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The biomechanical and physiological predictors of golf drive performance, before and after a hole-to-hole distance walk.

Andrew Green

Dissertation submitted to the Faculty of Health Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree Master of Science in Medicine (Physiology).

Johannesburg, 2012.

Declaration

I, Andrew Green hereby declare that the work presented in this dissertation is my own, except to the extent as outlined in the acknowledgments and contribution sections. This dissertation is being submitted to the Faculty of Health Science, University of the Witwatersrand, Johannesburg. It has not been submitted, in part or whole, for any other degree or examination in this university or any other university.

Signature of Candidate	Date

Abstract

The game of golf requires players to strike a ball towards a distant target in as few as possible shots. One key component to the successful completion of this goal is a proficient golf swing. The golf swing is composed of a sequence of highly complex biomechanical movements requiring coordinated body movements and postural control. In addition, walking (a fundamental part of the game of golf) may have interesting effects on golf drive performance however, to date, this is largely unknown. The objective of the study was to identify the physiological and biomechanical variables that predict golf drive performance and to assess the effects of a hole-to-hole distance walk on golf drive performance. Twenty-one amateur golfers volunteered to take part in the study. The golfers were divided into two groups based on their recent average scores: More Competitive Group ((MCG) n=13, scores≤88) and Irregular Social Group ((ISG) n=8, scores>89). Drive distance (resting ball position) and accuracy (perpendicular distance from target) were directly measured. Balance and hand-eye coordination were assessed using a modified stork test and a customised three dimensional maze respectively. Lean mass was determined using bioimpedance. To determine walking effects participants hit ten golf balls and then walked 500m before repeating the tests. Average balance duration of both legs (r=0.45 p=0.048) the left leg (r=0.44 p=0.041) and the right leg (r=0.44 p=0.041) were all significantly correlated to drive distance. The hand and eye coordination task was correlated with total drive distance (r=-0.60 R^2=0.36 p=0.008), but was not significantly associated with the centre of hit between the club face and ball. Significant contributors to a physiological model predictive of drive distance (R^2=0.667; p=0.001) included age (β=1.228) lean mass percentage (β=1.899) and left leg balance (β=1.542). A corresponding biomechanical model (R^2=0.9996; p=0.025; n=5) shows that leading arm angle (β=16.51), left elbow angle (β=-0.265) and lateral bend (β=-1.297) together significantly predict drive distance. Heart rate was significantly elevated following

the walk for all golfers but was not significantly different between the groups before or after the walk. The MCG had significantly longer drives following the walk ($p=0.018$). The changes in drive distance were correlated to the changes in right leg balance with eyes closed ($r=-0.62$ $R^2=0.38$ $p=0.003$). When considering changes in kinematic variables as a result of the walk, the change in the left knee angle at backswing ($r=0.84$ $R^2=0.71$ $p=0.017$) and the right femur aspect angle at contact were correlated to the change in drive distance ($r=0.87$ $R^2=0.75$ $p=0.025$). The physiological and biomechanical models described variables that predict golf drive performance, highlighting the importance of balance and the kinematics of the upper body segments during the swing. Furthermore this study identifies the beneficial effects of walking early in a round to golfers of better golf ability and the effects that such a hole-to-hole walk has on the physiological and biomechanical attributes of the golfer.

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Preface

In Chapter 1 I briefly discuss the general outline of the game of golf. Followed by a review of how golf performance is assessed and how it can potentially be optimized, from the physiological basis of such performance to the measurement of golfing skill through the application of biomechanics. I end chapter 1 by stating the main objectives of the study which is to identify the physiological and biomechanical parameters that predict golf drive performance and the assessment of the effects of a hole-to-hole distance walk on golf drive performance.

Chapter 2 describes the protocol and the equipment used to determine the physiological and biomechanical attributes of the golfers.

Chapter 3 summarizes the data collected in this dissertation, along with all data analyses and statistical tests.

Chapter 4 discusses the aims, their results and the possible contribution these findings make in understanding physiological and biomechanical aspects of golf drive performance. I highlight how the results generated here affect the current understanding of golf drive performance as seen in the literature. Additionally I identify possible limitation and strengths, along with scientific and practical implications of the current study.

Chapter 5 and 6 includes references, which is followed by a set of four appendices. The first appendix shows the ethics clearance certificate obtained prior to commencement of this study. Appendices 2 and 3 documents two emails and cover pages providing details of the two journal article submissions that have been generated from the work included in this dissertation. Appendix 4 describes the details of three additional papers co-authored by me during the candidature of the present master's degree.

Contributions

The design of all the experimental protocols within this dissertation was devised by me in conjunction with my supervisors Warrick McKinon and Samantha Kerr.

All data were collected by me, with assistance from Chloe Dafkin and Justin Phillips.

All MatLab algorithms specifically compiled for this dissertation were written by me and Warrick McKinon, or obtained from freely available (and acknowledged) sources.

