader to replicate the procedures employed in an experiment or even interpret the results of a study. Detailed reporting of methods is an important consideration, as comparing golf swing kinematics between subsets of golfers, or simply different experiments, is challenging when modelling procedures are not clear.

Biomechanics researchers typically strive to achieve best-practices in methods when investigating a common task. For example, walking gait has been extensively evaluated and much effort has been devoted to developing consistent kinematic and kinetic modelling approaches during walking so that data can be appropriately interpreted by clinicians and researcher alike [7, 147, 187, 188]. Overall, consistency of methods in the context of gait analysis has enhanced the ability to formulate rehabilitation or intervention strategies to assist individuals with walking impairments. To date there has not been a comprehensive approach taken in the evaluation of the golf swing. Such an approach should be considered by the golf community where analytical techniques need to be addressed using first principles, and the methods should be developed that exploit state of the art motion analysis technology.
Given there has been no such comprehensive evaluation of the golf swing, this chapter describes in detail the development of the methods used throughout this project. Specifically, the instrumentation, marker placement, and kinematic modelling procedures employed are elaborated upon to ensure clarity in regard to the experiments performed in this thesis.

3.2 Identifying key variables for analysis

As mentioned previously, a fundamental goal of the golf swing, and in particular the driver swing, is to propel the ball for maximum distance while ensuring accuracy of direction. The distance the ball travels is directly related to the velocity of the clubhead at the point of contact with golf ball and is largely determined by the intrinsic forces generated by the golfer [95, 151]. Due to the difficulty of measuring intrinsic forces, most golf researchers have examined angular displacement and angular velocity of body segments and joints during the golf swing, with both being related to force through Newton’s 2nd law \( F = ma \). Only moderate agreement exists regarding which segment and joint kinematic parameters to examine. In addition to various upper limb kinematic parameters, examination of axial rotation of the more proximal segments such as the thorax and pelvis have been most popular, probably due to the swing being widely viewed as a rotational motion. Furthermore, the commonly referred to proximal-to-distal sequence of movement principle [27, 153], has also likely influenced researchers interest in examining the larger more proximal segments.
Figure 3.1 A combination of wall and tripod mounted cameras placed in locations that minimised marker occlusion during the swing were used in this project. Optimal camera positioning was determined through pilot testing of a small group of golfers who were heterogeneous in physical stature.

This project primarily focuses on 3D angular motion and velocity of the larger proximal segments, including the thorax and the pelvis, and also the relative motion between both segments. Additionally, thorax-pelvis separation angle (X-Factor) which is defined as thorax planar rotation relative to pelvis planar rotation, was a focus of examination. While shot accuracy was beyond the scope of this project and not directly examined, maintaining accuracy of the task was critical. All golfers were given a consistent set of instructions such that they were requested to address the ball in a neutral position, imagine they were on the tee and hit their usual driver shot as straight as possible. Two vertical lines 0.5 m apart on the net were used as a guide,
with any shot that was not hit within the lines deemed ineligible and another driver swing was collected.

### 3.3 Motion capture system

A Vicon MX motion capture system (Vicon™, Oxford Metrics, Oxford, UK) consisting of eight MX13 cameras, MX hardware (1 × MX Net, 1 × MX Link and 1× MX Control) and MX software was used to examine 3D swing kinematics in this project. Pilot testing of a small group of golfers revealed that a combination of wall and tripod mounted cameras provided the least amount of marker occlusion (Figure 3.1).

The MX13 cameras feature multiple high-speed processors which perform real-time proprietary image processing (Figure 3.2). Each camera is made up of a distinct video camera, strobe head unit, lens and optical filter. The MX13 has a resolution of 1.3 million pixels (1280 horizontal × 1024 vertical) and is capable of capturing at 482 frames per second (fps) at full resolution. Frame rates of up to 2000 fps can be utilised, however such high frame rates lead to some windowing of the vertical image size. With effective aiming and calibration, issues associated with vertical windowing can be minimized. Each MX13 uses a CMOS sensor with an aspect ratio of 5:4, and rather than applying a black and white threshold, evaluates entire images using greyscale which enhances motion measurement accuracy [1]. The strobe unit on each camera emits near-infrared light which illuminates reflective markers that are attached to the subject. Reflected strobe light then passes through the lens filter, which only allows light through with the same spectral characteristics as the emitted strobe light,
Development and refinement of methods

which in turn is focused onto the cameras sensor plane as an image [1]. Each MX camera performs the majority of processing on-board, before marker trajectory data is sent to Vicon application software on a networked PC. The benefit of on-board processing is that high sampling rates can be captured easily and data reviewed for issues such as dropout in a timely manner.

**Figure 3.2** Eight VICON™ MX13 near-infrared cameras were used to collect retro-reflective marker data from markers placed on each subject. The MX13 camera has a resolution of 1.3 million pixels and a maximum sampling rate of 2000 fps.

Vicon Workstation version 5.1 (Vicon™, Oxford Metrics, Oxford, UK) software was used to capture marker trajectory data in this project. The reflective markers were 14 mm in diameter, and attached using low-allergenic double sided tape (Tesa, Pty. Ltd., Sydney, Australia) (see section 3.4 for details on marker placements). To allow for the identification of ball and club parameters, a sampling frequency of 500 Hz was used. At 500 Hz there was minimal vertical windowing, which still enabled effective coverage of the capture area. Calibration procedures associated with Vicon Workstation were undertaken in accordance with the manufacturer guidelines. The Vicon MX calibration procedure involves identifying both internal (focal length and
image distortion) and external (camera position and orientation) camera parameters, using a dynamic calibration process [1]. The simultaneous procedures of ‘Linearization’ (where optical distortion for each camera is calculated) and ‘Photogrammetric Calibration’ (where physical locations and orientations of cameras are calculated) determine camera parameters and apply appropriate corrections [1]. The dynamic calibration procedure was performed by using a 3-marker wand in the capture volume (4 × 4 × 3.5 m), which was followed by a static calibration procedure using a calibration frame to set the global coordinate system (GCS). In this project camera residuals less than 1 mm were deemed acceptable.

### 3.4 Marker placement and coordinate systems

Before a kinematic model can be developed, appropriate segment and reference coordinate systems must be selected. The following section outlines the rationale for marker locations used for the thorax and pelvis segments in this project and also details the marker location and derivation of the local coordinate system (LCS).

#### 3.4.1 Thorax

Thorax marker placement can be problematic when analysing the golf swing, as motion of the arms can potentially occlude markers attached to the chest or shoulder region. A variety of marker placements have been used by researchers, with some attaching markers over the shoulders (acromia), rather than the more difficult to visualise thorax segment [40, 54, 56, 115, 137, 138, 192, 193]. Acromia based markers can be problematic when modelling the trunk or thorax during the golf swing, as overestimation errors have been found to occur. Wheat et al. [180] and Nguyen and
Baker [146] have investigated how direct (markers attached directly to the thorax) and indirect (markers attached over the acromia) marker configurations affect the calculation of upper body kinematics. Wheat et al. [180] compared the calculation of thorax rotation angles of actual golf swing data, using a direct and indirect marker placement approach. At TBS, the indirect method overestimated thorax rotation by as much as 15° compared to the direct method. Nguyen and Baker [146] found similar results in their investigation comparing thorax kinematics in children with pathological gait using several different marker and modelling approaches. In their study, the indirect marker placement method resulted in thorax lateral tilt and rotation differences of 10° and 5°, respectively, compared to the direct marker placement method. Both studies highlight the need to carefully consider marker placements that can model the true movement of the body segment under investigation. Therefore, it was critical that a direct marker method approach should be adopted for the examination of thorax motion in the current project.

Four markers were used to represent the thorax (Figure 3.3) and were placed over (i) the spinous process of the seventh cervical vertebrae (C7), (ii) the spinous process of the tenth thoracic vertebrae (T10), (iii) the sternal notch, and (iv) the xiphoid process of the sternum. These marker placements are in agreement with those published by the Standardization and Terminology Committee of the International Society of Biomechanics [189].
Figure 3.3 The four thorax markers used in this project and the axes of the thorax coordinate system derived from the four markers.

From the marker placements described, a thorax coordinate system was derived where the origin was coincident with mid-point between the C7 and sternal notch markers (O_{Thx}). The z-axis was a vector (passing through O_{Thx}) directed from the mid-point of the T10 and xiphoid markers to the mid-point of the C7 and sternal markers. The y-axis was the cross product of the vector (passing through O_{Thx}) directed from the midpoint of the C7 and T10 markers to the mid-point of the sternal and xiphoid markers and the z-axis unit vector. Lastly, the x-axis was the cross product of the z- and x-axis unit vectors.
3.4.2 Pelvis

The pelvis is arguably a simpler segment to examine compared to the thorax given that marker occlusion is not as pronounced for the pelvis during the golf swing, the bony anatomical landmarks used are easy to locate, and the pelvis is a more accurate representation of a rigid body than the thorax. While the majority of biomechanical studies have used the anterior-superior iliac spine (ASIS) and posterior-superior iliac spine (PSIS) landmarks as marker reference points, some studies have placed markers on the iliac crests [10, 162]. Iliac crest configurations may improve visualisation when a low number of cameras are used, however an increased amount of soft tissue over the iliac crests compared to the ASISs and PSISs may lead to problems with accurate landmark identification and marker movement artefact [34, 114, 188].

In accordance with the recommendations in the study published by the Standardization and Terminology Committee of the International Society of Biomechanics [188], this project utilized four markers placed over four specific anatomical landmarks of the pelvis (Figure 3.4). These landmarks included (i) the right ASIS (ii) the left ASIS (iii) the right PSIS and (iv) the left PSIS.
Figure 3.4 The four pelvis markers used in this project and the axes of the pelvis coordinate system derived from the four markers.

Using the four pelvic markers described, the origin of the pelvis coincided with mid-point between two ASIS and two PSIS markers (O_{Pel}). The $y$-axis was a vector (passing through $O_{Pel}$) directed from the right ASIS marker to the left ASIS marker. The $z$-axis was the cross product of the vector (passing through $O_{Pel}$) directed from the midpoint of the two PSIS markers to the mid-point of the two ASIS markers and the $y$-axis unit vector. Lastly, the $x$-axis was the cross product of the $y$- and $z$-axis unit vectors.

3.4.3 Filtering marker trajectories

Filtering is an important procedure in biomechanical analyses where unwanted fluctuations (commonly categorised as noise) are removed from a signal. In the case
Development and refinement of methods

of 3D motion capture, where reflective markers are attached to the skin, noise can occur due to marker related movement artefact, marker dropout and unwanted reflective signals from other objects [34]. Digital filtering is a convenient and efficient method for removing these unwanted signals, however, the frequency range allowed to pass through must be determined prior to implementing the filtering routine. According to Enoka [60], an effective method for determining an appropriate cutoff frequency \( f_c \) is to undertake a residual analysis [73, 184]. This involves examining the difference (i.e. the residual) between the filtered and unfiltered signal at a range of \( f_c \)'s, to determine the optimal \( f_c \) which eliminates unwanted noise while not distorting the true signal.

In this project, residual analyses were performed on raw marker trajectories to determine optimal \( f_c \)'s for all markers and all subjects [60, 73, 184]. Data was filtered in 1 Hz increments from 1 Hz to 12 Hz and each filtered signal was compared to the original signal to determine residuals for each cutoff frequency. A linear regression line was fitted \( (R^2 = 0.85) \) to the residuals, and extended all the way to the y-axis. From this intercept, a line parallel to the x-axis was projected back to the residual curve and subsequently dropped down to the x-axis to determine the optimal \( f_c \) (See Figure 3.5) [154, 184]. Optimal \( f_c \)'s were then used in the filtering routine, whereby raw 3D marker trajectories were low pass filtered using a zero-lag fourth-order Butterworth digital filter in Matlab version 7.6.0 (MathWorks, Natick, MA).
Figure 3.5 An example of a residual analysis plot for the right ASIS marker for a female driver swing. The plot demonstrates an optimal cutoff frequency of 6 Hz based on a regression line fitted to the residuals ($R^2 = 0.85$). Filtering below this cutoff frequency would result in over filtering and distortion of the true signal.

3.4.3 Local coordinate system

The majority of golf kinematic studies to date have either reported incomplete methods concerning what reference frame was adopted in segment orientation calculations, or calculated body segment kinematics relative to a laboratory based GCS. The former is problematic as the results from these studies are difficult to interpret, and replicating each study is not possible based on the published methods. The latter is problematic as no two setup positions are exactly the same, whether it is from trial-to-trial or subject-to-subject. If a GCS is employed, there is a potential to decrease the accuracy of absolute segmental movement and therefore artificially
inflate variability [191]. For example, if a golfer adopts a different position between each trial where their alignment with a target may be different by say, 10°, there will be a 10° offset in kinematic data between trials. A body-centric LCS has the potential to reduce these offsets, as the coordinate system will adjust according to the golfer’s stance.

**Figure 3.6** A diagrammatical representation of the general setup of the golfer at ball address including the artificial grass mat, the ball, the left and right calcaneus markers, and the local coordinate system (LCS) used in this project.
To enhance intra-subject and inter-subject measurement accuracy, a LCS based on each individual golfer was created (Figure 3.6). The origin of the LCS was the mid-point between two markers placed over the right and left calcanei (O_{LCS}). The y-axis was a vector directed from the right calcaneus marker to the left calcaneus marker, the z-axis coincided with the GCS z-axis unit vector (passing through O_{LCS}) and the x-axis was the cross product of the y- and z-axis unit vectors.

### 3.5 Segmental motion

The 3D segment orientations reported in this project were calculated using Euler angle calculations. Euler angles involve a rotation matrix being parameterized in terms of three independent angles. An ordered sequence of rotations of a coordinate system are performed to give the attitude of one coordinate system (e.g. the pelvis) relative to another (e.g. the LCS) [46, 147]. The Euler angle method is widely used in biomechanics as it provides a representation of segment or joint orientation which is analogous to the anatomical representation that both clinicians and researchers commonly use [147, 191]. Although Euler angles are sequence dependent, the appropriate standardization of the sequence or order used by different researchers will allow for results to be more easily compared. In this project the relatively common sequence of sagittal (anterior-posterior tilt), coronal (lateral tilt) and transverse (axial rotation) plane rotation was used as recommended by both Nigg [147] and Zatsiorsky [191].
3.5.1 Segmental motion relative to LCS

The 3D orientations (attitude) of both the thorax and pelvis segments were calculated relative to the anatomical LCS described in section 3.4.3, using the Euler angle method. The order for both the thorax and pelvis were sagittal, coronal and transverse plane (y, x, z) rotation of each segment onto the LCS. Anti-clockwise rotations for the thorax and pelvis were deemed positive (Table 3.1). It should also be noted that linear displacement for each segment was calculated as the translation along each segments x-, y- and z-axes.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Axis</th>
<th>Positive Rotation</th>
<th>Direction</th>
<th>Reference Frame (child &gt;&gt; parent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorax</td>
<td>y</td>
<td>Anterior tilt</td>
<td>Anti-clockwise</td>
<td>Thorax &gt;&gt; LCS</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>Right lateral tilt</td>
<td>Anti-clockwise</td>
<td>Thorax &gt;&gt; LCS</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>Left axial rotation</td>
<td>Anti-clockwise</td>
<td>Thorax &gt;&gt; LCS</td>
</tr>
<tr>
<td>Pelvis</td>
<td>y</td>
<td>Anterior tilt</td>
<td>Anti-clockwise</td>
<td>Pelvis &gt;&gt; LCS</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>Right lateral tilt</td>
<td>Anti-clockwise</td>
<td>Pelvis &gt;&gt; LCS</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>Left axial rotation</td>
<td>Anti-clockwise</td>
<td>Pelvis &gt;&gt; LCS</td>
</tr>
<tr>
<td>Thorax-pelvis</td>
<td>y</td>
<td>Anterior tilt</td>
<td>Anti-clockwise</td>
<td>Thorax &gt;&gt; Pelvis</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>Right lateral tilt</td>
<td>Anti-clockwise</td>
<td>Thorax &gt;&gt; Pelvis</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>Left axial rotation</td>
<td>Anti-clockwise</td>
<td>Thorax &gt;&gt; Pelvis</td>
</tr>
</tbody>
</table>
3.5.2 Inter-segmental motion

The relative 3D motion between the thorax and pelvis segments was also calculated in this project. The thorax was deemed the ‘child’ and the pelvis deemed the ‘parent’, meaning that inter-segmental motion was represented as thorax motion relative to pelvis motion. The order was sagittal, coronal and transverse plane (y, x, z) rotation of the thorax onto the pelvis.

