MOVEMENT VARIABILITY AND STRENGTH AND CONDITIONING IN GOLF

by

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ABSTRACT

The detrimental nature of movement variability has recently been reconsidered with suggestions that it has a functional role to play in performance. Movements in golf can be attributed to the organismic, task and environmental constraints from which they emerge with these swing movements affecting shot outcomes. A three-dimensional analysis of address position variability revealed that higher skilled golfers present reduced alignment variability in angular relationships between the shoulders and stance compared to less skilled counterparts. Whilst there were no group differences in impact variability, both points in the swing displayed reducing variability from proximal to distal aspects of the kinetic chain.

With the popularity of strength and conditioning growing within the golfing world it has become important for coaches to be able to assess golfers' physical constraints. Two-dimensional analysis, representative of that used in coaching environments, assessed the relationship between the overhead squat and deterioration of posture in the golf swing. Results showed small but significant relationships between this test and golf swing postural kinematics. An 8-week intervention to address overhead squat physical constraints resulted in no change in 3D swing kinematics. Strength and conditioning as a stand-alone intervention provides no benefits to postural kinematics suggesting the need for coaching.

DEDICATION

To Charlie and Lilly,

Now I have finished studying for my PhD
I can devote even more time to being your daddy!
Here’s to a fun filled life together!
xx

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1.1. INTRODUCTION

Golf is a sport played by an estimated figure of 80 million people across the world (HSBC, 2012) with 3.36 million of those participating at least once a year on full length golf courses across GB (Sports Marketing Surveys Inc., 2014). Although the concept of golf is simple to grasp it is portrayed as one of the most technical sports to learn and master when all factors that impact upon performance are taken into account (Smith, 2013).

With research spanning decades it has been a quest for scientists and coaches alike to explore the technique of all elements of performance from the fine movements of the putting stroke through to the powerful, explosive movements of the drive. Initial, robust work in search of the perfect golf swing (Cochran and Stobbs, 1968) and research since then has led to the understanding that golfers are to be coached as individuals, their constraints are unique to them, their swing is equally unique and an exploration of how to improve performance continues with this in mind. Research has covered many of the key aspects of performance including biomechanical analysis of both movement and forces during the swing, psychology and performing under pressure, nutrition and hydration strategies, analysis of impact between the club and ball as well as the design of the equipment used.

With the elite end of the sport becoming populated by increasingly athletic golfers it is clear that research is needed into the movements golfers are creating across the ability spectrum. A recent example of the benefits that can be realised by the professional ranks is how Rory McIlroy's swing speed has reportedly increased by 5mph up to 121.56mph since 2010. This has been attributed to his body being faster and stronger through his work in the gym rather than any technical changes (Diaz, 2015). With this in mind a focus on physical constraints is also needed to establish how best to analyse and alter these in this increasingly power driven sport.

A problem that has traditionally existed in golf coaching is the meaning, and the understanding, of seeking consistency in performance. Suttie (2006) defines a mechanically sound and consistent swing as one in which the clubface, along with other variables being accounted for, moves through impact square to the target-line every single time a shot is played. A lot of emphasis is placed on producing a repeatable swing that will not break down under pressure (Zumerchik, 2002). What is not known is how much variability golfers can tolerate in the movements before this becomes detrimental to their performances.

When looking at the full swing it is important for a coach to firstly identify the individual's constraints, whether these are physical, task, or indeed the environment in which they find themselves. Zumerchik (2002) suggests that although athleticism to swing the golf club with timing is required, there are also mental and task constraints that the golfer must be able to deal with in order to make the most of their physical attributes and succeed in this sport. Secondly it is important to acknowledge that variability will always be a part of movement when seeking a "consistent" golf swing performance over numerous trials, towards the same target and with the same ball flight. Although this is not representative of on course behaviours it would appear to be important from a coaching perspective that the golfer can develop a movement that is repeatable in a practise environment that is robust to the effects of the on-course setting and pressures.

The role of variability has not been explored in the sport of golf until very recently (e.g. Bradshaw et al., 2009; Horan, Evans and Kavanagh, 2011) and coaches may be unaware of its function within the swing. It can be simple to identify when too much variability is hindering performance and ball flight which may take on various shaped trajectories (e.g. hooks, pull hooks, slice, push slice etc.). This is what a coach faces on a day to day basis when working with golfers who participate in the sport for recreational purposes only.

Variability is often viewed as a negative aspect of performance, hence why coaches strive for consistency in their golfers' swings. A need exists to assess whether variability is always detrimental to performance or if indeed there is a place for variation in the golf swing from shot to shot. With novice golfers, coaches may be able to reduce variability at a rapid rate with regular coaching. However, there is little understanding on how variability is used to aid golfing ability and research here will allow greater insights into how future coaching can employ methods and drills to enhance a golfer's "consistency" or their ability to overcome varying tasks and environments in performance. Analysis is required across the ability continuum to establish the levels of variability each standard of golfer exhibits at critical moments during the swing (i.e. address and impact), what role variability has to play in increasing levels of golfing performance and how this could impact upon future coaching of the swing.

Movement in the golf swing emerges from the physical constraints (as well as task and environmental) (Newell, 1986) that are dictated by the golfer's flexibility, strength, power, stability and mobility. It is therefore important that coaches, from both golf and strength and conditioning (S&C) backgrounds, are able to accurately assess these physical characteristics and understand how they may impact upon the golf swing.

Over recent years the game of golf has seen a change in the physique and approach of its top golfers to training for performance, with driving averages on the European Tour increasing by 4.94% from 273.2 yards in 2000 to 286.7 yards in 2014 (www.europeantour.com, n.d.a, n.d.b), with longer courses demanding increased driving and approach shot distances, and professionals looking to every aspect of sports science support in order to make gains over their rivals. In comparison the shot put, another explosive sports skill, has only seen increases of 1.06% with average distances increasing from 19.80m in 2000 to 20.01m in 2014 (www.iaaf.org, n.d.a, n.d.b). The blue ribbon event of athletics, the men's 100m sprint, has also only seen very small percentage improvements with the top 180 non-wind assisted times in 2014 being just 0.48% quicker than in 2000; 10.10secs compared to 10.15secs respectively (www.iaaf.org, n.d.c, n.d.d), however, this is an event where very small margins can be the difference between first and last place.

Perhaps equipment in golf has a lot to do with the increased distances but it now appears that the use of S&C is also a key factor to aid performance (Farrally et al., 2003). This is not only the case at the elite level but also in novice and club golfers who are seeking alternative ways to enhance performance alongside coaching and upgrades in equipment. With movement in mind, there have been many coaches and organisations keen to impress upon golfers that increases in these physical characteristics all have a role to play in achieving more success in modern golf (e.g. Titleist Performance Institute (TPI) and The C.H.E.K. Institute) with

TPI adding to this by claiming 22 of the top 35 golfers in the world are advised by a TPI certified professional (www.mytpi.com, n.d.d).

The link between physical assessment results (also known as musculo-skeletal profiling or screening) and golf swing kinematics (in particular “swing faults”) has been popularised and taught across the world by the organisations such as TPI since around 2006. Although the education of professional coaches is to be applauded it is vital that the golf related S&C content that is provided to the coaching world is underpinned by rigorous testing and research protocols. This will establish the true extent of the relationships between movement quality in assessment tests and swing kinematics. It is important that these relationships are known so that coaches understand what information they can gather and effectively use following movement assessments with their clients.

With S&C becoming an important tool to aid performance it is essential that more is understood about the effects physical adaptations can have on performance. If S&C coaches are able to improve the key physical attributes to golf and reduce / alter the physical constraints to movement then research needs to establish what effects these training adaptations have on golf swing kinematics. Along with the role of movement variability, S&C research is important to increase understanding of how coaching teams can achieve the process of assessing movement, reducing limitations and transferring these new attributes to performance. In this regard the research that follows analyses any differences in movement variability of high and low skilled golfers and the relationship S&C assessments and interventions have with the postural kinematics in the golf swing.

1.2. MOVEMENT VARIABILITY IN THE GOLF SWING

Abstract

Traditionally golf biomechanics has focussed upon achieving consistency in swing kinematics and kinetics, whilst variability was considered to be noise and dysfunctional. There has been a growing argument that variability is an intrinsic aspect of skilled motor performance and plays a functional role. Two types of variability are described: 'strategic shot selection' and 'movement variability'. In 'strategic shot selection' the outcome remains consistent but the swing kinematics / kinetics (resulting in the desired ball flight) are free to vary; 'movement variability' is the changes in swing kinematics and kinetics from trial to trial when the golfer attempts to hit the same shot. These changes will emerge due to constraints of the golfer's body, the environment and the task. Biomechanical research has focused upon aspects of technique such as elite vs. non-elite kinematics, kinetics, kinematic sequencing, peak angular velocities of body segments, wrist function, ground reaction forces and electromyography (EMG) mainly in the search for greater distance and clubhead velocity. To date very little is known about the impact of variability on this complex motor skill and it has yet to be fully researched to determine where the trade-off between functional and detrimental variability lies when in pursuit of enhanced performance outcomes.

Introduction

Since the beginning of golf, the skill of a 'perfect' swing has been pursued by golfers in order to achieve the ultimate goal, to ensure the ball ends up in the hole in as few shots as possible. The problem a golfer faces each time he/she addresses the ball is how to get the clubface back to contact with the correct combination of impact factors to achieve the desired ball flight and shot outcome. Working backwards from this point of impact, the forces presented within the golf swing must be organised to allow the clubhead to arrive at impact with the correct velocity, position, direction, angle of attack and orientation to send the ball on the intended ball flight. Since the publication of the seminal work on the golf swing by Cochran and Stobbs (1968) there have been many technical advances in motion analysis but not a congruent increase in the number and certainly the diversity of the quantitative investigation of the swing. It seems that there is a fascination with the driver and attaining the maximum possible shot distance with this club (e.g. Hume, Keogh, & Reid, 2005), whereas coaches strive for their golfers to achieve consistent and mechanically sound movements in their swings. Suttie (2006) defined such a swing as one that consistently delivers the clubface to the point of impact with the ball with a square alignment to the target line, maximal velocity and with the clubface perfectly vertical. Suttie (2006) suggests that this will allow only the loft to affect the trajectory of the ball flight which will travel on the correct path each time. The correct path being one that allows the ball to land on target following a consistent launch angle (including both the horizontal and vertical components), height, curvature and distance. This also assumes that each golf ball is struck from the centre of the clubface and aligned with the centre of gravity of the clubhead.

Whilst a mechanically sound swing definition is important, it is imperative that both coaches and researchers understand how swing characteristics prior to impact affect what happens between the club and ball at contact. A coach desiring consistency in their client's performance has its place in creating effective actions but the goal of this review is to highlight that there must also be an understanding that not all variability is detrimental to performance. These variable elements should be considered in what is a more complex skill than perhaps the examples above allude to, e.g. the centeredness of impact upon the clubface or the dynamic loft angle of the face at impact. Current biomechanical swing definitions are also without reference to the constraints the player faces on the course.

Setting any organism, environmental or task constraints aside and purely considering maximising ball displacement the player must achieve a high angular velocity of the clubhead and maximise the length of the arm-club lever regardless of the length of the club. Both of which must also be considered alongside the 5 impact factors of clubface alignment, swing path, angle of attack, centredness of strike (sweetspot) and clubhead speed (Tuxen, 2009; Wiren, 1990). Although these have not been rigorously reviewed to date, for the purposes of this Chapter (and the remaining Chapters), the discussions will be based around these assumptions. All of the above can affect the launch, flight and landing position of the golf ball when performing this complex action. Consideration must also be given to the occasions in golf where a full swing is the selected response but maximal velocity is not required. The initial horizontal launch angle is determined by the clubface alignment to the swing path, with this being the most influential factor at 85%, and the swing path itself being the second influential factor (15%) (Tuxen, 2009). Again, although this possibly reflects a simplistic view of one relationship between the impact factors it is useful for the purposes of this review. The variability within these impact factors is important when we consider an expert golfer using different ball flights to achieve desired shot outcomes. Whilst there are many variations in swing styles and movements, a golfer's swing is a 'highly coordinated and individual motion' (Nesbit, 2005) and it is at the point of contact with the ball which represents the critical feature of the swing.

These impact factors need to remain invariant as a group in order to achieve successful ball flights for a given goal. Because the ball flight is determined by the relations among these variables, they can vary as long as they are compensated by changes in the other variables. What we do not know at this stage is how much variability can be tolerated in the movement towards the critical moment of ball contact, nor where this variability can occur. A skilled performer will solve the movement problem to produce the desired impact factors for a given shot outcome relative to the external forces that are likely to be encountered by the ball post impact.

Bril, Rein, and Nonaka, (2010) proposed that skilled or dexterous actions are ones that comprise a combination of flexibility, precision, adaptability, smoothness, regularity, optimisation and swiftness. This dexterity is not revealed by the movements, but is more the relationship between the performer and the environment, where skilled movements harness rather than resist external forces to present a solution for any situation and condition (Bernstein, 1996). An elite golfer has to direct his/her actions to meet the required demands, interacting and adapting to the changing conditions from which he/she plays each shot on the course. It is the use of and coordination of such functional variability in shot selection and swing movements, with the chosen golf club, that can define a skilled performer.

Newell (1986) suggested that the coordination dynamics of an action emerge from the body self-organising movements in an optimal response to the task at hand and is constrained by three interacting areas (task, environment and organism). This is in opposition to cognitive motor control beliefs where there is a prescriptive knowledge structure in place to guide the movement in relation to the task, thus considering variability as system noise or error that decreases with increases in skill proficiency (Bartlett, Wheat, & Robins, 2007). Kugler, Kelso, and Turvey, (1980) proposed that a coordinated movement is one that harnesses the otherwise free variables into a behavioural unit. Control of this movement involves the formation of a set of parameters for the dynamic action and this controlled movement is then directed towards a specific goal in an optimal and successful manner which is termed ‘skill’.

This review aims to explore the factors that influence how sporting actions are performed from a constraints-led approach, drawing on previous research to define variability within golf. The notion that eliminating all variability within the swing is not necessarily the key to success will be explored alongside the constraints that can influence kinematics and kinetics with the potential for variability being a functional aid to performance. Considering the relationship between functional and detrimental variability in golf will improve our understanding of the swing and point to avenues of further research. Variability research has been conducted into many skills and sports such as: Volleyball (Handford, 2006), table tennis (Bootsma & van Wieringen, 1990); long jump approach phase (Lee, Lishman, & Thomson, 1982;

Scott, Li, & Davids, 1997), football chipping (Chow, Davids, Button, & Koh, 2007; Chow, Davids, Button, & Koh, 2008), and stone knapping (Bril et al., 2010). With so little direct research within golf to draw on it is difficult to be more than speculative until much needed further research is published. This paper therefore aims to discuss variability from a golfing context based on previous work in other areas of sport and manual skills. It is also worth noting at this point that to date there is a paucity of research conducted into the female game highlighting the need for larger comparability studies. The limited research that has been published in this important comparison has focused solely on the differences and not variability of movement within each gender (See Egret, Nicolle, & Dujardin, 2006; Neal, Lumsden, Holland, & Mason, 2007; Zheng, Barrentine, Fleisig, & Andrews, 2008b). Organismic constraints may present themselves depending upon the sex of the golfer but at this point research has not established these for either males or females. As Bartlett et al. (2007) proposed, by exploring the role of functional variability in any sporting movement it could elicit performer adaptations to environmental conditions, reduce injury risks, and facilitate changes in coordination patterns. This constraints led approach is currently missing from the sport of golf and in particular the research into this skill.

Theories and Data of Variability in Sport / Skills

Intra-subject Variability

When considering the goal of the golf swing it is important to recognise that very little research has been published on the variability in striking an object where both the performer's starting position and the object itself are stationary. To produce a specific ball flight and landing position many times, as in practice situations, golfers aim to apply a consistent force to the ball in order to achieve this outcome. Tool use is one such example of a comparable skill and early observations in this area came from Bernstein's (as cited in Gurfinkel & Cordo, 1998) analysis of hitting a chisel with a hammer. Many authors have since suggested that in any goal directed action the performer is not simply directed towards the goal but is directed by the goal and therefore the goal specifies the demands that have to be met by the performer in order to succeed (Bril et al, 2010; Shaw, 1987). Bernstein (1996) and Reed and Bril (1996) (as cited in Bril et al., 2010) highlighted that functional actions are not specified by the movements we create as such, but by the ability to meet the demands imposed by the environment.

Bernstein (as cited in Gurfinkel & Cordo, 1998) noted that when studying striking movements and locomotion it was inappropriate to study movement coordination at basic component levels of a skill and that the whole structure should be analysed as one. Bernstein showed that the striking movements had critical factors that the central nervous system takes into account (in this case the inertial forces). He then concluded that a task such as hitting a chisel with a hammer was made up of many small movements and that a change in one detail led to many other details being reorganised to meet the demands of the task at hand. This specifically relates to the golfing problem, where golfers are faced with a completely new task / environment each time they play a shot on the course. The lie of the ground, the position in which the ball sits and the address position that the golfer can achieve will always create an original goal and task for the player to overcome. In order to solve this problem, golfers must be adept at many strategies in order to succeed at any task presented to them in competition and this is where the role of practice demonstrates its important relationship with functional variability.

When playing to a set target, skilled golfers are able to produce and control a variety of ball flights through a change of set-up (address position), changing the club selection, or varying the movements of the swing using the same club. Savelsbergh, Davids, van der Kamp, and Bennett, (2003) proposed that this ability to adjust movement patterns to varying environments is an important characteristic displayed by skilled performers. However, a particular ball flight is dependent upon ball speed, vertical and horizontal launch angle, spin rates and spin axis orientation (Tuxen, 2008) and limiting movement variation could in turn relate to the production of consistent ball flights. Conversely, Bartlett et al. (2007) commented that outcome invariance does not necessarily mean movement invariance. Further investigation is needed to understand the relationships among the five impact factors and how much variability is tolerable. Following this, research must establish the levels of variability that can be tolerated in the macroscopic kinematics and kinetics of the golf swing before there is a detrimental effect upon this impact factor relationship. Understanding the trade-off between reduced movement variability and the use of variation in performance will allow us to understand the differences between skilled and unskilled golfers. With the goal of creating skilled performers in mind it is essential that within this review distinctions are made between the different types of variability that can be present within the golfing performance. These distinctions consist of “strategic shot selection”, where the golfer is able to make decisions about the solution to the goal e.g. what club, alignment, and ball flight is selected; “movement variability” which consists of functional and detrimental variability; and finally “inter-subject variability” in which the elite can be compared to the non-elite to establish critical factors in performance.

Strategic Shot Selection

In golf, strategic movement variability can be defined as the ability to produce the same final task outcome (i.e. the ball landing in the same position) with a variety of ball flights, use of different clubs and therefore swing mechanics. For example in windy conditions it may be necessary to play a low “punch” shot, where a longer club (lower loft) than normal is used for the required distance but the swing is kept short and the ball flight is lowered to minimise the effects of any wind. Such strategic shot selection is necessary to achieve different outcomes and manipulating the coordination patterns of our body’s movements allows us to do just this. The goal of golf has to be to create effective solutions that emerge in response to the given constraints that impose upon the golfer’s goal, including the environment, the task and the body’s own limitations.

Movement Variability

Movement variability can be defined as the shot variability where the task and strategy are known and therefore consistent ball flight, club and swing mechanics are called upon. This variability is influenced by the golfer's movements. Put simply it is the changes in swing kinematics and kinetics from trial to trial when the golfer attempts to hit the same shot. These changes will emerge due to constraints of the golfer's body (including the mind), the environment and the task. Bernstein (1967) commented that practice is a type of repetition without repetition, where the learner does not simply reproduce the skill many times in the same manner to achieve the goal. Practice is therefore when the learner, using deliberate practice, solves the motor problem many times through changing techniques that are perfected from trial to trial. This allows the golfer to establish functional variability.

Golfers need to establish functional variability through their practice in order to provide solutions to each shot presented to them on the course. In line with this it is imperative that research establishes how much kinematic and kinetic variation occurs in each phase of body movement to deliver repeated performances when seeking a consistent target and ball flight goal as this is currently unknown in golf. It could be that from the start of the downswing there is a window of opportunity to get the club into a position to achieve an effective impact position. Research needs to establish this and communicate the findings to coaches of this complex skill. In turn, coaches need to consider how to facilitate practise to encompass the benefits of functional variability for when the skill of the golf swing is transferred to varying conditions on the course.

Functional Movement Variability

Newell and Corcos (1993) demonstrated that movement variability has commonly been viewed as noise in the central nervous system and therefore classified as dysfunctional. However, dynamical systems theorists suggest that the variability in movements is an intrinsic part of skilled motor performance and as a result allows performers to adapt and be flexible in their dynamic sporting environment (Bartlett et al., 2007; Williams, Davids, & Williams, 1999). Some variability is useful in order to allow the emergence of the movement coordination to produce successful solutions towards the task goal. Without functional movement variability, constraints could become too imposing on the response and golfers could not adapt to incorrect positioning at any stage of the action. For example the set-up will never be identical even if the task goal is the same. Consequently, players have to produce swings with different, adapted characteristics, i.e. functional variability.

Detrimental Movement Variability

Within the golf swing it is clear that the reduction of variability around impact is a major concern of golf coaches (Hay, 1993; Suttie, 2006) in order to produce the desired response (ball flight). Too much variability in relation to the task goal can be termed as noise and will therefore disrupt the pattern of co-ordination enough to become detrimental to performance. If, based on previous research (e.g. Betzler, Monk, Wallace & Otto, 2012), we assume that the five impact factors are indeed the critical factors of successful golf shots then future work needs to establish where variability presents detrimental effects on these throughout the swing in both kinematic and kinetic analyses.

Inter-subject Variability (Elite vs. Non-elite)

Inter-subject variability is simply variation in the way different individuals hit the same shot orientated towards the same goal. The traditional view within movement science argues that movement noise and variability together lead to reductions in performance. Self-imposed strategic constraints are always present in the golf swing due to the golfer choosing to adopt a fixed address position with the two footed stance. Other constraints can also be observed within novice golfers who limit any 'strategic' variability in order to focus on reducing 'detrimental within movement' variability. This often occurs through the freezing of degrees of freedom (DOF, where DOF represents 'the number of variables that can be specified by the control system' (Latash, 1993). Bernstein (1967) stated that in order to coordinate a movement the performer would need to master the redundant DOF by linking two or more together (i.e. muscles or joints) to act together as a single unit. As the skill of the golfer improves the swing characteristics can be organised into a more flexible coordination of the joints and muscles which can be controlled as a whole.

Due to the paucity of sports variability research in which the performer is striking a stationary object it is necessary to look elsewhere for examples of such skills. Tool use in the form of stone knapping was examined by Bril et al. (2010). Stone knapping along with the golf swing are both regarded as complex actions within their respective fields. Both skills involve controlling various geometrical and dynamic parameters in order to achieve success. A variety of stone knapping studies provided conclusions that can be applied to the skill of the golf swing: an activation of a greater number of DOF can indicate a level of expertise, where the experts were able to vary their movement kinematics in a way that produced consistent kinetic energy leading to high levels of success towards different outcome goals. Novices and intermediates in the skill of stone knapping may have been aware of what they were to try and achieve but were less attuned to successful parameters therefore producing larger movements and expending increased amounts of energy for lower levels of success in return (producing a flake and control of flake size). It was this level of expertise and understanding that enabled the experts to utilise varying movement skills to repeatedly produce a stable critical factor of kinetic energy leading to success in the goal presented to them.

Glazier, Davids, and Bartlett (2003) suggest that the assumption of many sports biomechanists is that skilled motor performance is characterised by little variability between trials. This concurs with the opinions of swing coaches who look for a stable (minimal variability) approach to performance. Phillips, Davids, Renshaw, and Portus (2010) argued that the idea of a common optimal pattern of movement (in golf and other sports) has tended to tyrannise practice in sports pedagogy and has therefore distorted the learning and development of players / athletes for some time. As Chow, Davids, Hristovski, Araújo, and Passos (2011) alluded to, it is futile for these coaches to try and identify common swing patterns for each golfer to mimic because the goal of each individual should not be to reproduce another player's swing, but to assemble a personal and functional movement pattern which satisfies each shot's constraints. Handford (2006) also commented that coaches and athletes in many sports believe that stability and consistency in movement are essential characteristics of performance. The research based on serving in volleyball discussed by Handford (2006) suggests that some aspects of the movement need stability for successful outcomes while others can tolerate variability. In other sports, research conclusions have been drawn suggesting that experts are able to utilise a “homing in” or “zeroing in” process. This allows experts to reduce detrimental variability compared to novices at impact or at the critical point of performance (e.g. table tennis: Bootsma & van Wieringen (1990); long jump approach phase: Lee et al., 1982; Scott et al., 1997).

Many studies have focused upon the interaction of fluctuating execution variables compensating for other fluctuating execution variables which Bootsma and van Wieringen (1990) termed “compensatory variability”. Examples of the range of studies include pistol shooting (Arutyunyan, Gurfinkel, & Mirskii, 1969); footfall placement in the long jump approach run (Scott et al., 1997); throwing (e.g. Müller & Loosch, 1999); tennis serves (e.g. Carlton, Chow, & Shim, 2006). Handford (2006) commented that some aspects of performance that require stability may only become successful if other aspects are allowed to vary. Bartlett et al. (2007) further this by suggesting that the freeing of biomechanical DOF could assist in this compensatory strategy demonstrated by skilled performers. Bootsma and van Wieringen (1990) had previously stated that one has to make sure that the variability of movement does not serve a functional purpose before being dismissed as “noise”. It is therefore vital that golf research pays particular attention to the role of variability and as Bartlett et al. (2007) continued to state, we should accept that variability is crucially important in sports performance and attend to this within future golf biomechanics research.

Importance of Variability in Golf Swing Kinematics

To produce a desired outcome a movement system must be able to produce both stable (persistent) and flexible (variable) motor outputs (Davids, Glazier, Araújo, & Bartlett, 2003). This allows a player to adapt to the requirements of each shot (task) and the environment. Most research on the golf swing has studied variables that are considered of major importance to provide power, distance and direction for a successful drive (e.g. Hume et al., 2005; Nagao & Sawada, 1977; Neal & Wilson, 1985; Sanders & Owens, 1992; Wallace, Otto, & Nevill, 2007; Zheng, Barrentine, Fleisig, & Andrews, 2008a). This type of study fails to give a complete description of the swing (Dillman & Lange, 1994) and especially if one is looking to impact upon coaching practices.