Conference Presentations and Journal submissions

Conference Presentations:

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Journal submissions:

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Andrew Green, Chloe Dafkin, Samantha Kerr and Warrick McKinon. The effects of walking on golf drive performance in two groups of golfers with different skill levels. *South African Journal of Sports Medicine* (under review).

Note that during my candidature for this degree I also co-authored three additional journal articles in international journals (as detailed in appendix 4).

Chapter 1

Introduction

1.1 The game of golf

Golf has been played for over 500 years in one form or another (Penner, 2003). Today it is estimated that the game of golf is played by over 55 million people on over 30000 golf courses (Farrally *et al*., 2003).This worldwide popularity has resulted in the development of a multi-billion dollar industry (Farrally *et al*., 2003). A game of golf begins when the player places their ball in the designated area of the teeing ground. It is within this defined area that the golfer may make use of a tee, which is designed to elevate the ball above the playing surface. The golf drive is the best possible shot to achieve maximal distance and is normally played off a tee. In simple terms, the game of golf requires players to strike a ball over varying terrain into a small hole in the ground in as few as possible shots (Hume *et al*., 2005). In order to do this golf players must hit the ball over a large distance close to the limits of what is possible, approximately 300m for most individuals, aimed at very small targets (Hume *et al*., 2005). The laws of golf govern that a selection of no more than 14 clubs are used, and the use of these clubs requires a variety of shot types. The selection of clubs in a golfer's bag will be determined by their personal preference, with the "metal woods" and long irons used to achieve maximal distance. As the length of the club decreases the distance of the shot will decrease, however the accuracy and control of the shorter clubs is greater than that of the longer clubs. The most specialised club in the bag is the putter, which is not intended to be used for distance but is used for maximal control on the greens. The purpose of this club is to maintain a constant roll on the ball while manipulating the undulations of the surface culminating in guiding the ball into the target hole. Despite different shots covering different distances, each shot is counted with the ultimate score of the game being defined by lesser scores reflecting better performance. The distance of the drive will determine the distance of the approach shots, which may result in the ball ending closer to the hole, thus increasing the likelihood of reducing the golfers' scores (Hume *et al*., 2005). Due to the

nature of such a scoring system many golfers will focus on achieving maximal distance on each shot.

1.1.1 The quantification of golf performance

Performance in the game of golf has many different aspects namely: the distance and accuracy of the drive and approach shots, putting skill and the necessary decision making skills (Stevenson *et al*., 2009). The combination and interaction between these different aspects results in the players' scores (Hellström, 2009). Although most standard courses will allow for 72 shots to be taken (the par score), most amateur golfers will exceed this number. To establish an even playing field golfers are given a handicap (Doan *et al*., 2006), which allows for the subtraction or even addition of shots depending on their average ability over a certain number of recent golf games. Note however that the handicap is not a true reflection of each aspect of the game.

1.1.2 The different aspects of the golf game

Golf as a sport is multi-faceted and has been divided into three active phases by Hayes and colleagues (2009). These phases are discussed below:

The first active phase of golf is walking, as the game is usually completed on foot, with the player walking between shots, and not always on level terrain. In 18 holes of golf an average player can take more than 10000 steps equating to more than eight kilometres (Kobriger *et al*., 2006, Smith, 2010) and can take four hours or more to complete (Hayes *et al*., 2009). When the player is not walking they assume the static position which has been described as

the second phase of golf. Selicki and Segall (1996) estimated that only one per cent of the entire golf game is spent hitting the golf ball.

The third phase of golf is considered to be shot making. This aspect of the golf game is not limited to the biomechanical action of the golf swing, but also includes the decisions regarding the choice of club and intended shot and shot rehearsal. Incorrect club and shot selection is an integral element of golf and can result in scores increasing (decreasing performance).On a standard golf course with favourable conditions an average golfer may take more than 85 shots (Kobriger *et al*., 2006). This final (shot making) phase is clearly the most important phase because it is where goal oriented actions can be taken. Note also that in addition to this, shot making will affect the distance and duration of the walking phase.

The phases are not independent of one another. The effects of walks throughout the game of golf could contribute greatly to the outcomes of the intended shots (Bradshaw *et al*., 2009). Although walking is a fundamental part of the game of golf, knowledge of the effects of walking on golf shots is lacking and is one of the foci of the current dissertation.

1.1.3 Health benefits of playing golf

Golf is played by players of a wide age range, with many players only beginning in their young adult life. The effects of regular walking, and in this case of walking during the golf game is suggested as a form of long term wellbeing for middle-aged to elderly men (Parkkari *et al*., 2000). The risk of cardiovascular death is reduced by improving physical fitness levels (Blair *et al*., 1995, Erikssen *et al*., 1998, Parkkari *et al*., 2000). The fitness levels of golfers are less than other athletes due to the relatively low physical demands of golf (reviewed by Smith, 2010) nevertheless regular participation in golf can improve overall health and fitness.