3.5.3 Thorax-pelvis separation angle - ‘X-Factor’

Thorax-pelvis separation angle (X-Factor) is a commonly reported variable in studies of golf swing biomechanics and generally refers to the difference between thorax and pelvis rotation throughout the swing. It has frequently been reported as an important determinant of golf swing performance [4, 28, 40, 95, 128, 138], however inconsistency in results between studies has somewhat devalued its importance. It seems very likely that the reason for the inconsistency between studies is the variation in methods used to calculate the separation angle. The methods used have included:

1. Calculating the difference in ‘hip’ and ‘shoulder’ rotation based on an external electrogoniometer attached to each golfer’s upper and lower body, where data from six potentiometers was used to determine hip and shoulder rotation [132];

2. Calculating the difference between ‘hip’ and ‘shoulder’ angles from 3D video data, which were defined as the angles between a line parallel to the target and
a line joining the hip joint centre and shoulder joint centre, respectively [28, 40];

3. Calculating the difference in rotational position of the thorax and pelvis based on axial rotation data from electromagnetic sensors attached to the respective segments [33];

4. Calculating the difference between pelvis and ‘upper torso’ rotation angles from 3D motion analysis data [138]. Pelvis rotation was calculated as the angle about the long axis (i.e. vertical) of the pelvis and the global x-axis, and ‘upper torso’ rotation was calculated as the angle about the long axis (i.e. vertical) of the torso and the global x-axis [138]. Thorax-pelvis separation angle was the difference between these two angles.

McLean [128] first described thorax-pelvis separation angle as the difference, between ‘hip’ and ‘shoulder’ turn during the backswing when viewed from above. This description implies that both ‘hip’ and ‘shoulder’ turn are projected on to the horizontal plane. Therefore, to describe this interaction from a mechanical perspective, thorax-pelvis separation angle is the difference between thorax and pelvis axial rotation angles projected onto the horizontal plane (x-y plane).

The cross product of the angle created by the thorax and pelvis x-axis unit vectors projected onto the x-y plane of the LCS defines the thorax-pelvis separation angle in this project. Therefore when the thorax and pelvis are closely aligned, such as ball address, the thorax-pelvis separation angle is close to 0° (Figure 3.7). A negative
separation angle indicates pelvis planar rotation is leading thorax planar rotation (i.e. toward the target), with a more negative value representative of greater separation between thorax and pelvis angles. A positive separation angle indicates thorax planar rotation is leading pelvis planar rotation (i.e. toward the target).

Figure 3.7 Thorax-pelvis separation angle (X-Factor) for a skilled female golfer is displayed. The first vertical line represents TBS, while the second vertical line represents BC. The area bounded by these two lines is the downswing phase, and is typically where thorax-pelvis separation angle reaches its minimum or peak value.

3.6 Angular velocity

Angular velocity measurements in golf studies have typically been calculated as the time derivative of segment orientation data. However, quantifying angular velocity of a rigid body in 3D space is considerably more complicated than simply differentiating angular displacement. Perhaps the most overlooked feature in angular velocity calculations is that differentiating angular displacement reveals the relationship
between position and velocity, which is not equivalent to the relationship between segment orientation and angular velocity. This is described in detail by Zatsiorsky [191] who states that “because of the non-vectorial nature of the finite angular displacement, angular velocity is not equal to a time derivative of the orientation angle and cannot be obtained by immediate differentiation of any set of attitude angles” (pp.183). Therefore, it is misguided to simply calculate the first derivative of the angular displacement data described in Section 3.6 and assume this represents the true angular velocity of segments.

The complexity of examining a rigid body moving in 3D space is further illustrated by the fact that angular velocity vectors cannot simply be integrated to provide orientation information [58], which is possible for velocity-position relationships. While the integral of angular velocity can be calculated, it represents the traveled angular distance and not the corresponding orientation [191]. Determining the orientation of a rigid body through the integration of angular velocity, does not give a unique answer as the order of rotation affects the end result. To illustrate this, consider the example in Figure 3.8 (a) where the rigid body first rotates about the Z axis at an angular velocity of 90°/s (0, 0, 90°) followed by the X axis at a an angular velocity of 90°/s (90°, 0, 0). The rigid body will arrive at the position denoted by Jₙ after one second, followed by the position denoted by J₂ after a further second. Now consider changing the sequence of rotations (b), so that the first rotation is about the X axis and the second rotation is about the Z axis. This will result in a final position, K₂, which is different from J₂.
A more appropriate method for determining angular velocity is via direct transformation of the rotation matrix and its transpose [191]. A rotation matrix, \( R \), can be used to describe the relative attitude of two reference frames:

\[
R = \begin{bmatrix}
\cos X_x & \cos X_y & \cos X_z \\
\cos Y_x & \cos Y_y & \cos Y_z \\
\cos Z_x & \cos Z_y & \cos Z_z
\end{bmatrix}
\]  
(3.1)

In the context of this project, the rows of the rotation matrix (Eq. 3.1) describe the axes of the LCS (denoted by the upper case subscripts), whereas the columns of the rotation matrix describe the axes of the particular segment of interest (denoted by the
lower case subscripts). The columns are often referred to as the direction cosines, or the unit vector components (x, y, z axes), defining the orientation of each segment axis relative to the LCS frame [31]. Figure 3.9 illustrates how the relative attitude of two coordinate systems can be determined from the orientation of individual axes. In the illustration, α is the direction angle of Xx, β is the direction angle of Yx, and γ is the direction angle of Zx for a single axis. These combinations of angles fully describe the relationship between the single segment axis and the LCS. Direction angles are again determined for the remaining axes, (Xy, Yy, Zy, and Xz, Yz, Zz), to complete the rotation matrix.

Figure 3.9 A diagrammatical explanation of how the three direction angles for the x-axis unit vector of the segment of interest (e.g. thorax) are calculated relative to the LCS. For clarity the direction angles of the y- and z- axes unit vectors of the segment of interest have been omitted. Adapted from Zatsiorsky [191] pp.41.
As segment angular velocity depends on both (i) the rate of change of the direction cosines and (ii) the orientation or attitude of a segment, the Poisson equation described by Zatsiorsky [191] and Craig [46] should be used rather than simple differentiation of a set of orientation angles. The Poisson equation accounts for both the rate of change of the direction cosines (\( \tilde{\mathbf{R}} \)) and the orientation of the segment (\( \mathbf{R}^{-1} \)), and is given by:

\[
\begin{bmatrix}
\dot{\theta} \\
\end{bmatrix} = \begin{bmatrix}
\tilde{\mathbf{R}}
\end{bmatrix} \mathbf{R}^{-1}
\]

(3.2)

where the angular velocity matrix, \( \dot{\theta} \), of each segment with respect to the LCS is determined by multiplying the differentiated rotation matrix, \( \tilde{\mathbf{R}} \), by the inverse of the rotation matrix, \( \mathbf{R}^{-1} \). This method gives a true representation of angular velocity, and can differ quite considerably from the simple derivative method (Figure 3.10). In this project the Poisson method was used for both the thorax and pelvis relative to the LCS, and for the thorax relative to the pelvis (i.e. angular velocity of inter-segmental motion).
Figure 3.10 In the upper plot thorax lateral tilt angle during the driver swing of a skilled male golfer is presented. The lower plot presents the corresponding angular velocity profile using two different methods; the derivative method and Poisson equation method. The difference in velocity profiles between the two methods, including differences in peak values, can be clearly seen.

3.7 Summary

This chapter has provided a detailed explanation and justification of the methodological procedures developed in this project, with particular emphasis on the biomechanical modelling procedures adopted. The described methods can be easily replicated by other researchers and will assist in determining actual or ‘real’ differences between various cohorts of golfers. While certain constraints may prohibit researchers from replicating all procedures, a concerted effort should be made to at
least implement the principles outlined and demonstrate the same level of transparency offered in this chapter.
Chapter 4 - Thorax and pelvis kinematics during the downswing of male and female skilled golfers
This chapter has been published as an original paper in the Journal of Biomechanics. Horan, S.A., K. Evans, N.R. Morris, and J.J. Kavanagh (2010). Thorax and pelvis kinematics during the downswing of male and female skilled golfers. *Journal of Biomechanics, 43*(8):1456-1462. Figure and table numbers have been adapted to comply with the formatting of the thesis and the reference list has been omitted with references for this chapter included in the reference list for the entire thesis.

### 4.1 Introduction

In professional golf, male golfers typically generate higher clubhead speeds and therefore hit the ball further than female golfers [193]. While gender differences in physical characteristics may influence performance variables such as clubhead speed [98], it is also likely that differences in swing mechanics will influence performance outcomes. To date, detailed 3D kinematic profiles of the male and female golf swing, and in particular the downswing where there is a rapid expenditure of energy to generate high clubhead speeds, have not been reported. Understanding the mechanics required to perform the downswing is an essential precursor to improving performance, or reducing the occurrence of injury which differs between genders according to anatomical location [122].

Anecdotally, it has been suggested that optimally coordinating thorax and pelvis motion at the TBS and during the downswing enhances the power generated by active and passive structures of the trunk during the downswing [33]. Therefore, subgroups of golfers who are suggested to have different power output, such as males and
females, may exhibit subtle differences in movement patterns. Of the limited gender-related data available, it has been reported that skilled female golfers achieve a greater absolute rotational range of motion for the pelvis and the thorax than males during the full swing [56, 193]. However, differences observed in the absolute range of movement of the pelvis and the thorax do not necessarily reflect the dynamics of the task, or if differences in control exist between genders. Furthermore, the aforementioned findings were derived from plane-projection techniques of motion analysis, where six degrees of freedom for segmental motion cannot be fully described [191].

Axial rotation, anterior tilt and lateral tilt of the thorax and pelvis have been frequently reported for male golfers at discrete time points in the swing such as TBS and BC [28, 57, 132, 138, 192]. While these discrete data have provided valuable insight into golf swing characteristics, the dynamics of the task are still unclear [19, 77, 158]. Examining angular velocity of the adjacent thorax and pelvis segments can reveal how the neuromuscular system controls segment motion [156], and can also lead to an appreciation of how the final endpoint velocity of the golf club is achieved [151, 153]. Despite the importance attributed to high segmental angular velocities, thorax and pelvis velocities have only been reported at discrete events during the golf swing [115, 138, 192], most notably for the peak axial rotation velocity achieved during the swing [138, 192].

The purpose of this study was twofold. Firstly to present detailed 3D kinematic profiles of thorax and pelvis movement during the downswing, and secondly to determine if differences in 3D kinematics of the thorax and the pelvis exist between
male and female skilled golfers. It was hypothesized that female golfers would achieve greater thorax and pelvis axial rotation at TBS and BC than males. It was anticipated that males would achieve greater peak velocity, and greater velocity at BC, for all movement directions of the thorax and pelvis compared to females. It was also hypothesized that gender-differences would exist in the angular velocity-displacement relationships of the thorax and the pelvis during the downswing.

4.2 Materials and methods

4.2.1 Subjects

Nineteen male and nineteen female golfers volunteered to participate in the study (Table 4.1). All golfers were right-handed, free from injury at the time of testing, and were either playing or trainee golf professionals or competitive amateur golfers (handicap ≤4). For the purpose of this study playing and trainee golf professionals were credited with a handicap of 0. Written informed consent was obtained prior to data collection and all experimental procedures were approved by the Griffith University Human Research Ethics Committee.

4.2.2 Procedures

Four 14 mm retro-reflective markers were attached to the pelvis on the right and left anterior superior iliac spines (ASIS), and the right and left posterior superior iliac spines (PSIS) (Figure 4.1). Four markers were attached to the thorax over the suprasternal notch, xiphoid process, C7 spinous process and T10 spinous process. Markers were placed directly on thorax landmarks as shoulder based markers
overestimate thorax lateral tilt and axial rotation [146, 180]. Clubhead trajectory was tracked via a marker attached to the subject’s driver. To create a local coordinate system (LCS) for analysis (section 4.2.3), markers were attached to the right and left heel of the subject’s golf shoes which approximated the calcanei.

![Diagram of a skeleton with markers positioned on the thorax and pelvis segments, as well as the local coordinate system (LCS).]

**Figure 4.1** An example of the general stance adopted by each golfer at ball address. All marker locations and corresponding orthogonal coordinate systems are presented for the thorax and pelvis segments, and the local coordinate system (LCS).

Each subject performed a standardized 10 minute warm-up based on Fradkin et al., [68]. Subjects then familiarized themselves with the laboratory environment by hitting balls into a net. Golf balls covered in retro-reflective tape were hit from a rubber tee embedded in an artificial turf mat (1.8 × 1.8 m), into a net approximately three meters
away. Experimental testing consisted of each golfer hitting five full shots with their driver. Each golfer was instructed to address the ball in a neutral stance position, imagine they were on the tee, and hit their usual driver shot as straight as possible. Requesting the skilled golfers to hit the ball straight enhanced inter-subject task consistency, as varying the trajectory of the ball (i.e. fade or draw) may alter stance and swing characteristics. Two vertical lines 0.5 m apart on the net were used as a guide, which allowed the golfer to hit straight without placing restrictions on the golfer’s natural swing. If the shot was not within two vertical lines, the trial was deemed ineligible and another driver shot was collected.

4.2.3 Instrumentation and data analysis

Three-dimensional marker trajectories were collected using a 3D motion analysis system (Vicon, Oxford Metrics, Oxford, UK), consisting of eight MX13 near-infrared cameras, operating at 500Hz. Marker trajectories were modelled using custom-designed BodyBuilder software version 3.6 (Vicon, Oxford Metrics, Oxford, UK), and all other analyses were performed using custom-designed software in Matlab version 7.6.0 (MathWorks, Natick, MA). Data analysis was restricted to the downswing phase of the golf swing, defined as the period from TBS to BC. TBS was defined as the transition point where the pelvis stops rotating away from the target and begins rotating toward the target [180]. Data for the downswing phase was normalised to 101 points for each individual using piecewise cubic spline interpolation. After the underlying interpolation function was determined for 101 data points of the downswing, the same conditions were applied to 31 data points (30%) on either side of the downswing. Raw 3D coordinate data were filtered using a zero-lag fourth-order
low-pass Butterworth filter. Cut off frequencies for individual markers were between 6-10Hz, as determined through residual analysis [73] with an r2 threshold set at 0.85. Thorax and pelvis kinematics were calculated relative to a LCS based on the position of the heel markers at ball address (Figure 4.1). The origin of the LCS was the midpoint between the left and right heel markers. The y-axis was a vector oriented with the two heel markers. The LCS z-axis coincided with the global vertical and the LCS x-axis was the cross product of the plane formed between the LCS y- and z-axis. Thorax and pelvis modeling procedures were modified based on International Society of Biomechanics guidelines [188, 189]. Thrust, sway and lift were defined as translation along each segments x, y, and z axes respectively. Lateral tilt, anterior-posterior tilt, and axial rotation were defined as angular rotation about each segments x, y, and z axes respectively using Euler angle calculations. Angular velocity for the thorax and pelvis was determined using the Poisson equation described by Zatsiorsky [191] and Craig [46]:

\[
\dot{\theta} = \dot{\mathbf{R}} \mathbf{R}^{-1}
\]  

(4.1)

Thorax-pelvis separation angle (X-Factor) was the difference between thorax and pelvis axial rotation angles projected onto a horizontal plane. Specifically, X-Factor was the cross product of the angle created by the thorax and pelvis x-axis unit vectors projected onto the x-y plane of the LCS. Therefore when the thorax and pelvis are closely oriented, such as ball address, X-factor is close to 0°. A negative X-Factor indicates pelvis planar rotation is leading thorax planar rotation, with a more negative value representative of greater separation between thorax and pelvis angles. X-Factor rate of change was calculated as the derivative of X-Factor. Phase plane plots for both the thorax and pelvis were constructed by plotting angular velocity versus angular displacement for axial rotation, lateral tilt and anterior-posterior tilt. Clubhead and
ball speed were computed as the magnitude of the velocity vector calculated for the marker on the clubhead and the reflective golf ball respectively.

4.2.4 Dependent variables

The 3D position, orientation, and angular velocity of the thorax and pelvis, and the speed of the clubhead were calculated at TBS and BC. The amplitude of peak velocities was calculated for the thorax and the pelvis during the downswing. X-Factor, X-Factor rate of change, peak clubhead and ball speed were calculated for all trials.

4.2.5 Statistical analysis

One-way ANOVA with Bonferroni corrections was used to determine the effect of gender on subject and swing characteristics (age, handicap, height, body mass, arm span, peak clubhead speed, ball speed, downswing duration). Two-way ANCOVA was employed to examine the effect of gender and location (thorax and pelvis) on the dependent variables. Specifically, gender by location interactions with planned contrasts were used to examine the effect of gender on 3D linear displacement (thorax and pelvis), 3D angular kinematics (thorax and pelvis displacement and velocity), X-Factor (peak angle and velocity). To account for the effect that anthropometric differences may have on swing characteristics, the gender differences of height and body mass ($p$'s < 0.01) were entered as covariates into the statistical model. All analyses were conducted using SAS Version 9.1 for Windows (SAS Institute Inc., Cary, NC). The significance level was set at $p < 0.05$. Results are presented as means ± one standard deviation of the mean.
4.3 Results

4.3.1 Subject and swing characteristics

Male golfers were taller, had greater body mass and greater arm span compared to the female golfers. Males had shorter downswing durations, greater peak clubhead speed and greater ball speed than the females (Table 4.1).