Many aspects of the swing have been considered in the past such as wrist cocking and uncocking (e.g. Nagao & Sawada, 1977), ground reaction force and weight transfer patterns (e.g. Barrentine, Fleisig, & Johnson, 1994; Brown, Best, Ball, & Dowlan, 2002; Sanders & Owens, 1992; Wallace, Grimshaw, & Ashford,1994), kinematic sequencing and peak angular velocities of body segments (Cheetham et al., 2008; Neal et al., 2007) and EMG of the upper body (for a full review of EMG research refer to McHardy & Pollard, 2005). There have been further studies investigating how the body and clubs can create increased power, distance and accuracy (including the use of warm ups (e.g. Fradkin, Windley, Myers, Sell, & Lephart, 2008; Smoliga & Fradkin, 2008), determining angles of attack (e.g. Tuxen, 2008), and establishing the correct clubs for different golfing populations (e.g. Vengellow & Santiago, 2008) (for further review of the role of biomechanics in golf refer to Hume et al., 2005).

However, in relation to this review many of these studies have failed to consider the role of variability and its impact upon performance (ball flight and shot outcome) having instead mainly focused on clubhead velocity and calculated distance. This reinforces the need to conduct field-based research utilising higher sampling rates (≥200Hz) within golf as it is vital to assess the effect the performance has upon the ultimate goal of ball flight and to capture accurate data on the kinematics leading up to this critical phase as well as measuring the ball flight itself. For example Bradshaw et al. (2009) who assessed the variability within the golf swing of high and low handicap players and Egret et al. (2006) who assessed the kinematic differences between experienced male and female golfers used limited methodologies. Both of their VICON capture systems were operating at 50Hz which, as Bartlett (2007) stated, makes it unsuitable for the quantitative study of very fast sports movements. Egret et al. (2006) overcame the use of 50Hz sampling rates to track clubhead velocity by using a radar system (launch monitor).

Equally there is a need for consistency in the definition of points of interest within the swing, e.g. end of the backswing, start of the downswing, with different authors using various definitions (e.g. Zheng et al, 2008a *c.f.* Nesbit, 2005). Finally in many studies there is lack of presentation of a clear target to a golfer or in skilled golfers the required ball flight. With no clear objective set then variability can increase purely due to a change in shot type. Variability needs to be analysed within the golf swing but when doing so we need to ensure that methodologies are standardised and that appropriate technology and analysis is utilised in order to report true findings and recommendations to coaching populations.

Intra-subject Variability Data in Golf

Intra-subject variability has not been the focus of research to date and therefore is extremely under-represented. The swing itself is renowned as being one of the most difficult biomechanical motions in sport to execute, meaning a methodologically sound and detailed understanding of the mechanics of the golf swing would be beneficial to both golfers and coaches (Nesbit & Serrano, 2005). Previous research (e.g. Coleman & Rankin, 2005; Egret et al., 2006; Egret, Vincent, & Weber, 2003) has by and large failed to provide a detailed kinematic analysis due to the aforementioned methodological limitations, only a few swing variables being considered and a lack of analysis of their variability (standard deviations are the only representation of variance).

Recently a comparative study focusing on the variability of various static and dynamic kinematic measurements within the golf swings of high and low handicap players has been carried by Bradshaw et al. (2009). However, in using a video sampling rate of 50Hz it does not allow accurate assessment of intra-subject variability in the fast movement of the golf swing, where the clubhead can be moving at anything up to and over 60 m/s with a driver.

Many researchers have focused on ways to increase clubhead velocity (Jorgensen, 1970; Milburn, 1982; Neal & Wilson, 1985; Vaughan, 1981; Williams & Cavanagh, 1983). This has involved examination of ground reaction forces (GRF) (Ball & Best, 2007a, 2007b; Barrentine et al., 1994; Kawashima, Meshizuka, & Takeshita, 1998; Williams & Cavanagh, 1983), transfer of body weight (Brown et al., 2002; Rambarran & Kendall, 2001; Richards, Farrell, Kent, & Kraft, 1985; Wallace et al., 1994; Worsfold, Smith, & Dyson, 2008), the kinetic chain or kinematic sequence, together with the stretch shortening cycle, or as it is commonly known within golfing circles – the "x-factor stretch" (Cheetham et al., 2008; Milburn, 1982; Neal, Lumsden, Holland, & Mason, 2008). What has been lacking from this type of study is a consideration of what the increase in clubhead velocity does to the variability within the swing i.e. is an increase being obtained alongside an increase in detrimental movement variability.

Inter-subject Variability Data in Golf

Elite vs. Non-elite

Research to date has mainly focused upon the driver, some in more detail than others in an attempt to understand this skill better. Authors have sought to identify the 'perfect' model or one variation of it by looking at the kinematic characteristics of elite and non-elite swings (Cooper & Mather, 1994; Linning, 1994; Zheng et al., 2008a). These have been suggested to include the head remaining still while the shoulders rotate about it; the left shoulder dipping under the chin while the right shoulder turns behind the head; the knees remaining bent at impact; the left hip rotating on a horizontal plane while the right dips and rotates to allow the trail shoulder to dip under the chin as the torso turns towards impact (Cooper & Mather, 1994). Consistency when performing at an elite level is supported by Suttie (2006) and Hay (1993) who suggest a consistent impact is key to optimal performance.

Sanders and Owens (1992) have shown that elite golfers demonstrate a consistent movement of the swing hub (defined as the intersection of normals to the tangents of the clubhead path) rather than a fixed point and that the clubhead moved in a consistent path (SD = 3.6 cm at impact for the elite group compared to a SD ranging from 5.2 to 14.4 cm for the non-elite golfers). They suggested that rather than encourage novices to swing about a fixed hub (restricting DOF) coaches should encourage controlled lateral movement toward intended direction of ball flight. Therefore, instead of an uncontrolled movement pattern the coaches should seek a more controlled variability pattern around the hub.

Non-elite Kinematics

It is worth noting at this point that there are methodological issues regarding the selection of a sample of golfers. Consideration should always be paid to the ability level of the groupings used in so called 'elite' or 'non-elite' / 'novice' / 'beginner' golfers when comparing study findings. Samples have been categorised using both handicaps (hcp): (e.g. Zheng et al. 2008a) and skill ability (e.g. Kawashima et al. 1998) making comparisons across studies difficult and there may also be other variables playing a key part on the performance criteria in question. For example, two golfers with handicaps of 10 may have very different skill levels across the necessary tasks presented in golf. One may be highly skilled at driving and approach shots whereas the other may be more proficient at putting and short game skills but both still possess the same handicap. Establishing agreement in these definitions is a requirement of any research examining the golf swing.

Of the work on non-elite golfers Nesbit's (2005) study is the most useful. It produced a 3D analysis of the golf swing from a kinematic and kinetic standpoint using golfers of various abilities. Whilst there are no highly skilled golfers in the study it does provide an important insight into the variables of the swing over a large sample (n= 84) which had been missing from the literature, but there is a lack of intra-subject variability analysis. As a result it is hard to draw information on functional variability in the sample's swings and where coaches should focus their efforts in order to reduce variable noise. This study has shown the in-depth approach necessary to highlight inter-subject differences and common characteristics that can be used to determine skill levels. Through further analysis of the intra-subject kinematics and kinetics variability across many trials and across the ability spectrum the data may present patterns in each phase of the swing, thus answering the problems posed previously. It is this approach to analysis from which new coaching methodologies could be informed to create successful, efficient actions and coaching process.

Whilst this Chapter will not review individual kinematic variables in depth, consideration of the wrist movement, kinematic sequence and centre of pressure movements in the swing is instructive in illustrating the need to have a greater understanding of movement variability.

Wrist Kinematics

The wrists have been considered in many studies (Jorgensen, 1970; Linning, 1994; Nagao & Sawada, 1977; Sprigings & Neal, 2000; White, 2006; Zheng et al., 2008a) and different actions have been found between elite and non-elite golfers. Elite players tend to uncock (release of the wrists' positions set in the backswing and early downswing movements) their wrists later in the downswing and this uncocking is critical to achieving maximum clubhead velocity (Dillman & Lange, 1994; Jorgensen, 1970; White, 2006; Zheng et al., 2008a, 2008b). Recently, differences have been shown between male and female elite golfers which include the lower angular velocity of the wrists in the female swings (Zheng et al., 2008b). The DOF present at the wrist joint give the potential for a wide variety of movements during the swing. Currently we do not know how much and where movement variability exists within the swing, where the skill level differences lie or if there is a kinematic sequence for the wrists. With the potential for variable joint positioning there is also the need to examine if there is a decrease in movement variability ("zeroing in") as the action approaches impact with the ball.

Kinematic Sequence and Segmental Timings

When defining the kinetic chain Fleisig, Barrentine, Escamilla, and Andrews (1996) and others (e.g. Kreighbaum & Barthels, 1990) stated that, in co-ordinated human movement, motion, energy and momentum are transferred through sequential body segments in order to achieve maximum magnitude in the terminal segment. For golf this means that the transition into the downswing needs to utilise the summation of velocity principle in order to deliver the clubhead at maximal angular velocity to ball contact through the transfer of energy from proximal to distal segments (i.e. pelvis, torso, arms, and clubhead). If maximal velocity is desired then the timing of release of specific movements / joints also needs consideration in line with the summation of velocity principle (Burden, Grimshaw, & Wallace, 1998). This is where the proximal body segments reach peak angular velocity prior to more distal segments within the downswing. It is here that a critical invariant feature (i.e. the release of the pelvis, torso, arms and clubhead in sequence) prior to impact may be presented where the transfer of momentum is maximized by exploiting this biomechanical principle. Smeets, Frens, and Brenner (2002) concluded from their analysis of the successful variables necessary for the release of a dart that variability in any given parameter can be compensating for variability in another parameter. Further golf research is needed to assess the importance of variability in the sequence of the transition into the downswing and the temporal nature of segment release to achieve maximal clubhead velocity. It is precisely this sort of research that can allow identification of the variability tolerance within the macro-kinematics that affects the critical factors (i.e. the impact factors).

Whilst there is still uncertainty in our understanding of the swing, research is beginning to identify some interesting data to suggest that there is an optimal sequencing of peak segmental angular velocities in the golfer's kinematic sequence (Figure 1. See Cheetham et al., 2008 for a full discussion). There is little information currently available on the tolerable variation within the velocities and timings of the sequence present and how the sequence differs across the spectrum of abilities and between genders.

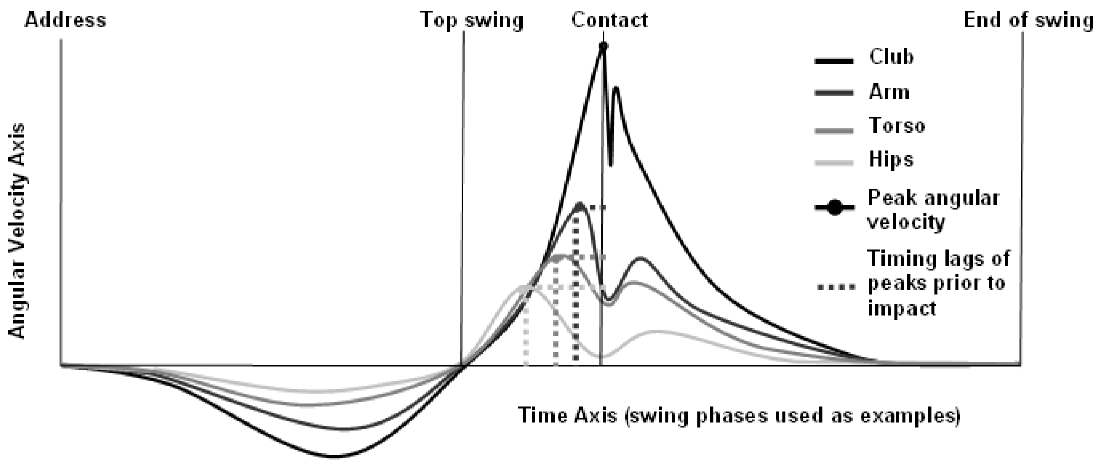

Figure 1 A Model of an Ideal Kinematic Sequence for a Golf Swing, Highlighting 4 Body Segments: Hips, Shoulders (Trunk), Wrists and Clubhead

Cheetham et al. (2008) compared novice amateurs and professionals, finding amateurs demonstrate poorer coordination presented through timing variability of the peak segmental rotational speeds prior to impact. This variability was shown by the standard deviations of the mean timing of the peak segmental (pelvis, thorax, arm) rotational speeds before impact. Amateurs showed larger values (38, 29 & 23 ms) compared to Professionals (19, 14 & 8 ms). The amateurs also produced swings where the proximal to distal sequence was incorrect with the arm peaking before the thorax.

This suggests that amateurs have not mastered a repeatable motor pattern and therefore sequencing / segmental timing between trials is possibly a factor of performance only seen in elite players. Once again one has to consider that even though amateurs present variable timings it is important to note that the clubface control may not be affected and although there may be a weaker speed transfer, their accuracy and ball flight may not be compromised. Button, MacLeod, Sanders, and Coleman (2003) suggested that compensatory variability may have a part to play along the kinematic chain in order to reduce the variability of the critical factors. For their study it was the reduced variability of the release parameters of the basketball in a free-throw situation, but parallels may be drawn to the golf club and ball impact and its preceding kinematic sequence.

Neal et al. (2007) found that the sequential building of the clubhead speed from proximal to distal segments was repeated throughout 25-30 trials for 25 highly skilled amateur golfers where miss-timed and well-timed shots were analysed against each other. The authors suggested that the reason the miss-timed shots were poorly hit was due to the clubface and ball interaction. Examination of the data shows that there were increases in the variability of kinematic and temporal measures between the well-timed shots and miss-timed trials for all body segments and the clubhead, as indicated by higher values for the standard error of mean (refer to Neal et al. (2007) for data analysis). This variation, although not significant may suggest that small changes could impact upon the critical factors occurring at contact. In order to assess the relationship between the tolerances of variability in the kinematic sequence and the critical factors of the skill further studies of this nature on an increased scale are necessary.

From the data of the Cheetham et al. (2008) and Neal et al. (2007) it is apparent that whilst research is confirming that there are fundamental proximal to distal sequences and timings within the golf swing that are critical for both novice and skilled players to maximise clubhead velocity and distance (comparable to other throwing or rotational power sports), there is also a tolerance of variation within these swing characteristics. Again it can be noted that there are coordination features that seem to correlate to skill level and that elite performers' solutions to the task, environment and organism constraints emerge through functional variability, whereas the amateurs appear not to have produced optimised performance (e.g. presenting a sequence that does not conform to the proximal to distal sequencing, possibly due to freezing of DOF). Research needs to consider where stability in coordination / swing characteristics and "zeroing in" on impact is required through the reduction of detrimental variability.

Centre of Pressure (Weight Distribution and Transfer)

Whilst there is no current work on the 'within movement variability' of weight distribution and the translation of the centre of pressure (CP), we do know that there is a distinction between elite and non-elite players. The elite players displace their CP further during the swing along the mediolateral axis (displacement of the CP in relation to a line parallel to the ball to target line), whereas the novice or unskilled player will possibly limit the CP displacement to maintain stability within the motor performance (Brown et al., 2002; Mason, McGann, & Herbert, 1995). It is the constraints and the freezing / unfreezing of DOF along the ability spectrum that need exploring to identify where the trade-off between functional and detrimental variability begin to allow non-elite players to become increasingly proficient in their task.

Not only is there movement variability between elite and non-elite golfers but also within these groups. Ball and Best (2007a) used a cluster analysis to identify whether "styles" of weight transfer occurred within golf swings. From a sample of 62 professional – novice golfers (handicap = 11±8) they found two styles of weight transfer regardless of ability. "Front foot" style players allowed their CP to displace towards the lead foot through the whole downswing and impact whereas "rear foot" players began their downswing by shifting their CP towards the lead foot followed by a shift back towards the rear foot as they approached impact and follow through. Although the inter-subject variability was taken into account within this study there was no consideration of the intra-subject variability that may have been present, within each style of CP displacement. There was also no analysis of ball flight or performance data within this study and they relied on CHS and handicap data to assume the effect on ability.

CP variance and movement coordination in golf is an underexplored area. By performing a study with a greater number of trials, participants and performance statistics it will provide potential for a powerful set of results that could be used directly to enhance both the low and high handicap players' swings.

Conclusion

Repeatable movements are undoubtedly important in the optimisation of technique but functional variability is another factor that coaches must consider. Due to the lack of exploration of this within the golf performance it is an area that is currently poorly understood within this sport.

Through practice elite performers develop the capacity to utilise variability in a functional manner to optimise skilled performance (Bernstein, 1967). Without a clear understanding of how much variability is functional it is impossible to optimise practice or to challenge the current coaching dogma of development of repeatable movement patterns. Harbourne and Stergiou (2009) present the argument that despite our enhanced scientific understanding of the role of variability in motor control and learning (in other sports and skills excluding golf) there is little dissemination of the research findings down to the practitioner. Unless this happens there will never be any translation of scientific research into strategies that can be used by the golf coaches. Currently, the lack of accurate and relevant research suggesting which features need to be invariant (critical factors of golf performance) and which should incorporate a degree of functional variability is hindering the motor control and learning aspects of golf coaching.

Studies must encompass investigation across ability levels and genders in ecologically valid settings in order to establish the effect of macroscopic kinematics and kinetics upon the critical swing features. This should be done in relation to ball flight and participants should be given direct instruction as to the ball flight goal in order to reduce 'strategic shot selections'. This will allow research to explore 'movement variability' and define the golf swing's critical features where consistency is required. Research can examine the need for ‘zeroing in’ or reduction of detrimental variability towards impact as well as examining the compensatory nature of the five impact factors together. Only when this has been achieved will research be able to impact upon the entire golfing population through the education of coaches and the implementation of Bernstein’s (1967) ideas of “repetition without repetition” for the performance development of this complex skill.

1.3. STRENGTH AND CONDITIONING FOR GOLF

Abstract

Golf is a moderate intensity sport with moments of a highly explosive and powerful nature. The lengthening of golf courses has been accompanied by the developments in equipment technology, and golfers training for increasingly powerful golf swings. The ability to increase drive distances allows golfers to play a shorter, more controlled approach shot into the green while maintaining a similar distance to fellow competitors. With this in mind, traditional views on avoidance of S&C, due to fears of losing flexibility and clubhead speed, have been replaced with an ever-growing popularity to train for potential benefits to golf performance. It would seem important for golfers to develop and possess the ability to control the clubhead during the golf swing and it may be possible that this can be realised through S&C interventions. However, research has currently not established the influence of S&C on golf performance with the main focus being placed on the outcome measures of clubhead speed and ball speed. Although increases here can lead to greater shot distances, they do not necessarily dictate levels of performance or lead to lower scores. Since the comprehensive review of literature conducted by Smith, Callister, and Lubans (2011), very few studies have assessed the kinematics of the golf swing alongside S&C interventions. Various training modalities have been studied, including golf specific strength programmes, plyometrics, isolated core and general strength training across periods of between 6 and 18 weeks. Other research has attempted to identify the physical characteristics associated with increased performance levels, focusing on gluteal strength, $\dot{V}O_{2max}$ values and strength demands related to increased clubhead and ball speeds. Low sample numbers, few

control groups and a paucity of analysis on golf swing kinematics has so far limited much of the research in the area of S&C interventions for golf. There is a need for research to further assess the impact of S&C interventions on golf swing kinematics and to analyse the nature of relationships between assessments of physical constraints and swing characteristics.

Strength and Conditioning for Golf

Strength and conditioning (S&C) has been used to improve performance in a variety of sports over many years. In golf however, it has only recently been accepted as a means to gain an advantage over competitors, with skilled golfers previously refraining from S&C due to fears of a loss of range of movement (ROM) (Alvarez, Sedano, Cuadrado and Redondo, 2012).

Golf is a moderate intensity sport that requires the golfer to possess a variety of physical characteristics. Hellström (2009) stated that golfers who improve their strength, power, flexibility and balance may have a "better swing" with a large ROM and increased production of forces and torque. Read and Lloyd (2014) have recently suggested that the role of the S&C coach within golf should be to focus predominantly on the increase of angular velocity by the golfer generating greater ground reaction forces and speed of movement through body segments. This should be combined with a focus on increasing the ability of golfers to safely decelerate post impact through increased strength. These suggestions pay no consideration to the notion that perhaps S&C also has a role in the golfer's ability to control the clubhead's path, face angle, angle of attack and centredness of strike towards and at the point of impact with the ball. It can be argued that the implementation of control over these additional impact factors is the role of the golf coach, but research needs to establish whether S&C can aid in this process through the improvement of physical characteristics and reduction / alteration of physical constraints.

Using Boyle's "joint by joint" approach (Boyle, 2010) it is necessary to present adequate ROM (ankles, hips, thoracic spine, and the gleno-humeral joint), and stability (through the knees, lumbar spine, and scapula) in an alternating pattern from the ground upwards. Seow, Chow, and Khong (1999) presented joint mobility data on 306 healthy participants ranging from 15 to 39 years and showed that joint ROM decreased with age and also females had consistently higher degree of mobility compared to their male counterparts. Riemann and Lephart (2002) suggest that the mechanisms that govern functional joint stability must be adaptable to various individual and task constraints. They continue to state that stability at a joint is achieved through a combination of static and dynamic components working together. The ligaments, friction, joint capsules and cartilage provide the static stability while the neuromotor control mechanisms controlling the muscles that cross the joint provide the dynamic stability. The dynamic component of joint stability is therefore governed by the ROM and strength of the muscles involved. As well as improving ROM, stability and strength through S&C work there are other physiological characteristics that may be necessary to allow effective performance to be achieved, these include a moderate aerobic capacity and balance (Latella, Yungchien, Yung-Shen, Sell, & Lephart, 2008; Lephart, Smoliga, Myers, Sell, & Tsai, 2007). Effective performance being defined as the ability to control the impact factors between club and ball to achieve the task outcome and maximise ball speed following impact with the clubface (Chapter 1.2; see also Betzler et al., 2012; Langdown, Bridge & Li, 2012).

Wells, Elmi and Thomas (2009) used the Leger multistage run test to establish predicted $\dot{V}O_{2max}$ values for 24 golfers aged 22.7±5.1 years. The mean $\dot{V}O_{2max}$ value was 50.6±5.8ml/kg/min for their group of elite amateur golfers (all of whom were members of the Canadian National Golf Teams, but no handicaps reported) suggesting that this is the approximate level of aerobic capacity necessary for elite performance. This is higher than previous research findings of 34.2±5.2ml/kg/min on the LPGA tour (Crews, Shirreffs, Thomas, Krahenbuhl, & Helfrich, 1986).

As Smith (2010) suggested the importance of the role of physical fitness for golf performance has historically not held much credit. In recent years the success of high profile golfers undertaking strength training programmes and conditioning routines has meant it is now a popular tool to improve performance and gain benefits such as increased clubhead speed (e.g. Thompson and Osness, 2004), drive distance (e.g. Latella et al., 2008; Lephart et al., 2007) and possibly reducing the effects of fatigue during tournaments, as implied by the increase in $\dot{V}O_{2max}$ values reported above (e.g. Crews et al., 1986; Wells et al., 2009).

Knowledge from other sports has been useful to allow a multidimensional approach to improve golf swing performance but as S&C popularity has grown, so too has the need for research from within the sport of golf to influence future training. Read and Lloyd (2014) suggest that whole body dynamic strength and power are necessary components of golf S&C programmes that should be considered by the golfer and S&C coach in order to obtain increased CHS. An increase in CHS does not necessarily lead to increased performance levels and research needs to investigate how this translates into performance outcome parameters. Hellström (2009) also proposed that muscle power is important to incorporate into training for increases in CHS but suggested that less powerful golfers may experience increases in CHS regardless of training design. Morrison and Chaconas (2014) propose that, whilst not forgetting the uniqueness of the golf swing, it would be important to use the same methods and basic principles used in other sports when developing power in golfers.

Loock, Grace and Semple (2013) suggested that strength demands of golf still require further research to establish which areas have an impact upon performance measures if any. They studied 101 recreational golfers (handicap was not reported) with an age range of 17-71 years to establish which selected fitness parameters were associated with CHS and carry distance (CD). Again, it should be noted that these are not performance parameters and increases in both may not necessarily be associated with increased performance and lower scores. They reported that the strength of the lower back was a key parameter when establishing the potential CHS and CD a golfer could achieve, it accounted for 36% of the CHS when using an iron and 31% for a driver. There were also weaker associations to demonstrate the importance of the gluteals, the pectorals and the quadriceps in the golf swing, with results of a 1 minute push up test and wall squat test accounting for 8% and 6% of driver CHS respectively. It is therefore important for interventions to improve physical strength in these areas for golfers to improve CHS and CD. However, as with the majority of S&C intervention studies in golf, no kinematic variables were considered and there was also no association made to accuracy or how changing the strength in these areas affected performance. It is crucial that when assessing the influence of an S&C intervention on the golfer's performance there is analysis of the kinematics or ball flight parameters (e.g. accuracy) and in the future an assessment of scoring ability resulting from the myogenic and neurogenic adaptations realised from the intervention. The reporting of just CHS or

CD does not allow the coaching population to understand the true kinematic and performance changes that have occurred. This is an area that needs further study.

Hellström (2009) and Betzler et al. (2012) suggested that being able to return the clubhead back to impact with reduced variability and therefore control over the impact factors would allow the golfer to become more successful. Hellström (2009) continued by suggesting that more research is needed into the physical and technical attributes that allow control over the clubhead and clubface angle to be maintained during the golf swing. Being able to control these impact factors will, to some extent, be dependent on the physiological characteristics of the golfer. As alluded to earlier, previous generations have opted against engagement in S&C programmes due to myths around a loss of flexibility associated with S&C work, thus fearing a detriment to performance (Alvarez et al., 2012).