Tsang and Hui-Chang, (2010) reported that golf should be incorporated into recovery therapy for stroke suffers, due to the many health benefits that result from this low impact sport. Health benefits of golf include the increase in aerobic capacity (Parkkari *et al*., 2000, Ikeda *et al*., 2008) and improved balance in the elderly when compared to their non-golf playing counterparts (Tsang and Hui-Chan, 2010). The latter study suggested that the improvement in balance will reduce the amount of falls that an elderly person may suffer. The overall fitness levels of the golfer are likely to affect golf performance (Keogh *et al*., 2009, Smith, 2010) and it is unlikely that completely sedentary individuals would perform as well as active golfers indicated by their potentially higher handicap values.

1.1.4 Optimizing golf performance

Many golfers seek to advance their game, through interventions which range from strength and flexibility training programs (Lephart *et al*., 2007), and instructional tuition to purchasing the latest equipment (Doan *et al.*, 2006).Possibly the most widely used tool for the enhancement of golf performance is actual practicing of the golf shots (Keogh and Hume, 2012). Golf practice should be more than merely hitting balls and must be goal orientated (Adlington, 1996, Keogh and Hume, 2012).

Improvements in the technology of golf equipment are likely to be a noteworthy contributor to golfing performance and cannot be overlooked. In addition, improvements in golf equipment aim to increase the enjoyment of the game for amateur golfer by making it easier to perform (Adlington, 1996, Farrally *et al*., 2003). Within a set of the 14 allowed golf clubs, each club has a specific and intended purpose (Penner, 2003). In general all clubs are designed to transfer maximal energy, while imparting minimal side spin the golfer must strike the ball at the centre of the club face (Penner, 2003, Keogh and Hume, 2012). Over recent

years the emphasis of new club designs has focused on reducing the amount of "off-centred hits" (Penner, 2003, Farrally *et al*., 2003). This can be seen by the increase in the club head volume most notably in the drivers and "metal-woods". The newer designs have resulted in an elliptical "sweet-spot" as opposed to the central screws of older woods. While having modern golf equipment is essential to the golfer's performance the method in which the power is generated is still the greatest factor to achieving maximal drive distance. Furthermore the physical conditioning of the golfer is likely to allow for the prolonged performance on the golf course.

1.2 The physiology of the golfer

The very nature of golf requires the individual to contend with various physiological disturbances ranging from cardiovascular responses to changes in nutritional and hydration states. In the section below I will discuss the current literature regarding the effects of physiology on golf performance.

1.2.1 The autonomic state of the golfer

Golfers are subject to the antagonistic effects of the autonomic nervous system, whereby the parasympathetic nervous system, which reduces heart rate, may allow a higher level of focus. However, increasing the level of sympathetic nervous system activity may improve the force of muscle contractions. The effects of walking in between shots and the muscular events that result in the golf swing itself will increase the oxygen consumption and sympathetic tone of the golfer to above resting levels, increasing the heart rate of the golfer. The resulting effects of the elevated heart rate on the golfers' abilities are unclear. Neumann and Thomas (2009)

showed that experienced golfers had a lower heart rate just prior to putting, when compared to novice players, indicating that experienced players are able to calm themselves before attempting the shot. Smith *et al*, (2003) showed that golfers suffering from "the yips", a form a performance anxiety, had an increased heart rate before attempting a putt and also noted that some professional golfers admitted to taking beta blockers in an attempt to reduce their heart rate (decrease sympathetic tone).

1.2.2 The possible effects of fatigue

Many golfers perceive fatigue in the latter stages of golf and show specifically their mental fatigue increases later in the round (Stevenson *et al*., 2009). Doan and colleagues (2007) showed a positive correlation between mental and physical fatigue and the duration of 36 consecutive holes. In a review by Smith (2010) it was suggested that fatigue in the latter stages of a golf game could lead to poor decision making, regarding either club or shot selection. Functional fatigue may lead to changes in the muscle firing or activation, leading to the reorganization of the multiple joint angles in an attempt to compensate for muscle fatigue (Tripp *et al*., 2004). Fatigue brought about by high intensity exercise has been shown to reduce the hand grip strength of tennis players, which is essential to maintaining control of the racquet (Davey *et al*., 2002). However the fatigue perceived during the golf game will not be due to high intensity exercise rather by the prolonged duration of time spent standing and walking. The effects of fatigue will be compounded by the terrain of the golf course along with environmental conditions. The mental and physical decline of the golfer towards the latter stages of the golf game may be compounded by homeostatic disturbances in hydration and nutrition (Welsh *et al*., 2002).

1.2.3 The effects of hydration and nutritional aspects.

A golfer may experience hypo-hydration and hypoglycaemia due to the length of time they will spend on the course during a round (Stevenson *et al*., 2009). Welsh and colleagues (2002) showed that mental and physical improvements were possible following intermittent high intensity exercise by ingesting carbohydrate drinks. Additionally Stevenson and colleagues (2009) showed that ingestion of caffeine and carbohydrate energy drinks can improve putting performance, attributing the difference to the delay in the onset of fatigue. Furthermore, Smith and colleagues (2012) showed that acute mild dehydration can reduce the distance and accuracy of a golf shot, along with the distance judgement.