Table 4.1 Physical and general swing characteristics of male and female golfers.

<table>
<thead>
<tr>
<th></th>
<th>Males (n = 19)</th>
<th>Females (n = 19)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>26 ± 7</td>
<td>25 ± 7</td>
<td>non-significant</td>
</tr>
<tr>
<td>Handicap (strokes)</td>
<td>0.6 ± 1.1</td>
<td>1.3 ± 1.6</td>
<td>non-significant</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.80 ± 0.05</td>
<td>1.67 ± 0.06</td>
<td>F(1, 36) = 52.93, p &lt; 0.01</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>80.2 ± 9.1</td>
<td>62.2 ± 9.6</td>
<td>F(1, 36) = 34.97, p &lt; 0.01</td>
</tr>
<tr>
<td>Arm span (m)</td>
<td>1.84 ± 0.05</td>
<td>1.69 ± 0.07</td>
<td>F(1, 36) = 59.27, p &lt; 0.01</td>
</tr>
<tr>
<td>Peak clubhead speed (m s(^{-1})) *</td>
<td>49.1 ± 3.6</td>
<td>40.4 ± 3.0</td>
<td>F(1, 36) = 85.80, p &lt; 0.01</td>
</tr>
<tr>
<td>Ball speed (m s(^{-1})) *</td>
<td>69.5 ± 5.2</td>
<td>57.2 ± 4.2</td>
<td>F(1, 36) = 87.84, p &lt; 0.01</td>
</tr>
<tr>
<td>Downswing duration (s)</td>
<td>0.31 ± 0.04</td>
<td>0.39 ± 0.08</td>
<td>F(1, 36) = 14.01, p &lt; 0.01</td>
</tr>
</tbody>
</table>

* Clubhead and ball speed represent the magnitude of the velocity vector calculated for the clubhead and ball respectively.
Figure 4.2 Ensemble averages for thorax and pelvis displacement in the x- (‘thrust’), y- (‘sway’) and z-direction (‘lift’) for both male and female golfers. All displacements are expressed relative to the address position. Shaded areas represent one standard deviation of the mean. The solid vertical line at 0% indicates TBS and the solid vertical line at 100% indicates BC.
Figure 4.3 Ensemble averages for thorax angles and velocities for axial rotation, lateral tilt and anterior-posterior tilt for both male and female golfers. Shaded areas represent one standard deviation of the mean. The solid vertical line at 0% indicates TBS and the solid vertical line at 100% indicates BC.
Figure 4.4 Ensemble averages for pelvis angles and velocities for axial rotation, lateral tilt and anterior-posterior tilt for both male and female golfers. Shaded areas represent one standard deviation of the mean. The solid vertical line at 0% indicates TBS and the solid vertical line at 100% indicates BC.
Figure 4.5 Mean phase plane trajectories for thorax and pelvis axial rotation, lateral tilt and anterior-posterior tilt, for both male and female golfers. Commencing close to zero velocity and moving in a clockwise direction, phase plane trajectories start at TBS and finish at BC.
4.3.2 Thorax and pelvis linear displacement

Male and female kinematic profiles for thorax and pelvis linear displacement are presented in Figure 4.2. Note that all figures in the current study illustrate the 3D kinematic profiles of thorax and pelvis movement from 30% before TBS until 30% after BC. ANCOVA identified significant gender differences for both thorax and pelvis sway at TBS and BC. At TBS males exhibited more thorax sway and more pelvis sway to the right than females, while at BC males exhibited less thorax sway and less pelvis sway to the left than females (Table 4.2). Note that Table 4.2 reports all statistically significant gender differences in the study. The unadjusted means reported in Table 4.2 correspond to averaged raw data, whereas the adjusted means are the results from the ANCOVA.

4.3.3 Thorax angular displacement and velocity

Male and female kinematic profiles for thorax angular displacement and velocity are presented in Figure 4.3. ANCOVA identified several significant gender differences for thorax motion during the downswing. At BC males exhibited less thorax axial rotation to the left and greater thorax axial rotation velocity than females (Table 4.2). At BC males also exhibited greater thorax lateral tilt to the right, and greater thorax lateral tilt velocity than females. Peak thorax lateral tilt velocity was greater for males compared to females. For thorax posterior tilt at BC, males exhibited greater thorax posterior tilt velocity than females. Peak thorax posterior tilt velocity was greater for males compared to females.
Table 4.2 Summary of significant differences for male and female swing kinematics.

<table>
<thead>
<tr>
<th>Linear Displacement</th>
<th>Thorax</th>
<th>Pelvis</th>
<th>Thorax</th>
<th>Pelvis</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBS Sway (cm)</td>
<td>-7.3 ± 2.7</td>
<td>-5.6</td>
<td>-6.1 ± 2.5</td>
<td>-5.6</td>
<td>F(1,35) = 15.99, p &lt; 0.01</td>
</tr>
<tr>
<td>BC Sway (cm)</td>
<td>-4.5 ± 3.1</td>
<td>-5.6</td>
<td>-5.1 ± 2.6</td>
<td>-3.8</td>
<td>F(1,35) = 15.79, p &lt; 0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angular Displacement</th>
<th>Thorax</th>
<th>Pelvis</th>
<th>Thorax</th>
<th>Pelvis</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBS A-P tilt (°)</td>
<td>24.7 ± 3.2</td>
<td>25.9</td>
<td>23.4 ± 5.7</td>
<td>7.0</td>
<td>F(1,35) = 12.82, p &lt; 0.01</td>
</tr>
<tr>
<td>BC A-P tilt (°)</td>
<td>4.7 ± 4.7</td>
<td>2.9</td>
<td>5.2 ± 5.7</td>
<td>3.6</td>
<td>F(1,35) = 13.23, p &lt; 0.01</td>
</tr>
<tr>
<td>BC Lateral tilt (°)</td>
<td>37.7 ± 5.7</td>
<td>34.3</td>
<td>33.2 ± 5.8</td>
<td>7.2</td>
<td>F(1,35) = 6.29, p = 0.02</td>
</tr>
<tr>
<td>BC Axial rot (°)</td>
<td>25.7 ± 8.1</td>
<td>31.4</td>
<td>29.3 ± 11.0</td>
<td>10.0</td>
<td>F(1,35) = 17.20, p &lt; 0.01</td>
</tr>
<tr>
<td>Pelvis</td>
<td>43.7 ± 9.9</td>
<td>51.7</td>
<td>49.6 ± 11.9</td>
<td>10.0</td>
<td>F(1,35) = 29.28, p &lt; 0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angular Velocity</th>
<th>Thorax</th>
<th>Pelvis</th>
<th>Thorax</th>
<th>Pelvis</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC A-P tilt (°/s)</td>
<td>-176 ± 45</td>
<td>-104</td>
<td>-103 ± 44</td>
<td>-78</td>
<td>F(1,35) = 48.61, p &lt; 0.01</td>
</tr>
<tr>
<td>BC Lateral tilt (°/s)</td>
<td>351 ± 56</td>
<td>255</td>
<td>257 ± 69</td>
<td>66</td>
<td>F(1,35) = 15.92, p &lt; 0.01</td>
</tr>
<tr>
<td>BC Axial rot (°/s)</td>
<td>371 ± 82</td>
<td>315</td>
<td>326 ± 82</td>
<td>109</td>
<td>F(1,35) = 16.89, p &lt; 0.01</td>
</tr>
<tr>
<td>Max A-P tilt (°/s)</td>
<td>-247 ± 43</td>
<td>-173</td>
<td>-173 ± 44</td>
<td>109</td>
<td>F(1,35) = 77.21, p &lt; 0.01</td>
</tr>
<tr>
<td>Max Lateral tilt (°/s)</td>
<td>-177 ± 37</td>
<td>-128</td>
<td>-127 ± 45</td>
<td>109</td>
<td>F(1,35) = 33.88, p &lt; 0.01</td>
</tr>
</tbody>
</table>

* Adjusted means are the least square means obtained from the ANCOVA after subject height and mass were entered as covariates.

4.3.4 Pelvis angular displacement and velocity

Male and female kinematic profiles for pelvis angular displacement and velocity are presented in Figure 4.4. ANCOVA identified several significant gender differences for pelvis motion during the downswing. At BC males exhibited less pelvis axial rotation to the left and greater pelvis lateral tilt to the right than females (Table 4.2). Males also exhibited greater pelvis lateral tilt velocity at BC, and greater peak pelvis tilt velocity compared to females. Furthermore, at TBS males exhibited less anterior
pelvis tilt, while at BC males exhibited greater posterior tilt velocity. Peak posterior tilt velocity was greater for males compared to females.

4.3.5 Phase Plane Trajectories

Mean thorax and pelvis phase plane trajectories for male and female golfers are displayed in Figure 4.5. Axial rotation phase plane trajectories were similar between genders for both thorax and pelvis motion. That is, males and females generated similar axial rotation velocities at similar axial rotation angles, over a similar range of movement for both the thorax and pelvis. However, phase plane trajectories for lateral and anterior-posterior tilt were dissimilar between genders. Both genders had similar thorax lateral tilt angular velocity-displacement relationships at TBS. However immediately after TBS, males were able to increase thorax lateral tilt velocity to a greater magnitude than females at similar thorax lateral tilt angles, and maintain the higher velocity until BC. Despite having similar pelvis lateral tilt angular velocity-displacement profiles, males had a greater range of lateral tilt for the pelvis, and consistently higher pelvis lateral tilt velocity than females from TBS to BC. Thorax anterior-posterior tilt phase plane trajectories were similar at TBS and immediately following TBS. However males had a greater range of thorax anterior tilt which corresponded to males generating higher thorax anterior tilt velocity compared to females, which was maintained until BC. Despite having similar pelvis anterior-posterior tilt phase plane trajectories, males had a greater range of anterior-posterior tilt for the pelvis, and consistently higher pelvis anterior-posterior tilt velocity than females from TBS to BC.
4.3.6 X-Factor

No gender differences were detected for any X-Factor dependent variables (Figure 4.6).

![Figure 4.6](image)

**Figure 4.6** Ensemble averages for X-Factor angle and X-Factor rate of change for male and female golfers. Shaded areas represent one standard deviation of the mean. The solid vertical line at 0% indicates TBS and the solid vertical line at 100% indicates BC.

4.4 Discussion

The purpose of this study was to profile the 3D kinematics of the thorax and pelvis during the downswing, and determine if differences exist between male and female skilled golfers. Displacement-velocity relationships of the thorax and pelvis were
examined during the downswing, with the aim of providing a greater understanding of
the coordination strategies required to perform the golf swing.

At TBS gender differences were present in the overall position of the upper body at
the beginning of the downswing, where the male golfers had greater thorax and pelvis
sway to the right compared to the female golfers. That is, relative to the body position
at ball address males positioned their upper body more towards the back leg.
Potentially, the position of the upper body when preparing to start the downswing
may have contributed to the gender differences observed in clubhead speed in the
present study. However, this issue is contentious as body segment position at TBS
may not play as great a role in increasing clubhead velocity compared to how body
weight is transferred between the legs during the downswing [16].

A confirmed hypothesis in the current study was that gender differences emerged for
thorax and pelvis axial rotation. While no differences were observed at TBS, females
had greater magnitude of axial rotation at BC for both the thorax and the pelvis. The
magnitude of axial rotation for the pelvis at TBS was similar to previous studies,
however axial rotation for the thorax was of a lesser magnitude [138, 193]. This
discrepancy may not only be due to differences in performance, but also due to
methodological issues. The current study modelled the thorax as a rigid body using a
marker set attached directly to thorax landmarks, whereas previous studies have
modelled the thorax using plane-projection techniques and markers attached to the
shoulders. The direct marker method is less prone to overestimation of transverse
plane rotations, and when used in conjunction with Euler angles is not affected by out
of plane motion [180]. Given that females had a reduced degree of thorax and pelvis
lateral tilt it appears that females adopted a position where their upper body was more upright than males at BC. A more upright posture at BC has been implicated as a preventative measure of low back pain in golfers [82], and may also compromise the ability to generate large upper body speeds [8].

As was hypothesized, males had greater velocity for thorax axial rotation, thorax and pelvis tilt to the right, and thorax tilt in the posterior direction at BC. Peak velocities were also greater for thorax and pelvis posterior tilt and right lateral tilt in males compared to females. Velocity-dependent contributions to stress placed on the spine should not be overlooked as increased velocity, particularly for lateral tilt, is known to substantially increase lumbar spine loads [121]. To date, the contribution of lateral thorax tilt, and in particular lateral thorax tilt velocity to the overall movement pattern of the golf swing has not been a focus of research. When the amplitude of thorax lateral tilt velocity and thorax axial rotation velocity are compared (Figure 3), thorax lateral tilt velocity for both genders was only marginally lower in magnitude than axial rotation velocity, a feature which was not observed for the pelvis. If the total speed of the thorax and pelvis is considered (magnitude of the resultant of all directions of motion), the thorax will move fastest primarily due to the large lateral tilt component. Consequently, the overall effect will be an increase in segment speed in a proximal-to-distal pattern, which is suggested to assist in generating large clubhead speeds [28, 134].

The phase plane portraits of the thorax and the pelvis provided insight into the motor control required in performing the downswing which may have been overlooked with discrete analyses. Overall, it was evident that differences in kinematics early in the
downswing resulted in males achieving a greater peak velocity than females, which was maintained through the latter half of the downswing. For instance, both genders rapidly increased thorax tilt velocity immediately following TBS and achieved peak velocity at an approximately neutral thorax position. However, during the initial thorax motion following TBS, males were able to increase lateral tilt velocity to a greater magnitude than females. The result of males achieving higher segment velocity early in the downswing was also reflected in the phase plane trajectories for tilt velocity in the posterior direction. Presumably, the greater body mass and physical characteristics of the male golfers was associated with increased physiological cross sectional area of muscle [3], thus facilitating greater absolute force production and greater velocity of movement compared to females when performing the same task [116].
Chapter 5 - Movement variability in the golf swing of male and female skilled golfers
This chapter has been published as an original paper in Medicine & Science in Sports & Exercise. Horan, S.A., K. Evans and J.J. Kavanagh (2011). Movement variability in the golf swing of male and female skilled golfers. Medicine & Science in Sports & Exercise, 43(8):1474-1483. Figure and table numbers have been adapted to comply with the formatting of the thesis and the reference list has been omitted with references for this chapter included in the reference list for the entire thesis.

4.1 Introduction

The golf swing is a whole body multi-joint movement, and coordinating the many degrees of freedom required to perform the task presents a considerable control challenge. Despite the complexity of the movement, skilled golfers are thought to perform the swing in a consistent manner so that they can strike the ball with repeated accuracy across multiple swings [157]. Although the movement of individual body segments is suggested to influence clubhead trajectory during the golf swing [28, 144], the degree of segment and inter-segment movement variability during the swing of skilled male and female golfers is unknown.

Variability in motor output is an inherent characteristic of the human neuromotor system [112, 145]. In multi-joint tasks that require precision of an end-point effector, the variability of individual segment trajectories may be substantially greater than the variability of the end-point trajectory [9, 24, 75]. This feature was perhaps best illustrated in the classic study of Bernstein [24], where the movement of professional blacksmiths were described when repeatedly hitting a chisel. Considerable variability
was observed for individual joints of the upper body, yet the trajectory of the hammer tip was consistent with each strike, particularly at the point of impact. If similar features of control were evident in the golf swing, the degree of variability of the thorax and pelvis would not necessarily be reflected in hand and clubhead trajectories during the downswing. Instead, segmental movement variability would be organised to ensure consistent hand motion from trial-to-trial, particularly at BC where precision of the clubhead trajectory is most critical [183]. Interestingly, the only study to exclusively examine movement variability in skilled and unskilled golfers during the full golf swing did not observe any group differences in variability at TBS or BC, but did identify differences in lead wrist angle and trail forearm angle variability at mid-backswing [25]. However in this investigation, 3D movement of the golf swing was measured using planar-based video analysis, and only selective trunk, arm and club kinematics were reported. More detailed analysis of the downswing phase, with particular focus on segment and inter-segment movement variability of the thorax and pelvis, along with examination of hand and clubhead trajectory would provide greater insight into movement variability during the golf swing.