Smith, Callister and Lubans (2011) conducted a comprehensive search of the literature in the area of S&C for golf performance and therefore this review focuses on subsequent research in this area. The research up until this date had included exercises that used a selection of machine weights, free weights, resistance bands, medicine balls, and flexibility components. The golf performance measure that was common to most papers was the change in CHS following an intervention. Since this review, there have been a number of S&C interventions to study the effects on golfing performance, many of which have low sample numbers and fail to assess the swing kinematics following an intervention thus making it difficult to draw conclusions on S&C benefits to golf swing enhancement.

Alvarez, et al. (2012) assessed the impact of an 18 week strength training programme on a group of low-handicap golfers. As the design was not an 8-10 month longitudinal study it was severely limited by the small sample size of n=5 males in both a control and intervention group. Despite the limitations of the design Alvarez et al. (2012) did report some significant results. The control group followed a standard physical conditioning programme for golf while the intervention group completed that same programme altered to include 2 sessions of maximal strength work for 6 weeks, followed by explosive strength training, weight training and plyometric exercises for a further 6 weeks and then golf specific training for 6 weeks. Their exercises were chosen to replicate those used within the golf swing (see McHardy and Pollard, 2005 for full review of the active muscles) in order to enhance the performance variables of ball speed (BS) and club mean acceleration. The golf specific portion included swinging with weighted golf clubs, and acceleration training with a tubing system for 3 sessions per week.

They found that following the initial 12 weeks the strength and explosive strength significantly increased through testing of 1-repetition maximum (1-RM) (for horizontal bench press, barbell squat, seated row, triceps cable push down, seated calf extension and seated barbell military press) and jump height (for both the squat jump and counter movement jump) respectively. This was reflected in the launch data with an increase of 7% in BS. Results showed that even after 6 weeks of golf specific training and a 5 week detraining period the increases in maximal and explosive strength were maintained. This is encouraging for those golfers who are training in an “off-season” and using a maintenance programme during their season. Alvarez et al. (2012) suggested that an important aim of training for low-handicap golfers should be to increase golf specific strength and that further studies should be conducted using high-speed 3D analysis to assess the impact of training on the kinematics of the golf swing. As shown, very few studies have used kinematics within their analysis, perhaps because it is a simpler methodological design to just assess the outcome measures with a launch monitor.

One of the few to analyse the kinematics of the movement prior to and following an intervention was a plyometric study by Bull and Bridge (2012). Results following an 8-week plyometric intervention demonstrated the golfers had significantly higher lead arm and hand speeds in the downswing, increased maximum x-factor, again during the downswing, and maximum rate of recoil of the x-factor. They did not measure CHS or BS but following the 3D kinematic analysis they suggested that using golf specific plyometric training could lead to increases in these performance measures.

Following S&C interventions it could be expected that the BS would increase, as was reported by Alvarez et al. (2012). However, it was shown that after the first 6 weeks of their intervention no changes had occurred with golfing performance (BS and clubhead acceleration) and it was not until after a further 6 weeks of explosive strength training that there was a significant increase in the performance outcome variables. This may suggest that where maximal strength and explosive strength are not the key components of an intervention i.e. to change ROM or flexibility, then perhaps it would be unrealistic to expect CHS and resultant BS to be increased.

Various authors (Alvarez et al., 2012; Campo et al., 2009; Manolopoulos, Papadopoulos, Salonikidis, Katartzi and Poluha, 2004) have emphasised the point that coaching should be used alongside physical interventions in order to incorporate changes into the specified sporting movements. This does have inherent problems for research (each individual will require different coaching interventions) but in a practical coaching situation with individual golfers this may allow effective transfer of physical gains into performance. A longitudinal case study design would be well suited to this research and could include an integrated approach providing both S&C and coaching interventions to a number of individuals to address specific goals reflective of their constraints.

Weston, Coleman and Spears (2013) studied the effects of an 8-week isolated core intervention on CHS and ball spin parameters in club golfers (hcp = 11.2±6.1). Their intervention produce significantly increased CHS compared to the control group with a 3.6% rise for the intervention group of 18 golfers. They used 8 exercises to increase the strength of the core but only used one endurance test to assess the changes following the intervention. Core endurance is not necessarily reflective of the role of the core during the golf swing due to the isometric nature of the test compared to the dynamic activity involved in the golf swing. Therefore the choice of the core endurance test is not valid when relating to the outcome measures. Weston et al. (2013) did acknowledge that the translation of the increased core endurance into performance gains may be questionable given the nature of the test and its relationship to golfing handicap. There is also a complete lack of analysis of the effect on the kinematics of the golf swing and indeed the relationship of the intervention to performance measures, such as the change in shots per round pre and post intervention. The intervention group were not monitored for quality or quantity of sessions and the use of a launch monitor without any swing kinematic analysis resulted in calculated data being produced by the launch monitor and analysed, which in turn, raises concerns over the accuracy of the reported launch data.

The statistical analysis revealed a likely small effect of isolated core training on CHS and core endurance and reductions in CHS variability and backspin (these were both calculated variables). The increase in CHS in the intervention group may well be attributable to increases in core strength but without further testing (e.g. EMG) of the core musculature through the golf swing or through 1-RM testing it is difficult and, as Weston et al. (2013) suggest, would be naive to suggest that all the exercises used here have impacted upon performance. This makes it difficult to justify using this exact programme again for golfers' training. In fact Read and Lloyd (2014) argue that training the core in isolation may not be the most effective approach and suggest that strength and power training should be targeted at the extremities with anti-motion exercises incorporated into a programme to help reduce the risk of spinal injuries. McGill (2010) has stated that power is not developed in the core and that it acts only as a transmitter of power. It is possible that the exercises employed within Weston et al.'s (2013) study may have developed the muscles of the hips which McGill (2010) suggested are responsible for power generation and Hellström (2009) stated that strong musculature in the legs and hips leads to large forces and torques towards the ground. This may explain the increased CHS in this study and it fits within the definition they provide of the core (i.e. including the musculature of the upper legs).

Continuing with this definition, Callaway et al. (2012) previously found that golfers with a lower handicap were more likely to have increased pelvis rotation speed compared to higher handicap players. It is feasible to suggest that this may be due to more effective motor patterns and increased skill levels rather than / alongside physiological variation which can be a major limitation of different skill group comparisons. Instead Callaway et al. (2012) concluded that this was due to increased gluteals strength, specifically the gluteus maximus and medius. The low handicap group presented a mean strength for right and left gluteus maximus = 30.5% and 30.6% of body weight respectively. The high handicap group presented right and left gluteus maximus strength mean = 21.9% and 20.7% respectively. Similar results were reported for the gluteus medius demonstrating that an S&C intervention for the high handicap group could provide important gains that are necessary for subsequent performance since the gluteals play a vital role in the golf swing (McHardy and Pollard, 2005).

Others have reported that the gluteus maximus provides a large role in hip stabilisation during the swing (e.g. McHardy and Pollard, 2005; Watkins, Uppal, Perry, Pink, and Dinsay, 1996) and therefore this lends to conducting assessment on movement patterns that utilise the gluteus maximus and also to providing interventions that increase their strength. The overhead squat is one such test that assesses the strength of the lower body (Boyle, 2004) and has been suggested to be associated with a golfer’s ability to maintain posture throughout the golf swing (Phillips, 2013). However, to date no research has formally assessed this association.

Lamberth, Hale, Knight, Boyd, and Luczak (2013) conducted a six week strength and functional training intervention study on what they termed highly-skilled golfers. Unfortunately without reporting the mean handicap statistics of the groups it is difficult to agree with their classification of skill level. It was stated they were all ≤8 which is a category 2 / category 1 golfer. It has been suggested previously (Chapter 1.2; Langdown et al., 2012) that as the handicap system does not distinguish between golfing skills it is important to not assume that the golfers are highly-skilled at the skill being examined in any such research study.

A 6-week general S&C programme was performed, but a lack of detail in the paper surrounding when the large number of exercises were used (i.e. in which sessions) does not allow any specific replication of this programme to be achieved. Strength and flexibility testing on the control group was also omitted which does not allow a true comparison to the intervention group. Although a small sample (n=10, 5 in each group) was used, increases in strength were seen in the bench press and leg press 1-RM testing but this did not result in increased CHS. There was in fact a 3.9% and 1.9% decrease in CHS in the experimental group and control group respectively. Lamberth et al. (2013) proposed that this was due to neural adaptations rather than any myogenic adaptations and suggested that this may have affected the variability presented in the swing but did not commit to increased or decreased levels being presented. It was also proposed that the kinematics of the swing may have altered but again as with so many intervention studies this was not tested and CHS was the only outcome measure. They concluded that future research should not only capture clubhead and launch outcome measures but also make use of 3D motion analysis systems to assess levels of swing variability and the kinematics of the golf swing. The following studies look to address both of these issues with address and impact variability being considered initially followed by studies into the use of the overhead deep squat (OHS) in both assessment and as a target for improved strength and ROM. As discussed, interventions to improve the strength and ROM in golfers has already been shown to have an impact on outcome measures in some cases but could also potentially have an impact upon the kinematics of the golf swing and this needs further investigation.

1.4. AIMS OF THE THESIS

The two key foci of the thesis that are based on a constraints led approach are movement variability in the golf swing and the use of strength and conditioning in golf. Within each of these areas the research aimed to assess the goal directed response dynamics (i.e. movements) that emerged from the imposed constraints and allow coaching populations to understand the role both areas play when applying to performance.

Movement Variability

This research aimed to assess the difference between high-skilled and low-skilled golfer's movement variability at both address and impact. It was deemed important to understand whether higher skilled golfers demonstrate reduced detrimental variability, or whether they exhibit increased levels of functional variability to allow a more effective address and impact positions to occur which are features of skilled performance in golf. Further analysis also aimed to assess the whole group to distinguish any funnelling of variability across the selected body segments.

Strength and Conditioning

The aim of the strength and conditioning research was to analyse possible relationships between physical constraints presented through the overhead squat assessment test and the deterioration of posture in the golf swing as proposed by TPI. Following this an intervention was used to manipulate the physical constraints within the performance of the overhead squat and establish if changes in range of movement, flexibility and strength resulted in altered postural swing kinematics.

1.5. STRUCTURE OF THE THESIS

The following chapters will explore the role of movement variability in the golf swing and the overhead squat S&C assessment tool used to predict postural variables in the golf swing.

The address position has been highlighted as a critical moment in performance. Chapter 2 analyses the differences between high and low skilled golfers' variability in the set up position.

Chapter 3 continues the analysis of the differences between high and low skilled golfers' movement variability at the critical moment of impact between the golf club and ball.

The OHS is an accessible tool that can be performed by golfers in a coaching setting to assess some of the constraints from which each golfer's movements emerge. Chapter 4 continues to explore the constraints led approach by analysing the possible relationship between the overhead squat assessment and the golf swing.

Chapter 5 employs an 8 week S&C intervention to improve the OHS kinematics and subsequently assess the impact of the reduced physical constraints on 3D postural swing kinematics against a control group of golfers.

The discussion (Chapter 6) draws the research together and explores the impact upon performance and future coaching. Recommendations and limitations are reported to guide future research in the area of movement assessment in the golf swing both from a constraints led approach and the use of S&C with golfers across the spectrum of abilities.

2. ADDRESS POSITION VARIABILITY IN GOLFERS OF DIFFERING SKILL LEVEL

Abstract

This study aimed to determine whether differences in variability at address exist between golfers of low and high handicap. A consistent shot type was attempted by 20 golfers from 2 skill groups over 10-15 shots with a mid-iron. Kinematic analysis revealed only one significant difference between skill levels: the alignment relationship between the stance and shoulders, with the high skill golfers demonstrating reduced variability. Whole group variability in the distance between the ball and the midpoints of the stance, pelvis and shoulder was significantly reduced as midpoints became more superior. Alignment variability also significantly decreased towards distal segments of the kinematic sequence where variable error decreased between the alignment of stance relative to shoulders and pelvis relative to shoulders with no effect of skill level. Results suggest the more distal segments of the kinematic sequence present a greater need for reduced detrimental variability. Coaches should ensure that golfers understand the importance of shoulder alignment in relation to the stance and how on course slopes and lies can influence the positions presented at address for distal segments of the golf swing kinematic sequence.

Introduction

Until recently movement variability was traditionally considered to be a negative feature in motor control that should be removed or minimised yet it may provide a performer with greater flexibility and adaptability to conditions (Glazier, 2011). Golf is a sport in which players perform a closed skill to meet highly variable task requirements from shot to shot.

Variability in golf has previously been described as consisting of strategic shot selection and movement variability (Chapter 1.2; Langdown et al., 2012). Strategic shot selection is defined as the variability that occurs when the outcome remains consistent (i.e. the ball landing in the same position), but with a variety of address positions, club selections, ball flights, and swing mechanics. Movement variability concerns the changes in swing kinematics and kinetics from trial to trial when the golfer attempts to hit the same shot and therefore produce consistent ball flight (i.e. direction, curvature, distance and elevation), club and swing mechanics. This movement variability can be either functional or detrimental to shot execution. Functional movement variability aids performance and will allow behaviour to emerge from the task, environmental and organism constraints placed upon the golfer (Chapter 1.2; Langdown et al., 2012). Opposed to this, detrimental variability reduces a golfers' ability to meet the desired shot outcomes (ball flight). To achieve a consistent ball flight a golfer must minimise the variability in the five governing impact factors (Tuxen, 2009). Any variability in them can be considered detrimental to the production of the desired outcome (Chapter 1.2; Langdown et al., 2012). This is supported by the finding that more skilled golfers exhibited significantly less variability from shot to shot in the five impact factors of clubhead speed, centeredness of strike, angle of attack, club path, and face angle at impact as well as efficiency of strike (resultant ball speed as a direct result of clubhead speed: coefficient of restitution) compared to less skilled golfers (Betzler et al., 2012).

Reduced variability in factors governing movement outcome accuracy has also been found in table tennis (Bootsma & van Wieringen, 1990) and basketball (Miller, 2002). Miller (2002) reported a decreasing level of movement variability moving from toe to ball in basketball free throw kinematics, suggesting that towards the accuracy dominated end of the kinematic sequence expert performers present reduced variability. Variation during the golf swing could follow a similar pattern to this with the variation at the point of impact resultant from variation at address of the ball and throughout the swing movement before impact (Chapter 1.2; Langdown et al., 2012).

The importance of the address position is supported by Cochran and Stobbs' (1968) finding that once a golfer has started their downswing the movement cannot be adjusted as a result of its short duration, necessitating any adjustments to task are at address or potentially in the backswing. Golfers will often change their address position in response to a strategic shot selection decision to alter the ball flight of a shot to produce the desired outcome. Alternatively, a golfer may choose to maintain their address position and use within movement variation to produce different ball flights. The latter involves the manipulation of the impact factors in order to take advantage of D Plane principles (Jorgensen, 1999; Tuxen, 2009) rather than altering the address position. D Plane principles take into account the clubhead direction (determined by angle of attack and club path) and clubface orientation at impact (determined by dynamic loft and face angle) in order to determine the horizontal and vertical launch angles, spin axis and spin loft of each shot (see Jorgensen, 1999) and ultimately the resultant ball flight.

Variability in the address position may also occur as a result of the variety of conditions in which a ball is found at rest on the course during a round of golf. By definition the addressing of the golf ball indicates that the golfer is preparing to play the shot in question. The golfer sets up to hit the shot in the desired direction, with the required force, and the required ball flight curvature and elevation for the ball to land at the intended target. Golf coaches suggest that the address position (including the stance width, posture, grip position and body segment alignment) could provide the setting for the rest of the swing dynamics and that once address is achieved the rest of the swing will be a by-product of setup at address (e.g. Mann, Griffin & Yocom, 1998; Toski, Flick & Dennis, 1984). Should this prove to be the case then it could be hypothesised that skilled golfers would present less variability at address compared to unskilled golfers. This is supported by Bradshaw et al. (2009) who reported reduced variability in skilled golfers compared to unskilled golfers in stance width (biological variability (BCV): Skilled =1.4±0.3%, unskilled =1.9±0.6%) and trunk angle (measured on the sagittal plane; BCV: Skilled =1.5±1.1%, unskilled =4.0±1.5%). However, four further variables showed no differences with skill level.

Although various studies have recently begun the exploration of variability in the golf swing (Bradshaw et al., 2009; Horan et al., 2011) it is still unknown what variability exists in many kinematic parameters (Langdown et al., 2012). Bradshaw et al. (2009) and Horan et al. (2011) have recently studied the kinematic variability that occurs within the swings of high vs. low handicapped golfers and male vs.

female golfers, respectively. Interestingly, both male and female golfers showed decreasing hand variability at mid-downswing compared to top of the backswing and impact compared to mid-downswing even though they used different coordination strategies to zero in on impact (Horan et al., 2011). Clubhead trajectory was also shown to follow the same funnelling trend. There is the possibility that the address position need not be identical even for repeated shots with a consistent strategic shot selection as any variation could be accounted for within functional movement variability (Chapter 1.2; Langdown et al., 2012). This variability could be useful to allow a movement response to emerge towards a task goal (Bril et al., 2010). However, it is hypothesised that there is likely to be a limit to the ability to adapt to address position variability and at some point variation will become detrimental. Further research is needed to assess this tolerance level.

This study aimed to determine whether differences in variability at address exist between high skilled golfers and lesser skilled golfers. It was hypothesised that the more highly skilled golfers would present less variability within their address position due to a reduction of detrimental variability when setting up to the golf ball.

Method

Participants

A convenience sample of 17 male and 3 female golfers between the ages of 18 years and 27 years (*M* ± SD: HSG = 21±1 years and LSG = 21±2 years) were recruited from local golf clubs after local ethics committee approval. All participants were injury free and did not report pain during their golf swing. Participants were separated into groups by skill level by CONGU handicap (high (HSG): *n*=10, 8 males and 2 females: Category 1: handicaps up to 5.4 & professionals with a mean clubhead speed of 39.2 m/s. Low (LSG) *n*=10 Category 3: handicaps of 12.5-20.4 with a mean clubhead speed of 37.2 m/s). Although the handicap system is not ideal as it does not identify specific skills which contribute to a lower handicap it does present the overall skill level of the golfer within the sport.

Procedure

All participants performed 10-15 swings that were captured at 250Hz using a 13 camera VICON™ MX system. Cameras were calibrated according to the manufacturer's instructions and the calibration was accepted when RMSE was less than 1.5mm. Spherical 1cm reflective markers were placed on 30 anatomical landmarks on a participant by a single researcher (Figure 2). The authors acknowledge that placement of markers on the skin is subject to skin movement during the swing but great care was taken to minimise this effect. In addition, three markers were placed on the club: Clubhead (Superior aspect of toe); Mid-Shaft; Club-High (Inferior aspect of the grip), and reflective tape was placed on the ball.

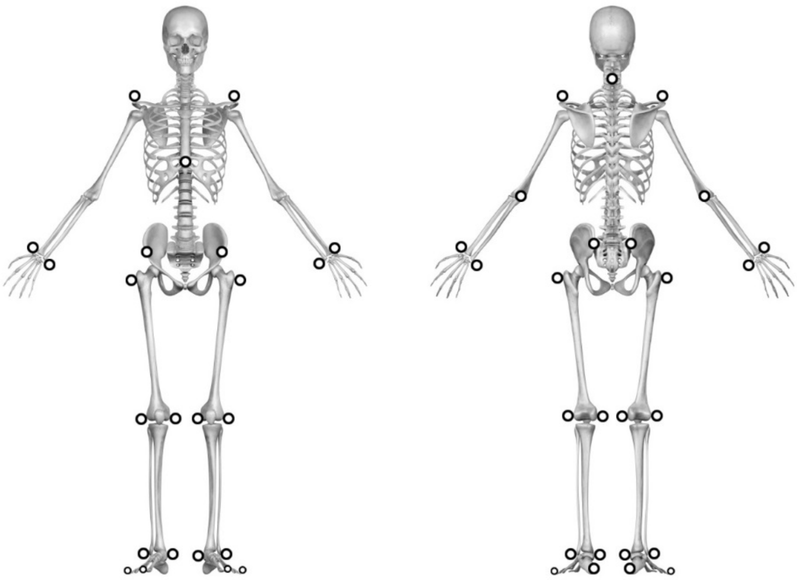

Figure 2 Placement of Reflective Markers on 30 Anatomical Landmarks

Participants performed a self-selected warm up which also acted as a familiarisation period towards the laboratory set up (Figure 3), target, and anatomical markers. Participants used their own mid iron (6 or 7-iron) and were asked to stand on the calibrated and marked golf mat, address the ball and perform their normal swing to produce a consistent ball flight with maximum accuracy and distance towards an identified target hanging 5 metres away within a golf net. So if a golfer normally hit a right to left ball flight (i.e. a right handed golfer's draw ball flight) when practicing and in competition then they were asked to try and produce this ball flight across all trials with maximum clubhead speed and accuracy towards the target. These instructions were designed to limit task related variability (i.e.

strategic variability) so that any variability seen would be of a within movement nature.

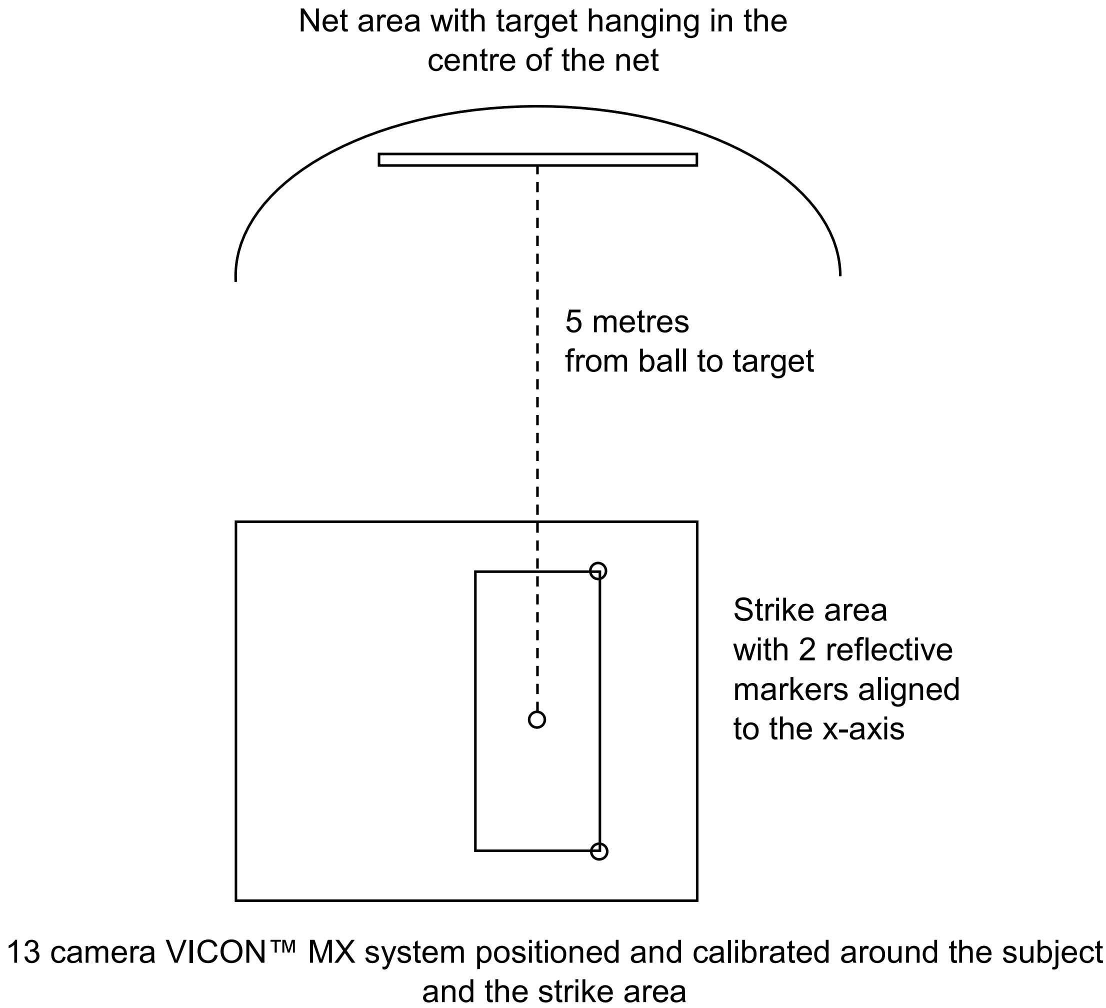

Figure 3 Laboratory Set Up

Selection of Variables

A panel of 8 expert coaches from the Professional Golfers' Association of Great Britain and Ireland membership were provided with a list of possible variables and consulted on the importance of the consistency of each of these when measuring a golfer's position at address. Coaches provided qualitative feedback on each proposed variable and from this the following (Table 1) were selected to be measured. This allowed representative research to examine the variables that were considered important to coaches.

Swing Processing

After reconstruction and labelling of marker trajectories, each individual's swing raw data files were exported from the VICON™ Nexus system. The x-axis represented the ball to target line (i.e. any movement of a mediolateral nature), the y-axis represented the anterioposterior movements and the z-axis represented any vertical movements. Functions and scripts were written for data processing in Excel and allowed address to be identified through an average linear velocity threshold for the clubhead in the x-axis , where velocities of >-0.47mm$\cdot$s^{-1} were considered as the start of the backswing. Linear functions were used as the markers were stable at address to the ball. Where markers were not visible at address the trials were removed from analysis. All valid trials were used in the analysis and each golfer provided a minimum of 10 swings.