1.2.4 The role of strength and flexibility on golf performance

A common focus for golf research is the intervention of training programs which aim to improve a combination of balance, flexibility and functional strength (Smith, 2010). Drive distance is thought to be maximised by improving the physical condition of the golfer (Hume *et al*., 2005). Physical contributors to longer drive distances were suggested to include strength, muscle power, muscle balance and aerobic conditioning (Hume *et al*., 2005). In support of this contention golfers with lower handicaps have been shown to have better flexibility, balance and functional strength than their less accomplished counterparts (Sell *et al*., 2007). Moreover, improving the physical attributes of the golfer could increase the club head speed (Doan *et al*., 2006, Lephart *et al*., 2007, Thompson *et al*., 2007), which in turn could increase drive distance. Many studies seem to have ignored other aspects of physiological function that might be important such as muscle contractility (rather than strength) and neurological factors such as disinhibition in the golf swing may yield more insights. Muscular endurance (isometric prone hold) was shown to have no significant

relationship with maximal club head speed (Keogh *et al*., 2009). Fletcher and Hartwell (2004) identified the importance of a combined weights and plyometrics training program and how club head speed and drive distance could be improved. This combined weights and plyometrics training program, which made use of exercises mimicking the prestretch that occurs in the backswing. Furthermore the participants did not undergo muscle hypertrophy but rather improved muscle fibre motor unit recruitment (Fletcher and Hartwell, 2004).Although very controversial the stretch shortening cycle may be advantageous to the golfer, as the muscles used to rotate during the backswing will be stretched and the same muscles will rapidly undergo concentric contraction releasing the elastic energy during the downswing (Hume *et al*., 2005). The subsections below specifically focus on what is currently known about the role that strength and flexibility have on golf drive performance.

1.2.4.1 Strength

Golf specific training in the past normally focused on the technical and tactical aspects of the game (Gordon *et al*., 2009); however over recent years there has been a shift in the training regime both of the professional and amateur golfer to incorporate strength and flexibility training. In a study by Gordon *et al* (2009) on 15 amateur golfers, chest strength and trunk rotational power (medicine ball hip toss test) correlated to club head speed. Hellström (2009) discussed how electromyography studies have shown how the pectoralis major muscle is active during the downswing. This muscle however would mainly contribute to the rapid adduction of the right arm while the left muscle may actually decelerate the left arm (Hellström, 2009). Sell and colleagues (2007) tested, amongst other aspects, the strength of golfers with a range of handicaps. The golfers were grouped based on handicap and core strength along with isolated shoulder strengths. Their results indicated that more proficient golfers had better shoulder and core strength (Sell *et al*., 2007). The core muscle groups,

including the lower back, pelvis and hips are all required to generate the high rotational velocity movements of the torso needed for a successful golf swing. Keogh and colleagues (2009) compared the strength of two groups of golfers based on handicap, and found that the ability to perform specific tasks such as the bench press and the hack squat were both significantly correlated to club head velocity. More importantly they found that a golf specific exercise, in this case the woodchop (Keogh *et al*., 2009) was correlated to club head velocity and the ability to perform the exercise was different in the two groups. The starting position of the woodchop (as per Keogh *et al*., 2009) exercise similar to the address position, while holding the weighted cables with their arms parallel to the ground. The golfer then rotates their trunk and hips as they would during the downswing the position that they would make contact with the ball. The isokinetic left and right torso rotation performed in the Sell and colleagues (2007) study, the hip toss test performed by Gordon and colleagues (2009) and the woodchop (Keogh *et al*., 2009) are assessments of muscular strength that are more likely to predict golf performance as they allow for the generation of power over the whole body and do not isolate one specific muscle group. These exercises mimic the golf swing and may thereby improve the body segment sequencing of motor unit contraction resulting in a more efficient transfer of power (Lephart *et al*., 2007). The effect that strength has on the golf swing and the indirect nature of the muscle mass, reflecting muscular power cannot be linearly related to increased swing performance, because too much muscle mass may reduce the range of motion and the flexibility of the golfer (Keogh *et al*., 2009).To compliment this, Lephart and colleagues (2007) noted that strength should be increased by improving neuromuscular function rather than an increase in muscle mass. Improving the neuromuscular function will improve the rate of muscle fibre recruitment and the force of muscle fibre contraction (Higbie *et al*., 1996), without imposing the restrictions of increasing the muscles cross sectional area. Additionally, Higbie and colleagues (1996) showed that similar changes

in strength can occur via hypertrophy (increasing the cross sectional area) or via neurological improvements. The strength improvements via neuromuscular improvements would therefore be advantageous to improving golf performance as not to restrict the body's range of motion during the swing.