Currently there is no consensus concerning the role of gender in controlling multi-joint tasks that require precision of an end-point effector. Instead, it appears that gender related differences in variability are task specific [152, 163] and may in part be influenced by differences in movement velocity. While 3D thorax and pelvis kinematics of male and female skilled golfers have been shown to be similar during the downswing, gender differences in movement velocity exist [92, 193]. In particular, male golfers are able to achieve greater segmental velocity at BC, and greater overall maximum velocity for the thorax and pelvis segments compared to
females. Although the relationship between segment velocity and variability is unclear, and yet to be studied for the golf swing, it is possible that the scaling of joint torques that drive the motion of the golf swing are gender-specific and may be reflected by different variability in movement. Gender-related differences in variability may not only be present at the level of segmental movement, but also for coordination between segments during the swing. The importance of thorax-pelvis coordination with respect to performance is emphasized frequently [28, 33, 40, 138, 192], however no investigation into the role of coordination variability in the golf swing has occurred. Analyses of coordination that address the dynamical nature of movement, combined with more common approaches that examine continuous movement at discrete intervals, are likely to provide greater understanding of the motor control required to perform the golf swing [19, 106].

The purpose of this study was to determine if differences in movement variability exist between male and female skilled golfers during the downswing. It was hypothesized that skilled female golfers would exhibit greater thorax and pelvis variability, and therefore greater variability in thorax-pelvis coupling than skilled male golfers. It was anticipated that these differences would be least evident at the TBS, and most evident during mid-downswing (MID) and at BC when thorax and pelvis motion have the highest velocity. It was also hypothesized that hand and clubhead trajectory variability would be similar between genders when performing the same goal directed task, and that hand and clubhead trajectory variability would progressively decrease from TBS to MID to BC given that it is at BC when precision of movement is most critical.
5.2 Methods

5.2.1 Subjects

Nineteen males (mean ± standard deviation, age = 26 ± 7 yr, handicap = 0.6 ± 1.1) and 19 females (age = 25 ± 7 years, handicap = 1.3 ± 1.6) volunteered to participate in the study. All subjects were either professional or competitive amateur golfers, played golf right-handed, and were free from musculoskeletal injury at the time of testing as determined by an experienced physiotherapist (SH). The professional golfers that volunteered were credited with a handicap of 0 for the purpose of this study. To ensure only highly skilled golfers were recruited, competitive amateur golfers were only included if they had a registered Australian handicap ≤ 4. Written informed consent was obtained prior to data collection and all experimental procedures were approved by the Griffith University Human Research Ethics Committee.

5.2.2 Instrumentation and procedures

The instrumentation and procedures for data collection have been described in detail in the previous chapter [92]. Briefly, retro-reflective markers were attached to the pelvis on the right and left ASIS’s and PSIS’s. Four markers were attached to the thorax over the suprasternal notch, xiphoid process, C7 and T10 spinous processes. Clubhead trajectory was tracked via a marker attached to the subject’s driver. To create a LCS for kinematic modelling, markers were attached to the right and left heel of the subject’s golf shoes which approximated the calcanei. Three-dimensional marker trajectories were collected at 500 Hz using a 3D Vicon motion analysis system and modelled using BodyBuilder software version 3.6 (Oxford Metrics, Oxford, UK).
All other data analyses were performed using custom-designed software in Matlab version 7.8.0 (The MathWorks, Natick, MA). Raw 3D coordinate data were filtered using a zero-lag fourth-order low-pass Butterworth filter. Cut-off frequencies for individual markers were between 6 and 10 Hz, as determined through residual analysis [73] with an $r^2$ threshold set at 0.85.

Thorax and pelvis angular displacement was calculated relative to the LCS based on the position of the heel markers at ball address. The origin of the LCS was the midpoint between the left and right heel markers. The y-axis was a vector directed towards the target and oriented with the two heel markers. The LCS z-axis coincided with the global vertical and the LCS x-axis was the cross product of the plane formed between the LCS y- and z-axis. In the present study, thorax and pelvis segment definitions were based on International Society of Biomechanics guidelines [189]. The origin of our pelvis coordinate system was the midpoint of the two ASIS and two PSIS markers, with the pelvis z-axis directed cephalad, y-axis directed toward the left side of the pelvis, and the x-axis directed anterior. The thorax coordinate system was represented in the same manner as the pelvis, however the origin of the coordinate system was located at the midpoint of the C7 marker and the marker over the suprasternal notch. Lateral tilt, anterior-posterior tilt, and axial rotation were defined as angular rotation about each segments x, y, and z axes respectively using Euler angles.

Experimental testing consisted of each golfer hitting five full shots with their own driver from a rubber tee embedded in an artificial turf mat into a net approximately 3 m away. Each golfer was instructed to address the ball in a neutral stance position,
imagine they were on a tee, and hit their usual driver shot as far and as straight as possible. To ensure task consistency, two vertical lines were placed 0.5 m apart on the net, and any shot that was not between the vertical lines was considered a mis-trial and another shot was performed.

5.2.3 Data analysis

Data analysis was based on the downswing phase defined as the period from TBS to BC. TBS was defined as the transition point where the pelvis stops axially rotating away from the target and begins rotating towards the target. Data for the downswing phase were normalised to 101 points for each individual using piecewise cubic spline interpolation, which enabled swing data to be reported as 0-100% of the downswing cycle, and therefore kinematic variability at the discrete events of TBS, MID and BC could be examined (Figure 5.1). As it was also of interest to examine variability during the phases associated with TBS, MID and BC a further 20% of swing data on either side of the downswing was required to be normalised (Figure 5.1). Therefore data could be examined from -20% to 120% relative to the downswing.

Segment movement variability was examined at the discrete events of TBS, MID, and BC. The sample standard deviation was calculated for each subject’s five trials in the anterior-posterior tilt, lateral tilt, and axial rotation directions for the thorax and pelvis. Segment movement variability was also examined at three continuous phases: TBS ± 20%, MID ± 20%, and BC ± 20% of the downswing. Thorax and pelvis kinematics were examined across these continuous phases using the spanning set, which is comprised of vectors that describe the possible linear combinations for a system of equations [110, 111, 113]. A greater number of linear combinations indicate
a greater number of solutions, or greater trial-to-trial variability about a mean ensemble curve [110]. The upper and lower standard deviation curves about a mean ensemble curve form the basis of the vectors for analysis, where polynomials are created which characterise these standard deviation curves. In the present study, a 7th order polynomial was found to account for > 99.9% of variance in angular displacement standard deviation curves. The vectors in the spanning set were defined by a vector space mapped from the polynomial coefficients. Coordinate mapping was employed, which allowed the properties of the polynomials to reflect a familiar coordinate system i.e. the characteristics of the standard deviation about the ensemble curve [111, 113]. The magnitude of the spanning set was the norm distance between the vectors created from the polynomial coefficients. A greater magnitude indicates greater distance between the vectors and therefore greater variability.

Variability in thorax-pelvis coupling across each golfer’s five trials was quantified for TBS ± 20%, MID ± 20%, and BC ± 20% using the average coefficient of correspondence. Average coefficient of correspondence examines inter-segment coupling by quantifying the variability of angle-angle data across multiple trials [169]. Vectors are generated between successive frames of normalised data, where each vector describes the direction and amplitude of change in relative motion between each data point [169, 179]. The average direction and amplitude of each frame-frame vector is combined and averaged over the entire length of the trial to describe the overall vector deviation. Several vector coding techniques encode data with an integer value which describes a kinematic profile, however the ability of average coefficient of correspondence to describe relative motion is enhanced as the ratio scale of trial-to-trial data is preserved. The average coefficient of correspondence calculates a scalar
value between 0 and 1, where 1 indicates perfect repeatability of thorax-pelvis coupling.

![Diagram showing TBS, MID, and BC points during the downswing phase](image)

**Figure 5.1** Kinematic data were normalised to the downswing phase (0-100%) of the golf swing. Variability was examined at three discrete points (TBS, MID, BC) and three continuous phases (TBS ± 20%, MID ± 20%, and BC ± 20%) associated with the downswing. Data from the three discrete points were used in the standard deviation analysis, whereas data from the three continuous phases were used in the spanning set and average coefficient of correspondence analyses.

### 5.2.4 Statistical analysis

A between-within two-way repeated measures ANOVA was employed to examine the effect of gender (male and female) and phase (TBS, MID, and BC) on the dependent measures (standard deviation, spanning set, average coefficient of correspondence). While significant main effects of gender and phase were detected for all dependent measures (all \( p \) values <0.03), the relevance of these effects were limited. That is, as data is collapsed across conditions to calculate main effects there were no clear
indication where gender differences occurred during the downswing. Therefore, gender by phase interaction effects with planned contrasts were the basis of the current study’s analysis. The mixed model employed in the study accounted for both fixed and random effects, with low Akaike information criterion indicating an appropriately selected model. All statistical analyses were performed using SAS for Windows Version 9.1 (SAS Institute Inc., Cary, NC). The level of significance was set at $p < 0.05$ and effect sizes (ES) were reported as Cohen’s $d$ [39].

5.3 Results

5.3.1 Descriptive data for subjects

Male golfers were significantly taller (mean ± standard deviation, male = 1.80 ± 0.05 m, female = 1.67 ± 0.06 m, $F(1,36) = 52.93, p < 0.01$), had greater body mass (male = 80.2 ± 9.1 kg, female = 62.2 ± 9.6 kg, $F(1,36) = 34.97, p < 0.01$), arm span (male = 1.84 ± 0.05 m, female = 1.69 ± 0.07 m, $F(1,36) = 59.27, p < 0.01$), and clubhead speed (male = 49.1 ± 3.6 m.s$^{-1}$, female = 40.4 ± 3.0 m.s$^{-1}$, $F(1,36) = 85.80, p < 0.01$) compared to the female golfers.
Figure 5.2 Representative data for 3D angular displacement for the thorax and pelvis segments from 5 trials, for a single male and a single female subject. Dotted vertical lines at 0% and 100% represent TBS and BC, respectively.
Figure 5.3 Standard deviations for 3D angular displacement of the thorax and pelvis segments. Standard deviations were computed from five swings at three discrete data points (TBS, MID, and BC) for each individual. An ‘*’ indicates a significant difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.
Figure 5.4 Spanning sets for 3D angular displacement of the thorax and pelvis segments. Spanning sets were computed from five full swings at three continuous phases (TBS ± 20%, MID ± 20%, and BC ± 20%) for each individual. An ‘∗’ indicates a significant difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.
5.3.2 Between-gender differences during the downswing

**Variability in thorax and pelvis motion.** In general, thorax and pelvis kinematics were similar for the male and female golfers (Figure 5.2), however several gender differences in variability emerged throughout the downswing. Female golfers had significantly higher thorax axial rotation standard deviation at BC than males \((F(1,37) = 5.97, p = 0.02, \text{ES} = 0.81)\), and significantly higher pelvis axial rotation standard deviation at MID \((F(1,37) = 7.09, p = 0.01, \text{ES} = 0.89)\) and BC \((F(1,37) = 3.98, p = 0.04, \text{ES} = 0.66)\) compared to males (Figure 5.3). Similarly, female golfers had significantly higher thorax axial rotation spanning sets at BC than males \((F(1,37) = 5.75, p = 0.02, \text{ES} = 0.80)\), and significantly higher pelvis axial rotation spanning sets at MID \((F(1,37) = 7.21, p = 0.01, \text{ES} = 0.90)\) and BC \((F(1,37) = 3.99, p = 0.04, \text{ES} = 0.65)\) compared to males (Figure 5.4).

**Thorax-pelvis coupling.** Patterns of angle-angle data for thorax-pelvis coupling were comparable between genders for axial rotation, however the range of motion was different for the anterior-posterior and lateral tilt directions (Figure 5.5). Female golfers had significantly lower anterior-posterior tilt, lateral tilt, and axial rotation average coefficient of correspondence values at the MID (anterior-posterior tilt: \(F(1,37) = 12.13, p < 0.01, \text{ES} = 1.16\); lateral tilt: \(F(1,37) = 6.24, p = 0.01, \text{ES} = 0.83\); axial rotation: \(F(1,37) = 9.26, p = 0.01, \text{ES} = 1.01\)) and BC (anterior-posterior tilt: \(F(1,37) = 15.41, p < 0.01, \text{ES} = 1.31\); lateral tilt: \(F(1,37) = 9.12, p < 0.01, \text{ES} = 1.01\); axial rotation: \(F(1,37) = 12.70, p < 0.01, \text{ES} = 1.09\)) phases compared to males.
Figure 5.5 Representative angle-angle plots for thorax and pelvis data for a single female and male subject (left column). Average coefficient of correspondence was computed from angle-angle data, from the downswing of five swings for each subject (right column). Average coefficient of correspondence was calculated at three continuous phases (TBS ± 20%, MID ± 20%, and BC ± 20%). An ‘**’ indicates a significant difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.
Figure 5.6 Standard deviations and spanning sets for hand and clubhead trajectory. Standard deviation was computed at the three discrete points (TBS, MID, and BC), while spanning set was computed at the three continuous phases (TBS ± 20%, MID ± 20%, and BC ± 20%). An ‘*’ indicates a significant difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.

Hand and clubhead trajectory. Gender differences were only observed for the trajectory of the hand, where females exhibited significantly higher standard deviation ($F(1,37) = 6.21, p = 0.02, ES = 0.83$) and significantly higher spanning sets ($F(1,37) = 6.61, p = 0.01, ES = 0.86$) at TBS compared to males (Figure 5.6).
5.3.3 Within-gender differences during the downswing

Variability in thorax and pelvis motion. The female golfers had significantly increased thorax axial rotation and pelvis axial rotation standard deviations at MID compared to TBS (thorax: $F(1,37) = 7.00, p = 0.01, ES = 0.56$; pelvis: $F(1,37) = 14.66, p < 0.01, ES = 1.00$) (Figure 5.3). Similarly, females had significantly increased thorax axial rotation and pelvis axial rotation spanning sets at MID compared to TBS (thorax: $F(1,37) = 10.87, p < 0.01, ES = 0.66$; pelvis: $F(1,37) = 16.50, p < 0.01, ES = 1.04$) (Figure 5.4). The male golfers had significantly increased thorax axial rotation standard deviation at MID compared to BC ($F(1,37) = 5.48, p = 0.02, ES = 0.60$) and similarly significantly increased thorax axial rotation spanning sets at MID compared to BC ($F(1,37) = 5.06, p = 0.03, ES = 0.57$).

Thorax-pelvis coupling. Female golfers exhibited significantly increased anterior-posterior tilt average coefficient of correspondence values at MID compared to TBS ($F(1,37) = 43.46, p < 0.01, ES = 1.99$) and at BC compared to MID ($F(1,37) = 20.90, p < 0.01, ES = 0.99$) (Figure 5.5). Females also exhibited significantly increased lateral tilt and axial rotation average coefficient of correspondence values at MID compared to TBS (lateral tilt: $F(1,37) = 15.91, p < 0.01, ES = 1.11$; axial rotation: $F(1,37) = 43.04, p < 0.01, ES = 2.06$). Males exhibited significantly increased anterior-posterior tilt average coefficient of correspondence values at MID compared to TBS ($F(1,37) = 82.68, p < 0.01, ES = 2.66$) and at BC compared to MID ($F(1,37) = 8.60, p < 0.01, ES = 1.13$). Male golfers also exhibited significantly increased lateral tilt and axial rotation average coefficient of correspondence values at MID compared to TBS (lateral tilt: $F(1,37) = 30.69, p < 0.01, ES = 2.11$; axial rotation: $F(1,37) = 52.78, p < 0.01, ES = 2.10$).
**Hand and clubhead trajectory.** Female golfers had significantly increased hand trajectory standard deviation at TBS compared to MID ($F(1,37) = 17.27, p < 0.01, ES = 1.08$) and at MID compared to BC ($F(1,37) = 5.00, p = 0.03, ES = 0.54$) (Figure 5.6). Similarly, females had significantly increased hand trajectory spanning sets at TBS compared to MID ($F(1,37) = 20.89, p < 0.01, ES = 1.02$) and at MID compared to BC ($F(1,37) = 8.85, p < 0.01, ES = 0.57$). For the male golfers, significantly increased hand trajectory standard deviation was evident at MID compared to BC ($F(1,37) = 8.09, p = 0.03, ES = 0.95$) while similarly, significantly increased hand trajectory spanning sets were evident at MID compared to BC ($F(1,37) = 11.59, p < 0.01, ES = 1.11$).

For the trajectory of the clubhead, females exhibited significantly increased standard deviation at TBS compared to MID ($F(1,37) = 16.82, p < 0.01, ES = 0.61$) and at MID compared to BC ($F(1,37) = 21.01, p < 0.01, ES = 1.35$). Similarly, females exhibited significantly increased clubhead trajectory spanning sets at TBS compared to MID ($F(1,37) = 6.32, p = 0.02, ES = 0.47$) and at MID compared to BC ($F(1,37) = 15.39, p < 0.01, ES = 0.78$). For the males, significantly increased clubhead trajectory standard deviation was evident at TBS compared to MID ($F(1,37) = 15.60, p < 0.01, ES = 0.74$) and at MID compared to BC ($F(1,37) = 10.52, p < 0.01, ES = 1.11$). Significantly increased clubhead trajectory spanning sets for males were also observed at TBS compared to MID ($F(1,37) = 17.84, p < 0.01, ES = 0.81$) and at MID compared to BC ($F(1,37) = 10.20, p < 0.01, ES = 0.87$).
5.4 Discussion

The present study is the first to directly examine segment and inter-segment variability across phases of the downswing in male and female skilled golfers. The results indicate that although there are gender differences in movement variability for the thorax and pelvis, both genders achieve similar consistency in hand and clubhead trajectories in the final phases of the downswing. Supporting our hypotheses, skilled female golfers exhibited greater thorax and pelvis variability and greater variability in thorax-pelvis coupling than skilled male golfers.