Data Analysis

To assess the variability between trials (within golfer) and between levels of skill (HSG compared to LSG) variable error measures were used (Schmidt and Lee, 2005) where Variable Error (VE) = ($\sqrt{\sum(x_i - M)^2/n}$) and x_i is the value of the selected variable for each trial, M is the mean average of this variable for all shots played and n is the number of shots played. Variable error was chosen as it represents the variability or inconsistency of movement outcomes around an individual's mean movement. VE calculations do not suggest there is a model address position that is measured against but instead allows a consistent set-up to be reported as such even if the technique or body positions are not ideal from a coaching view. All data were checked for approximation to the normal distribution, and group and individual means and standard deviations were calculated. Natural log transformations were used to normalise for stance width VE and a log to base 10 for shoulder tilt VE data. Independent *t*-tests were used to assess any effect of skill level on the VE of the address parameters measured. Repeated measures ANOVAs were used to assess any differences in VE between variable groups of distance (stance, pelvis and shoulder mid-points to ball), alignment (pelvis-stance; shoulder-stance; shoulder-pelvis) and tilt (pelvis; shoulder). Where Mauchly's test showed that the assumption of sphericity was violated, degrees of freedom were corrected using Huynh-Feldt estimates. When significant effects were observed post-hoc tests with a Bonferroni correction were used to identify where differences existed between measures. All data analysis was carried out using SPSS 19.0 and data are reported as mean and standard deviation unless otherwise stated.

Table 1 Static Variables Measured at Address Position

Variable	Definition
Stance Width	Transverse plane projection of the vector between left 1st toe and right 1st toe.
Distance of Stance to Ball	True distance to the ball from the middle of the stance (determined by the midpoint of the vector between the 1st toe of each foot).
Distance of Pelvis to Ball	True distance of the centre of the pelvis to the ball (centre pelvis was taken as the midpoint of the vector between the left and right ASIS).
Distance of Shoulder to Ball	True distance of the centre of the shoulder line to the ball (centre of the shoulder line was taken as the midpoint of the transverse plane projection of the vector between the left and right acromion processes).
Pelvic Tilt	Hip tilt in the frontal plane around the sagittal/anterior-posterior (AP) axis (determined using the tangent of the transverse plane projection of the vector between the left and right ASIS).
Shoulder Tilt	Shoulder tilt in the frontal plane around the sagittal/anterior-posterior (AP) axis (determined using the tangent of the transverse plane projection of the vector between the left and right acromion processes).
Stance to Pelvis Alignment	Angle of the pelvis in relation to the stance (open or closed).
Stance to Shoulder Alignment	Angle of the shoulders in relation to the stance (open or closed).
Pelvis to Shoulder Alignment	Angle of the shoulders in relation to the pelvis (open or closed).

Results

Independent *t*-tests found a significant difference in the VE of angle differences in the shoulders to stance alignment between the skill groups ($t(18)=2.32$, $p=.032$, $r=.48$), with HSG exhibiting significantly reduced variability in shoulder alignment in relation to the stance when addressing the ball (Table 2). There were no other differences in VE between the two skill groups (Table 2).

Significant differences were found in VE of the distance ($F(1.2,24.4)=39.0$, $p<.001$, $\omega^2=.0.44$) and alignment ($F(2,38)=6.3$, $p=.004$, $\omega^2=.05$) variable groups, whilst no differences were found in the tilt group ($F(1,19)=.7$, $p=.41$, $\omega^2=.00$). Bonferroni post-hoc comparisons revealed significant differences in VE between all variables in the distance group ($p<0.001$, Table 2). Stance to ball distance exhibited the highest variable error in this group with the VE of shoulder to ball distance being approximately half its value (Table 2). Post-hoc comparisons for the alignment variable group showed a significant difference between VE for the alignment of stance relative to shoulders and pelvis relative to shoulders ($p=0.006$, Table 2).

Table 2 Mean ± Standard Deviation for Variable Error (VE) for each Variable

Address Variable	Whole Group VE	High skill group VE	Low Skill Group VE
Stance Width (mm)	12.1±5.0	10.0±2.3	14.2±6.1
Distance of Stance to Ball (mm)	11.6±3.2$^{\#}$	11.0±3.0	12.3±3.3
Distance of Pelvis to Ball (mm)	7.3±1.6$^{\#}$	7.0±1.0	7.7±2.1
Distance of Shoulder to Ball (mm)	5.9±1.8$^{\#}$	6.0±2.0	5.7±1.7
Pelvis Tilt (°)	0.6±0.3	0.6±0.4	0.5±0.1
Shoulder Tilt (°)	0.5±0.3	0.4±0.1	0.6±0.4
Pelvis to Stance Alignment (°)	1.2±0.4	1.0±0.4	1.4±0.4
Shoulder to Stance Alignment (°)	1.2±0.5$^{\$}$	1.0±0.4*	1.5±0.4*
Shoulder to Pelvis Alignment (°)	1.0±0.4$^{\$}$	0.9±0.4	1.0±0.3

Note. *indicates a significant difference between groups ($p<0.05$), $^{\#\$}$indicate significant differences between variables.

Discussion

This study has examined whether there were differences in the variability of specified address position parameters between high and low skilled golfers. Little support to accept the hypothesis that golfers of a higher skill level will show less variability was found, with the only difference between groups being observed in the relative alignment of the shoulders and stance. These limited differences between skill levels is in agreement with the findings of Bradshaw et al. (2009) who only found variability of stance width and trunk angle to differ between groups. However, in contrast to Bradshaw et al., (2009) the current data do not show a difference in stance width variability between skill levels.

Shoulder alignment has the potential to impact upon swing plane, clubhead path and angle of attack of the clubhead to the ball, and therefore variability in this alignment may result in inconsistent ball striking. It should also be considered that variability at address could be compensated for during the swing movements. Horan et al. (2011) have suggested that these compensatory movements during the swing or a funnelling of variability towards the critical point of impact may mean that not all address variables influence swing performance. The same authors demonstrated that as the golfer approached impact with the ball the variability of the hand and clubhead trajectories both funnelled or "zeroed in" (Horan et al., 2011). The finding here that the VE in distance to the ball is significantly reduced from the stance, through the pelvis and up to the shoulder midpoint is consistent with a potential general form of funnelling towards the more distal segments of the kinematic sequence of the golf swing. The larger variation in the stance to ball distance would suggest that as long as it does not fall outside of a given tolerance, it is of less importance to performance than the shoulder and pelvis to ball distances. This is perhaps not surprising given that a golfer will only experience relatively consistent underfoot conditions when standing on tee boxes and in between will find their stance affected by sloping ball lies from side to side and back to front. A necessary skill for a golfer may therefore be to be able to compensate for this necessary variability in foot placement with reduced variability at both the pelvis and the shoulders. The importance of this reduced variability is shown when we consider the VE as a percentage of the mean for these distances. For the stance to ball measurement this is 2% whereas for the shoulder to ball it is 0.4%.

Additional support for the importance of the shoulder and more distal sequence segmental positions can be found in the relative alignment of each segment. VE was significantly reduced for the shoulder alignment relative to the pelvis compared to the shoulder alignment relative to the stance. The precision of shoulder positioning at address may well stem from the need to produce complex movements in segments distal to this in the kinematic sequence such as those where the body interacts with the club i.e. the hands (Nesbit & McGinnis, 2009) and the need to reduce variability in the hands towards impact (Horan et al., 2011). The lower shot to shot variability of highly skilled golfers compared to their lower skilled counterparts in terms of club speed, efficiency of strike, centeredness of strike, angle of attack, club path, and face angle at impact (Betzler et al., 2012) also supports the need to reduce variability towards impact.

The similarities in VE between low and high skill golfers was not hypothesised given the differences in scoring that must exist in these golfers on the golf course as shown by their handicaps. It is possible that given the nature of the repeated shots made in this study allowed for a learning effect in the less skilled golfers whereby they were able to settle into a consistent pattern of addressing the ball that would not be possible with the varied conditions that occur between shots on the golf course. A recommendation for future work is to explore the possibility that increased group differences could be found in a representative research environment and whether the results found here were perhaps influenced by a learning effect.

Whilst there is variability shown in golfers' address positions there will be an upper limit to this for each parameter associated with a successful set-up to the golf ball. Geisler (2001) has suggested that the knees should be flexed to 20-25°, the trunk flexed at the hips by approximately 45° and with a shoulder tilt (around the sagittal/anterior-posterior (AP) axis) of approximately 16°. These figures were proposed to allow control of the movement and to produce maximal power. This approach of specifying recommendations does not allow for individual differences in physical, task or even environmental constraints and therefore research needs to establish variability tolerances rather than set figures for joint angles and positions. In doing this a wider sample of golfers should be considered including novices and additional swing phases used. Future work should also consider which parameters of the address position can influence impact and ball flight variability which are critical factors in performance (Chapter 1.2; see also Betzler et al., 2012; Langdown et al., 2012).

Conclusion

This study has shown that little difference exists in variable error of the address position between low and high skilled golfers with the only difference being found in the alignment of the shoulders in relation to the stance. A decreasing variable error has been found in distance to ball and alignment measurements for those body parts closer to the distal or accuracy end of the golf swing's kinematic sequence, which is consistent with evidence from other target orientated sports (e.g. Miller, 2002). Golfers need to be coached to present distal segments at address with minimal variability not only on flat surfaces (i.e. range mats or tee boxes) but across various course conditions. Particular attention should be paid to the variability of alignment of the shoulders relative to the stance. With a larger sample further interesting results may be found and the low number of female participants in this study limits the ability to provide comparisons between genders. This study provides a snapshot of address position variability and does not indicate how this affects any variability later in the swing. Further research is needed to fully elucidate the most important parameters in which coaches should seek reduced variability at both address and throughout the swing movement in order to minimise impact variability once a strategic shot selection has been made.

3. IMPACT POSITION VARIABILITY IN GOLFERS OF DIFFERING SKILL LEVEL

Abstract

This study examined the variable error (VE) for the golf impact position of high and low skilled golfers. A consistent shot type was employed by 20 golfers from 2 skill groups over 10-15 shots with a mid-iron. Analysis reported similar positional variability across categories. Significant differences were found for the whole group in VE of the distance of various body segments to the ball ($p<.001$) where variability reduced across the distance of the ball to the midpoint of the stance, compared to the pelvis and shoulders. Alignment variability significantly decreased towards distal segments of the kinematic sequence with VE for the alignment relationships of pelvis-stance compared to shoulder-stance and shoulder-pelvis showing reduced levels ($p<.001$) in the low skilled golfers. Tilt variability in the frontal plane around the sagittal / anterior-posterior (AP) axis also presented significantly reduced levels from the pelvis to the shoulders ($p<.001$) with no effect of skill level. Conclusions suggest that coaches should pay particular attention to the variability presented at the distal end of the kinematic sequence and the alignment of the pelvis in relation to the stance.

Introduction

Most sports possess critical features that contribute to the successful performance of a skill (McPherson, 1990) and if modified too greatly these critical features can affect the outcome and can result in detriments to performance (Arend & Higgins, 1976). In ball sports these features are often most prevalent at the moment of impact between either a sports implement or human performer and the ball. Critical impact factors at the instant of contact govern the parameters of ball launch and flight and subsequent shot outcome.

In golf, the impact factors of angle of attack, centredness of strike (impact location on the clubhead relative to the centre of gravity), clubface alignment (in relation to the target line), path of the clubhead and clubhead velocity (Tuxen, 2009) present the areas in which coaches strive for reduced detrimental variability (Chapter 1.2; Langdown et al., 2012). Betzler, et al. (2012) have shown that more highly skilled golfers exhibited significantly reduced shot variability in clubhead velocity, efficiency of strike (resultant ball speed as a direct result of clubhead speed: coefficient of restitution), centeredness of strike, angle of attack, club path, and face angle at impact compared to less skilled golfers.

Reduced variability in factors governing movement outcome accuracy has also been found in table tennis (Bootsma & van Wieringen, 1990) and basketball (Miller, 2002). Miller (2002) reported a decreasing level of movement variability moving from toe to ball in basketball free throw kinematics, suggesting that towards the accuracy dominated end of the kinematic sequence expert performers present reduced variability. The impact position of a golfer's body could follow this pattern with reduced kinematic variability in the body segments that have influence upon the accuracy of strike of the golf ball i.e. reduced variability from foot position through to the hand and clubhead positions (Chapter 1.2; Langdown et al., 2012).

Behaviour has been suggested to emerge from a system of constraints when performing a goal orientated task rather than a consistent motor programme (Newell, 1986). This would suggest that movement variability to meet a task outcome will exist. Such variability may be detrimental or functional to the movement outcome and it is important for golf coaches to understand the role that movement variability plays within the swing. Chapter 2 has shown that address variability in alignment between the shoulders and stance is reduced for more highly skilled golfers compared to less skilled golfers (Langdown, Bridge & Li, 2013a). Chapter 2 also reported that distance, alignment and tilt variability decreased across proximal to distal body segments when addressing the golf ball. These findings emphasise the importance of reducing variability in the body segments that have an increasing effect on performance accuracy.

Coaches (e.g. Hebron, 2001; Mann et al., 1998) suggest that the address positions a player adopts can influence impact with the ball. Mann et al. (1998) have suggested that the position of the ball relative to the stance has a critical influence over the angle of attack and that the body reacts in the attempt to “find” the ball with the clubhead, in fact they state that the ball position affects the swing more than any other alignment factor. As well as the angle of attack as suggested by Mann et al. (1998), there will also be other effects on factors such as club path and club face orientation at impact which will alter the resultant ball flight. Mann et al. (1998) continued by suggesting that compensations are important if the ball has been positioned poorly at address. This shows the importance of address and how variability here will have subsequent effects on the position of the body at impact as the golfer solves the movement problem of returning the club to the ball to attempt to meet the task goal. The problem of address variability and consequential impact position variability becomes increasingly difficult when moving away from the flat surfaces of a range bay or the tee boxes on the course; research is yet to establish how golfers cope with this environmental factor.

Limited research exists into the variability of body positions at the moment of clubhead impact with the golf ball. Horan et al. (2011) reported that both male and female golfers showed decreasing hand position variability from the top of the backswing through to ball contact even though they used different coordination strategies to zero in on impact. Clubhead trajectory was also shown to follow a similar funnelling trend. Bradshaw et al. (2009) recently studied the kinematic variability that occurs within the swings of high vs. low handicapped golfers using 2D video analysis and found no differences between skill levels for the variability presented in the trunk, lead wrist and elbow angles at impact. However, it must be remembered that a true representation of the movement of the swing is only achievable through 3D kinematic analysis.

With suggestions that the impact factors form the critical features of golf swing performance (Chapter 1.2; Langdown et al., 2012) it is crucial that the movements of the body are also analysed to see if these are affected by skill level. The five impact factors are all influenced by the position the golfer sets at address to the golf ball and movements the golfer makes during the downswing which emerge from the environmental, organism and task constraints. However, it is suggested (Cochran & Stobbs, 1968) that if the golfer needs to make movement adjustments to the swing this has to be done within the backswing as the duration of the downswing to impact is too short. This notion is supported by research (e.g. Verbruggen & Logan, 2009) suggesting that typically, participants can inhibit or change a specific response when a stop signal is presented close to the moment of stimulus presentation (in this case the beginning of the swing), but they cannot inhibit or change their movement when the stop signal is presented close to the moment of response execution (i.e. the downswing moving towards impact) (Cochran & Stobbs, 1968). Other sports have shown that there is a “zeroing in” or “homing in” process that allows variability to be minimised towards the critical phase of performance (e.g. impact) (e.g. table tennis: Bootsma & van Wieringen, 1990; long jump approach phase: Lee, et al., 1982; Scott et al., 1997).

This study aims to inform coaches of how a golfer’s ability level may influence variability in impact positions and its changing magnitude in the proximal to distal segments of the golfer’s body at the point of impact between the clubhead and the golf ball. It is hypothesised that more highly skilled golfers will present reduced variability at impact compared to less skilled golfers across body position variables. If the critical features of the golf shot with a midiron are the impact factors then this would suggest that with increasing skill level will come increasing proficiency at presenting an impact position that maximises control of distance and accuracy towards a given goal. This hypothesis has also been founded on elite players in other sports exhibiting a funnelling or “zeroing in” of movement towards impact in the sports of table tennis (Bootsma & van Wieringen, 1990) and long jump approach run (Lee et al., 1982; Scott et al., 1997).

Method

Participants

A convenience sample of 20 golfers (17 male and 3 female) were recruited following local committee ethics approval and formed high and low handicap groups which included golfers between the ages of 18 years and 27 years (*M* ± SD: HSG = 21±1 yr and LSG = 21±2 yr). Participants were categorised by CONGU handicap (high (HSG): *n*=10 Category 1: handicaps up to 5.4 & professionals with a mean clubhead speed of 39.2 m/s. Low (LSG) *n*=10 Category 3: handicaps of 12.5-20.4 with a mean clubhead speed of 37.2 m/s). This method of categorisation is common practice within golf research but does not identify areas of specific skill that contributes to a lower handicap. It merely represents each individual's overall skill levels relative to their home course. All participants reported that they were injury free and experienced no pain during their golf swing.

Procedure

All participants performed 10-15 swings with their own mid iron (6 or 7-iron) that were captured at 250Hz using a 13 camera VICON™ MX system and 34 reflective markers. All participants were asked to address the ball and perform their normal swing to produce a consistent ball flight with maximum accuracy and distance towards an identified target on a golf net. For a full description of the experimental procedure see Chapter 2; Langdown et al. (2013a).

Selection of Variables

Variables were selected based on address variables presented in Chapter 2 and Langdown et al. (2013a), where a panel of expert coaches from the Professional Golfers' Association of Great Britain and Ireland membership were consulted on the importance of the consistency of a number of variables that measured a golfer's position at address. It was important to see the influence of these positions at impact in order to assess the effect of various body segments in relation to the critical moment in the swing. The following variables (Table 3) were selected to be measured.

Swing Processing

After reconstruction and labelling of marker trajectories, each individual's swing raw data files were exported from the VICON™ Nexus system as a comma separated values file. Functions and scripts were written for data processing in Excel and allowed impact to be identified through an average of 2 frames (1 prior and 1 post impact) or a single frame (where the clubhead was in contact with the ball) depending upon captured positions of the clubhead. Positional data analysis allowed all variables to be measured at impact over the series of shots played. Where markers were not visible at impact the trials were removed from analysis (2 trials).

Table 3 Static Variables Measured at Impact Position

Variable	Definition
Distance of Stance to Ball	True distance to the ball from the middle of the stance (determined by the midpoint of the vector between the 1st toe of each foot).
Distance of Pelvis to Ball	True distance of the centre of the pelvis to the ball (centre pelvis was taken as the midpoint of the vector between the left and right ASIS).
Distance of Shoulder to Ball	True distance of the centre of the shoulder line to the ball (centre of the shoulder line was taken as the midpoint of the transverse plane projection of the vector between the left and right acromion processes).
Pelvic Tilt	Hip tilt in the frontal plane around the sagittal/anterior-posterior (AP) axis (determined using the tangent of the transverse plane projection of the vector between the left and right ASIS).
Shoulder Tilt	Shoulder tilt in the frontal plane around the sagittal/anterior-posterior (AP) axis (determined using the tangent of the transverse plane projection of the vector between the left and right acromion processes).
Pelvis-Stance Alignment	Angular relationship of the pelvis and stance (open or closed).
Shoulder-Stance Alignment	Angular relationship of the shoulders and stance (open or closed).
Shoulder-Pelvis Alignment	Angular relationship of the shoulders and pelvis (open or closed).

Data Analysis

All data were checked for approximation to the normal distribution, and group and individual means and standard deviations were calculated. Natural log transformations were used to normalise for shoulder tilt, pelvis-stance alignment, and shoulder-pelvis alignment variable error, log to base 10 for pelvis and shoulder distance to ball variable error and a reciprocal transformation for shoulder-stance alignment variable error data. To assess the variability between trials (within golfer) and between levels of skill (HSG compared to LSG) variable error measures were used (Schmidt & Lee, 2005) where Variable Error (VE) = ($\sqrt{\sum(x_i - M)^2/n}$) and x_i is the value of the selected variable for each trial, M is the mean average of this variable for all shots played and *n* is the number of shots played. Mixed factorial MANOVAs (repeated factor: VE, group factor: skill level) were used to assess any differences in VE between variable groups of distance (a 3 x 2 MANOVA, impact variable x skill category using stance, pelvis and shoulder mid-points to ball), alignment (a 3 x 2 MANOVA, impact variable x skill category using angular relationships for pelvis-stance; shoulder-stance; shoulder-pelvis) and tilt (a 2 x 2 MANOVA, impact variable x skill category using pelvis; shoulder). When significant effects were observed post-hoc tests with Bonferroni correction were used. All data analyses were carried out with SPSS 20.0 and data are reported as mean and standard deviation unless otherwise stated.

Results

The mixed-factorial MANOVA analysis showed there to be a significant main effect across the whole group in VE (Table 4) of the distance (Wilk's λ=0.33, $F(2,17)=17.5$, $p<.001$, $\eta\rho^2=0.67$), alignment (Wilk's λ=0.43, $F(2,17)=11.21$, $p<.001$, $\eta\rho^2=0.569$) and tilt (Wilk's λ=0.42, $F(1,18)=24.5$, $p<.001$, $\eta\rho^2=0.58$) variable groups.

Distance VE

Overall whole group contrasts revealed no significant difference between any of the distance to ball VE variables ($F(1,18)=.202$, p=.659, $\eta\rho^2=0.01$). A significant interaction was found between skill categories and distance VE (Wilk's λ=0.611, $F(2,17)=5.413$, $p=.015$, $\eta\rho^2=0.389$). The pattern of variability was different between groups, where the HSG showed a reduction of VE moving from the stance distance to the ball, to the pelvis and then shoulders. LSG presented a different pattern where the shoulders presented increased VE compared to the pelvis distance to the ball (Table 4). However, Bonferroni post-hoc comparisons presented no differences between groups in any of the separate distance parameter variable errors (stance: $p=.351$; pelvis: $p=.273$; shoulders: $p=.295$). Distance VE of the stance to ball exhibited the most variability in this group with the distance VE of both the pelvis to ball and shoulder to ball being approximately 68% of its value (Table 4). When VE was considered within each category of skill the same pattern was found: Stance distance VE was significantly greater than both pelvis (HSG = $p=.035$; LSG = $p<.001$) and shoulder distance (HSG = $p=.015$; LSG = $p=.017$) VE but there was no significant difference between pelvis and shoulder distance VE (HSG = *p*=.227; LSG = *p*=.404).

Alignment VE

Overall whole group contrasts revealed no significant differences between the impact alignment VE variables (*F*(1,18)=.633, p=.436, $\eta\rho^2$=0.03). A significant interaction was found between skill categories and alignment relationships VE (Wilk's λ=0.57, *F*(2,17)=6.38, *p*=.009, $\eta\rho^2$=0.43) showing that the pattern of variability was different. HSG produced a reduced shoulder-stance alignment relationship VE compared to the pelvis-stance and shoulder-pelvis, whereas LSG demonstrated the lowest VE in their shoulder-pelvis alignment relationship. Again, Bonferroni post-hoc comparisons presented no VE differences between skill categories in any of the separate alignment relationship variables (pelvis-stance alignment relationship: *p*=.069; shoulder-pelvis: *p*=.626; shoulder-stance: *p*=.274, Table 4). The largest alignment VE exhibited in this group was the pelvis-stance relationship, with both the alignment VE of the shoulder-pelvis and shoulder-stance being approximately 80% of its value (Table 4). When VE was considered within each category of skill, differences were found for LSG: a reduction in VE was found between shoulder-stance alignment compared to pelvis-stance alignment (*p*=.007, Table 4) and between shoulder-pelvis alignment compared to pelvis-stance alignment (*p*<.001). HSG presented no significant differences between all alignment variables.

Tilt VE

VE was significantly reduced in shoulder tilt compared to pelvic tilt at impact (Wilk's λ=0.42, $F(1,18)$=24.5, p<.001, $\eta\rho^2$=0.58). There was no interaction effect of group (Wilk's λ=0.92, $F(1,18)$=1.57, p=.23, $\eta\rho^2$=0.08) with both HSG and LSG showing similar VE levels in each segment.

Table 4 Mean ± *SD* for Variable Error (VE) for each Variable

Impact Variable	Whole Group VE	High skill group VE	Low Skill Group VE
Distance of Stance to Ball (mm)	11.01±3.05$^{\#}$	10.23±2.48	11.80±3.48
Distance of Pelvis to Ball (mm)	7.55±1.91$^{\#}$	8.02±1.97	7.08±1.82
Distance of Shoulder to Ball (mm)	7.52±2.31$^{\#}$	6.97±1.79	8.06±2.73
Pelvis Tilt (°)	1.23±0.49$^{£}$	1.26±0.47	1.21±0.54
Shoulder Tilt (°)	1.09±0.36$^{£}$	0.96±0.22	1.22±0.44
Pelvis-Stance Alignment (°)	2.31±0.93$^{\$}$	1.92±0.43	2.69±1.14
Shoulder-Stance Alignment (°)	1.87±0.83$^{\$}$	1.67±0.66	2.08±0.97
Shoulder-Pelvis Alignment (°)	1.85±0.98$^{\$}$	1.92±0.83	1.78±1.16

Note. $^{\#£\$}$ indicate significant differences between variables ($p < 0.05$).

Discussion

This study has examined whether there were differences in the variability of specified body impact position parameters between high and low skilled golfers. Whilst overall VE in each group of variables was different between skills groups there were no differences between groups in the VE of the separate body position measurements at impact. Looking at Table 4 there was no consistent pattern of higher or lower variability between the groups and therefore the current work provides no support for the acceptance of the hypothesis that golfers of a higher skill level will show less variability. Results from Bradshaw et al. (2009) also suggest this, with no variability differences found between high and low skilled golfers at impact for trunk angle, and both lead wrist and elbow angles.

Horan et al. (2011) have demonstrated that although the male and female swings emerged with different upper body movement strategies during the downswing there was a common trend of the variability of hand and clubhead trajectory sequentially decreasing during the downswing to the point of impact with the ball. Other sports have shown similar patterns of funnelling towards impact with Bootsma and van Wieringen (1990) finding that the variation in the direction of a table tennis bat decreases toward the moment of impact with the ball in a forehand drive. This funnelling effect in golf has to be attributed to movements of segments of the body in relation to the task (i.e. to attempt to get the clubhead to strike the ball in a manner that achieves the goal of the task). The funnelling of movement variability of the golf club has to be initiated within the golfer’s body segments during the downswing. The results of the current study show that there is a significant reduction in positional variability at impact from proximal to distal segments of the body, moving along the kinetic chain (Hume et al., 2005) of the golf swing. From the stance upwards, the segments that initiate the transition into the downswing (i.e. the pelvis (Cheetham et al., 2008)) present the largest amount of VE in position from trial-trial with the shoulders presenting the least.