1.2.4.2 Flexibility

In order to execute an effective golf swing the golfer requires a high range of motion around many major skeletal joints. Having greater flexibility at the joints may allow for more mechanical power to be developed around that joint due to an increased angle of rotation over which force can be applied (Gordon *et al*., 2009). Despite this hypothesis the flexibility of the trunk was not significantly correlated to club head speed (Gordon *et al*., 2009) where the flexibility of the trunk was tested using a trunk rotation resistance training machine. Lephart and colleagues (2007) showed that specific training regime, torso flexibility could be enhanced. Additionally, Sell and colleagues (2007) demonstrated how golfers of better ability have better range of motion and flexibility at the shoulders, hips and torso. The importance of flexibility may be particularly notable when considering the separation of the shoulders and hips, known as X-factor (Sell *et al*., 2007). The X-factor is a term created to measure the separation of the shoulders and hips resulting from their rotations (Hume *et al*., 2005). The value of X-factor changes throughout the swing and is highest during the downswing phase (Cole and Grimshaw, 2009).

X-factor may be increase through improving the stability of the pelvis by strengthening of the core muscles and increasing the torso flexibility (Lephart *et al*, 2007). In opposition, Keogh and colleagues (2009) showed that flexibility had very little effect on club head velocity. Wells and colleagues (2009) used a sit-and-reach test to determine the golfer's flexibility and

found a negative correlation with drive carry distance which is counterintuitive. It is likely that the sit-and-reach test, which mainly tests hamstring and lower back flexibility and does so in only one dimension, is not a reliable measure for flexibility needed to effectively perform the golf swing. It should be noted that the flexibility of the legs and lower back during the golf swing where the legs are required to maintain a stable base for which the pelvic and shoulder girdles can rotate is a complex set of variables and not a simple stretching action of the lower back and hamstrings. The golfer needs to acquire the ability to synergise the antagonistic effects of strength and flexibility to maximize the rotational power of the golf swing (Gordon *et al*., 2009) with linear flexion/extension being of lesser importance. Improving muscle functionality while maintaining a high level of flexibility seems to be beneficial to golf swing performance. The extent of the range of motion of many joints used in the swing were shown to have no relationship with club head velocity (Keogh *et al*., 2009).

1.2.5.1 *The need for balance and postural control*

The game of golf requires participants to adopt various body positions throughout the swing, involving well developed postural control and balance. Furthermore the ability to balance is compounded by the varying terrain and playing surfaces of the golf course.

Vereeck and colleagues (2008, page 67) state that "balance is a complex motor skill requiring central processing of vestibular, visual, and somatosensory information to activate the musculoskeletal system to produce postural actions." Hrysomallis (2011, page 222) defines static balance as "the ability to maintain a base of support with minimal movement" and further classifies dynamic balance "as the ability to perform a task while maintaining or regaining a stable position or the ability to maintain or regain balance on an unstable surface with minimal extraneous motion." An effective golf swing requires both static and dynamic

balance. Added to the standard requirements for balance and posture, inherent to golf, additional complications inherent to the game of golf the demands of golf may dictate whether the golfer will play their shot off even or undulating terrain. Whether on flat or more challenging surfaces, the need for dynamic balance to assist the golfer in transferring their weight efficiently is paramount to the outcome of the shot (Hrysomallis, 2011).

Over a wide variety of sporting activities more proficient athletes are shown to have better balance than their less accomplished counterparts (Hrysomallis, 2011). The same finding has been shown to be valid in golf with the study by Sell and colleagues (2007) showing that better golfers have a greater ability to balance on the right leg with eyes open. It is likely that such improvements in balance ability are a consequence of practising the motions and their ability to respond to proprioceptive and visual inputs (Hrysomallis, 2011). Added to the role of proprioception purely concerned with balance, Tsang and Hui-Chang (2004) discuss the importance of limb proprioception in maintaining posture and in the generation of smooth coordinated movements. Lephart and colleagues (2007) proposed that balance may be enhanced following a training program and showed that greater drive distance was achieved. In the sections below I separately describe the importance of dynamic balance and what is colloquially knows to golfers as the "weight shift".

1.2.5.2 Dynamic balance and "weight shift"

The weight shift is a key factor in the assessment of the golf swing (Hume *et al*., 2005) and is likely to be a strong indicator of golf shot performance (Horan *et al*., 2010, Best and Ball, 2012). The weight shift is related to the movement of the whole body centre of mass that results from the movement of the arms and the rotation of the torso. However the weight shift

is more likely the consequential movement of the centre of pressure movement along the base of support (an area defined between the ground and feet) (Best and Ball, 2012).