Regardless of whether standard deviation or spanning set was employed as a measure of movement variability, similar results were obtained for the analysis of the male and female downswing. Gender differences were present in the latter half of the downswing, where females had greater axial rotation variability for the pelvis at MID and BC and the thorax at BC. The role that gender plays in rapid striking tasks has not been clearly established. In particular, how gender affects the control of accuracy dependent multi-joint tasks, or even if movement variability differences exist during functional tasks, is largely unknown. Greater absolute error and variable error has been observed for females when undertaking coincidence timing activities (open chain) [150, 186], and for lower limb segment axial rotation during cutting manoeuvres (closed chain) [130]. Given that during treadmill walking joint variability has been reported to be lower in females than males [18], gender-related kinematic variability appears to be task dependent considering the higher levels of variability observed for females in this study. A goal directed task such as the golf swing imposes a task constraint on movement [89] and any differences, or similarities, in
multi-segmental motion can reveal fundamental strategies required to strike the ball [106]. Although variability differed between genders for the thorax and pelvis in the latter half of the downswing, variability was the same for male and female hand and clubhead trajectories. Therefore, it is apparent that the dynamics of the arms play an important role in regulating the accuracy of the clubhead trajectory. Future research into control mechanisms of the golf swing will benefit from a focused examination of arm segment motion, and the coordination between trunk and arm motion during the downswing.

Maximising end point accuracy in the final phases of a rapid movement task has been observed in other tasks such as when striking a stationary ball [167] and in reaching tasks involving single [148] and multiple joints [80]. In agreement, our findings suggest that kinematic variability is also influenced by accuracy demands in the final phases of the downswing, although not necessarily by the initial phases of movement when generating power may be more of a priority. In regards to gender-specific strategies, thorax and pelvis axial rotation variability increased early in the female downswing before remaining consistent through to BC. In contrast, males remained consistent throughout the downswing except for lower thorax variability in the latter half of the downswing. Despite the motion of the thorax and pelvis both genders progressively decreased hand and clubhead trajectory variability throughout the downswing, once again supporting the notion that the arms play an important regulatory role in guiding the trajectory of the clubhead.

Thorax-pelvis coupling was consistent between swings for all movement directions, particularly in the latter half of the downswing. Interestingly, the variability of thorax-
pelvis coupling was higher at TBS than MID and BC which is associated with the transitional movement pattern from the backswing to the downswing. That is, during the TBS phase of skilled golfers the pelvis begins rotating towards the target while the thorax is still rotating away; hence the segments are momentarily rotating in opposite directions [28, 138]. Although never formally examined, this is a voluntary movement strategy suggested to exploit a SSC in trunk muscles which assist in generating high upper body segment velocities early in the downswing [33, 138]. As average coefficient of correspondence integrates both the magnitude and direction of angle-angle data over successive trials, segments rotating in opposite directions will result in lower average coefficient of correspondence [86, 179]. Therefore, it should be noted that lower average coefficient of correspondence values at the TBS phase found in this study may not reflect decreased coordination, but rather the change in direction of segmental movement.

Similar to the results for thorax and pelvis axial rotation, the consistency of thorax-pelvis coupling for the female golfers was lower than for the male golfers in the latter half of the downswing for all directions of movement. Although gender differences in coupling variability were evident, the variability of end-point trajectories was similar between genders throughout the downswing phase. While it is important to maintain low levels of variability of the clubhead, males and females appeared to utilise different coordination strategies to achieve this. The origins of segment and inter-segment movement variability are not well understood, however it could be argued that the observed gender differences originate from the variability associated primarily with motor execution processes. The neuro-mechanical processes associated with goal directed movements, such as hitting a golf ball, can be divided into three
stages; localization, planning and motor execution [175]. Localization involves processing the location of the target and end-effector, while the movement planning stage involves the selection of motor commands that produce the intended movement. Although variability at any stage can ultimately affect the outcome, the task of hitting the golf ball was well defined and fixed from trial-to-trial. Therefore the motor execution stage is most likely where differences in consistency arise during the downswing of skilled golfers.

Certain methodological issues should be considered in studies of movement variability. When measuring 3D kinematics via traditional marker based optoelectronic systems, variability of measurement can be increased when different testers apply markers and when measurements are made over different sessions [124]. In the current study these potential sources of variability were minimised as a single examiner applied all markers, and swings from the same session were analysed without the reapplication of markers. Any variability in measurement was most likely a result of (i) the inherent motor variability associated with the task and (ii) the error associated with movement of markers on the skin. While skin marker movement error is difficult to eliminate, it is likely to be systematic and will in part be accounted for by the filtering process. The question of whether to use a standardised club for all golfers is also a point of interest. Detailed simulations using a shoulder-arm-club model have illustrated that manipulating properties of the club such as length, inertia, and shaft compliance will alter the torque required to drive the club [159]. Therefore if the golfer is instructed to use a club that is not familiar to them, a swing pattern that is different to their natural swing may emerge. While we did not measure clubhead or shaft parameters, it is unlikely that gender-related differences in golf swing
kinematics are solely the result of discrepancies of each individual’s golf club. For example, changing selective club and shaft parameters such as increasing club length by up to 10 cm or altering shaft compliance, produces only modest increases in clubhead speed (1-2.5%) [159]. It is more likely that differences in kinematic variability were due to intrinsic factors such as gender related differences in anthropometrics, strength, and the associated differences in neuromuscular recruitment strategies required when performing the same task.

The findings of this study can be extended in the future by exploring the causal relationship between neuromotor variability and the accuracy of striking the ball. It would be of considerable interest to coaches and clinicians to determine if pelvis and/or thorax segment motion has a substantial influence on the direction of ball travel or whether the arm segments are the main regulators of clubhead trajectory. Furthermore, the current study explicitly examined the kinematics of skilled golfers and the results should not be generalised beyond this. Examining how coordination differs among skill levels or golfers playing with injury, and how changes in these measures correspond to improving golf performance, would be of interest to coaches and clinicians alike.

The present study revealed that gender differences exist for trunk movement variability, but not hand and clubhead trajectory variability during the downswing of skilled golfers. The similar levels of hand and clubhead variability exhibited by males and females, regardless of the variability in the larger more proximal segments, suggests that the arms play a regulatory role in guiding the trajectory of the clubhead. It is apparent that the priority of skilled golfers is to progressively minimise hand and
clubhead trajectory variability towards BC, despite the individual motion or coupling of the thorax and pelvis.
Chapter 6 - Swing kinematics of male and female skilled golfers following putting practice
This chapter has been submitted as an original paper to The British Journal of Sports Medicine. Horan, S.A., K. Evans, N.R. Morris, and J.J. Kavanagh. Swing kinematics of male and female skilled golfers following putting practice. (Under Review). Figure and table numbers have been adapted to comply with the formatting of the thesis and the reference list has been omitted with references for this chapter included in the reference list for the entire thesis.

6.1 Introduction

Investigations of the golf swing have typically examined upper body kinematics immediately following a simple warm up routine or brief familiarisation session. However, kinematic profiles observed immediately after a warm up may not reflect movement patterns following extended periods of activity, such as during a round, throughout a tournament, or even during a practice session. Several recent investigations have examined the effect of prolonged sport-specific tasks on the performance of multi-segment movements, and revealed that movement patterns can adapt over time to ensure that performance is maintained [51, 90, 103]. Therefore, it is critical for the design of future golf studies, and the interpretation of previous studies, to determine if golf swing kinematics are altered following golf-specific interventions. Surprisingly, it is unknown if specific attributes of the full golf swing are altered following prolonged practice, or if prolonged practice affects males and females differently.

To ensure consistent and accurate swing patterns, skilled golfers spend a considerable amount of time practicing. Professional golfers will often hit in excess of 300 shots
per session [79, 170], and make over 2000 swings per week [99]. This can equate to practice sessions in the order of 6-10 hours in duration [170]. In addition to the full swing, skilled golfers spend a significant proportion of time practicing putting [117]. Putting and the full swing both require the golfer to maintain a relatively anteriorly tilted trunk position. However, unlike the full swing the putting stroke involves minimal amounts of motion. The prolonged static postures adopted during putting practice significantly challenges the trunk and hip extensors[63], and leads to changes in posture and segmental orientation during the full golf swing [63, 178]. It stands to reason that if segmental orientation is affected with putting practice, so too will the ability to generate segmental velocity, which is arguably the most important performance measure of the full golf swing.

Current evidence suggests that males and females respond differently to endurance or fatiguing tasks [88, 96]. In general, females are more resistant than males to endurance based activities that involve low to moderate intensity isometric contractions of muscles across a single joint [37, 96, 190]. For higher intensity dynamic movement tasks, and contractions that involve multiple muscles or joints, gender differences are far less pronounced [23, 96, 104]. For example, similar trunk extensor endurance times have been reported for male and female athletes during the Biering-Sørensen test; however the endurance times for female athletes during a side bridge task are reduced compared to males [63]. While prolonged putting is considered an endurance task that predominantly involves an isometric contraction of the trunk extensors, the physical requirements of the task are likely to be different for males and females and may influence the gender response. Although a few studies
have investigated gender differences in swing kinematics [56, 92, 193], none have examined differences following a golf-specific intervention.

The purpose of this study was to compare the effect of 40 minutes of putting practice on full swing kinematics in male and female skilled golfers. It was hypothesised that following the putting intervention differences in thorax and pelvis orientation angles would be most evident for females compared to males, and that angular velocity would be affected in females more than males. The results of this study will provide further insight into thorax and pelvis control strategies following a typical practice putting session, and assist in guiding appropriate practice habits and routines.

6.2 Methods

6.2.1 Subjects

Nineteen male and 17 female skilled golfers volunteered to participate in the study. All golfers were right-handed, free from pain or injury, and were either playing or trainee golf professionals or competitive amateur golfers (handicap ≤ 4). Written informed consent was obtained prior to data collection and all experimental procedures were approved by the relevant institution’s Human Research Ethics Committee.

6.2.2 Experimental protocol

All data were collected in a laboratory setting. Upon arrival subjects were interviewed to ascertain practice habits. Injury history and anthropometric measurements
including height and mass were recorded. Subjects then undertook a standardized 10 minute warm-up based on that of Fradkin et al. [68], which included whole body movements and dynamic stretches of the major muscle groups involved in the golf swing, followed by hitting practice shots with a variety of clubs including their driver. The experimental setup consisted of hitting golf balls covered in retro-reflective tape from a rubber tee embedded in an artificial turf mat (1.8 × 1.8 m) into a net approximately 3 m away. All subjects were instructed to address the ball in a neutral stance position, imagine they were on the tee, and hit their usual driver shot as straight as possible. Five full swings with their own driver were collected for each subject.

After five initial swings were collected, each golfer undertook a 40 minute putting intervention, which involved hitting putts along a mat to a hole from a range of self-selected distances [63]. Subjects were free to walk around the putting area, and were instructed not to sit or rest at any point during the 40 minute session. The intervention was intended to simulate a typical practice putting session, where subjects experience the same physical requirements and demands associated with putting practice at a course or driving range. To enhance intra-subject repeatability, all reflective markers used in the capture of 3D swing data remained attached to the subject during the putting task [31, 124]. Immediately following the completion of the putting task, subjects performed another five full swings with their driver.

6.2.3 Kinematic data collection and modelling

Three-dimensional marker trajectories were collected at 500 Hz using a 3D Vicon motion analysis system and modelled using BodyBuilder software version 3.6 (Oxford Metrics, Oxford, UK). Retro-reflective markers were attached to the pelvis
on the right and left anterior-superior iliac spines and posterior-superior iliac spines. Markers were attached to the thorax over the suprasternal notch, xiphoi process, C7 and T10 spinous processes. A LCS used for kinematic modelling was created, by attaching markers to the right and left heel of the subject’s golf shoes which approximated the calcanei [92]. Clubhead trajectory was tracked via a marker attached to the subject’s driver. Raw 3D coordinate data were filtered using a zero-lag fourth-order low-pass Butterworth filter. Cut-off frequencies for individual markers were between 6 and 10 Hz, as determined through residual analysis [73, 184] with an $r^2$ threshold set at 0.85.

Thorax and pelvis kinematics were calculated relative to a LCS based on the position of the heel markers at ball address. The origin of the LCS was the midpoint between the left and right heel markers. The $y$-axis was a vector oriented with the two heel markers and directed towards the target. The LCS $z$-axis coincided with the global vertical and the LCS $x$-axis was the cross product of the plane formed between the LCS $y$- and $z$-axes. Modeling procedures for the thorax and pelvis were based on International Society of Biomechanics guidelines [188, 189]. In addition to thorax and pelvis motion relative to a LCS, the motion of the thorax relative to the pelvis (thorax-pelvis) was also calculated. Lateral tilt, anterior-posterior tilt, and axial rotation were defined as angular rotation of the child segment about the parent segment $x$, $y$, and $z$ axes respectively, using Euler angle calculations. Thorax, pelvis and thorax-pelvis angular velocities were determined using the Poisson equation described by Zatsiorsky [191] and Craig [46], while clubhead and ball speed were calculated as the magnitude of the velocity vector determined from the clubhead marker and reflective golf ball, respectively.
6.2.4 Data analysis

All data analyses were performed using custom-designed software in Matlab version 7.8.0 (MathWorks, Natick, MA). In the present study kinematic data were examined at discrete points in the golf swing, as well as continuously during the downswing. For the discrete analysis, angular displacement at the time points of address, top of backswing TBS and BC were calculated. address was defined as the frame immediately prior to the club starting the backswing, TBS as the frame where the pelvis stops axially rotating away from the target and begins rotating towards the target and BC as the frame where the ball first starts to move. Additionally, the magnitude of peak angular velocity during the downswing phase was determined for the pelvis, thorax, and pelvis-thorax interactions.

For the continuous analysis, kinematic data were analyzed over the entire downswing phase of the swing, defined as the period from TBS to BC. Downswing data were normalised to 101 points for each individual using piecewise cubic spline interpolation. After normalisation, repeatability of continuous segment angular velocity data was quantified using the coefficient of multiple determination (CMD) [101]. The CMD is a measure of waveform repeatability for which a value of 0 indicates no repeatability between waveforms, and 1 indicates perfect agreement between waveforms. To determine the effect of 40 minutes of putting on the consistency of velocity profiles, CMDs were calculated for the 5 swings pre and 5 swings post putting task.
6.2.5 Statistical analysis

As gender differences exist in thorax and pelvis angular displacement and velocity at TBS and BC for skilled male and female golfers [92], change scores were calculated by taking the difference between pre- and post-intervention for each variable (thorax, pelvis and thorax-pelvis angular displacements and velocities) at address, TBS and BC. Positive change scores indicate an increase in angular displacement or velocity post putting intervention, while negative change scores indicate a decrease in angular displacement or velocity post putting intervention. One-way ANOVA (SPSS for Windows 17.0, SPSS, Chicago, IL, USA) was used to test for differences in change scores between males and females. Assumptions of normality were checked and confirmed by plotting the dependent variables using quantile-quantile plots in SPSS. Repeated measures ANOVA with Tukey’s HSD (Honestly Significant Difference) were used to test for differences between CMDs for male and female participant’s pre and post putting intervention. All results are presented as the mean ± one standard error of the mean (SEM) unless otherwise stated. The level of significance was set at \( p < 0.05 \), and ES’s were reported as Cohen’s \( d \) [39].

6.3 Results

6.3.1 Descriptive subject data

Male golfers were significantly taller and had greater body mass than females (Table 6.1). No gender differences were identified for handicap, golf playing experience or practice hours per week. No differences in clubhead or ball speed were identified pre- to post-intervention.
Table 6.1 Descriptive data for all participants (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Males (n=19)</th>
<th>Females (n=17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>26 ± 7</td>
<td>24 ± 7</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>80.2 ± 9.1</td>
<td>61.9 ± 10.1*</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.80 ± 0.05</td>
<td>1.67 ± 0.06*</td>
</tr>
<tr>
<td>Handicap (strokes)</td>
<td>0.6 ± 1.1</td>
<td>1.4 ± 1.7</td>
</tr>
<tr>
<td>Playing experience (yrs)</td>
<td>12 ± 7</td>
<td>11 ± 7</td>
</tr>
<tr>
<td>Practice per week (hrs)</td>
<td>14 ± 8</td>
<td>17 ± 12</td>
</tr>
</tbody>
</table>

* Indicates significant gender difference at $p < 0.05$ level

6.3.2 Thorax and pelvis angular displacement at discrete points in the golf swing

Females had significantly greater changes scores at address, TBS and BC (Table 6.2). Specifically, female golfers had less thorax and pelvis anterior-posterior tilt at address, less thorax and thorax-pelvis axial rotation at TBS, and less thorax and pelvis axial rotation and pelvis lateral tilt at BC from pre- to post-putting conditions.