The higher the skill of a golfer the lower the shot to shot variability in clubhead speed, efficiency of strike, centeredness of strike, angle of attack, club path, and face angle at impact (Betzler et al., 2012). The hands and clubhead positional VE were not analysed in this study but future research should aim to see if this trend continues across these segments and into the clubhead's position and whether this is the critical feature that distinguishes between skill levels. Horan et al. (2011) have already established that these segments do not differ between male and females but only tested skilled golfers and so their results cannot be extended to other ability levels. If lesser skilled golfers are unable to continue the funnelling of variability to the same extent as skilled golfers then golf coaches should ensure that their methods of teaching address this problem.

With the emergence of increasing levels of 3D analysis in the sport of golf it may soon be feasible for coaches to monitor and compare a golfer's variability in body segments and control of the clubhead (i.e. stance, pelvis, shoulders, hands and clubhead) against future established tolerance levels that allows variability to be functional. They should also focus their attention to the critical features of performance: the impact factors where the clubhead strikes the ball. Penner (2003) suggested that the position of the clubhead at the top of the backswing and its movement during the transition phase (first 100ms) into the downswing were critical features of the swing to influence impact with the ball. Bradshaw et al. (2009) also suggest that the address, half backswing, and top of the backswing are the instances where consistency of position is critical to performance. It is possible that the transition phase is where the level of variability in the impact factors is set in motion with Cochran and Stobbs' (1968) experiments suggesting that golfers are unable to react after this phase of the swing.

HSG presented no differences across the alignment angular relationships between stance, pelvis and shoulders. LSG did not exhibit this alignment pattern with the VE of the pelvis-stance angular relationship being significantly larger than both shoulder-pelvis and shoulder-stance angular relationships. Coaches should therefore consider this key area in order to progress the LSG swing. The pelvis-stance variability is the key alignment relationship to decrease detrimental variability in LSG. This area merits further study of 3D pelvic positions with larger samples in order to establish whether this is indeed a critical feature of ability levels. As we have previously shown at address (Chapter 2; Langdown et al., 2013a) there is a reduction of variability from stance up through the pelvis to the shoulders in distance to the ball, alignment relationships between body segments, and pelvis and shoulder tilt. This would suggest that players are able to reduce variability toward the distal end of the kinematic sequence. It is suggested that the need to produce complex movements in distal segments such as the hands and clubhead could justify the need to reduce variability toward the distal segments of the kinematic sequence.

It was not expected that high and low skilled golfers would demonstrate similar VE in their body position at impact. This may be true of all golfers between professional and handicap category 3, but it is possible that given the nature of the repeated shots made in this study there was a learning effect in the less skilled golfers whereby they were able to settle into a consistent pattern of hitting shots towards the specified target. Golfers in the current study did not see the entire ball flight and it may be that this extrinsic knowledge of results and potential subsequent adaptation to the swing for the next shot may show that differences in variability do exist between highly skilled and less skilled golfers. A recommendation for future work is to explore the VE presented when a player can see the entire ball flight and also on varying slopes and ball lies for repeated trials which promotes a more representative performance setting (Pinder, Davids, Renshaw & Araújo, 2011) for the golfer.

Conclusion

This study has shown that no differences exist in variable error of individual body impact position parameters between low and high skilled golfers, although overall statistical differences were observed across all whole group parameters. A decreasing variable error has been found in distance to ball, alignment, and tilt measurements for those body segments closer to the distal or accuracy end of the golf swing's kinematic sequence, which is consistent with evidence from other target orientated sports (e.g. Bootsma & van Wieringen, 1990). Further research is needed to fully elucidate how the reduction of variability toward the distal segments of the body affect the variability of movement at the hands and clubhead and what the levels of tolerance are for variability across the segments of the body. Representative research should focus upon the effects of varying slopes and ball lies on the swing's kinematic variability and consider the impact of a golfer receiving knowledge of the ball flight in this work. Coaches should consider reducing the detrimental variability in the pelvis-stance alignment relationship with LSG in order to improve this group's performance. In practical terms, this requires the coaches to create a more consistent impact position through the pelvis with less skilled golfers. Though this may be difficult for coaches to analyse at impact it may be useful to reduce alignment variability at address which may ultimately dictate the backswing and impact positions (Chapter 2; Langdown et al., 2013a).

4. THE INFLUENCE OF THE OVERHEAD DEEP SQUAT ON THE GOLF SWING

Abstract

This study aimed to explore any relationship between the musculo-skeletal screening overhead squat (OHS) test and the kinematics of the golf swing and whether restricted overhead squat mechanics leads to a loss of posture in the backswing and downswing of 6-iron golf shots. 14 golfers of mixed ability were asked to play 15 shots towards a specified target on a driving range with the same ball flight and swing mechanics. From these 15 a random sample of 5 shots were selected for analysis. Multiple backward stepwise regressions are reported for the relationship between the OHS range of movement and the golf swing kinematic variables. Significant relationships were found between the OHS variable torso angle and the swing kinematics variables of shoulder distance to ball at address and knee width at impact. Further research is required to assess the cause of these relationships. Pearson product moment correlation coefficient results also showed that there was a negative relationship between the OHS variables with a greater torso anterior lean relating to a smaller knee angle in the OHS. The results may reflect various limitations of specific muscle groups or joints that are components of the OHS, for example, a possible lack of strength in the gluteals or trail hip external hip rotation in the participants. The gluteals are necessary to maintain control and separation of the knees during the golf swing and also maintain posture. This again needs further research to establish whether increasing the strength in the gluteals or other muscle groups, and mobility of joints can affect swing kinematics and OHS performance.

Introduction

The overhead deep squat is a test commonly used to assess the closed kinetic chain of the bilateral, symmetrical functional mobility of the dorsi-flexion of the ankles, the flexion of the knees and hips, the extension of the thoracic spine, the flexion and abduction of the shoulders (Cook, 2003; Cook, Burton & Hoogenboom, 2006) and strength of the lower body (Boyle, 2004). The Titleist Performance Institute (TPI) popularised the notion that a poor range of movement within the overhead squat (OHS) test (i.e. not breaking parallel with the thighs in relation to the floor, the arms moving forwards of the toes, the torso moving into anterior lean and not staying at least parallel to the shin angle and the heels failing to remain on the floor) would result in a loss of posture during the golf swing (early extension*,* Phillips, 2013).

Golf posture is adopted in the set-up position (address of the ball) and coaching advocates that the spine angle is set through flexion at the ankles, knees and hips and is maintained throughout the backswing and downswing towards impact (e.g. Breed & Midland, 2008). A loss or deterioration of posture could indicate that there is excessive extension within these joints during the backswing or downswing, hence the terms early extension or loss of posture. TPI claimed (Phillips, 2013) that 67% of 90,000 golfers tested present early extension (loss of posture) during their swing whereas 99% of 100 Tour golfers (PGA, European and LPGA) do not present this loss of posture and as such they suggest that this may be one of the biggest influences on ball striking. Phillips (2013) continued by stating that if a golfer is restricted in the OHS test they will find it difficult to maintain forward flexion (sagittal flexion) of the torso through the hips and through side flexion (lateroflexion) of the spine during the rotation of the swing and will therefore move towards the ball during the backswing or downswing. This includes an extension of the hips into the backswing (standing tall) as opposed to the golfer's spine moving into side flexion through its rotation away from the target resulting in a lowering of the lead shoulder (Derksen, Van Riel, and Snijders, 1996). Loss of posture in the downswing may manifest itself through poor timing of the combination of spinal forward and lateral flexion throughout the rotation, and then through impact and the follow-through. An early extension of the hips, resulting in the torso moving to a more upright position and the pelvis moving towards the golf ball, leaves little room for the arms to swing through, potentially impacting upon the movement of the club. This can be coupled with the head position lifting with the torso or increased flexion of the spine in an attempt to maintain the head's position as the early extension of the hips occurs. This deterioration of posture in the downswing may also be a direct result of the movements made in the backswing. The purpose of the backswing is to set the body up to provide a powerful and accurate downswing through the stretching of muscles and alignment of the body and clubhead (Hume et al., 2005). Although suggestions have been made regarding a loss of posture in the downswing there has been no research published to date.

Cook et al. (2006) suggested that poor mobility through the upper torso can be associated with restricted glenohumeral and thoracic mobility, and previous research provides support for this (e.g. Kebaetse, McClure and Pratt, 1999) with suggestions that a slouched posture can result in altered scapula kinematics and reduced muscular force through abduction of the arm. Sizer, Brismée and Cook (2007) suggested that several anatomical components will also influence the available movement of the thoracic spine including the intervertebral discs and the structure of the vertebrae. Crawford and Jull (1993) found that performing a bilateral arm elevation, as used in the overhead squat (and the golf swing), can induce a degree of thoracic extension. This accounted for 50% of younger female participants' thoracic extension and almost 70% for older participants' extension, who are more likely to suffer with kyphotic posture. Cook et al. (1993) proposed that this type of skeletal limitation would impair mobility of the spine. Further research has added evidence to this with 3D mechanics of the spine being influenced by arm and shoulder movements and vice versa (Theodoridis & Ruston, 2002). Therefore, if there is already significant loss of mobility within this area it is possible that this could inhibit the overhead squat mechanics.

Poor mobility in the lower body (where the overhead squat does not allow the performer to break parallel with the thighs in relation to the floor) can be associated with limited dorsi-flexion or hip flexion (Cook et al., 2006). Boyle (2004) stated that it is important to assess the squat based on the thigh's relationship to the ground rather than aiming to achieve a 90 degree knee angle. This can often be achieved well before the thigh reaches an optimal parallel position, therefore not demonstrating full range of movement through the test. As Cook (2003) stated, mobility and stability need to coexist in order that efficient movement emerges towards the goal of achieving the full OHS. Stability is also needed through the gluteals during the swing and EMG studies (e.g. Okuda, Armstrong, Tsunezumi, & Yoshiike, 2002) have identified that in right-handed golfers the right gluteus maximus is highly active during the beginning of the downswing and the acceleration phase towards impact (see McHardy & Pollard, 2005, for a full review). Hellström (2008) suggested that clubhead speed could be influenced by the strength of the gluteals (and other lower body muscles); the squat is an effective method to assess the functional strength of these muscles, alternatively if load is introduced the maximal strength can be assessed.

The action of sitting back in the squat allows the recruitment of the gluteus maximus which are particularly prevalent in a deeper squat (i.e. where the participant is reaching and passing a parallel position with their thigh) (Chiu, Heiler and Sorenson, 2009). If the torso presents excessive anterior lean it does produce greater torque at the knee joint which is why the quadriceps become the dominant muscles to support the body. Chiu et al. (2009) also proposed that another biomechanical advantage to sitting back into the squat position and recruiting the gluteus maximus is that it can prevent knee valgus through the reduction of necessary ankle dorsi-flexion. A sitting back method does shift the centre of mass posteriorly; however this can cause compensatory movements to occur such as the anterior shift of the torso to maintain balance (Chiu et al., 2009). If this movement is not possible due to lack of ROM in hip flexion and strength in the back muscles and gluteals then flexion and anterior lean of the spine will occur or the athlete will be unable to proceed further with the squat.

Although Cook et al. (2006) suggest that the squat is the ready position for many sports, especially those that require lower body power, it is not the required position for golfers to adopt prior to hitting the ball. However, it is important to understand the physical limitations presented by each golfer through assessments such as the OHS which can be used to assess both stability and mobility throughout the body. Boyle (2004) attributes increased squatting strength to the development of speed and the production of increased ground reaction force (GRF) which is a vital component in the production of clubhead speed in golf performance (Richards et al., 1985; Vaughan, 1981; Williams & Kavanagh, 1983). To increase the clubhead speed it is necessary to push down through the legs and through the feet on the ground and to create considerable GRF (Hume et al., 2005). This suggests that the squat is a useful exercise to use within a training environment to allow strength and power outputs to increase within golfers, but does not support the link between restricted squat mechanics and a deterioration of posture in the swing.

The restriction of movement can have an impact upon sports techniques and specifically, golf swing technique can have a large impact upon performance (Hume et al., 2005). McTeigue, Lamb, and Mottram (1994) reported significant differences in spine angles at impact compared to address but this was not attributed to any specific physical limitations or indeed to a kinematic swing fault. Splitting the spine angles into the primary (flexion at the hips, which does not alter spine flexion or extension) and secondary (right lateral shoulder tilt, which is not necessarily governed by lateral flexion but could be due to scapula and shoulder mechanics) it was found that there was a 9 degree increase in posture (extension at the hip leading to a standing up action) in the primary angle (34° at impact compared with 45° at address) and a 12 degree decrease in the secondary angle at impact (28° at impact compared with 16° at address). It is reasonable to expect that the golfer will adopt a different position at impact compared to address due to the rotation elements of the swing, but how much change in posture is tolerable before impact factors are affected, and therefore becomes detrimental to performance, needs further investigation. Other studies have analysed the link between physical attributes and the kinematics of the golf swing (e.g. Gulgin, Schulte and Crawley, 2014; Hellström & Tinmark, 2008; Neal, Abernethy, Moran, & Parker, 1990). Neal et al. (1990) proposed that through increases in joint ranges of motion it may be possible to add distance to golf shots. Increasing strength and power are important to improving shot distance (Bull & Bridge, 2012; Lephart et al., 2007; Nesbit & Serrano, 2005; Reyes, 2002) and results show that peak power output from the squat jump and the 1-repetition max for the squat were both significantly correlated with clubhead speed (Hellström, 2008).

Hellström and Tinmark (2008) found that there were links between stability tests and the kinematics of the golf swing. A reduction in stability in the prone bridge test and the one-legged squat were associated with an increased level of sway of the upper body in the backswing. Decreased stability in the one-legged squat and the supine hip extension tests were also associated with increased pelvis and upper torso rotation into the backswing. This can lead to a lack of separation between the pelvis and torso resulting in reduced power through the stretch-shortening cycle. The lumbopelvic area should have limited rotation into the backswing with the pelvic muscles creating a stable base for the torso to rotate around (McHardy and Pollard, 2005). Aside from the golf swing, it has also been shown that lumbopelvic rotation is generally limited, with Ha, Saber-Sheikh, Moore and Jones (2013) finding that axial rotation ranges from 14°-16° between L1 and sacrum and others reporting even lower values of 6-8° (Troke, Moore, Maillardet, & Cheek, 2005). A lack of control over pelvic rotation in the backswing will have an impact upon the amount of stretch created between the pelvis and torso, and consequently affect the acceleration into the downswing due to a smaller stretch-shortening action. The right side obliques and the right gluteus medius will not be able to work against the stable base of the pelvis, where the left lateral leg and lumbopelvic stabilisers should be strongly activated, when producing rotation towards impact (McHardy & Pollard, 2005).

A recent study into the TPI screening tests with 36 golfers (Gulgin et al., 2014) found that there were significant relationships between the Toe Touch test and early hip extension in the swing, right gluteals (trail side) strength and early hip extension as well as loss of posture . It was suggested that golfers who demonstrated a limited OHS were twice as likely to early extend (through the hips thrusting towards the ball) in the downswing. According to their results 67% of those that could not OHS showed a degree of early hip extension in the downswing. There are a number of limitation to this work with only 4 shots being analysed using a golf coaching software package that does not allow digitisation of body landmarks (Gulgin et al., 2014). In addition, screening tests were conducted and rated subjectively and not measured or filmed and digitised for exact measurements. The results of this study (Gulgin et al., 2014) do not therefore allow for the degree of limitation to be related to its impact on swing kinematics or provide a strong indication of a link between physical and technical issues.

The current study aims to highlight the link between the overhead deep squat and the deterioration / loss of posture at impact compared to the address position. It is hypothesised that with a reduced range of movement through the overhead squat test there will be increased loss of posture at the impact position in the swing.

Method

Experimental Approach to the Problem

Variables were selected based on the proposed link between the possible physical restrictions and the perceived impact upon golf swing technical faults. Variables were measured in the OHS test (Table 5), swing kinematics (Table 6) and using Trackman® (Doppler radar launch monitor) data on clubhead speed (CHS) and ball speed (BS) for participant descriptive data.

Participants

Fourteen participants comprising of 11 male and 3 female golfers between the ages of 24-76 years old (M=54±18years) were recruited from local golf clubs after local ethics committee approval. The participants were of mixed ability but all played golf right handed and possessed a CONGU handicap (hcp=18±10, range=1-36, 6-iron CHS=72.77±10.38mph, BS=95.32±14.56mph; female n=3, age=60±15 years, hcp=30±6, hcp range=24-36, CHS=60.26±4.12mph, BS=77.09±6.71mph; male n=11, age=52 ±20 years, hcp=15±8, hcp range=1-24, CHS=76.19±8.77mph, BS=100.28±11.83mph). All participants were injury free and did not report pain during their golf swing or physical activity. Although the handicap system is not ideal as it does not identify specific skills which contribute to a lower handicap it does present the overall skill level of the golfer within the sport.

Table 5 Variables Selected for Musculoskeletal Profiling

Variable	Definition
OHS Torso Angle	The angle between the hip, C7, and vertical. The smaller the angle presented the less anterior lean (forward tilt from the hips) seen within the OHS. Accompanied with a small knee flexion angle this represents better range of movement in the test.
OHS Knee Angle	The angle between the ankle, knee and hip. The smaller the angle presented the greater the flexion at the knee. This results in a lower squat position.
OHS Shin Angle	The angle presented by the shin relative to vertical. The smaller the angle the greater dorsiflexion presented through the ankle at the deepest position in the squat.
OHS Arm Angle	The angle presented by the forearm relative to vertical. The smaller the angle the closer the arms are to vertical at the deepest position in the squat.

Table 6 Static Variables Measured at Address and Impact

Variable	Definition
Distance of Knee to Ball	The distance between the rear (right) lateral knee marker and the ball.
Distance of Pelvis to Ball	The distance between the head of the femur marker and the ball.
Distance of Shoulder to Ball	The distance from the head of the humerus marker and the ball.
Distance of Head to Ball	The distance of the head to the ball as measured from the tip of the nose.
Pelvic Tilt	Hip tilt in the frontal plane around the sagittal axis (determined using the tangent of the transverse plane projection of the vector between the left and right ASIS).
Shoulder Tilt	Shoulder tilt in the frontal plane around the sagittal axis (determined using the tangent of the transverse plane projection of the vector between the left and right acromion processes).
Shaft Angle	The angle of the shaft in relation to the vertical axis from a face on camera position (along the sagittal axis. A positive angle represents delofting of the club where the grip is ahead of, or closer to the target than the clubhead. A negative angle represents adding loft with the grip further away from the target. This variable was also considered from a down the line camera position (along the frontal axis). An increasingly positive angle represents the shaft being closer to vertical.
Knee Width	The width of the knees when observed from the face on camera position (determined using the width between the left and right patella markers).

Procedures

Spherical 1cm high contrast markers were placed on 33 anatomical landmarks on each participant by a single researcher (Figure 3). The authors acknowledge that placement of markers on the skin and clothing is subject to small movement during the swing.

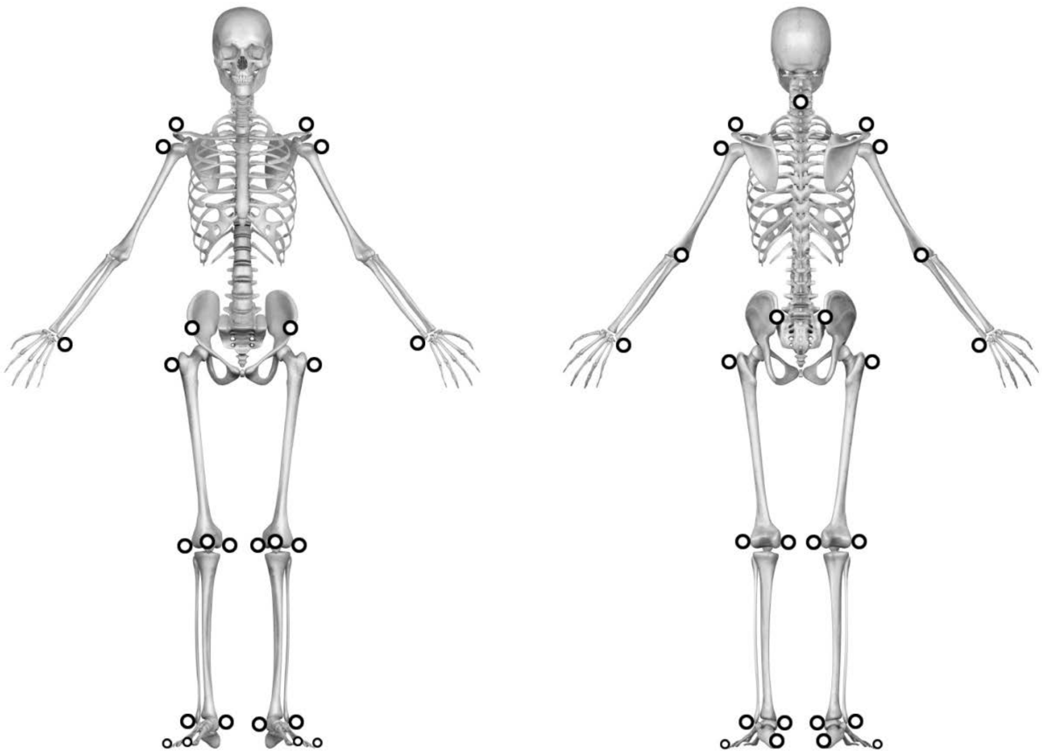

Figure 4 Placement of Reflective Markers on 31 Anatomical Landmarks

Prior to any activity all participants undertook a physical screening process. The OHS test was conducted and recorded using a Canon 60D DSLR camera which was aligned to a calibrated area using high contrast markers and participants were directly aligned side on (perpendicular to the sagittal plane, along the frontal axis) and then face on (perpendicular to the frontal plane, along the sagittal axis) to the camera within this area. Participants were asked to assume a comfortable stance with the feet slightly wider than shoulder width apart and the feet parallel. Hand width was set by placing a bar on the head and adjusting the elbows to 90° before fully extending the arms to above the head. Following a demonstration, participants completed an OHS to as low a position as possible while keeping the heels on the floor and the arms straight. Each golfer's OHS was digitised and all variables were measured (Table 5) using Tracker software (version 4.72).

All participants executed 15 shots with their own 6-iron (of which 5 randomly selected shots were analysed) that were captured at 300Hz using 2 Casio EX-F1 high speed cameras and a Trackman® 2.0 launch monitor (to collect CHS and BS data for presentation of these participant performance characteristics). Cameras were positioned according to the PGA guidelines for coaches to set up video analysis for kinematic analysis of the golf swing. One camera was positioned "down the line" where the camera was at hand height when each golfer assumed their address position, and parallel to the ball to target line. The other camera was "face on" and was perpendicular to the ball to target line at the same height as the hands at address. The Trackman® launch monitor was positioned directly behind the ball and was aligned to a specified target on the range of which the golfers were informed prior to testing.

The spherical high contrast markers remained in place for the swing analysis and in addition to the anatomical identification, calibration markers were placed on a 1 metre vertical measurement ruler and on each corner of a 142.4cm^2 golf mat from which every shot was played and golfers were aligned to. As stated, cameras were aligned to the player's hand height and perpendicular to their stance and the calibration markers for both "down the line" and "face on" views. This allowed a two-dimensional scale to be used for the subsequent video analysis. A spot was also marked on the golf mat for the placement of the ball each time to allow variability at address to be solely down to the individual swing kinematics, rather than the position of the ball, which also helped to reduce perspective error.

Following the musculoskeletal profiling test participants performed a self-selected warm up which also acted as a familiarisation period towards the range set up, target, and anatomical markers. Participants were asked to address the ball and perform their normal swing to produce a consistent ball flight with maximum accuracy and distance towards an identified target on a golf range. These instructions were designed to limit task related variability (i.e. strategic variability) so that any variability seen would be of a 'within movement' nature.

Definition of Key Positions in the Swing

Analysis of the address and impact positions took place using digitisation of the anatomical landmarks. Address was defined as the stable position prior to takeaway (the frame prior to the first movement of the club or any body segment away from the target). Impact was defined as the moment of club and ball contact or where this was not captured by the cameras an average of the frame prior to and post ball contact.

Swing Processing

For each variable manual digitisation occurred for each key position frame in the swing using Tracker software (version 4.72).

Statistical Analyses

All data were checked for approximation to the normal distribution, and group and individual means and standard deviations were calculated. Dependent t-tests were used to assess if there was a significant difference in position between address and impact during the swing. Pearson product moment correlation coefficients (r) were calculated to assess any linear relationship between the OHS test variables.

Focussed multiple backward stepwise regression analyses were used to assess the impact of OHS variables on specific swing variables. This included analysis of any variables that could be related back to the OHS test (Table 7).

Alpha levels were set to $p<.05$. All data analyses were carried out using SPSS 20.0 and data are reported as mean and standard deviation unless otherwise stated.

Table 7 Swing Variables Analysed and their Proposed Link to the OHS

Swing Kinematic Variable	Swing Position	Proposed Link to OHS
Knee width (Sagittal axis)	Address & Impact	Linking to the OHS's ability to highlight limitations with the strength of the gluteals and the ability to avoid knee valgus.
Distance of the knees, hips, shoulder and head to the ball (assessed from the camera on the frontal axis)	Address & Impact	To assess the influence of the OHS on the posture kinematics of flexion at the ankle, knee and hip and any lifting of the head.
Shaft angle (assessed from the camera on the frontal axis)	Address & Impact	To assess the influence of early extension / loss of posture and the resultant change in club position.
Shaft angle (assessed from the camera on the sagittal axis)	Impact	To assess the influence of any loss of posture on the shaft lean at impact. At address the shaft angle could purely be altered by a movement of the hands and arms and therefore is of no interest in this study.
Shoulder tilt (assessed from the camera on the sagittal axis)	Impact	To assess the impact of the OHS on changes in shoulder plane possibly resulting from loss of posture. With decreases in the ability to OHS it has been suggested that due to possible early extension (Phillips, 2013) it could be expected that there is a greater need for lateral shoulder tilt.
Pelvic tilt (assessed from the camera on the sagittal axis)	Impact	To assess the influence of OHS on loss of posture causing increased hip tilt as the space for the arms to swing through becomes limited.