The shifting of weight from one leg to the other during the golf swing requires a high level of dynamic balance (Tsang and Hui-Chang,2010).In this regard, balance has been related to the execution and accuracy of the approach shot and the weight being shifted during the swing (Wells *et al*., 2009). When trying to identify the underlying mechanism of improved balance in golfers Tsang and Hui-Chang (2010) suggested that the percentage of time during the gait cycle that is spent on one leg is the most likely cause of improved balance. During walking there is a need to maintain balance on a single leg while whole body centre of mass position is shifted forward. Furthermore the end phase of the golf swing places a high percentage of weight on one leg, which may improve single leg balance (Tsang and Hui-Chang, 2010).Thus, regular practice and execution of the golf swing has been suggested to improve balance and therefore reduce the risk of falls in older patients (Tsang and Hui-Chang, 2010). Tsang and Hui-Chang (2010) also identified that the dynamic balance of older golfers was more pronounced than non-golfers, as demonstrated with less body sway in response to an external perturbation. The physical demands of golf, walking and swing, may explain the non-significant difference between elderly golfers and young non golfers (Tsang and Hui-Chang, 2004). The complex set of physiological determinants of stability and balance which comprises several factors, all differently influenced by the various aspects of a golf game (arm movements during the swing, walking and the possible influences of warming up and fatigue), may obscure any influence that age plays in determining balance and stability in non-golfers of different ages. Older golfers and Tai Chi practitioners were shown to have a more acute sense of knee joint position which allowed for a greater limit of stability and more refined coordinated lower limb movements (Tsang and Hui-Chang, 2004). These results show the importance of knee joint proprioception being fundamental to controlling the

dynamic balance needed during the weight shift occurring during the golf swing (Tsang and Hui-Chang, 2004).

A golfer needs to transfer energy from his muscles and potential energy as a result of his body position to the ball in the most efficient manner possible. By reducing sway in arbitrary directions during the swing, for example the created energy is kept in the kinetic chain and not "lost" to auxiliary muscles which maintain balance. Consequently authors have advocated the need to maintain a firm base of support over which a golfer's centre of mass can be shifted within (Sell *et al*., 2007). Poorly timed transfer of weight may, in this way, move a golfers centre of mass towards the boundaries of the base of support created by a golfers feet leading to instability and under rotation of the pelvic and shoulder girdles in order to prevent falling (Sell *et al*., 2007). The ability to balance is needed in the shot making phase of golf, as good balance assists in the weight transfer and is also particularly needed when the shot played is not on an even surface (Hrysomallis, 2011).

As previously stated the movement of a golfer's centre of mass is the major cause of the shifting golfer's centre of pressure movement or "weight shift" (Hume *et al*. 2005).Weight transfer from one leg to another is vital to a successful golf swing (Hume *et al*., 2005) and a golfer's ability to control their balance also contributes to a successful swing (Smith, 2010). Good balance in turn is needed to create a stable base around which the pelvic and shoulder girdles can rotate (Gordon *et al*., 2009) allowing maximum momentum to be transferred to the golf ball (Thompson *et al*., 2007, Worsfold *et al*., 2008, Jagacinski *et al*., 2009). Wrobel and colleagues (2012) showed how better golfers are able to make minor changes in their posture during the swing to eliminate the momentum shift in their centre of mass due to the momentum of their arms. It is minor changes to the stance that allow successful golfers to have well defined base of support over which they can balance. In addition, a change in

movement of the centre of mass only in the desired trajectories allows a golfer to compensate for the position and momentum of the golf club (Burden *et al*., 1998, Smith, 2010).

1.2.6 Whole body and fine motor coordination

The golfer needs to collect information gathered from the sensory organs (visual, vestibular, proprioceptive and somatosensory input) and use this information to produce the action of the golf swing (Selicki and Segall, 1996). The ability to control the movements and position of whole body, culminating in hand movement is a highly complex task (Natarajan and Malliga 2011). Eye-hand-club coordination is the ability to control hand position based on the information received from the eyes. This physiological aspect of golf is hypothesized to be an important aspect of golf driving skill. Unlike in other sports where hand-eye coordination are important performance related attributes the coordination skills necessary for golf are compounded by properties of the golf club such as club length. This non-physiological extension of the kinetic chain is essential to the transfer of power to the ball, making knowledge of the club head path fundamental to a successful golf swing. Interestingly, many golfers claim to get a "feel" of the shot without knowing the shot's outcomes through the contact made between the club and ball (Neal *et al*., 2007).

Knight, (2004) mentioned that the effects of sensory feedback in the novice golf is largely undeveloped when it comes to determining positive and negative outcomes of the shot. The control of the club is vital to the outcome of the shot (Knight, 2004) and the position at which the clubface strikes the ball is known to be a major contributor to the resulting flight of the ball (Neal *et al*., 2007). Better golfers have been shown to compensate for errors that may occur in the swing (Bradshaw *et al*., 2009). The compensatory measures undertaken by highly skilled golfers may be a function of their hand-eye coordination. Arm, hand and club

movement themselves, are important factors to consider when examining the factors that contribute to successful coordination of the golf swing. These will be further described under the biomechanical properties of the golf swing (section 1.3).