6.3.3 Thorax and pelvis angular velocity at discrete points in the downswing

Females had significantly greater changes scores for peak thorax-pelvis lateral tilt velocity, where females had lower peak velocity from pre- to post-putting conditions (males: $10.0 ± 2.3 \degree/s$, females: $-5.3 ± 4.1 \degree/s$, $F_{1,34} = 11.02, p = 0.002, ES = 1.14$). No gender differences were identified for any angular velocity measurement at TBS or BC.
Table 6.2 Change scores for angular displacement variables following putting

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Males</th>
<th>Females</th>
<th>F-statistic</th>
<th>p value</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD Pelvis A-P tilt</td>
<td>-0.2 ± 0.2</td>
<td>-1.3 ± 0.2</td>
<td>$F_{1,34} = 7.20$</td>
<td>0.010</td>
<td>0.92</td>
</tr>
<tr>
<td>Thorax A-P tilt</td>
<td>-0.3 ± 0.1</td>
<td>-1.6 ± 0.2</td>
<td>$F_{1,34} = 29.71$</td>
<td>&lt; 0.001</td>
<td>1.88</td>
</tr>
<tr>
<td>TBS Thorax axial rot</td>
<td>-0.1 ± 0.4</td>
<td>-4.1 ± 0.5</td>
<td>$F_{1,34} = 41.42$</td>
<td>&lt; 0.001</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>0.1 ± 0.3</td>
<td>-2.9 ± 0.5</td>
<td>$F_{1,34} = 19.08$</td>
<td>&lt; 0.001</td>
<td>1.51</td>
</tr>
<tr>
<td>BC Pelvis lat tilt</td>
<td>0.3 ± 0.2</td>
<td>-0.6 ± 0.3</td>
<td>$F_{1,34} = 5.25$</td>
<td>0.020</td>
<td>0.78</td>
</tr>
<tr>
<td>Pelvis axial rot</td>
<td>-0.1 ± 0.3</td>
<td>-2.4 ± 0.5</td>
<td>$F_{1,34} = 14.98$</td>
<td>&lt; 0.001</td>
<td>1.34</td>
</tr>
<tr>
<td>Thorax axial rot</td>
<td>-0.2 ± 0.3</td>
<td>-2.2 ± 0.5</td>
<td>$F_{1,34} = 10.72$</td>
<td>0.002</td>
<td>1.13</td>
</tr>
</tbody>
</table>

ES = effect size (Cohen’s $d$); ADD = address position

6.3.4 Repeatability of thorax and pelvis angular velocity in the downswing

Overall CMDs were high, with all values ranging from 0.902 to 0.991 across both genders and pre- and post-putting. For the female golfers, CMD’s decreased from pre- to post-putting for thorax and thorax-pelvis axial rotation velocity (Table 6.3). For the male golfers, CMD’s decreased from pre- to post-putting for thorax-pelvis axial rotation velocity.
Table 6.3 CMDs calculated from continuous velocity data pre and post 40 mins of putting

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
<th>Mean Difference (95% CI)</th>
<th>p value</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thx axial rot</td>
<td>F</td>
<td>0.989 ± 0.002</td>
<td>0.968 ± 0.008</td>
<td>0.021 (0.004 - 0.038)</td>
<td>0.015</td>
</tr>
<tr>
<td>Thx-pel rot</td>
<td>F</td>
<td>0.962 ± 0.017</td>
<td>0.936 ± 0.022</td>
<td>0.026 (0.004 - 0.048)</td>
<td>0.023</td>
</tr>
<tr>
<td>Thx-pel rot</td>
<td>M</td>
<td>0.940 ± 0.016</td>
<td>0.912 ± 0.020</td>
<td>0.028 (0.007 - 0.049)</td>
<td>0.010</td>
</tr>
</tbody>
</table>

6.4 Discussion

This study is the first to examine the effect of a practice putting intervention on upper body kinematics during the full golf swing of both male and female skilled golfers. Thorax and pelvis angular displacement was examined at discrete events during the golf swing to determine if upper body orientation was affected by the intervention. Given that coordinated motion of the thorax and pelvis is a key factor in generating clubhead speed [33, 138], it was also of interest to determine if changes in segment orientation were accompanied by changes in angular velocity. It was hypothesised that following the putting intervention differences in thorax and pelvis orientation angles would be most evident for females compared to males, and that thorax and pelvis angular velocity would be affected in females more than males.

A confirmed hypothesis of this study was that gender differences in thorax and pelvis orientation emerged following 40 minutes of putting. At address, females had a greater change in thorax and pelvis orientation than males, where a more upright posture was adopted by the females after the intervention. While there is no evidence that pelvis or thorax orientation at address has a causal effect on the dynamics of the
downswing, it does indicate that the intervention affected how female golfers position their upper bodies over the ball at address. An important finding that does relate to the downswing was that females had less magnitude of thorax and pelvis rotation at both TBS and BC following the intervention. Furthermore, the relative rotation between the two segments was also less in females at TBS and BC. Arguably, the coordination between segments is more reflective of functional performance than the motion of individuals segments [19]. Therefore, it stands to reason that altered coordination of thorax-pelvic rotation for females at TBS and BC could affect velocity characteristics throughout the downswing.

While gender-related orientation differences were most evident for axial rotation at TBS and BC, velocity differences were not observed at these downswing events. Instead, females had lower thorax-pelvis lateral tilt peak velocity following the intervention, suggesting that males and females are affected differently following 40 minutes of putting. It is likely that a degree of trunk extensor muscle fatigue was experienced by the golfers in the current study, as the current putting intervention has been shown to decrease extensor endurance time for the Biering-Sørensen test by 21% in elite male golfers [63]. Fatigued trunk extensors can lead to impaired proprioceptive acuity [168], altered muscle spindle activity [53], an increase in the common drive to motor units [43], and the number of motor units required to perform the task [43]. Such neuromuscular adaptations could lead to a reduced capacity to regulate trunk motion, particularly during a complex 3D movement such as the golf swing.
Interestingly, despite differences in peak velocity characteristics following the intervention, both groups were able to produce similar clubhead and ball velocities. A compensation strategy was most likely employed to achieve the goal of maintaining high clubhead speeds. Although not a feature of this study, it cannot be ruled out that the neuromuscular system altered the role that the arms play during the swing to ensure high clubhead speeds were maintained. Possible compensatory roles of the arms have been previously observed in skilled golfers, where low levels of hand and clubhead movement variability exist despite relatively high levels of thorax and pelvis movement variability [91]. Prioritising movement control of the endpoint effector is a common observation in many goal directed tasks, and even when fatigued, displacement and velocity of endpoint effectors can remain invariant despite changes in proximal segment kinematics [45, 66]. Future work should involve specific examination of the arms and their role in generating high segment and clubhead velocity.

CMD analysis of segment velocities revealed several important findings which would not have been highlighted by examining peak velocities alone. While males and females demonstrated similarly high levels of repeatability for thorax and pelvis angular velocity over successive downswings, following the putting task both genders displayed decreased repeatability of thorax-pelvis axial rotation velocity. However, this reduced repeatability did not affect clubhead and ball velocity following the putting intervention. Decreased intra-subject repeatability of trunk velocity profiles without corresponding changes in clubhead velocity suggests that fluctuations in the velocity at the level of the trunk may be refined via segments distal to the thorax. Furthermore, different coordination strategies may be employed following the putting
Experiment 3

intervention where unfatigued muscles of the arms, or less fatigued muscles of the trunk are recruited to complete the goal-directed task [45, 70]. Madigan and colleagues [119] investigated joint kinematic variability following a trunk extensor fatiguing task, and similar to the current study found lower consistency of trunk and hip joint angular displacements and velocities, albeit for an upright standing task. Decreased consistency of kinematic profiles suggests that over multiple swings or trials, different motor control patterns emerge while the overall goal of the task is preserved [66].

The findings from this study have important implications for the design of future golf studies, and the interpretation of previously reported results. Currently, there is debate over whether the validity of laboratory based analyses reflect actual golf performance [48, 62]. Instead, there may be just as much importance in considering the physiological status of the golfers at the time of swing assessment. We have shown that swing kinematics are different following a simple warm-up compared to a functional task that is reflective of what occurs in a true golf setting. Furthermore, given that the putting intervention had a greater influence on female kinematics, factors such as gender should be more closely considered in golf studies. Although males and females respond to fatiguing tasks differently [88, 96, 97, 190], it is well recognised that the mechanisms of fatigue are specific to the requirements of the task [96]. Therefore the results of this study are relevant to the intervention prescribed. From a practical perspective, golfers and golf instructors should carefully consider the duration of training or instruction sessions, particularly when working with different genders. While more rigorous investigation is warranted, endurance training programs aimed at improving a golfers ability to manage static golf postures may also be of
benefit to skilled golfers [63]. The results from past or future golf studies conducted in tightly controlled settings not representative of real golfing environments should be generalised to field based settings with appropriate caution.
Chapter 7 - General discussion
7.1 Summary of experimental findings

The purpose of this project was to examine the movement patterns of the trunk during the golf swing in a group of male and female skilled golfers. It was envisaged that the results of this project would clarify the means by which skilled male golfers move their trunk during the full golf swing and add new knowledge on the pattern of movement adopted by female golfers. The following section of the general discussion provides a summary of the findings from each experimental chapter that comprised this project.

Chapter 4 - Experiment 1. Thorax and pelvis kinematics during the downswing of male and female skilled golfers

The aims of this chapter were to present detailed 3D kinematic profiles of thorax and pelvis motion during the downswing, and determine if differences in kinematics exist between male and female skilled golfers. At BC males had greater pelvis posterior tilt, greater thorax and pelvis lateral tilt to the right, and less thorax and pelvis axial rotation to the left compared to females. Male golfers achieved greater peak thorax and pelvis angular velocity, and angular velocity at BC, in the anterior-posterior and lateral tilt directions. Phase plane trajectories revealed that males and females had similar thorax lateral tilt and anterior-posterior tilt angular velocity-displacement relationships at TBS, yet by BC males had greater tilt angles and velocities compared to females. These results suggest that male and female skilled golfers have different kinematics for thorax and pelvis motion. What might be considered optimal swing kinematics for male golfers should not be generalized to female golfers.
Chapter 5 - Experiment 2. Movement variability in the golf swing of skilled male and female golfers

The aim of this chapter was to determine if differences in movement variability existed between male and female skilled golfers during the downswing of the full golf swing. Compared to males, females exhibited higher thorax and pelvis variability for axial rotation at the mid-point of the downswing and BC. Similarly, thorax-pelvis coupling variability was higher for females than males at both the mid-point of the downswing and BC. Regardless of thorax and pelvis motion, the variability of hand and clubhead trajectory sequentially decreased from TBS to BC for both males and females. Overall, the results suggest that male and female skilled golfers utilise different upper body movement strategies during the downswing while achieving similarly low levels of clubhead trajectory variability at BC. It was also apparent that the priority of skilled golfers during the swing was to progressively minimise hand and clubhead trajectory variability towards BC, despite individual motion or coupling of the thorax and pelvis.

Chapter 6 - Experiment 3. Swing kinematics of male and female skilled golfers following putting practice

The purpose of this chapter was to determine if 40 minutes of putting practice affects thorax and pelvis kinematics during the full swing of male and female skilled golfers. Female golfers had less thorax and pelvis anterior-posterior tilt at address, less thorax and thorax-pelvis axial rotation at top of backswing, and less thorax and pelvis axial rotation and pelvis lateral tilt at BC pre- to post-putting. Analysis of peak angular velocities revealed females had significantly lower thorax-pelvis lateral tilt velocity
General discussion

pre- to post-putting. For repeatability analysis, females exhibited significantly lower CMDs for thorax and thorax-pelvis axial rotation velocity, while males exhibited significantly lower CMDs for thorax-pelvis axial rotation velocity only following the putting intervention. In summary, an endurance based practice putting intervention affects females’ thorax and pelvis orientation angles and velocities to a greater extent than males. Interestingly, clubhead speed for both males and females was unaffected by the intervention, suggesting different coordination strategies may be employed where unfatigued muscles of the arms, or less fatigued muscles of the trunk, are recruited to complete the goal-directed task.

7.2 Synthesis of findings

The aim of this project was to examine the movement patterns of the thorax and pelvis during the downswing of male and female skilled golfers. It was envisaged that this project would clarify the means by which skilled male golfers move both their thorax and pelvis during the full golf swing and add new knowledge regarding the pattern of movement adopted by skilled female golfers. In this section all findings from the project are discussed and the implications for skilled golfers are reviewed. Finally, research questions for possible future studies are identified.

7.2.1 New insights into the swing kinematics of skilled golfers

A concerted effort was made to comprehensively describe the 3D kinematics of the thorax and pelvis during the full swing. Gold standard motion analysis technology and contemporary biomechanical modelling techniques were used to provide new insight into the dynamics and coordination of trunk motion during the downswing. Using
discrete and continuous analyses of 3D motion, and analyses that examine coupling of upper body segment motion, the role of the upper body during the golf swing has been further clarified.

Predictably, linear displacement, angular displacement, and angular velocity magnitudes were significantly different between the thorax and pelvis segments. However, despite the magnitude based differences, the 3D linear displacement, angular displacement and angular velocity profiles shared similar patterns amongst skilled golfers. While it is difficult to compare the pattern of upper body motion with previous investigations that use different methods, the magnitude of angular displacement and velocities showed general agreement with golf literature [56, 138, 192]. In addition to magnitude-based differences between segments, the timing of pelvis motion generally preceded that of the thorax for all three-dimensions of motion. While previous investigations have demonstrated this relationship for axial rotation [28], the present study is the first to reveal such timing relationships for lateral and anterior-posterior movement. The most notable difference observed between thorax and pelvis motion was the greater contribution of lateral tilt velocity to the overall motion of the thorax. This feature of the downswing has not previously been identified, largely due to researchers focusing their attention only on axial rotation (Also see Appendix A) [28, 40, 115, 138]. In terms of golf-related injury, this finding may have important implications as large lateral tilt velocities substantially increase compressive and shear loads in the lumbar spine [121]. The relationship between large lateral tilt velocities and performance is unclear. However, it does appear that the dynamics of the thorax and pelvis are both important contributors to the velocity
generated at the clubhead, which is considered a key measure of golf swing performance [115, 138].

In regard to movement variability, this project was the first to quantify variability at the level of the end-point effector (i.e. golf clubhead), and also at the level of the body. Such an approach is more revealing than examining each segment in isolation, as it accounts for the underlying variability in movement dynamics which may influence variability of the end-point effector [74]. This project revealed that overall, skilled golfers are able perform the golf swing in a consistent manner from trial to trial. This was confirmed by the low levels of trunk movement variability, throughout the entire downswing. While hand and clubhead motion also demonstrated low levels of variability, an observable decrease in variability was evident near BC. This is not unexpected, given that for most goal directed tasks there is a requirement for high accuracy when hitting, kicking or striking an object. During the golf swing, any inaccuracy between the ball and club collision will significantly influence shot outcome.

Coupling of thorax and pelvis motion was also consistent throughout the downswing in skilled golfers, as evidenced by the high cross-correlations over repeated swings. Coupling is essentially an indicator of the coordination or synchrony of motion between two segments. In this project, coupling of thorax and pelvis motion ($R^2 = 0.92$) was significantly greater than thorax and head motion ($R^2 = 0.76$), indicating a much more tightly controlled relationship. Considering the complexity of trunk motion during the downswing, this strong coupling relationship potentially reflects a simplified motor control strategy to control redundant degrees of freedom.
Conversely, the more variable coupling relationship between the thorax and head, suggests that no single control strategy exists for head motion during the downswing of skilled golfers. This should not be surprising given the head is not a segment within the links from the feet to the club, and therefore has little role in generating power. Moreover, the head can move independently without directly affecting motion of the club.

7.2.2 New insights into gender differences in golf swing kinematics

Overall, the general pattern of motion during the full swing was similar for male and female skilled golfers. However, this project was the first to reveal selective gender differences in the kinematics and coordination of the thorax and pelvis during the downswing of skilled golfers. Interestingly, the majority of gender related differences were in the sagittal and frontal planes of motion and not axial rotation (which most researchers have reported previously). Females adopted a posture at BC where they exhibited less lateral and anterior tilt of their thorax and pelvis compared to males, and were also in a position where their upper body was more rotated toward the target. This combined position equated to females being in a relatively more upright position at BC. It may be speculated that the different postures exhibited at BC, where high spinal loads occur and the majority of injuries are reported [93, 122], may be an important underlying factor the higher frequency of lower back injuries in male golfers.