Results

Dependent t-tests demonstrated a significant difference between the position of the golfer at address and the position that they adopted at the point of impact for most of the kinematic variables (Table 8).

Changes between Address and Impact

A multiple backward stepwise regression analysis revealed no significant relationships between the OHS variables and the changes in swing kinematic variables between address and impact.

Address

The multiple backward stepwise regression analysis showed at address only the OHS torso angle was shown to be a significant predictor of variance of shoulder distance to the ball (Table 9) accounting for approximately 30% (Adj R^2 = .243). Increased OHS torso angles resulted in decreased distance from the shoulders to the ball at address.

Table 8 Mean ± Standard Deviation for each Swing Kinematic Variable between Address and Impact

Variable	Address	Impact	p-value	r^2	Observed Power
Distance of Knee to Ball (cm)	73.42±5.97**	69.63±4.70**	.004	.48	.38
Distance of Pelvis to Ball (cm)	103.28±7.76**	96.47±6.23**	.000	.77	.76
Distance of Shoulder to Ball (cm)	113.68±4.84	113.91±6.21	.739	.01	.05
Distance of Nose to Ball X (cm)	31.28±4.55*	32.89±5.01*	.011	.40	.28
Distance of Nose to Ball Y (cm)	110.02±6.43	109.20±6.66	.305	.08	.06
Distance of Nose to Ball (cm)	114.49±5.95	114.15±6.55	.648	.02	.05
Shaft Angle (°)	34.64±3.27**	29.33±2.78**	.000	.83	.82
Face On Shoulder Tilt (°)	-13.72±2.95**	-19.14±4.5**	.001	.58	.52
Face On Shaft Angle (°)	2.96±2.77	3.26±3.29	.805	.00	.05
Face On Knee Width	29.52±4.61*	26.76±6.85*	.032	.31	.19

Note *t-test values that indicates a significant difference between address and impact (p<0.05)

** t-test values that indicates a significant difference between address and impact (p<0.01)

Table 9 Predictors of Shoulder Distance to Ball at Address using a Backward Stepwise Multiple Regression Analysis of all 4 OHS Variables

		Shoulder Distance to Ball at address			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	117.204	17.460		[77.708, 156.701]
	OHS_Arm_Angle	-.046	.078	-.201	[-.224, .131]
	OHS_Shin_Angle	.205	.335	.191	[-.553, .963]
	OHS_Knee_Angle	-.056	.083	-.242	[-.244, .132]
	OHS_Torso_Angle	-.231	.169	-.636	[-.614, .152]
Step 2	Constant	115.728	16.707		[78.502, 152.955]
	OHS_Shin_Angle	.256	.313	.239	[-.441, .954]
	OHS_Knee_Angle	-.070	.077	-.302	[-.242, .102]
	OHS_Torso _Angle	-.293	.129	-.806	[-.579, -.006]
Step 3	Constant	127.230	8.914		[107.610, 146.850]
	OHS_Knee_Angle	-.045	.070	-.196	[-.199, .109]
	OHS Torso Angle	-.240	.110	-.661	[-.481, .001]
Step 4	Constant	122.042	3.843		[113.669, 130.415]
	OHS Torso Angle	-.199	.088	-.549*	[-.390, -.008]

Note. R^2 = .393 for Step 1, ΔR^2 = -.024 for step 2, ΔR^2 = -.042 for step 3, ΔR^2 = -.026 for step 4. * $p < .05$.

Impact

Results of the multiple backward stepwise regression showed that only the OHS torso angle was a significant predictor of variance of knee width at impact (Table 10), accounting for approximately 33% (28% when adjusted for sample size and number of regressors). There was a significant negative relationship between the OHS torso angle and the knee width at impact (r = -.577, *p* = .031): as the torso generated increased anterior lean from flexion at the hips during the OHS test the knee width at impact was shown to decrease.

Pearson product moment correlation coefficient showed some OHS variables were found to be significantly correlated to each other and this is important to note. It can explain the results linked to the swing kinematics as well as the depth and quality of the range of movement each participant demonstrated in the OHS. Torso angle showed a significant negative correlation to knee angle (r = -.572, *p* = .032) indicating that when the torso had increased anterior lean the participants were able to drop lower into the squat position and therefore decreasing the knee angle and vice versa. Due to scapula mechanics the torso angle was significantly correlated to arm angle (r = .593, *p* = .025) demonstrating that when the torso angle shows reduced anterior lean the arms are able to stay more towards vertical. No other relationships were found to be significant.

Table 10 Predictors of Knee Width at Impact using a Backward Stepwise Multiple Regression Analysis of all 4 OHS Variables

		Knee Width at impact			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	36.848	24.063		[-17.585, 91.281]
	OHS_Arm_Angle	.026	.108	.079	[-.219, .270]
	OHS_Shin_Angle	-.207	.462	-.136	[-1.252, .838]
	OHS_Knee_Angle	.121	.115	.368	[-.139, .380]
	OHS_Torso_Angle	-.188	.233	-.365	[-.716, .340]
Step 2	Constant	37.666	22.663		[-12.831, 88.162]
	OHS_Shin_Angle	-.235	.425	-.155	[-1.182, .711]
	OHS_Knee_Angle	.128	.105	.391	[-.105, .362]
	OHS_Torso_Angle	-.153	.174	-.298	[-.542, .235]
Step 3	Constant	27.107	11.884		[.951, 53.264]
	OHS_Knee_Angle	.106	.093	.322	[-.100, .311]
	OHS_Torso_Angle	-.202	.146	-.393	[-.523, .120]
Step 4	Constant	39.191	5.314		[27.613, 50.769]
	OHS Torso Angle	-.297	.121	-.577*	[-.561, -.033]

Note. R^2 = .424 for Step 1, ΔR^2 = -.004 for step 2, ΔR^2 = -.018 for step 3, ΔR^2 = -.070 for step 4. * p < .05.

Discussion

TPI has suggested that restricted OHS test results are related to loss of posture in the golf swing at impact. Loss of posture in the golf swing can affect the impact positions between club and ball, potentially leading to less accuracy and distance. This can be due to the “early extension” of the hips and a standing up action. The results show that although there is a shifting of the hips towards the ball there is no significant difference between the position of the shoulders at address and impact. Previous studies (Chapters 2 & 3; Langdown et al., 2013a, 2013b) have shown that the variability of shoulder position is reduced compared to other body segments and have suggested that the funnelling of variability exists in a proximal to distal fashion towards the accuracy end of the golf swing. The lack of change in position of the shoulders would suggest that the golfers are able to compensate for other body segment movements during the swing in order to arrive at impact with a similar shoulder position.

Although there were many significant differences between the body positions at address and impact there was only one kinematic variables at address (shoulder distance to the ball) and one kinematic variable at impact (knee width) attributable to the OHS test results. There were no significant predictors of address to impact posture kinematic changes when using the OHS variables. This suggests that the hypothesis of any of the loss of posture variables measured here in the golf swing being linked to the screening results of the OHS should be rejected and as such, contradicts the suggestions of TPI (Phillips, 2013).

Even if participants displayed a ROM during the OHS test that allowed the thighs to break parallel with the ground, the feet to remain parallel to each other, the heels to stay down, the arms and hands to stay within the footfall and the torso and shin angle to be parallel, the golfer may not utilise this range in their swing. This could be due to the development of swing characteristics over a number of years and the strength of the attractor from which the swing emerges. Future research should establish whether increasing the ROM in the OHS would allow the golfer to explore new ranges and utilise the increased mobility / strength during their swing.

Address results suggest that poor squat mechanics affect the set-up position that the golfer adopts to the ball. Of particular interest is the increased anterior lean of the torso in the OHS leading to the golfer's shoulders setting up closer to the ball. This may imply a lack of thoracic extension (among other physical limitations) that presents itself in both the OHS test and also the address position leading to the shoulders being closer to the ball. With this comes potential swing compensations such as possible restrictions with rotation (if the reduced distance to the ball is accompanied with increased thoracic kyphosis or loss of scapula control and stability). Booth (2005) highlights that reduced scapula stability and control alongside thoracic kyphosis can lead to excessive protraction of the scapulae as a compensation for reduced thoracic rotation during the swing. The plane on which the club is swung (swing plane) is suggested to be influenced by the address posture and may also be due to the stance distance to the ball; too much spine angle at address (flexion at the hips) and the swing is more likely to be too vertical (i.e. swinging increasingly up and down) whereas decreased anterior torso lean is more likely to present a shallow plane (i.e. swinging around the body) (Breed & Midland, 2008). The other potential issue could be a reduction in space for the club to pass through to impact leading to further compensations or poor contact with the ball.

Impact results showed that the greater the torso anterior lean in the OHS the narrower the knees at impact. There may be many reasons for this relationship. Two possible explanations, which need further 3D kinematic examination, are a lack of strength in the gluteals or simply a limited ROM in external rotation through the trail hip. Gluteal strength is thought to be necessary to maintain control and separation of the knees (knee valgus) in the golf swing as well as to maintain posture (Phillips, 2013), although again this needs further testing. The gluteals are also a key group of muscles that allow the overhead squat to be performed with a sitting back action and less anterior torso lean (Chiu et al., 2009). Secondly, the lack of external hip rotation may lead to knee valgus through the downswing, especially on the trail side where the knee may move laterally to compensate for the limitation. Or indeed a combination of the two may be a possible cause. Internal hip rotation is required to produce a deep OHS and it is therefore possible that other screening tests (e.g. passive hip rotation tests) are required to assess the causes of knee width reduction at impact.

The gluteals play a role in weight transfer and hip rotation which is a key component of the kinematic sequence in the downswing (Callaway et al., 2012; McHardy & Pollard, 2005) and as suggested, should the gluteals be weak or inhibited, this may lead to the trail knee collapsing earlier (knee valgus), or limited ROM at the hip. In the OHS the gluteals play a vital role in allowing the golfer to reach a “break parallel” position (with the thighs) at the bottom of the squat (Chiu, et al., 2009). With a lack of gluteal strength, coupled with an inability to maintain thoracic extension, the golfer’s torso may inevitably show increase anterior lean through flexion at the hips and a loss of thoracic extension.

The issue with the measurement of the OHS is that if the torso remains upright and the knee angle is greater than that which allows a thigh parallel position this will indicate a poor squat. However, if the knee angle is reduced through flexion it may also coincide with increased anterior lean of the torso which may still indicate a number of physical limitations. Gluteal strength in this scenario could prevent the golfer falling backwards when moving lower into the squat and thoracic extension would allow the golfer to maintain an increased upright torso posture that was at least parallel to the shin angle. The results show a significant negative correlation between the torso lean and the knee angles during the OHS indicating that when there is a poor squatting technique (or ROM) the golfer can compensate in one area to try and achieve a lower position.

Further research should be conducted with an increased sample size and interventions applied to the OHS performance. The results have shown that the deterioration of posture between address and impact (in the form of statistically significant changes in joint angles and distances of body segments to the ball, Table 8) does exist in these golfers, but this cannot be attributed to the OHS at present and more work needs to be done in this area to see how the strength of muscle groups and the ROM of the golfer’s body can affect performance.

Limitations

There were only 14 participants within this study and therefore future research needs to extend this sample in order to generalise results to wider golfing populations. However, a strength of this sample was that the golfers tested included a wide range of ages and this is a rare characteristic of golf research where the majority of studies utilise either younger golfers or a specific older population. A larger sample and a wide spread of participants should continue to be used so that the coaches are able to apply the results to their general client base.

2D video analysis does have its limitations (see Bartlett, 2007) for kinematic analysis and does have inherent perspective errors especially with the rotation of joints (e.g. the pelvis; i.e. when measuring the distance of the pelvis to the ball at impact) therefore leading to minor measurement errors. However, this is a common tool for PGA Professionals to use in the field of golf coaching and this study aimed to replicate those methods. It is important that research is representative of a performance setting (Pinder et al., 2011) and applicable to the coaches that are to use these results to alter technique and performance. The use of a range facility enabled participants to see their ball flight and reflect on this as they would in a real golfing environment. 3D analysis is becoming increasingly available to players and PGA Professionals alike but at this moment it is not the norm to be used on a daily basis. Further research should explore the relationship between physical constraints and swing kinematics (swing faults) to understand the true nature of how the body can impact upon performance. Training programmes should also be tested to establish whether this can impact upon ROM and the swing kinematics presented at critical phases of the swing (e.g. Bull & Bridge, 2012).

The power of this study (e.g. Table 8) was affected by the sample size (n=14). In order to reduce the chance of accepting Type II errors for loss of posture between address and impact and achieving power of 0.8 (Field, 2013) based on the effect size presented by each variable in this study a sample size of between n=19-86 would have been needed for the following variables: Distance of Knee to Ball, Face on Knee Width and Distance of Nose to Ball. However, all other variables would have required a sample size in excess of n=1616 which was beyond this study. In order to reach adequate power (80% confidence) for the results of the OHS torso angle being used to predict shoulder-ball distance at address and knee width at impact sample sizes of n=33 and n=30 would have been required respectively. This may have allowed further small but significant predictors to emerge but further increases in sample size would be needed to ensure 80% confidence was achieved across all results. This exploratory research allows future a-priori power calculations for sample sizes to be completed using the effect sizes presented to ensure any loss of posture variables were of a power ≥0.8. In the future, research with a larger sample should be studied but maintaining the same range of handicaps and ages to ensure that research is not purely focused towards the elite end of the ability spectrum.

Conclusion

This study has shown there is a significant change in posture from address to impact; however, this is not attributable to the OHS as has previously been suggested. There may be a variety of reasons for the relationships between the increased anterior lean in the OHS and knee valgus at impact and the predictors of address shoulder positions. The excessive adduction of the trail knee at impact may not be an issue that affects the outcome performance variables, and this should be explored further. Research should be conducted into the role that S&C interventions can play upon the performance of the OHS and whether this has subsequent effects on swing kinematics.

Researchers are encouraged to explore representative research (Pinder et al., 2011) that focuses on a wider range of ability levels and ages through their research so that more effective dissemination of findings can be passed to and applied by coaches who work with a diverse population of golfers. Previous research has focused on specific groups of players and this has led to the coach comparing players to what the elite kinematics suggest. It is feasible to suggest that there will be research findings that will differentiate a category 4 handicap golfer to category 3, category 2 etc.

Coaches are encouraged to monitor the deterioration / loss of posture from address to impact and the knee width at impact which may indicate technical or physical limitations preventing the golfer from producing a more efficient movement throughout the swing. Further 3D kinematic research in relation to performance outcome measures is needed before any physical results from the use of the OHS test can be disseminated to the coaching population and to suggest any attribution to change in ball flight.

5. THE INFLUENCE OF AN 8 WEEK STRENGTH AND CORRECTIVE EXERCISE INTERVENTION ON THE OVERHEAD DEEP SQUAT AND GOLF SWING KINEMATICS

Abstract

The performance of the overhead squat (OHS) test has previously been suggested to influence the kinematics of the golf swing and in particular the loss of posture during backswing and downswing; however this theory has not yet been tested. This study aimed to assess this hypothesis through an intervention to improve OHS performance and to analyse the impact of physical changes. 37 golfers of mixed ability (hcp=14.8±13.3, range=Pro-36) were randomly split into a control group (n=16) and an intervention (n=21) group who completed an 8 week strength and flexibility programme focussing on improving various components of the OHS. Pre and post intervention 3D 6-iron swing kinematics were captured at 240Hz (Polhemus Liberty tracking system). Pre and post musculo-skeletal assessments showed a significant decrease in OHS thigh angle (i.e. golfers obtained lower squat positions), as well as significant increases in flexibility and strength. Results showed there to be no significant changes in 3D swing kinematics between groups and over pre and post testing for address, top of the backswing and impact. Regression analysis revealed no significant predictors at address but that the 4 measured components of the OHS were significant predictors of various swing kinematic posture variables at the top of the backswing and impact for the whole group. These may, however, be spurious relationships because if they were indeed true predictors of the postural variables then it could be expected that swing changes would be observed following the intervention. Although the intervention group had significant

physical changes it is possible that extensive coaching is needed for the increased range of movement and strength to be used within their swings. As the results showed no kinematic swing changes following the intervention it is not possible to suggest that the OHS is a useful assessment tool for postural swing faults. It may however be a useful assessment tool for strength and range of movement, provided that the S&C coach allows for any motor learning to take place prior to utilising results on which to form conditioning programmes. It is therefore not recommended that coaches assess the OHS performance to understand whether loss of posture seen in the swing is as a result of technique or physical limitations as there may be many other variables that can impact upon this relationship, not just the OHS.

Introduction

It has been previously shown that the overhead squat (OHS) anterior torso lean influenced the shoulder distance to the ball at address and knee width at impact in the golf swing (Chapter 4; Langdown, Bridge & Li, submitted). Although this did not affect the shot characteristics, as measured by a Doppler radar launch monitor, it is important to understand how changing the body's capabilities can affect golf performance. The previous study into the relationship between the OHS and the golf swing kinematics was designed to replicate the methods used most commonly by golf coaches. This current study aims to continue testing the suggestions by The Titleist Performance Institute (TPI) that restrictions in the OHS test can translate to a loss of posture and early hip extension (pelvic thrust) in the backswing and downswing of an individual's golf swing (TPI, n.d.a, n.d.b).

The OHS is an important functional screening tool which is used to assess both the upper and lower body through the closed kinetic chain of the bilateral, symmetrical functional mobility of ankle dorsi-flexion, knee and hip flexion through the lowering of the pelvis towards the floor, thoracic spine extension, shoulder flexion and abduction through the maintenance of posture and arms vertical above the shoulder joint (Cook, 2003; Cook et al., 2006) and strength of the lower body (Boyle, 2004) to include the gluteals and quadriceps. It has been suggested in the golf literature that a failure to complete a full OHS indicates a generalised stiffness and asymmetry in the musculature of the lower body (e.g. TPI, n.d.a; Verstegen & Williams, 2009).

Loss of posture in the swing has been hypothesised to relate to many other swing faults such as a flat shoulder plane (TPI, n.d.c), changes in swing plane, angle of attack, timing, balance and rhythm (TPI, n.d.b) among others. Roberts and Haney (2009) suggest that the physical causes of a loss of posture can be a lack of core mobility and strength, or instability in the lower body. They also suggest that a loss of posture can lead to ‘thin shots’ (where the bottom of the clubhead strikes around the centre of the golf ball) or a ‘topped shot’ (where the bottom of the clubhead strikes the top of the golf ball) which will both cause a significant loss of distance and control over ball flight.

McHardy and Pollard (2005) reviewed 9 EMG studies within golf and proposed that during the phases of the swing the following muscles are active and important to performance (Table 11). There is a large cross over from these findings to the muscles involved in the OHS which may imply that by increasing the strength and flexibility of specific muscles the swing can be influenced and the kinematics of the swing altered. The lower the squat is performed the greater the activity of the gluteus maximus (Caterisano et al., 2002), which suggests that golfers who cannot achieve a full OHS may not have the ability to effectively use, or the strength, in the gluteus maximus which ultimately plays a key role within their golf swing (Table 11). The gluteus maximus is the largest and most superficial of the gluteal muscles and primarily acts as a powerful hip extensor (Kang, Jeon, Kwon, Cynn, and Choi, 2013). Other roles it performs include transfer of force to the upper body and prevention of lower limb injuries (Kang et al., 2013). With this in mind it is important that the glutei maximi are well trained and strengthened. Wilson, Ferris, Heckler, Maitland, and Taylor (2004) suggested that the best exercise to activate the gluteus maximus was the full squat.

Table 11 Most Active Muscles in the Golf Swing

Swing Phase	Lower Body		Upper Body	
	Trail Side	Lead Side	Trail Side	Lead Side
Backswing	Semimembranosus and the long head of the biceps femoris	Erector spinae and adominal oblique	Upper and middle trapezius	Subscapularis and upper serratus anterior
Forward swing	Upper and lower gluteus maximus and biceps femoris	Vastus lateralis and adductor magnus	Pectoralis major and upper serratus anterior	Rhomboids and middle trapezius
Acceleration	Adominal oblique and gluteus medius	Biceps femoris, upper and lower gluteus maximus and vastus lateralis	Pectoralis major and upper serratus anterior	Pectoralis major and levator scapulae

Adapted from McHardy and Pollard (2005).

Note. Backswing = from address to the top of the backswing; Forward swing = from the top of the backswing to a horizontal club position in the downswing; Acceleration phase = from the horizontal club position in the forward swing to impact.

Various studies have analysed the effect of exercise intervention programmes on the outcome measures of the golf swing (e.g. CHS & BS). Bull & Bridge (2012) suggest that the difficulty with just using this outcome based approach is that it does not consider changes within the swing kinematics or allow the separation of the effects of each training method on golf performance. Lephart et al. (2007) used an 8-week golf specific exercise programme aimed at improving lower body stability, hip flexion and extension flexibility, torso rotational strength and flexibility and shoulder flexibility through 3-4 training sessions per week. They found the intervention improved a variety of strength, flexibility and balance variables along with increases in upper-torso rotational velocity which led to a 5.2% increase in calculated clubhead velocity, 5.0% increase in ball speed, and a 7.7% increase in carry distance. Their intervention was a home based programme involving 15 trained male golfers who all took part in the intervention so there was no control group present.

Another study without a control group (Doan, Newton, Kwon, & Kraemer, 2006) used an 11 week intervention which produced significant increases in all of the strength, power, and flexibility variables measured. Using 16 highly skilled collegiate golfers who trained 3 times per week, the study analysed effects on clubhead speed for 15 driver shots (1.62% increase), consistency (defined as the standard deviation of the launch angle of the golf ball and the clubface angle at impact: no change reported) and putting distance control (only the male participants showed significantly reduced putting error with a reduction of 29.56% in distance to the hole over a 15ft putt).

Fletcher and Hartwell (2004) used an 8-week weights and golf specific medicine ball plyometric training intervention with 11 male golfers (split into an intervention group (n = 6) and a control group (n = 5)) who were asked to train twice a week. They reported no change in the control group for both clubhead speed and drive distance but a significant clubhead speed increase of 1.5% for the intervention group.

Although all of these studies described above add valuable information about the effects of training on performance outcomes it is necessary to understand whether there are any changes in the kinematics of the swing following an intervention study. Hellström (2009) stated that there is little research on the effect of physical conditioning on the 3D swing kinematics. One such study conducted by Bull and Bridge (2012) examined the effects of an 8-week golf specific plyometric training programme on the kinematics of the golf swing using a sample of 16 category 1 and professional golfers (equally split into control and intervention groups). The intervention group completed 2 plyometric sessions per week and although they reported no change in body positions during the swing they did find increased maximum x-factor, maximum rate of recoil, and peak speeds of lead arm and hand. Clubhead speed and ball flight outcome variables were not measured within this study and this was identified as a limitation to their research.

Callaway et al. (2012) assessed the relationship between the strength of the gluteus medius, gluteus maximus and the handicap of 56 golfers. They found that there was a significant difference between the high and low handicap groups when testing the strength of both the gluteus maximus and gluteus medius. The findings also indicated that alongside this difference in strength there were also implications on the swing. The peak pelvis rotation speed was significantly higher for the low handicap group (503 d/s) compared to the high handicap group (380 d/s). However, the methods used to collect this data were limited by a 3 sensor system measuring only 3 DOF which means that any change in lift, thrust or lateral sway and slide would have been absent from this swing kinematic data.

Following on from the findings of Chapter 4 (Langdown et al., submitted) this study aimed to provide an intervention to alter the ROM in the OHS test to examine the relationship between changes in physical abilities and swing kinematics. As suggested in Chapter 4, 3D analysis will be used to provide increased understanding of any possible relationship between the OHS screening test and the swing.

Method

Participants

41 participants comprising of 29 male and 12 female golfers between the ages of 15-68 years old (M = 39.68±11.62years) were recruited from local golf clubs after local ethics committee approval and randomly assigned to an intervention group (*n*=21) or a control group (*n*=16). The final control group included 16 participants after 4 withdrew from the study. All participants completed consent forms and indicated they were pain and injury free and fit to participate in the study.

The participants were of mixed ability but all possessed a CONGU handicap (See Table 12 for participant characteristics). The intervention group had a split of males (n=12) and females (n=9), and a mean handicap = 16.14±14.30. The control group was again comprised of males (n=14) and females (n=2) with a mean handicap = 13.00±11.99. It was felt important to consider a range of abilities so category 1 or Professionals and category 3-5 were therefore recruited.

Table 12 Participant Characteristics

Group	n	Handicap	Age
Whole	37	14.8±13.3	39.7±11.6
Male	26	10.2±10.0	38.2±11.6
Female	11	25.7±13.9	43.1±11.5
Intervention	21	16.1±14.3	39.7±11.1
	Male = 12	Male = 7.7±9.2	Male = 35.2±9.6
	Female = 9	Female = 27.4±12.0	Female = 45.7±10.6
Control	16	13.0±12.0	39.7±12.7
	Male = 14	Male = 12.3±10.6	Male = 40.9±12.8
	Female = 2	Female = 18.0±25.5	Female = 31.5±10.6
Category 1-	18	2.8±2.4	34.5±11.1
Professional	Male = 16	Male = 3.2±2.3	Male = 36.1±10.7
	Female = 2	Female = 0±0	Female = 22.0±2.8
Categories 3-5	19	26.1±8.3	44.6±10.1
	Male = 10	Male = 21.3±6.8	Male = 41.7±12.6
	Female = 9	Female = 31.4±6.4	Female = 47.8±5.4

Note. Participants who withdrew from the study were not included in the statistics.

Procedure

A between group repeated measures procedure was employed to assess the effect of an 8-week strength and flexibility intervention on the 3D kinematics in the golf swing.

Prior to any analysis of the golf swing all participants undertook a physical screening process. The OHS screening test was conducted and recorded using a Canon 60D DSLR camera fitted with a Canon 18-200mm f/3.5-5.6 IS Telephoto Lens. Calibration frames were filmed and high-contrast markers were placed upon 8 anatomical landmarks (Figure 4) for digitisation purposes.