In respect of coordination in general and the movement of the proximal body segments, skilled golfers were shown to focus on the coordination of the whole body movement (particularly overall thorax and pelvis rotations) rather than the individual rotations of each segment (Knight, 2004, Zheng *et al*., 2008, Tsang and Hui-Chang, 2010, Horan and Kavanagh, 2012, Keogh and Hume, 2012). It is likely that the central nervous system has developed the most efficient method of activating muscles to produce a relatively effortless motion(Horan and Kavanagh, 2012). A review by Langdown and colleagues (2012) suggested that an individual must find a way to reduce the unused degrees of freedom around the particular joints by linking or activating the surrounding muscles, to produce a smooth coordinated movement. This development is likely to take place over many purposeful practice sessions (Bradshaw *et al*., 2009 Horan and Kavanagh, 2012). Jagacinski and colleagues (2009) suggested that golfers need to get the coordination of the body segments and weight shift working together to execute efficient shots. It is only when all of the aspects of the golf swing are combined efficiently that the shot will be well executed. It is essential for a golfer to sequence movements of the body segments correctly to square the clubface at ball contact (MacKenzie, 2012). The resulting whole body coordination may include what is commonly known as “timing of the swing”, which is needed for accuracy over the large distances of the golf drive (Bradshaw *et al*., 2009). Neal and colleagues (2007) showed, in a group of highly proficient golfers, that the difference in well and badly timed shots may be related to the sound or feel of the club striking the ball as perceived by the golfer, rather than their perception of segment coordination. The golf swing is a skill that is learned and eventually refined over a long period of time (Bradshaw *et al*., 2009). It will be during these

endless hours of practice that the golfer may develop the necessary coordination strategies that will result in an optimised whole body coordination sequence.

1.3 Biomechanics: The measurement of golf skill

The golf swing has been described as a highly complex biomechanical movement (Burden *et al*., 1998, McHardy and Pollard, 2005, Nesbit and Serrano, 2005) that requires precisely timed muscle contractions (Kim *et al*., 2004, Cole and Grimshaw, 2008). In general terms, it should be emphasised that the overall purpose of the golf swing is to develop a maximal amount of kinetic energy to be transferred directly to the golf ball (Nesbit and Serrano, 2005). Indeed, the displacement of the golf ball (from tee to eventual point of rest) has been shown to be a direct function of linear club head velocity (Penner, 2003, Hume *et al*., 2005, Wallace *et al*., 2007). As a consequence of this relationship, golf instruction is often focused on achieving maximal club head velocity at ball impact. Despite this, it should be noted that increasing the club head velocity alone may not result in an overall distance increase, due to other factors such as spin which may affect the accuracy and distance of the shot (Hume *et al*., 2005). The achievement of lower golfing round scores depends only the distances that are achieved in the optimal direction rather than the pure ability to attain greater drive distances.

The biomechanical quantification of variables describing the golf swing not only informs questions about optimal technique but also highlights flaws in the swing of golfers and may infer possible cause of fatigue or injury. The leading causes of injury in amateur golfers have been ascribed to poor swing technique (Mitchell *et al*., 2003, Kim *et al*., 2004) and the high range of motion that the arms experience (McHardy and Pollard, 2005). To prevent injury many coaches suggest altering the swing to imitate the swings of professional golfers (Smith, 2010). Theoretically emulating a professional's swing may prove to be advantageous

however this may not always be practical because professional golfers vary in their swing techniques (Simon *et al*., 2005). In an observational commentary by Adlington (1996) it was suggested that all golf swings are unique and that the development of the swing should be dictated by the abilities of the individual golfer. In reality it should be noted that new swing techniques that may in fact supersede the abilities of current golfing professionals, may be repressed by the emulation of these "ideal swings". In addition, Smith (2010) suggested that optimal swing design should be constrained by the physical limits of the individual.

The function of the golf swing is to transfer the energy, generated by the body segments, to the golf ball on impact (Nesbit and Serreno, 2005). The components of the swing include the movement of the arms and club as a lever and the transfer of weight along with balance and projection of the centre of mass (Burden *et al*., 1998, Hume *et al*., 2005, Smith, 2010). In order to describe what has generally evolved as a successful golf swing, golfers and researchers have subdivided the golf swing into distinctive phases (Hume *et al*., 2005).These phases have been used to describe characteristic body positions during the various golf swing phases (Bradshaw *et al*., 2009) during which a golfer is also required to maintain a certain level of functional balance. The four major phases in the golf swing are: address, backswing, ball contact and follow through (Hume *et al*., 2005). The position of various body segments and the distribution of the body mass at specific phases of the golf swing have been shown to significantly influence the velocity of the club head (Bradshaw *et al*., 2009), which ultimately leads to increased golf ball displacement (Penner, 2003, Hume *et al*., 2005, Wallace *et al*., 2007). Biomechanical factors that affect the performance of the golf shot are discussed in further detail hereafter.