In contrast to previous investigations [56, 193], the absence of gender differences in thorax and pelvis angular displacement (i.e. axial rotation) at TBS was unexpected. Of the two studies in the literature that have investigated female swing kinematics, both
have reported greater thorax and pelvis rotation at TBS compared to males. In the current project, and the investigations of Egret et al., and Zheng et al., all gender comparisons were made utilising the same methodological procedures i.e. the same methods were applied to both males and females. Therefore, it is likely that differences in subject specific factors (e.g. anthropometrics, neuromuscular mechanics, skill level) or data/statistical analyses, contributed to the observed discrepancies rather than methodological differences. Phase plane trajectories were able to provide some insight into this issue by illustrating that both males and females exhibited similar thorax and pelvis trajectories at TBS, yet by mid-downswing and BC differences in upper body dynamics emerged, particularly for the lateral and anterior-posterior directions. This suggests that males and females utilised different motor control strategies during the downswing, which ultimately led to males achieving higher segment velocities at BC. Factors such as increased physiological cross sectional area of muscle for males may have facilitated the generation of greater force and therefore greater velocities than females, however further investigation of neuromuscular mechanics during the golf swing is required.

The findings of higher variability and lower consistency of thorax-pelvis coupling during the latter downswing for females further supports gender-specific motor control strategies during the downswing. A particularly interesting finding was the absence of any gender differences for hand and clubhead variability at MID and BC. As the task of hitting the golf ball is the same for both genders, both males and females would need to exhibit similarly low levels of hand and clubhead variability just prior to BC to optimise the outcome of a shot. While no other peer-reviewed golf study exists on this topic, investigations of multi-joint goal directed tasks have
commonly revealed that variability of the endpoint is generally lower than that of the individual segment trajectories [9, 24]. In this project, the similar levels of hand and clubhead variability in the presence of higher trunk variability, indicate that the segments between the trunk and club (i.e. arms) may play an important regulatory role in ensuring consistent ball-club collisions.

Putting is a commonly practiced golfing task, which involves the maintenance of a mostly static position. When performed repetitively over prolonged periods, putting can significantly challenge the physical endurance of a golfer. In this project, 40 minutes of continuous putting was challenging enough to effect upper body kinematics and coordination following the putting intervention. Although the putting task had a relatively small effect on the swing kinematics of male golfers, the differences following the intervention were more pronounced for females. That is, females produced less rotation of their thorax and pelvis at TBS and BC than their male counterparts. The relative difference between thorax and pelvis rotation at these discrete points was also less for females compared to males. Additionally, females were unable to achieve the same magnitude of angular velocity for thorax-pelvis lateral tilt following the putting intervention. The combined result of these findings suggests that male and female skilled golfers are affected differently by a prolonged putting task. In regard to other human movement tasks, few researchers have directly examined the gender effect of fatiguing or endurance based tasks on trunk kinematics. For lower limb tasks, however, gender differences in kinematics have been observed following fatiguing interventions [104, 129]. For example, the effect of a fatiguing type task on the jump landing has been shown to lead to kinematic and kinetic changes which potentially place females at a greater risk of injury [104, 129]. While
males and females in this project demonstrated different responses following an endurance based task, it is well established that this response is also dependent on the type of endurance task and whether it is primarily a dynamic or isometric type task [88, 96].

Interestingly, despite the observed alterations in trunk kinematics and dynamics following putting practice, both males and females were able to maintain similar clubhead velocities. The maintenance of an outcome based variable such as clubhead speed, even after a prolonged endurance task, indicates that the neuromuscular system may have altered the role of the arms and hands during the swing to ensure the maintenance of high clubhead speeds. While the arms and hands were not investigated directly, the overall results of this project support the suggestion that the upper limbs may play a significant role in ‘fine-tuning’ the golf swing prior to BC.

7.3 Future directions

7.3.1 Methodological considerations

In this project the thorax and pelvis were intentionally chosen as the focus of examination, as both play an important role in the development of speed and power during the swing. While many recent investigations have emphasised the importance of trunk motion during the golf swing, none have comprehensively examined 3D kinematics in a manner like was undertaken in the current project. By systematically examining thorax and pelvis motion in three-dimensions, it was revealed that the sagittal and frontal planes of motion contributed substantially to the overall motion of the trunk during the full swing. Consequently, researchers who examine trunk motion
during the golf swing should carefully consider whether the methodological procedures chosen can accurately represent the motion that occurs. The assumption that axial rotation is the only motion worthy of investigation should be reconsidered in future golf swing investigations. At this current point in time, adopting marker configurations and biomechanical modelling procedures in accordance with those outlined in Chapter 3 is likely to benefit researchers investigating trunk kinematics, as they have the capacity to account for errors such as out of plane motion and overestimation of motion due to indirect marker placements. Although trunk motion was the focus of this thesis, lower body and arm motion were not investigated in this cohort of golfers. To fully appreciate the complexity of the full golf swing, there is likely to be benefit in examining both regions in the future.

The results from the experimental chapters of this thesis indicate that the arms may play a vital role in the downswing of skilled golfers. As such, there would be value in building upon the current methods by including the upper limbs in future analyses of the golf swing. In this project shoulder, elbow and wrist joint motion was not directly investigated, thereby making it difficult to draw any firm conclusions on the specific role of each respective upper limb joint. The mechanics of the upper limbs, and in particular the shoulder joints, are especially challenging to model. This is largely due to the complexity of the humeral-scapula relationship, the difficulty in securing markers directly over bony landmarks, and the substantial 3D range of motion available at the gleno-humeral joint [108, 176]. Despite these difficulties, advances in marker configurations and modelling procedures have meant researchers have been able to effectively model shoulder motion in high velocity sports such as tennis and cricket bowling [35, 59, 154, 155]. Future examinations of golf swing kinematics,
whether from a performance or injury perspective, should include the upper limbs and trunk segments and attempt to utilize ‘current best practices’ in the modelling and reporting of data. Researchers could also make significant headway into the understanding of the underlying motor control and coordination required to perform the swing, by developing upon the frequent reporting of kinematic data at discrete swing events.

In this project a gold standard optoelectronic 3D motion analysis system was chosen primarily due to its high accuracy, ability to capture at high sampling rates and unobtrusive nature of the system. While many researchers have successfully used optoelectronic systems to investigate golf swing mechanics, some have argued that the swings collected in a laboratory environment may not be representative of a golfer’s swing on the course or driving range. In addition, clubhead and ball velocity data and ball impact location on a net were the primary indicators of shot performance in this project and may not be completely representative of shots made on a course. The presence of environmental factors such as lighting, directional cues, and sound and perceived spatial constraints, have also been proposed as having the potential to influence the consistency and outcome of each shot [47]. While there is merit in the use of optoelectronic systems in locations where golfers can hit shots in more realistic environments (e.g. hitting from an indoor setting to an outdoor range), investigation of the feasibility and effect on accuracy and reliability of golf swing data is still required.

### 7.3.2 Implications for performance

The current project provides a detailed examination of the mechanics of the trunk during the full driver swing. Like many previous kinematic studies of the golf swing,
the primary performance outcome measure reported in this project was clubhead speed. While high clubhead speeds are inextricably linked to hitting the golf ball further, it is important to acknowledge that other factors, including shot accuracy can also influence successful performance. Therefore, examining performance measures such as shot accuracy or scoring average in conjunction with swing kinematics is likely to provide added information in regard to what constitutes a successful golf shot. Technology such as Doppler radar or actual physical measurement of ball displacement both have the capability of quantifying these performance measures and could be easily employed in future studies. Additionally, there would also be benefit in examining the full swing while using other clubs. Despite driving distance and accuracy being considered one of the most critical determinants of success in professional golf [87] and given that the driver shot was the only shot type examined in this thesis, examining full shots with other clubs is likely to be of value as they too can significantly influence golf performance.

From a practical perspective the gender specific results from the endurance based intervention, and the clear differences in kinematics in the lateral and anterior-posterior directions, suggest that there may be benefit in examining the effect of gender specific golf exercise programs. Programs aimed at improving the strength and endurance of the trunk musculature responsible for sagittal and frontal plane motion may have performance as well as injury prevention benefits not yet elucidated. Of the few investigations that have examined the effect of golf-specific training programs, most have demonstrated positive effects on performance outcomes [115, 172]. However, very few of those investigations have included female subjects. Further,
more guided, gender-specific investigations of the benefits and effectiveness of such programs are warranted.

7.4 Conclusion

In this thesis, a comprehensive description of the 3D kinematics of the thorax and pelvis during the downswing of male and female skilled golfers was reported using gold standard biomechanical procedures. While the general patterns of trunk movement were similar between genders, the results demonstrate that males and females exhibit different dynamics and control of movement, particularly for frontal and sagittal plane motion of the trunk. The effect of a specific practice task on swing kinematics was gender specific, further supporting the notion that males and females exhibit differences in swing mechanics. Interestingly, the results from Experiments two and three suggested a potentially important role of the upper limbs in ‘fine-tuning’ the outcome of a shot in the latter part of the downswing.
Appendix A - The control of upper body segment speed and velocity during the golf swing
This appendix has been published as an original paper in Sports Biomechanics. Horan, S.A. and J.J. Kavanagh (2012). The control of upper body segment speed and velocity during the golf swing. Sports Biomechanics, 11(2), 165-174. Figure and table numbers have been adapted to comply with the formatting of the thesis and the reference list has been omitted with references for this appendix included in the reference list for the entire thesis.

1. Introduction

The motion of the head, thorax and pelvis are considered to be critical to a successful and repeatable golf swing in professional golfers [138, 185]. Understanding the dynamics of upper body motion becomes particularly relevant when one considers that the golf swing is a powerful short duration movement that allows for minimal feedback and error correction during the task. Recent evidence suggests that skilled golfers are able to perform the golf swing in a relatively invariant manner [25, 91]. However, to gain further insight to the control strategy employed during the golf swing, a more detailed examination of the dynamics of the head, thorax and pelvis is warranted.

Sports scientists and biomechanists have frequently used the amplitude and timing of 3D peak velocity [118, 138, 192] as well as total speed of segment movement [63, 174] to describe golf swing dynamics. However, these two measures have not been used in conjunction, and therefore, interpretation of speed and velocity of individual body segments performing the same task may not be consistent. From a biomechanical perspective velocity is a vector measurement that provides information
about the 3D orientation of a body segment, and in particular, the rate of change in orientation. Reporting the total speed of a body segment also describes the rate of change in motion, however, it is a scalar measurement that does not account for orientation, and as a result certain subtleties of the golf swing may be lost in analysis. For example, while it is commonly accepted that total thorax speed exceeds total pelvis speed during the downswing, examining velocity profiles of individual segments allows for a greater understanding of which movement directions contribute most to the difference. It is of considerable interest to determine if different information is extracted from the golf swing depending on whether segmental motion is partitioned into 3D components or if a global representation of segment motion is examined.

The relationship between golf swing performance and inter-segment dynamics has typically been focussed towards the thorax and pelvis. Although never formally investigated, it has been proposed that specific patterns of thorax-pelvis motion during the downswing are related to more powerful swings in certain individuals [28, 33]. Interestingly, although a large extent of golf coaching literature highlights the importance of maintaining stable head motion [4, 185], little empirical evidence exists concerning head-thorax coordination during the golf swing. The timing of segment motion and thorax-pelvis separation has revealed that in skilled golfers, the motion of the pelvis precedes the motion of the thorax during the downswing [28, 33, 174]. However, the control strategies adopted by individuals when performing the golf swing are not well understood.
It has been proposed that to control the many degrees of freedom present in the neuromuscular system, the central nervous system reduces the complexity of control by activating functionally cooperative muscles as a group rather than individually [24]. Simplified functionality is further exploited with practice, where a more optimal strategy for movement is formulated by the neuromuscular system [160]. If this concept is extended to the motor output of well practiced skilled golfers, a simplified control strategy would be reflected by similar motor output between segments and between directions. Horan et al. [92] have observed similar patterns of motion between segments and within segments, particularly for the thorax where lateral tilt and axial rotation velocities exhibit very similar amplitude and phasing relationships. Analyses that examine coupling between upper body segments and between directions of movement may reveal important control strategies not yet realised.

The purpose of this study was to examine the relationship between head, thorax and pelvis motion, during the downswing in professional golfers. The amplitude and timing of peak segment speed, as well as the peak velocity for individual movement directions, was compared between segments. It was hypothesised that the thorax would exhibit the greatest total speed of movement due to the importance attributed to the trunk in assisting in the generation of power during the downswing. It was also hypothesised that coupling for the thorax and pelvis would be greater than for the head and thorax, due to the importance of thorax-pelvis interactions during the downswing. Collectively, it is expected that the results of this study will provide further insight into the control strategies adopted in the largest and most proximal segments of the body, by professional golfers.
2. Materials and methods

2.1 Subjects

Fourteen male professional golfers (mean ± standard deviation; age 27 ± 8 yrs, height 1.79 ± 0.04 m, mass 81.2 ± 9.6 kg, golf playing experience 13.3 ± 8 yrs, practice per week 14 ± 9.6 hrs) volunteered for the study. All golfers were free from injury at the time of testing as determined by an experienced physiotherapist (SH). Written informed consent was obtained prior to data collection, and all experimental procedures were approved by the Griffith University Human Research Ethics Committee.

2.2 Data collection

Four retro-reflective markers were attached to the head on the right and left sides of the frontal eminence and right and left sides of the occipital protuberance. Four markers were attached to the pelvis on the right and left anterior-superior iliac spines and posterior superior iliac spines. Four markers were attached to the thorax over the suprasternal notch, xiphoid process, C7 and T10 spinous processes. To create a LCS for kinematic analysis, a further two markers were attached to the right and left heel of the subject’s golf shoes which approximated the calcanei.

3D marker trajectories were collected using an optoelectronic motion analysis system (Vicon, Oxford Metrics, Oxford, UK), consisting of eight MX13 near-infrared cameras, operating at 500Hz. Raw 3D coordinate data were filtered using a zero-lag fourth-order low-pass Butterworth filter, with cut-off frequencies for individual
markers (6-10Hz) determined via residual analysis [73]. Filtered marker trajectories were subsequently modeled using custom-designed BodyBuilder software, version 3.6 (Vicon, Oxford Metrics, Oxford, UK).

Once all markers were attached, each participant performed a standardized 10 minute warm-up which included large dynamic movements, static stretches and graded air swings [68]. Participants then familiarised themselves with the laboratory environment by hitting golf balls covered in retro-reflective tape from a rubber tee embedded in an artificial turf mat (1.8 × 1.8 m) into a net approximately three meters away. Data collection consisted of each participant hitting five full shots with their driver. Participants were instructed to imagine they were standing on the tee, adopt a neutral stance position, and hit their usual driver shot as straight as possible. Two vertical lines placed on the net 0.5 m apart were used as an aiming guide and if any shot was not between the two lines, it was deemed ineligible and a further trial was collected. In the current study, only 4% of shots were repeated after being deemed ineligible.

2.3 Data analysis

Head, thorax and pelvis kinematics were calculated relative to a LCS created from the position of the heel markers at ball address [92]. The origin of the LCS was the midpoint between the left and right heel markers. The y-axis was a vector oriented with the two heel markers. The LCS z-axis was coincidental with the global vertical and the LCS x-axis was the cross product of the plane formed between the LCS y- and z-axis. Lateral tilt, forward tilt, and axial rotation were defined as angular rotation about each segments x, y, and z axes respectively. As no two setup positions are
exactly the same, a body-centric LCS has the potential to avoid offsets in the data compared to a GCS as a LCS can adjust according to a golfer’s stance. 3D angular kinematics were determined using the Euler angle decomposition method. Speed of the head, thorax and pelvis were calculated as the square root of the squared sum of lateral tilt, forward tilt and axial rotation angular velocity. Calculation of angular velocity of the head, thorax and pelvis was performed using the Poisson equation, as described by Zatsiorsky [191] and Craig [46].

All data analyses were based on the downswing phase and performed using custom written software in Matlab version 7.8.0 (The MathWorks, Natick, MA). In this study the downswing phase was defined from the top of backswing, that is minimum pelvis axial rotation away from the target, to BC. Data for the downswing phase were normalised to 101 points for each individual using piecewise cubic spline interpolation, enabling swing data to be reported as 0-100% of the downswing cycle. Peak speeds and timing of the peak speeds during the downswing were calculated for the head, thorax and pelvis. Peak velocity and the timing of the peak velocity during the downswing were also calculated for forward tilt, lateral tilt, and axial rotation of the head, thorax and pelvis segments.