All participants were asked to assume a comfortable stance with the feet slightly wider than shoulder width apart and the feet parallel, aligned side on to the camera. Hand width was set by placing a bar on the head and adjusting the elbows to 90° before fully extending the arms to above the head. Following a demonstration, participants completed an OHS to as low a position as possible while keeping the heels on the floor and the arms straight. Each OHS was digitised and all variables were measured (Table 13) using Tracker software (version 4.72).

Other screening assessments were conducted by the same experienced practitioner, who, using a goniometer and attached level, measured the ROM for internal and external hip rotation (supine passive rotation tests), external shoulder rotation (active tests in-standing and in 6-iron posture) and seated thoracic rotation, as well as the active flexibility of the latissimus dorsi and hamstrings. Gluteal strength endurance / inhibition was assessed through a timed bridge single leg extension hold. A single leg balance test was also timed for each side to assess static standing stability pre and post intervention.

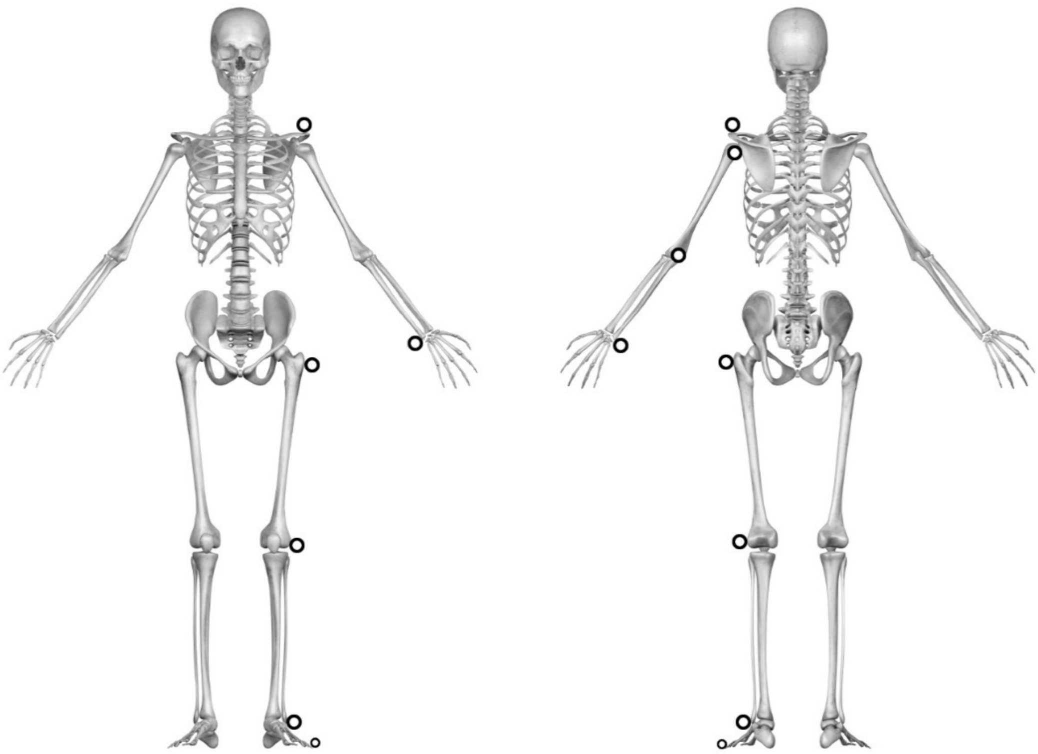

Figure 5 High Contrast Anatomical Landmarks for OHS Digitisation

Table 13 OHS Variables Selected and Measurement Definitions

Variable	Definition of measurement
OHS Torso Angle	The angle between the hip, C7, and vertical. The smaller the angle presented the less anterior lean (forward tilt from the hips) seen within the OHS. Accompanied with a small knee flexion angle this represents better range of movement in the test.
OHS Thigh Angle	The angle between vertical, the knee and hip. The smaller the angle presented the greater the flexion at the knee. This results in a lower squat position.
OHS Shin Angle	The angle presented by the shin relative to vertical. The smaller the angle the greater dorsiflexion presented through the ankle at the deepest position in the squat.
OHS Arm Angle	The angle presented by the forearm relative to vertical. The smaller the angle the closer the arms are to vertical at the deepest position in the squat.

All participants executed a minimum of 15 shots (M = 15.49±2.48) with their own 6-iron for both pre and post testing. These shots were captured at 240Hz using a Polhemus Liberty electromagnetic tracking system (Polhemus Inc., Colchester, VT, USA). Ball flight and impact data were collected using a Trackman® 2.0 launch monitor and participants were instructed to use a normal swing for consistent ball flight with maximum accuracy and distance towards a specified target. These instructions were used to limit task related variability (i.e. strategic variability) so that any variability seen would be of a within movement nature (Chapter 1.2; Langdown et al., 2012).

The Polhemus system is a real-time, six degrees of freedom motion capture system that, according to the manufacturer, has a static accuracy of .76mm RMS for the sensors' X, Y and Z position and .15° RMS for their orientation (Polhemus, 2012; see also Bull & Bridge, 2012 for further details). A Velcro body harness was used to attach sensors to each participant and to ensure any wires offered no interference to their swing. Sensors were attached to selected body landmarks: middle of second metacarpal on dorsal side left hand, lateral and proximal section of left humerus, centre of forehead, third vertebrae thoracic spine and lumbo-sacral joint (pelvis).

A static calibration of a further 13 anatomical landmarks, using a 20 cm pointer pen, was carried out according to the manufacturer's instructions. This was done to allow the sensors to be located within the magnetic field created by the transmitter (Table 14).

Table 14 Anatomical Landmarks for Polhemus Static Calibration

Sensor	**Anatomical Landmark for a right handed golfer**
1	Lateral head of second metacarpal on the left hand
2	Medial wrist at the head of the ulna (lead hand)
3	Lateral wrist at the head of the styloid process of the radius (left hand)
4	Medial head at the medial epicondyle of the humerus on the left arm
5	Centre of the left shoulder joint
6	Centre of the right shoulder joint
7	Right lateral ribs high on midline just below the armpit
8	Right lateral ribs on the midline of the rib cage
9	Distal-medial (left side) of the head at the external auditory meatus
10	Distal-lateral (right side) of the head at the external auditory meatus
11	Vertex of the head right greater trochanter
12	Vertex of the head left greater trochanter
13	The superior point (mid coronal plane) of the left iliac crest

The Trackman® launch monitor was positioned on the ball to target line and participants were informed of the specified target prior to testing. Each golf ball was placed on a marked spot on the golf mat to allow variability at address to be solely down to the participant's set up position rather than the position of the ball on the mat.

Following calibration participants performed a self-selected warm up which also acted as a familiarisation period towards the motion analysis system, harness, sensors, range set-up and specified target.

Selection of variables

Kinematic variables were calculated for each shot using the 3D golf biomechanics software (AMM 3D-Golf™ system). Variables were selected based on the suggested link between the possible physical restrictions in the OHS and the impact upon posture within the golf swing. 4 variables (Table 13) were selected to be measured in the OHS test, with 6 for swing 3D kinematics (Table 15) and clubhead speed (CHS) and ball speed (BS) for Trackman® launch and ball flight data.

Definition of Key Positions in the Swing

Address was defined as the first point at which angular speed of the shaft is less than 10deg/s (or the time point before the shaft begins moving into the backswing). Top of the backswing was defined as the point at which the angular speed of the club shaft is at a minimum after the address position. This represents the moment of change from backswing to downswing. Impact was defined as the frame where the clubhead is closest to the original address position before impact with the ball (AMM, n.d.).

Table 15 Static Kinematic Variables Measured at Address, Top of the Backswing and Impact

Variable	Definition (www.amm3d.com, n.d.)
SpnAxisFwdTltBF	Forward tilt angle of a line from mid-AC joints to mid-hip joints; measured from a down-the-line view. Tilting forwards is a positive measure of movement towards the ball and backwards gives a negative value of tilting away from the ball; with vertical as the zero point; measured in degrees.
SpineFEJCS	Forward-backward tilt of the thorax measured with respect to the pelvis; measured around a side-to-side axis through the pelvis; Flexion is forward with respect to the pelvis and Extension is backwards with respect to the pelvis; note that the amount of spine rotation is irrelevant to this measurement; it is the measurement of how much an up-down thorax rod is bent forward with respect to the pelvis; this measurement moves with the pelvis; calculated using the JCS method; measured in degrees (S. Cheetham & P. Cheetham, personal communication, February 14, 2014).
PlvThrst	The linear translation of the pelvis along the y-axis towards or away from the ball with respect to the centre point between the two hip joints, measured in inches.
PlvLift	The linear translation of the pelvis along the z-axis upwards or downwards towards the ground with respect to the centre point between the two hip joints, measured in inches.
UBdyThr	The linear translation of the torso along the y-axis towards or away from the ball with respect to the centre point between the two acromioclavicular (AC) joints, measured in inches.
UBdyLift	The linear translation of the torso along the z-axis upwards or downwards towards the ground with respect to the centre point between the two AC joints, measured in inches.

Training Intervention

Each participant in the intervention group undertook 3-4 strength, myofascial release and flexibility sessions per week for an 8 week period (compliance: mean = 25 sessions; range = 15-36 sessions; mode = 24). For the duration of the 8 weeks both groups of participants were asked to refrain from changes to their swing through golf lessons and were to continue with their normal practice and playing routine. Prior to completing each session the intervention group participants were instructed to complete a 15 minute dynamic warm up. The warm up consisted of aerobic pulse raisers (jogging, side steps, carioca) followed by dynamic stretches (walking calf raises, hamstrings leg swings, walking lunges, open / close the gate hip rotations, horizontal and vertical arm throws and torso and pelvic dissociation rotations). Participants then followed the strength exercise intervention (Table 16) followed by the myofascial release and flexibility intervention (Table 17; this also acted as a cool down for participants).

Selection of Exercises

Exercises were selected to focus on the goals of increasing gluteal strength, thoracic extension, shoulder mobility and scapular stability, stability around the lumbopelvic area and overall flexibility required to complete an OHS. It has previously been shown that the OHS requires all of these physical qualities to allow for a full range of movement during this test (Boyle, 2004; Cook, 2003; Cook et al., 2006).

Table 16 Strength Exercise Intervention

Exercise	Band / Resistance	Reps	Sets
3 Position Bridge	-	6 x up to 60s hold (3 each side)	2
Crab Walks	Mini-band above knees and resistance band held behind the back	15 steps each way	2
Side Plank with Rotation	-	6 each side	2
Speed Skaters	Mini-band above knees	6 each side hold for 3s	2
Heels Up Squats	Mini-band above the knees	6 with raising arms	1
Arm Drops	Theraband	6 each side	2
Standing Ys, Ws, Ts	Theraband	6 on each letter	2

Table 17 Myofascial Release and Flexibility Intervention

Stretch / Myofascial Release	Duration
Calf Myofascial Release	Roll for 30s on both sides
Gastrocnemius (calf 1)	30s hold each side
Soleus (calf 2)	30s hold each side
Glutes Myofascial Release	Roll for 30s on both sides
Glutes Stretch	30s hold each side
TFL Myofascial Release	Roll for 30s on both sides
Mid Back Myofascial Release	Roll for 30s
Thoracic Stretch	30s hold
Supine Chest Stretch on Roller	1min
Kneeling Chest Stretch: Arm on Gym Ball at 90°	30s hold each side
Latissimus Dorsi Myofascial Release	Roll for 30s on both sides
Latissimus Dorsi Stretch: Twisted Prayer Stretch	30s hold each side
Half-Kneeling Hip Flexors Stretch	30s hold each side
Assisted Hamstrings Leg Raise (resistance band)	30s hold each side

Data Analysis

All data were checked for approximation to the normal distribution, and group and individual means and standard deviations were calculated. Mixed-factorial MANOVA tests were used to assess if there was a significant difference in the pre and post intervention swing kinematic variables at address, top of the backswing and at impact and between groups. Dependent t-tests were used to assess changes between pre and post intervention OHS variables for each group. A backward stepwise multiple regression analysis assessed whether the OHS variables could be used to predict the 3D kinematic variables at each key position in the golf swing. For all tests alpha levels were set to $p<.05$, all data analyses were carried out using SPSS 20.0 and data are reported as mean and standard deviation unless otherwise stated.

Results

The intervention showed a significant decrease in OHS thigh angle (i.e. golfers obtained lower squat positions; Table 18) (p<.001), significant increases in gluteal strength (left p<.001; right p<.001), thoracic mobility (rotation) (left p<.001; right p<.001), lat flexibility (p=.028), external shoulder rotation (standing left side p=.038; standing right side p<.001; in posture left side p=.001; in posture right side p=.001), hamstrings flexibility (left p<.001; right p=.001), and single leg balance (left p=.032; right p=.001). The control group showed no change in OHS variables but did show a significant decrease in lat length (p = .020). Both left and right internal and external hip rotation showed significant increases for both groups (intervention p<.001 for all 4 measures; control left internal p=.001, right p=.007 external left p=.005, right p=.027) but with the intervention group showing an average gain of 10.3° for the 4 measurements compared to 4.3° for the control group.

A mixed-factorial MANOVA showed there to be no significant changes in 3D swing kinematics between groups and over both pre and post testing for address (Wilk's λ=.88, $F(1,70)$=1.42, p=.219, $\eta\rho^2$=.12), top of the backswing (Wilk's λ=.98, $F(1,70)$=.20, p=.977, $\eta\rho^2$=.02) and impact (Wilk's λ=.99, $F(1,70)$=.12, p=.994, $\eta\rho^2$=.01) (Table 19).

Table 18 Mean ± Standard Deviation for each OHS Variable

Variable	Whole Group		Intervention Group		Control Group	
	Pre	Post	Pre	Post	Pre	Post
Torso Angle (°)	36.72±10.69	37.58±8.56	39.44±10.02	39.08±8.58	33.14±10.79	35.62±8.40
Thigh Angle (°)	103.65±20.71**	88.14±19.21**	108.96±18.78**	84.15±19.20**	96.67±21.63	93.37±18.51
Shin Angle (°)	55.60±5.51	55.95±6.22	55.33±5.57	56.21±5.88	55.95±5.59	55.60±6.82
Arm Angle (°)	35.23±19.58	34.75±17.12	37.32±21.87	36.27±18.47	32.49±16.37	32.75±15.53

Note. Symbols indicates a significant difference between OHS variables within groups between pre and post testing

*(p<0.05) **(p <.001).

Table 19 Group Mean ± Standard Deviation for each Swing Kinematic Variable

Variable	**Address**				**Top**				**Impact**			
	Intervention		Control		Intervention		Control		Intervention		Control	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
SpnAxisFwdTltBF (°)	35.86 ±5.00	35.14 ±5.28	37.63 ±4.40	36.84 ±5.81	33.67 ±7.72	34.44 ±7.12	35.17 ±5.38	36.97 ±6.42	28.66 ±4.57	28.85 ±5.53	28.33 ±5.19	28.99 ±5.42
SpineFEJCS (°)	29.19 ±10.38	26.14 ±14.86	32.21 ±13.35	31.93 ±10.85	-4.82 ±9.89	-12.12 ±16.66	-2.88 ±18.67	-5.01 ±13.02	38.18 ±11.42	35.79 ±13.37	38.00 ±10.80	38.52 ±9.67
PlvThrst (in)	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00	2.13 ±1.49	1.84 ±1.20	1.88 ±0.91	1.55 ±1.00	1.86 ±1.10	1.99 ±1.09	2.26 ±1.34	2.01 ±1.54
PlvLift (in)	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00	-0.83 ±0.81	-0.95 ±0.80	-1.15 ±0.68	-1.21 ±0.81	0.06 ±0.83	0.00 ±0.89	0.10 ±1.06	0.03 ±1.09
UBdyThr (in)	0.00 ±0.00	0.00 ±0.00	0.00 ±0.01	0.00 ±0.01	1.38 ±1.19	1.56 ±1.09	1.05 ±1.19	1.48 ±1.43	-0.82 ±1.61	-0.46 ±1.60	-0.95 ±1.03	-0.75 ±1.27
UBdyLift (in)	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00	0.00 ±0.00	-0.60 ±1.37	-0.88 ±1.52	-0.76 ±0.97	-1.30 ±1.53	0.65 ±1.16	0.55 ±1.04	1.42 ±1.25	1.09 ±1.31

A backward stepwise multiple regression analysis revealed the following at the three selected phases of the swing for whole group analysis:

Address

No significant predictors of address posture variables using the OHS.

Top of the Backswing

OHS Torso Lean is a significant predictor of Upper Body Lift (R^2=.300, p<.001; Table 20), Pelvic Lift (R^2=.109, p=.046; Table 21) and Spine Axis Forward Tilt (R^2=.164, p=.013; Table 22). OHS Arm angle is a significant predictor of Pelvic Thrust (R^2=.187, p=.007; Table 23).

Impact

OHS Torso Lean is a significant predictor of Spine Flexion / Extension (R^2=.119, p=.037; Table 24). OHS Shin Angle is a significant predictor of Upper Body Lift (R^2=.119, p=.037; Table 25).

Trackman data showed there to be no significant change to clubhead speed (Whole Group p = .820; Intervention p = .873; Control p = .850) or ball speed (Whole Group p = .786; Intervention p = .890; Control p = .750). Clubhead speed actually reduced post intervention by 0.88% for the whole group, by 0.95% for the intervention group and by 0.79% for the control group (Table 26).

Table 20 Multiple Backward Stepwise Regression Analysis of each OHS Variables' Influence on Upper Body Lift at the Top of the Backswing

		Upper Body Lift at top of the backswing			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	-6.718	2.390		[-11.586, -1.849]
	OHS Arm Angle	.017	.014	.193	[-.011, .045]
	OHS Torso Angle	.073	.030	.412	[.012, 1.33]
	OHS Thigh Angle	.007	.012	.084	[-.018, .031]
	OHS Shin Angle	.031	.038	.127	[-.046, .108]
Step 2	Constant	-5.992	1.976		[-10.012, -1.973]
	OHS Arm Angle	.017	.014	.197	[-.010, .045]
	OHS Torso Angle	.077	.028	.436	[.020, .135]
	OHS Shin Angle	.025	.036	.104	[-.048, .098]
Step 3	Constant	-4.775	.956		[-6.718, -2.833]
	OHS Arm Angle	.018	.014	.202	[-.010, .046]
	OHS Torso Angle	.082	.027	.464	[.027, .138]
Step 4	Constant	-4.713	.965		[-6.671, -2.755]
	OHS Torso Angle	.097	.025	.548***	[.046, .148]

Note. R^2 = .350 for Step 1, ΔR^2 = -.006 for step 2, ΔR^2 = -.010 for step 3, ΔR^2 = -.034 for step 4. *** $p < .001$.

Table 21 Multiple Backward Stepwise Regression Analysis of each OHS Variables' Influence on Pelvic Lift at the Top of the Backswing

		Pelvic Lift at top of the backswing			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	-2.086	1.481		[-5.103, .931]
	OHS Arm Angle	-.002	.009	-.041	[-.019, .016]
	OHS Torso Angle	.033	.018	.353	[-.004, .071]
	OHS Thigh Angle	-2.656E-005	.007	-.001	[-.015, .015]
	OHS Shin Angle	-.003	.023	-.022	[-.050, .045]
Step 2	Constant	-2.089	1.219		[-4.569, .390]
	OHS Arm Angle	-.002	.008	-.041	[-.019, .015]
	OHS Torso Angle	.033	.017	.353	[-.002, .069]
	OHS Shin Angle	-.003	.022	-.022	[-.048, .042]
Step 3	Constant	-2.223	.585		[-3.413, -1.034]
	OHS Arm Angle	-.002	.008	-.042	[-.019, .015]
	OHS Torso Angle	.033	.017	.347	[-.001, .067]
Step 4	Constant	-2.230	.577		[-3.401, -1.060]
	OHS Torso Angle	.031	.015	.330*	[.001, .061]

Note. R^2 = .111 for Step 1, ΔR^2 = .000 for step 2, ΔR^2 = .000 for step 3, ΔR^2 = -.001 for step 4. * $p < .05$.

Table 22 Multiple Backward Stepwise Regression Analysis of each OHS Variables' Influence on Spine Axis Forward Tilt at the Top of the Backswing

		Spine Axis Forward Tilt at top of the backswing			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	49.956	12.056		[25.398, 74.514]
	OHS Arm Angle	-.069	.070	-.173	[-.212, .074]
	OHS Torso Angle	-.255	.150	-.318	[-.560, .050]
	OHS Thigh Angle	-.015	.061	-.042	[-.139, .108]
	OHS Shin Angle	-.020	.190	-.018	[-.408, .368]
Step 2	Constant	48.882	6.233		[36.201, 61.564]
	OHS Arm Angle	-.070	.069	-.174	[-.210, .071]
	OHS Torso Angle	-.259	.141	-.324	[-.546, .027]
	OHS Thigh Angle	-.013	.057	-.037	[-.130, .104]
Step 3	Constant	47.967	4.768		[38.277, 57.658]
	OHS Arm Angle	-.070	.068	-.175	[-.208, .068]
	OHS Torso Angle	-.266	.136	-.332	[-.542, .010]
Step 4	Constant	47.722	4.767		[38.045, 57.400]
	OHS Torso Angle	-.324	.124	-.405*	[-.576, -.073]

Note. R^2 = .191 for Step 1, ΔR^2 = .000 for step 2, ΔR^2 = -.001 for step 3, ΔR^2 = -.025 for step 4. * $p < .05$.

Table 23 Multiple Backward Stepwise Regression Analysis of each OHS Variables' Influence on Pelvic Thrust at the Top of the Backswing

		Pelvic Thrust at top of the backswing			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	.399	1.873		[-3.416, 4.214]
	OHS Arm Angle	.021	.011	.325	[-.001, .043]
	OHS Torso Angle	.037	.023	.287	[-.010, .085]
	OHS Thigh Angle	.001	.009	.018	[-.018, .020]
	OHS Shin Angle	-.016	.030	-.091	[-.076, .044]
Step 2	Constant	.514	1.541		[-2.622, 3.650]
	OHS Arm Angle	.021	.011	.326	[-.001, .043]
	OHS Torso Angle	.038	.022	.293	[-.007, .083]
	OHS Shin Angle	-.017	.028	-.096	[-.074, .040]
Step 3	Constant	-.308	.744		[-1.821, 1.205]
	OHS Arm Angle	.021	.011	.322	[-.001, .042]
	OHS Torso Angle	.035	.021	.267	[-.009, .078]
Step 4	Constant	.742	.382		[-.033, 1.517]
	OHS Arm Angle	.028	.010	.433**	[.008, .048]

Note. R^2 = .255 for Step 1, ΔR^2 = .000 for step 2, ΔR^2 = -.008 for step 3, ΔR^2 = -.059 for step 4. ** $p < .01$.

Table 24 Multiple Backward Stepwise Regression Analysis of each OHS Variables' Influence on Spine Flexion / Extension at Impact

		Spine Flexion / Extension at impact			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	47.513	21.421		[3.881, 91.146]
	OHS Arm Angle	-.065	.125	-.094	[-.319, .189]
	OHS Torso Angle	-.447	.266	-.323	[-.989, .095]
	OHS Thigh Angle	-.038	.108	-.061	[-.257, .182]
	OHS Shin Angle	.211	.338	.111	[-.477, .900]
Step 2	Constant	43.414	17.657		[7.491, 79.336]
	OHS Arm Angle	-.067	.123	-.097	[-.317, .183]
	OHS Torso Angle	-.471	.253	-.341	[-.987, .044]
	OHS Shin Angle	.243	.321	.128	[-.410, .896]
Step 3	Constant	43.531	17.473		[8.022, 79.040]
	OHS Arm Angle	-.526	.231	-.380	[-.994, -.057]
	OHS Torso Angle	.236	.317	.124	[-.409, .881]
Step 4	Constant	54.866	8.453		[37.706, 72.026]
	OHS Arm Angle	-.476	.219	-.344*	[-.922, -.031]

Note. R^2 = .144 for Step 1, ΔR^2 = -.003 for step 2, ΔR^2 = -.008 for step 3, ΔR^2 = -.014 for step 4. * $p < .05$.

Table 25 Multiple Backward Stepwise Regression Analysis of each OHS Variables' Influence on Upper Body Lift at Impact

		Upper Body Lift at impact			
Step	**Variable**	***B***	***SE B***	**β**	**95% CI**
Step 1	Constant	-2.572	2.119		[-6.889, 1.745]
	OHS Arm Angle	.009	.012	.138	[-.016, .035]
	OHS Torso Angle	-.028	.026	-.204	[-.082, .026]
	OHS Thigh Angle	.000	.011	.005	[-.021, .022]
	OHS Shin Angle	.073	.033	.383	[.004, .141]
Step 2	Constant	-2.539	1.744		[-6.086, 1.008]
	OHS Arm Angle	.010	.012	.138	[-.015, .034]
	OHS Torso Angle	-.028	.025	-.203	[-.079, .023]
	OHS Shin Angle	.072	.032	.381	[.008, .137]
Step 3	Constant	-2.556	1.734		[-6.079, .967]
	OHS Torso Angle	-.020	.023	-.147	[-.067, .026]
	OHS Shin Angle	.073	.031	.387	[.009, .137]
Step 4	Constant	-2.866	1.692		[-6.301, .569]
	OHS Shin Angle	.065	.030	$.345^{*}$	[.004, .126]

Note. R^2 = .154 for Step 1, ΔR^2 = .000 for step 2, ΔR^2 = -.016 for step 3, ΔR^2 = -.020 for step 4. * $p < .05$.

Table 26 Trackman Data for Pre and Post Intervention Testing

Kinematic Variable at Impact	Mean ± SD					
	Whole Group		**Intervention Group**		**Control Group**	
	Pre	Post	Pre	Post	Pre	Post
Clubhead Speed (m/s)	34.4±5.8	34.1±5.5	33.0±6.5	32.7±6.0	36.2±4.3	35.9±4.1
Ball Speed (m/s)	44.6±8.5	44.1±8.3	42.8±9.6	42.4±9.5	47.0±6.2	46.3±5.9

Note. Symbols indicates a significant difference between pre and post intervention within groups * (p<0.05), ** (P<.001).

Discussion

The intervention successfully altered the strength and flexibility of the golfers' gluteals, external shoulder rotation, latissimus dorsi (lats), thoracic mobility and single leg balance over the course of 8 weeks. The OHS has also significantly changed with the lower squatting pattern demonstrating a significant improvement in flexibility and strength through those muscles that are involved (e.g. through gluteal strength, lat flexibility, and possible improvements in calf flexibility and thoracic extension etc. through myofascial release work included in the intervention).

Although significant strength, flexibility and OHS ROM changes were achieved by the intervention group they were unable to directly use these new capacities in their golf swings. It is possible that although there has been a significant physical change in the intervention groups they have not had the time to change technically, or that these changes are not an important factor for the swing kinematics. Their swing kinematics have not changed automatically through the intervention and this may be due to the attractor state from which their swing emerges being too strong to simply create a new swing action. Therefore, it is likely they will need extensive coaching to incorporate new ROM and strength within their golf swing. Previous research has also found similar patterns where successful interventions have resulted in little or no performance changes (Scarfe, 2011).

Research needs to explore the ecological validity of this intervention further. It is possible that the change in strength endurance produced through completion of the intervention could influence performance towards the end of the 18 holes of golf and future research could assess this.

Alongside this finding that no swing kinematic changes occurred following the physical intervention there was also no significant impact upon the clubhead and ball speeds. This result is similar to the results from Lamberth et al. (2013) who conducted a 6-week strength and functional training programme with 5 golfers (additional 5 in control group) and reported no significant changes in clubhead speed following significant improvements in strength. However, it is contradictory to other previous research which has shown increases in clubhead speed following physical interventions (e.g. Doan et al, 2006; Fletcher & Hartwell, 2004; Lephart et al, 2007). A possible explanation for this discrepancy in findings could be that this is the only research study to take place in a driving range studio that faces out onto a range. The first testing took place in the summer with the second testing taking place in much colder autumn conditions. It is possible that there may be seasonal influences that can affect golf performance that has prevented increases in clubhead speed in this study even though the golfers were able to warm up adequately prior to testing.

The OHS assessment test has been made popular within golf by TPI and they have emphasised links between the results of this test and the swing characteristics of golfers. They suggest that if the golfer cannot perform a full OHS then there will be some loss of posture during the backswing and downswing (TPI, n.d.a, n.d.b). The results of the current study suggest that a small, but reliable percentage of the swing posture variables can be predicted by aspects of the OHS. However, when the OHS mechanics had been manipulated through the intervention no significant change in postural swing kinematics was seen, therefore this relationship does not exist once manipulation has taken place. This suggests any relationship is a spurious one and within the context of the study's limitations, leads to the argument that the OHS is not a good predictor of loss of posture in the golf swing and that other variables will also have an influence on whether posture can be maintained during the backswing and downswing. These results cannot therefore be termed a predictive relationship between the OHS and the postural kinematics of the golf swing.

There may be many possible physical explanations for the results of the small relationship between the increased anterior torso lean in the OHS and the upper body lift in the backswing (i.e. standing up out of posture, also known as loss of posture). It may even be due to other variables not tested within this current study as when the OHS was improved through the intervention no change was noted in the kinematics of the golf swing.

S&C coaches should be encouraged to look for a lack of thoracic extension which would lead to increased anterior lean in the OHS and an inability to extend through the spine into the top of the backswing position during the golf swing. Lifting the upper body and the pelvis, and thrusting the pelvis forward leads to a loss of posture but may allow the golfer to compensate for a possible lack of thoracic extension and possible tightness in the lats (especially the lead side). Flexibility in the lats was shown to be a very small but significant predictor of pelvic thrust (Table 23), but again results show that with no swing kinematic changes after increasing this physical constraint this is not a good predictor of pelvic thrust and that other variables may be influencing this movement pattern. From a physical perspective this pelvic thrust combined with the lifting of both the pelvis and the torso could lead to a reduction in the stretch on the lats but also a loss of posture as discussed previously. Once again the OHS will be useful for S&C coaches to understand the limitations on ROM and strength within a golfer's body in order to provide conditioning programmes to improve these. It should be noted that there is no evidence to suggest that the OHS should be used by golf coaches to predict loss of posture during the golf swing. Other significant results presented a very small impact ($R^2 < .2$) so further research is needed with larger samples in order to fully establish the influence of the OHS on posture kinematics and indeed the nature of these relationships.

There were limitations to this study that need to be considered for future research. Seasonal differences could have influenced the results from pre to post testing. However, it is important that research is conducted that is representative of the on course situation that golfers will compete in (Pinder et al., 2011). Lab based experiments, although controlled, provide the golfer with an artificial situation in which to perform with very little ball flight to observe and no real target to play towards. The analysis of most variables in this study were underpowered compared to the value of .8 which was suggested by Field (2013) to be deemed an appropriate level of confidence. However, post-hoc analysis of power revealed that to achieve 80% confidence in the analysis of pre-post swing kinematic variables would have required a sample size of n=1232 and for the significant backward stepwise regression results a sample of at least n=101 was required. Potentially other small predictors may have emerged had the sample size been considerably larger. Results should therefore be interpreted within the context of these limitations.

No kinematic swing changes through golf tuition were allowed during the intervention period which has to be considered in future research of this nature. With controlled tuition alongside the intervention it may allow for swing kinematics to be positively altered alongside changes in ROM, strength and flexibility. This may also result in increased performance benefits within the outcome data of clubhead and ball speeds as well as other impact factors and launch conditions.

Conclusion

From a practical application perspective it is important for physical developments to be made through S&C however it should not be assumed that swing kinematics or even performance outcomes will alter automatically with changes in ROM, flexibility and strength. This study demonstrates that swing kinematics do not automatically change following an S&C / flexibility intervention, however, future research needs to establish if the changes are coachable to produce an impact upon performance and alter the attractor state that the golfer's current swing emerges from. It is also important to highlight that where possible 3D analysis should be used to assess the link between technical and physical limitations as it is easy for limited conclusions to be drawn based upon 2D video analysis.

S&C coaches should continue to perform assessments of the OHS with their golfers to understand whether there are physical restrictions or weakness through the body's joints and muscles. However, caution should be exercised when using the results to allow any OHS motor learning issues to be addressed prior to drawing conclusions from this assessment tool. Effective S&C interventions to improve physical restrictions, followed by golf coaching, could provide a potential impact upon future performance and the ability to maintain posture throughout the golf swing. Loss of posture during the swing may still be due to learnt movement behaviour or physical constraints, but coaches should be aware that, within the context of the limitations of the research, the results of this study show that the OHS is not a useful predictor of these postural kinematics. Future research may highlight whether it is important for golfers who demonstrate physical limitations in ROM and strength to be encouraged to work with S&C coaches. If so, it is possible that extensive coaching alongside physical development may lead to swing kinematic changes incorporating new ROM and strength within the golf swing. Where deterioration of posture occurs with golfers who can already achieve a full OHS it becomes the coach's role, alongside the S&C coach, to establish if there are other variables affecting performance in the golf swing. As long as no other physical restrictions are identified the golf coach should begin to implement technical corrections to fix this "technical swing fault".

It is possible to alter the squat mechanics of golfers through a physical intervention targeting specific weaknesses and restrictions in flexibility. Future research now needs to establish how golf coaches are able to work with golfers to ensure they can positively manipulate the swing kinematics in order to utilise the gains in strength and flexibility in the swing. Only then will the golfer's performance truly benefit from an S&C intervention programme.

6. DISCUSSION

Main Aim

Movement variability has often been viewed as a detriment to successful performance, especially within the coaching world. This view has recently been challenged and suggestions that variability can also be functional and provide adaptability to changing task environments have emerged (Chapter 1.2; see also Glazier, 2011; Langdown et al., 2012).

The body of research set out in the previous chapters aimed to establish whether there were movement variability differences between high skilled and low skilled golfers. Following this, the research assessed the relationship between ROM and golf swing performance. Previous research in sport (e.g. Bootsma & van Wieringen, 1990; Scott et al., 1997) and other skills (e.g. stone knapping – where impact occurred between a hammer and the stone (Bril et al., 2010)) had suggested that high skilled athletes or performers were able to funnel their variability towards the critical moment of the task. Research into long jump movement variability (Lee et al., 1982; Scott et al., 1997) established that elite long jumpers were able to adjust their stride length producing reduced variability towards take-off from the board. In contrast the low skilled jumpers showed increased levels of stride length variability as they approached the board. Bartlett et al. (2007) proposed that research into the variability of sporting movements could aid performance through changes in co-ordination patterns and increase the level of understanding of the role of functional variability.

The research presented previously in chapters 2 to 5 was designed to assess the influence of movement variability and the link between assessed movement patterns and golf swing kinematics. In contrast to the previous research (e.g. Lee et al., 1982; Scott et al., 1997) there were very few differences between the high and low skilled participants and indeed funnelling of variability was not just limited to the high skilled golfers.

Chapter 2 – Address Position Variability in Golfers of Differing Skill Level

This chapter aimed to establish the address variability differences between high and low skilled golfers. With setup being considered a key positional moment influencing the performance of the golf swing by coaches (e.g. Mann et al., 1998; Toski et al., 1984) it was hypothesised that higher skilled golfers would show reduced levels of variability in address postural kinematics. Results provided little support for the acceptance of this hypothesis.

The kinematic analysis of address highlighted just one significant difference between skill levels: the alignment relationship between the stance and shoulders, with the higher skilled golfers demonstrating reduced variability. This suggests that when tasked with hitting the same shot, with the same club and ball flight towards a specified target they are able to adopt less varied positions between the stance and shoulder angles in relation to the ball to target line. This may have important consequences on resultant swing kinematics such as swing plane, clubhead path and angle of approach of the clubhead to the ball, variability in this alignment may therefore result in inconsistent ball striking. As discussed within Chapter 3 it should also be considered that variability at address could be compensated for during the swing movements. This potentially means that variability of alignment at address can be tolerated to a certain level. However, that tolerance has yet to be established and coaches should exercise caution when allowing address variability for a specified task. Future research should consider these levels of tolerance and assess the influence of address variability on the subsequent swing kinematics.

It is also important to note here that when analysing the address position of lower skilled golfers, although the variability of many parameters may not be significantly different to those values of the higher skilled players, the actual setup position may prove to be ineffective in producing the desired ball flight. For example a right-handed golfer may be presenting low levels of variability in alignments of body segments but with their alignment too far left of target (open) each time they setup to the golf ball. Initially this is likely to be more detrimental to performance than the levels of variability presented across trials. From a coaching perspective it is important to first adjust the address posture and body segment alignment in relation to the target before attending to the reduction of detrimental variability across numerous task executions. Results would suggest that coaches should also ensure they pay attention to the low skilled golfer’s shoulder alignment variability and build a set-up routine that allows detrimental variability to be reduced within this area. With increased task difficulty (e.g. playing from a sloping lie with the ball above or below the feet) it may become even more important to ensure that the distal end of the kinematic sequence has reduced detrimental variability but is able to utilise functional variations in movement to emerge with a successful shot and ball flight.

Future representational research is needed to establish how on course swing variability affects performance in both a functional and detrimental manner.

Chapter 3 – Impact Position Variability in Golfers of Differing Skill Level

This study reported no variability differences between skilled and less skilled performers at impact. This suggests that it is the kinematics of the swing rather than the variability of these movements that separates the two skill levels. Bradshaw et al. (2009) found similar results when comparing variability levels at impact between high and low skilled golfers for trunk, lead wrist and elbow angles. Although no differences were found between skill categories in the current study (Chapter 3), there were findings that could aid future coaching of the golf swing. The findings of reduced variability presented at the distal end of the kinetic chain (in this case the shoulders) would suggest that the coaches initial attention should be less concerned about the body segments closer to the ground (e.g. the stance and to some extent the pelvis too) when coaching golfers to reduce variability.

Various funnelling of variability from the stance through to the shoulders at both the address (Chapter 2) and impact positions (Chapter 3) of the golf swing were observed. Funnelling was reported across some, but not all, of the distance of the body segment to the ball and alignment relationship variables. This supports previous research (e.g. Bootsma & van Wieringen, 1990; Scott et al., 1997) where movement variability has decreased close to the critical moment of performance. In this case the variability has decreased higher up the kinetic chain where the shoulders are presenting reduced variability in distance to the ball compared to the pelvis and the stance. This is not just demonstrated by the skilled golfers but also by those less skilled, suggesting that this is a common feature of golfers from category 3 and better.

Similar funnelling of variability was reported for alignment variables where, again, results showed that the higher up the kinetic chain the lower the variability across trials. For the impact position only the lower skilled golfers exhibited any significant funnelling and conclusions were drawn that coaches should ensure they pay particular attention to the stance to pelvis alignment relationship to reduce potential detrimental variability. Future research should establish why the high skilled golfers did not exhibit this funnelling of variability and explore whether they use increased levels of functional variability at the distal end of the kinetic chain to allow effective ball striking from the centre of the clubhead. Functional variability here would allow them to compensate for other movements made during the swing by adjusting the pelvis and shoulder positions.

Without the use of 3D analysis systems it may be difficult for coaches to assess positional variability themselves within coaching sessions. However, using the results from these studies should allow coaches to ensure that when working with low skilled golfers they pay particular attention to the alignment and positioning of the shoulders in relation to the stance at address and look to reduce the movement variability of the pelvis alignment in relation to the stance at impact. If the golfer can arrive at impact with reduced variability across all alignment relationships it may lead to increasingly effective impacts between clubhead and ball. In contrast by reducing the variability at the pelvis in relation to the stance in lower skilled golfers it may also allow for functional variability to increase at the shoulders. Neither of these suggestions guarantees increased levels of performance because the arms and hands also need to move effectively to present the clubface at impact with the golf ball with reduced variability, or maximising the use of functional variability to compensate for prior movements lower down the kinetic chain. Currently only Horan et al.'s (2011) work has investigated the variability of hand and club movement variability reporting that both male and female golfers presented a funnelling trend of variability from the top of the backswing to impact.

Research should continue to analyse variability throughout the backswing and downswing to assess the funnelling of the hands and clubhead positional variability. To establish if there is a difference between ability levels it would be advantageous to assess this variability across a wider spectrum of golfers than solely category one (including professionals) and category three as was achieved in Chapters 2 and 3. Increased sample sizes and, as highlighted previously, representational on course research would allow the role of functional variability to be identified further within specific golf settings.

Chapter 4 – The Influence of the Overhead Squat on the Golf Swing

Movement outcomes can be attributed to the constraints from which they emerge (Newell, 1986). As well as the task and environment there are physical limitations that act to constrain the movements that form the golf swing. These physical constraints include the available ROM, strength, power and stability. In particular, the ROM they possess will always constrain the golfer's swing kinematics to a lesser or greater extent. This study aimed to assess the relationship between any OHS movement constraints and the postural kinematics that emerged during the swing.

In particular a hypothesised link (by TPI: Phillips, 2013) between the OHS and deterioration of posture (often termed loss of posture or early extension) from address to impact was assessed. Chapter 4 set to establish if the OHS was indeed an accurate assessment tool for the loss of posture variables in the golf swing.

As previously discussed (see Chapter 4 and 5) the OHS is a valuable assessment tool in order to identify the functional ROM through various joints and the strength of the glutes and lower body (Boyle, 2004; Cook, 2003; Cook et al., 2006).

Significant changes in position from address to impact were evident as golfers try to maximise the transfer of energy from body, to club, to ball in line with the selected task objective. A loss of posture could be attributable to early hip extension during the back / downswing and lead to the pelvis moving up and closer to the ball. However, no OHS variable was found to be an effective predictor of this change in position. When analysing the relationship between the OHS and the posture at address there was a small but significant finding in that the OHS torso angle accounted for 30% of the distance of the shoulders to the ball variable. This has implications to performance and in particular the ability to strike the ball cleanly from the centre of the clubface without the need to protract the scapula and shoulders in order to “reach” for the ball. The greater the torso angle in the OHS (i.e. an inability to maintain a more upright torso position) the closer the shoulders were to the ball at address. This potentially highlights a lack of thoracic extension or a counter movement of the upper body in response to weakness in the lower body. The ability to produce thoracic extension while in posture is important as it means the golfer is able to adopt a position from which they can rotate and therefore swing with a steeper plane (not excessively steep) as opposed to an increasingly upright position at address which can encourage a flatter swing plane that encourages the golf club to be swung around the body (e.g. Breed & Midland, 2008). If a golfer who has limited thoracic extension opts to allow the shoulders to remain closer to the golf ball it is likely that a kyphotic position will be adopted which in turn will affect the rotation of the spine and the resultant swing plane.

At impact the OHS torso angle was again the only variable that was a small but significant predictor of any of the postural swing kinematics. In this case it was the knee width at impact that the torso angle in the OHS could be attributed to (28%). As discussed, this could be due to a number of reasons including that it is a spurious and negligible result. Two suggestions were made as to the potential physical restrictions that could cause this movement to occur: 1. a lack of strength in the gluteals leading to increased anterior torso lean presented in the OHS assessment test and also leading to knee valgus at impact during the golf swing and 2. limited external rotation through the trail hip causing the knee to collapse inwards through the downswing and at the point of impact. Having discussed the potential physical limitations, it is also possible that this is a learnt movement and therefore becomes either a conceptual or motor control issue that the coach can work to eliminate or reduce.

It has been shown that the gluteals play a vital role in allowing the golfer to reach a “break parallel” position (with the thighs) at the bottom of the OHS (Chiu et al., 2009). It was suggested that with a potential lack of gluteal strength and an inability to extend through the thoracic region of the vertebral column, the golfer’s torso may well present increased anterior torso lean in the OHS. However, caution has to be taken with this suggestion due to the measurement of the OHS; if the golfer was able to maintain torso extension it may be that they simply did not drop low enough through the lower body movement with the thigh not moving below parallel to the floor. This would result in a restricted squat through assessment of the thigh angle but not through assessment of the torso aligning parallel to the shin angle. This was allowed for with a backward stepwise regression analysis being used to take into account the contribution of all variables in the OHS.

The practical application of this study's results (Chapter 4) suggest that it is important to establish training programmes that allow the torso angle to maintain a parallel alignment to the shins but also to increase the depth of the OHS. Having said this, it is also important for golf coaches to understand that the results indicate that the OHS has limited implications on the deterioration of posture during the golf swing.

2D video analysis was employed for this study as it was deemed representative of what a golf coach could do in their day to day coaching. It is not without its limitations though, especially from perspective error (Bartlett, 2007) but it is important that research is representative of both performance settings (Pinder et al., 2011) and also from a coach application perspective.

It was concluded that deterioration of posture does take place in golfer's swing kinematics (due to the changes seen in pelvic distance to the ball (i.e. lift and thrust) between address and impact) but currently this cannot be solely attributed to the restrictions seen within the OHS. Further research has been suggested to increase the sample sizes used due to the implications on power in this study and it is acknowledged that the small sample used may have led to a higher risk of Type II errors in some variables.

Following this study it was deemed important to try and manipulate the physical constraints presented in the overhead squat mechanics through interventions to assess whether this could alter the amount of loss of posture during the golf swing. If so this would allow coaches to utilise S&C techniques to overcome loss of posture kinematics in their coaching of the golf swing.

Chapter 5 – The Influence of an 8 Week Strength and Corrective Exercise Intervention on the Overhead Deep Squat and Golf Swing Kinematics

With consideration paid to the previous study (Chapter 4) it was necessary to use 3D analysis to fully establish the relationship between the OHS and loss of posture in the golf swing. More importantly the aim of this study was to establish whether by increasing the quality of the OHS mechanics this would then reduce any early extension of the hips and standing up movements through the torso and pelvis, or indeed, have any impact upon postural variables during the golf swing.

Results from this study again indicated that there are some small but significant predictors of loss of posture variables in the golf swing from completing the OHS. However, the key finding was that no kinematic swing changes occurred between pre and post intervention 3D analysis. Therefore, the relationships between the OHS and postural kinematics may be spurious ones that cannot be solely relied upon to predict a golfer's ability to avoid deterioration of their posture. It is vital that golf coaches are not led to assume that this is the definitive test to establishing reasons for loss of posture both at the top of the backswing and at impact. Results from this research should be used to raise awareness of this and allow coaches to exercise caution when using this test as an assessment of why swing faults may be occurring. Further research in this area is required as the current study only utilised a sample of n=37. Whilst this is a larger sample than many physical intervention studies for golf, Type II errors are still a possibility. Power analysis of the swing kinematic changes pre to post intervention revealed that a sample of n=1232 would be required for each variable to reach a power of .8. For those variables that were shown to be small but significant predictors of the swing kinematics a sample size of n=101 was required for all to reach an acceptable power. Based on the effect size and power analysis this should be the minimum target for future work.

This intervention has shown that the OHS mechanics can be altered and the range of movement through joints and strength in certain muscles can be increased. Therefore the OHS can be a useful tool for S&C coaches to use prior to compiling a conditioning programme. The S&C intervention to improve the OHS mechanics is also a valuable tool for S&C coaches to implement prior to adding load to a client's programme. Recommendations should also be given to allow golfers to learn the movement of the OHS before its results are used to govern exercises in programmes. There may be an element of motor learning required prior to performing the most mechanically sound movement that the golfer can achieve given their current ROM, flexibility and strength and this may not be seen with initial attempts. The use of a learning period in future studies may alter the results and highlight stronger links between the OHS and the deterioration of posture in the golf swing, however, this needs to be explored further.

Conclusions from this study suggested that the OHS is not the only tool for golf coaches to use as an assessment of a golfer's ability to stay in posture. The OHS is not the only variable that will contribute to loss of posture and therefore golf coaches should allow S&C coaches to assess ROM and strength and also look themselves for other possible explanations of loss of posture within each individual from a physical constraints stand point.

This study raises further research questions of how coaching can impact upon movement mechanics and whether the attractor state from which the golf swing emerges is able to be altered. Through physical conditioning it is possible for myogenic and / or neurogenic adaptations to be achieved by the golfer, therefore altering physical constraints imposed on movement outcomes. New ROM and strength does not automatically change the movement pattern, however, research has not yet shown whether coaching will be able to alter golf swing kinematics or indeed reduce detrimental variability. Therefore, using S&C as a standalone intervention cannot be recommended to aid postural corrections within golf. As a result coaches and golfers themselves should consider whether any benefits can be realised from S&C interventions if the golfer is not currently engaging in regular coaching.

Caution should also be exercised where highlighted previously around the movement based claims made by organisations (e.g. TPI). These need to be proven with research before results can be generalised confidently to all, or even specific groups of the golfing population. Future work is therefore required to establish whether coaching alongside S&C training adaptations can be effective in altering swing kinematics and the movement's attractor state. This may also have an influence on the amount of variability that is presented over the course of numerous trials with the same goal. Questions arise over whether the increases in ROM and strength achieved through S&C interventions will lead to increased variability within the critical moments of the golf swing, or whether higher skilled golfers are able to adapt better to these reduced physical constraints.

It is recommended that research is continued in representative environments (Pinder et al., 2011) including increased use of on course and in competition research where possible. Golf coaches should continue to monitor both variability and quality of the golf swing kinematics in line with the results of this research.

Summary of Findings and Further Investigation

From the research presented in Chapters 2 and 3 it is now known that there little difference in variability between high and low skilled golfers across distance and alignment parameters at 2 key positions in the swing, namely address and impact. Future research needs to look at the entire downswing phase to establish what occurs in the moments leading to impact with the ball. As there are very few difference between the ability levels with regards to the stance, pelvis and shoulder movement variability at address and impact it supports the need for further assessment of the hands and club (see Horan et al., 2011).

We know that pelvis alignment variability is a key area to focus on in relation to the stance with low skilled golfers as this presented the largest variability in relation to the stance at impact. We also know that the distal end of the kinematic sequence / kinetic chain is vital to the effectiveness of ball striking and any variability here needs to be functional to allow for compensatory movements towards impact. In order to produce an effective impact with the ball the club needs to make contact with the ball with a centred strike relative to the centre of gravity of the clubhead. It would therefore seem logical, and perhaps part of the game of golf, that the funnelling of variability needs to occur towards the distal end of the kinetic chain to allow this to happen. However, research is needed to establish if it is the ability to reduce the detrimental variability in clubface angle, club path, angle of attack, clubhead speed and centredness of strike (the five impact factors) which will determine the resultant ball flight and thus the success of any given shot on the golf course, and ultimately contribute to the handicap of any amateur golfer performing the shots.

The second key focus of the research was to establish whether the physical constraints on movement could be assessed and used to predict the nature of posture deterioration in the golf swing as has been proposed by TPI (Phillips, 2013). It was clear that, within the context of the limitations of the research, the OHS does not link to loss of posture and therefore it cannot be deemed a useful predictor for golf swing postural kinematics. It may still have a place when used as an S&C test to assess physical constraints and then combined with interventions with the aim of improving physical limitations. However, Chapter 5 has shown that even by improving OHS limitations it does not mean that the swing kinematics will change automatically. This raises a question over the role for S&C in golf. As a standalone intervention, the results of the current study, suggest that S&C should not be recommended for golfers looking to reduce postural deterioration in their golf swing as it has been shown to have no benefit.

The OHS can be useful to establish physical constraints but should not be relied upon solely to assess causes for loss of posture in the golf swing. Conversely, the lack of benefits from physical interventions on the kinematics raises a strong case for the investigation of coaching as a tool to integrate new ROM, flexibility, strength, and power into performance and for different movements to emerge from the altered physical constraints. As suggested previously research must now explore whether coaching interventions are indeed able to change postural kinematics and the attractors from which the golfer's movement patterns currently emerge. This should be performed in line with interventions designed to improve the OHS and other screening assessment tests to elicit physical adaptations such as changes in ROM, flexibility, strength and power.

It is known that the constraints from the participant, the task and the environment will always dictate the movement that emerges within the golf swing. However, the roles of variability and S&C have begun to be established within the sport of golf and across the varying levels of ability that choose to play and compete. Coaches should be increasingly aware of the areas in which to focus following this research and future work should look to aid their methods of reducing detrimental variability, utilising functional variability and incorporating altered physical constraints into the performance kinematics of their local golfing population's swings.

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