Cross-correlation analysis in accordance with the method outlined by Derrick & Thomas [50] was used to examine inter-segment coupling between the continuous time-series signals of the head and thorax, and the thorax and pelvis. Intra-segment coupling was determined by applying cross-correlation analysis between directions of movement for each segment. Cross-correlation analyses were applied to normalised downswing velocities where the strength of coupling, R², and the phasing difference
between velocity data were revealed. The resolution of phasing was one percent of the
downswing and each cross-correlation performed was set to a maximum phasing
difference (i.e. lag) of 50 samples to ensure at least half the data were overlapping.
For the purposes of this study $R^2$ values $> 0.8$ were defined as high, $R^2$ values
between 0.7-0.8 were defined as moderate and $R^2$ values $< 0.7$ as low [177]. As cross-
correlation coefficients are not normally distributed, $R^2$ values for all trials were
averaged by taking the Fisher Z-transformations of the absolute cross-correlation
coefficient values [50]. In this study, a positive phasing value for between-segment
and within-segment correlations indicated the second named segment was leading the
first named segment. Phasing was determined by taking the average of the time lags
across the five captured swings.

2.4 Statistical analyses

Amplitude and timing of peak velocity, and amplitude and timing of peak speed were
examined using ANOVA (SPSS for Windows 17.0, SPSS, Chicago, Illinois), with
significant main effects evaluated using Tukey’s HSD (Honestly Significant
Difference) test. For the speed and velocity analyses, a between-segment and within-
segment approach was adopted. Although Tukey’s HSD test is adjusted to account for
multiple comparisons, the primary focus of this study was to compare either the same
segment across different directions or between segments across the same direction.
Therefore, only physiologically relevant pair-wise comparisons are reported. The
level of significance was set at $p < 0.05$. 
3. Results

Average clubhead and ball speed for the professional golfers in this study was 50.1 ± 2.1 m/s and 70.6 ± 4.2 m/s (mean ± SD) respectively. Representative speed and velocity profiles for a single male professional golfer are presented in Figures 1 and 2, respectively. Peak speed was typically reached in the latter half of the downswing and was greatest for the thorax, followed by the pelvis and then the head. A notable feature of the velocity profiles was the similar patterns of thorax lateral tilt and axial rotation velocity, whereas, pelvis lateral tilt was approximately half the amplitude of pelvis axial rotation.

Figure 1. Representative head, thorax and pelvis speed for five trials of a male professional golfer using a driver. The speeds from the five trials are expressed relative to the downswing.
3.1 Speed

The thorax had significantly greater peak speed than the pelvis ($p < 0.001$) and head ($p < 0.001$), and the pelvis had significantly greater peak speed than the head ($p < 0.001$) (Table 1). No significant differences were detected for the timing of peak speeds between segments. The strength of coupling for thorax-pelvis speed was high (Table 2). Strength of coupling was also high for head-thorax correlations, however, an additional feature of head-thorax correlations was the relatively large variability in correlation coefficients. The predominantly negative phasing for the head-thorax
speed indicated that the head lead the thorax, while thorax-pelvis phasing indicated the pelvis predominantly lead the thorax during the downswing.

**Table 1.** Amplitude of peak speed and peak velocity for each segment and direction with respect to the timing of peaks within the downswing.

<table>
<thead>
<tr>
<th></th>
<th>Peak Speed (°/s)</th>
<th>Percent of Downswing</th>
<th>Direction</th>
<th>Peak Velocity (°/s)</th>
<th>Percent of Downswing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>210 ± 56</td>
<td>79 ± 19</td>
<td>Forward tilt</td>
<td>115 ± 65 2,3</td>
<td>82 ± 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lateral tilt</td>
<td>156 ± 57 a</td>
<td>67 ± 23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial rotation</td>
<td>67 ± 114</td>
<td>77 ± 19</td>
</tr>
<tr>
<td><strong>Thorax</strong></td>
<td>650 ± 60 1,3</td>
<td>83 ± 9</td>
<td>Forward tilt</td>
<td>-197 ± 29</td>
<td>95 ± 5 1,a,b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lateral tilt</td>
<td>406 ± 50 1,3,c</td>
<td>78 ± 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial rotation</td>
<td>491 ± 54 1,b,c</td>
<td>77 ± 12</td>
</tr>
<tr>
<td><strong>Pelvis</strong></td>
<td>507 ± 52 1</td>
<td>76 ± 5</td>
<td>Forward tilt</td>
<td>-177 ± 36</td>
<td>89 ± 8 1,a,c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lateral tilt</td>
<td>188 ± 52 c</td>
<td>81 ± 6 1,a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial rotation</td>
<td>464 ± 46 1,b,c</td>
<td>71 ± 6</td>
</tr>
</tbody>
</table>

Between-segment: 1 significantly different from head, 2 significantly different from thorax, 3 significantly different from pelvis

Within-segment: a significantly different from axial rotation, b significantly different from lateral tilt, c significantly different from forward tilt
Table 2. Maximum cross-correlation coefficients ($R^2$) and phasing for between-segment and within-segment analyses.

<table>
<thead>
<tr>
<th></th>
<th>Max $R^2$</th>
<th>Positive $R^2$</th>
<th>Phasing</th>
<th>-:0:+</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed: between-segment coupling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head-thorax Speed</td>
<td>0.83 ± 0.17</td>
<td>100%</td>
<td>-6 ± 8</td>
<td>55:45:0</td>
</tr>
<tr>
<td>Thorax-pelvis Speed</td>
<td>0.99 ± 0.01</td>
<td>100%</td>
<td>3 ± 3</td>
<td>0:28:72</td>
</tr>
<tr>
<td><strong>Velocity: between-segment coupling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head-thorax Forward tilt</td>
<td>0.78 ± 0.14</td>
<td>29%</td>
<td>-4 ± 7</td>
<td>59:36:5</td>
</tr>
<tr>
<td>Lateral tilt</td>
<td>0.86 ± 0.13</td>
<td>100%</td>
<td>-12 ± 11</td>
<td>67:29:4</td>
</tr>
<tr>
<td>Axial rotation</td>
<td>0.65 ± 0.19</td>
<td>57%</td>
<td>-10 ± 19</td>
<td>64:17:19</td>
</tr>
<tr>
<td>Thorax-pelvis Forward tilt</td>
<td>0.87 ± 0.14</td>
<td>100%</td>
<td>2 ± 7</td>
<td>0:75:25</td>
</tr>
<tr>
<td>Lateral tilt</td>
<td>0.91 ± 0.10</td>
<td>100%</td>
<td>-2 ± 3</td>
<td>50:36:14</td>
</tr>
<tr>
<td>Axial Rotation</td>
<td>0.98 ± 0.01</td>
<td>100%</td>
<td>4 ± 5</td>
<td>2:9:80</td>
</tr>
<tr>
<td><strong>Velocity: within-segment coupling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head</td>
<td>Forward tilt-lateral tilt</td>
<td>0.70 ± 0.12</td>
<td>89%</td>
<td>23 ± 15</td>
</tr>
<tr>
<td></td>
<td>Forward tilt-axial rotation</td>
<td>0.63 ± 0.15</td>
<td>53%</td>
<td>15 ± 14</td>
</tr>
<tr>
<td></td>
<td>Lateral tilt-axial rotation</td>
<td>0.63 ± 0.21</td>
<td>70%</td>
<td>-3 ± 13</td>
</tr>
<tr>
<td>Thorax</td>
<td>Forward tilt-lateral tilt</td>
<td>0.79 ± 0.11</td>
<td>0%</td>
<td>5 ± 7</td>
</tr>
<tr>
<td></td>
<td>Forward tilt-axial rotation</td>
<td>0.80 ± 0.11</td>
<td>0%</td>
<td>7 ± 8</td>
</tr>
<tr>
<td></td>
<td>Lateral tilt-axial rotation</td>
<td>0.98 ± 0.05</td>
<td>100%</td>
<td>0 ± 3</td>
</tr>
<tr>
<td>Pelvis</td>
<td>Forward tilt-lateral tilt</td>
<td>0.86 ± 0.11</td>
<td>0%</td>
<td>3 ± 7</td>
</tr>
<tr>
<td></td>
<td>Forward tilt-axial rotation</td>
<td>0.85 ± 0.11</td>
<td>0%</td>
<td>9 ± 6</td>
</tr>
<tr>
<td></td>
<td>Lateral tilt-axial rotation</td>
<td>0.91 ± 0.08</td>
<td>100%</td>
<td>5 ± 4</td>
</tr>
</tbody>
</table>

Positive $R^2$ represent the percentage of subjects with maximum $R^2$ values that were positive. A positive phasing value for between-segment and within-segment correlations indicated the second named segment was leading the first named segment. -:0:+ represents the percentage of trials that exhibited either negative, zero, or positive phasing values respectively.
3.2 Velocity: between-segment analysis

Forward tilt peak velocity for the head was significantly greater than the pelvis ($p < 0.001$) and thorax ($p < 0.001$) (Table 1). Lateral tilt peak velocity was significantly greater for the thorax compared to the head ($p < 0.001$) and the thorax compared to the pelvis ($p < 0.001$). Axial rotation peak velocity was greater for the thorax compared to the head ($p < 0.001$) and the pelvis compared to the head ($p < 0.001$). Analysis of timing of peak velocities revealed that thorax forward tilt peak velocity occurred later in the downswing than head forward tilt peak velocity ($p < 0.001$).

Head-thorax correlation coefficients were generally lower than the thorax-pelvis correlation coefficients (Table 2). High $R^2$ values were observed for thorax-pelvis axial rotation. The phasing for head-thorax velocity were overall negative in each direction indicating head velocity lead thorax velocity. However, it should be noted that this phase relationship was variable between subjects as evidenced by high SD’s and the spread of negative, zero, and positive time lags. Similar to speed, thorax-pelvis velocity phasing for the axial rotation direction were predominately positive, indicating the pelvis was leading the thorax.

3.3 Velocity: within-segment analysis

Head peak velocity was significantly greater for lateral tilt than axial rotation ($p = 0.021$) (Table 1). Thorax peak velocity was greater for axial rotation than lateral tilt ($p < 0.001$) and forward tilt ($p < 0.001$), and thorax lateral tilt peak velocity was greater than thorax forward tilt peak velocity ($p < 0.001$). Pelvis peak velocity was greater for axial rotation than lateral tilt ($p < 0.001$) and forward tilt ($p < 0.001$), and pelvis lateral tilt peak velocity was greater than pelvis forward tilt peak velocity ($p < 0.001$).
Analysis of timing of peak velocities revealed that thorax forward tilt peak velocity occurred later in the downswing cycle compared to thorax lateral tilt ($p < 0.001$) and thorax axial rotation peak velocity ($p < 0.001$). Pelvis forward tilt peak velocity occurred later in the downswing cycle compared to pelvis lateral tilt ($p = 0.013$) and pelvis axial rotation peak velocity ($p < 0.001$), while pelvis lateral tilt peak velocity occurred later than pelvis axial rotation peak velocity ($p < 0.001$). Overall the head correlation coefficients were lower than the thorax and pelvis correlation coefficients for all within-segment couplings (Table 2). The number of positive $R^2$ values was also generally mixed for the head indicating that a single movement strategy did not exist amongst professional golfers. The highest correlation coefficients were for axial rotation-lateral tilt velocity for both the thorax and the pelvis, indicating strong coupling relationships during the downswing. Thorax and pelvis phasing values were generally positive, indicating the second direction in the pair was leading the first. The thorax lateral tilt-axial rotation velocity pair, which had the highest $R^2$ values, exhibited a predominately in phase relationship across all subjects presumably as a strategy to ensure high velocities.

4. Discussion

The purpose of this study was to examine the relationship between head, thorax and pelvis motion during the downswing in professional golfers. Amplitude and timing of peak segment speed as well as the peak velocity for individual movement directions were investigated. Strength of coupling and phasing were also analysed between-segments and within-segments with the aim of providing a greater understanding of control strategies utilized by professional golfers during the golf swing.
Examining the amplitude of peak velocity in conjunction with the amplitude of peak speed was able to highlight important differences between segments that may not have been revealed by examining speed or velocity in isolation. As was hypothesised the thorax exhibited the greatest speed of angular movement compared to the pelvis and head, which is in agreement with other studies that have examined segmental speeds in skilled golfers [63, 140, 174]. Interestingly, peak axial rotation velocities were not significantly different between the thorax and pelvis during the downswing. While peak pelvis axial rotation velocity in this study is similar to others [115, 138], the magnitude of thorax axial rotation velocity is considerably lower than previous investigations of similar level golfers [138]. This discrepancy may in part be explained by differences in kinematic modelling, where previous studies have reported segment motion relative to a global plane and used indirect marker placements to model thorax motion. The indirect marker method is prone to overestimating thorax rotation [180] and potentially contributed to the observed velocity discrepancies. The current study examined individual directions of motion and revealed that while axial rotation of the thorax segment is the highest contributor to thorax speed, lateral tilt also plays a key role in generating high overall angular speed of the thorax. An added benefit of partitioning the movement into directions is that multi-directional analyses of coupling can be performed, allowing for a greater understanding of the motor control strategies adopted for the complex task requirements of the golf swing.

A unique feature of the current study was that cross-correlation analyses were applied to continuous kinematic data to examine coordination, as opposed to solely examining the timing of upper body motion at discrete events during the downswing. The results
of the between-segment analyses indicated that, in general, thorax-pelvis couplings were observed to be highest with head-thorax couplings noticeably lower. Of particular note, axial rotation coupling between the thorax and pelvis approached an $R^2$ value of 1, indicating very strong congruence between the velocity profiles of both segments. These findings confirm the importance that previous researchers have attributed to the relationship between thorax and pelvis displacement using analyses such as thorax-pelvis separation angle, or X-Factor [28, 33, 40, 138]. However, high thorax-pelvis correlation coefficients for forward tilt and lateral tilt velocities suggest that researchers and coaches must not solely rely on axial rotation-based analyses if they are to fully appreciate the coordination required to perform the golf swing. It is also important to appreciate that the relatively low coupling between the head and thorax suggests that no single control strategy exists for skilled golfers. Previous investigations of head motion during the golf swing have reported that compared to unskilled golfers, skilled golfers exhibit greater translational motion of the head during both the backswing and downswing [157]. This in conjunction with our finding of lower coupling suggests that skilled golfers do not necessarily need to regulate head motion to the same extent as thorax motion. This should not be surprising considering that the head is not a segment within the links from the feet to the golf club, and therefore, can move independently without affecting club motion. Accordingly, golf coaches may need to provide instruction on the general pattern of head motion but remain flexible enough to permit different control strategies amongst their students.

It has long been suggested that implementing a control strategy where motion of the pelvis leads motion of the thorax during the downswing assists in optimising club
head speed, yet this feature has only recently been studied quantitatively [174]. While studies have reported between-segment timing of upper body motion during the downswing, some significantly different [174] and some not [140], the analyses in the current study did not detect timing differences between the thorax and pelvis. However, the within-segment analysis of coupling was able to reveal strategies that skilled golfers employ to potentially increase speed of the upper body during the downswing. The thorax and pelvis exhibited strong coupling between directions, particularly for the lateral tilt-axial rotation direction. This coordination strategy implies that skilled golfers place a greater importance on regulating the global motion of the thorax and pelvis rather than independently regulating motion in each direction. This finding has important practical implications for golf coaches. Through practice, the CNS can modify a pattern of muscle activity in an effort to utilise the most effective and simple movement strategy [32]. When instructing highly practised golfers, changes in technique may be difficult to maintain due to a reliance on a highly developed, simplified, and ingrained control strategy. Coaches should also recognise that due to a lack of practice and repetition, unskilled golfers may not have refined their control strategy and hence perform less fluid movements that are regulated according to direction. In the future it would be of considerable interest to determine whether the same coupling relationships observed for skilled golfers exist for unskilled golfers.

5. Conclusion

The present study confirmed that the thorax segment has the highest peak speeds and peak velocities for the upper body during the downswing of professional golfers. It was also apparent from the large contributions of lateral tilt velocity to total segment
angular speed, that analyses of thorax dynamics should not be merely restricted to the axial rotation direction. Analyses of coupling revealed that very strong coupling relationships exist for the thorax and pelvis, but not so for the head and thorax. The relatively large variability in head and thorax coupling suggests that no single control strategy exists for skilled golfers, and that coaches may need to provide instruction on the general pattern of head motion but remain flexible enough to permit different control strategies. Furthermore, the strong coupling between the thorax and pelvis is presumably a method for simplifying the motor control strategies during the downswing, and a way of ensuring consistent motor patterns.
Appendix B - Warm up routine
**Golf specific warm-up - Adapted from Fradkin et al., (2004)**

**Part A – 4x brisk exercises to increase blood flow (3 - 4 mins)**

1. Windmills  
2. Squats  
3. Trunk twists  
4. Wall push ups

**Part B – 8x static stretches held for 15 secs and 2 x repetitions each (8 mins)**

1. Posterior shoulder  
2. Pecs stretch  
3. Trunk stretch  
4. Hamstring – ½ squat  
5. Low back – arching  
6. Chest – rotation  
7. Wrist – flexion stretch  
8. Forearm – extensors

**Part C – Air Swings with golf club gradually increasing in ROM (4 - 5 mins)**

1. Air swings
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