1.3.1 Mathematical model of the golf swing and the kinetic chain

A mathematical model describing the golf swing was originally developed by Cochran and Stobbs in 1968 for the Royal Society Golf Group with the goal of optimizing golf performance (Coleman and Rankin, 2005). The golf swing was modelled as a double pendulum and divided the upper body and club system as two links (Penner, 2003, Coleman and Rankin, 2005). The first link included the shoulders and arms, which rotated around a central hub derived from their attachment to the trunk via the shoulders and the second link included the wrists and the club complex (Penner, 2003). There was however a possible flaw in the proposed double pendulum model which required the left elbow, included in the upper link, to be straight, ignoring the possibly important contribution that movement around the elbow hinge joint may add. This flaw in the mathematical model lead to the development of the triple link model, which includes the angle created at the left elbow (Penner, 2003, Nesbit, 2005). The latter kinetic chain of the upper body and the golf club relies on the summation of forces to produce the power which is then transferred to the ball (Hume *et al*., 2005). The principle of the summation of forces is that the proximal body segments will transfer the torque to the more distal segments and the resulting torque will be greater than the sum of the individual segmental forces (Hume *et al*., 2005). For example this model predicts that a delay in the release of the trunk rotation (proximal segment) will impart more kinetic energy to the arms (distal segment) and eventually impart more kinetic energy on the golf ball. A model as described is able to explain how movements of the forearm, hands and finally the club can be used to generate maximal energy when the unhinging of the wrists is delayed thereby allowing the optimal rotational energy generated in the forearms to be transferred to the hands and finally the club (Chu *et al*., 2010). In addition to the initial descriptions of descriptive mathematical models, application of these models to further the understanding of different factors on golf swing performance, have yielded interesting

results. Hume and colleagues (2005) suggested that increasing the angular velocity of the club head at impact would maximise the displacement of the golf ball. Penner (2003) agrees with this contention suggesting that the club head speed at impact is the primary determinant of drive distance. These two statements along with the mathematical models would suggest that by increasing your swing speed or by delaying the release of the body segment angles will result in the golf ball being hit further.

Using models such as those described have shown that the greater the wrist hinge angle before the impact of the ball leads to a greater club head speed (Penner, 2003, Chu *et al*., 2010). Further biomechanical analysis by Bradshaw and colleagues (2009) showed that the position of upper body segments at the top of the golf swing, will affect the overall performance of the shot. In contrast Nesbit (2005) showed that swinging harder may not result in higher club head velocity. A smoother swing pattern may be more efficient at transferring the energy between body segments and eventually to the ball (Nesbit and Serreno, 2005). Additionally Penner (2003) mentions that the alteration of one aspect in the swing to increase the club head velocity may have detrimental effects on the timing and coordination of body segments.

The importance of striking the golf ball in the centre of the clubface is vital to the outcomes of the shot. If the golf ball is struck slightly off centre on the club face it will be imparted with side spin which will affect the overall direction of the shot (Penner, 2003). A reduction in the centeredness of strike error is possible when the kinetic chain linkage is performed on a single plane ensuring that the club is on the same plane when it makes contact with the ball. (MacKenzie, 2012).The single plane refers to the plane established by the seventh cervical vertebrate, left elbow and wrist joints, when the golfer is in the address position (Coleman and Rankin, 2005). The position of the hands relative to this latter plane are important, if the hands are below the plane early in the downswing the club face will be square at ball impact.

However if the hands are above the plane the club face will not be square at ball impact (MacKenzie, 2012). A noteworthy oversimplification the latter simplified assessment of the golf swing is the two-dimensional projections and the definitions of the plane. Many planes can be created over the body-club complex, in two dimensions. The problem however is the three-dimensional nature of the golf swing. Coleman and Rankin (2005) showed that the arms will leave the plane of the left arm, created at address, on the downswing, adding that contact with the ball may not be made if the arms do not leave the plane. MacKenzie (2012) investigated the effects of the body segments position on the swing plane using computer simulations and showed that a single plane may not be beneficial to all golfers. Furthermore the planes created by the golfer's body do not remain constant and also vary between golfers (MacKenzie, 2012).

1.3.2 Biomechanics of the legs and centre of mass movement

The previously described mathematical models do not account for the power and stability created by the lower body. Nesbit and Serreno (2005) devised a model which incorporated the internal power contributions of the lower limbs and showed that the power generated in the golf swing is mainly due to the lumbar segment followed by the right hip. The legs are not only important for generating a small amount of energy but are responsible for the creation of a stable base, around which the pelvis and torso can rotate (Nesbit and Serreno, 2005). Penner (2003) mentioned that skilled golfers generated more power from their legs, while less skilled players relied solely on the power generated from the torso and arms. Force development from the whole body during the golf swing should be initiated from the ground up (Hellström, 2009). The power should originate in the legs and be compounded by the rotational power of the hips and torso and finally transferred to the club via the central hub

and arms. The power generated in the legs is closely linked to the movement of the centre of mass (Hume *et al*., 2005). This "weight shift" from the left leg to the right leg during the backswing and the return of the weight to the left leg during the follow through requires a level of dynamic balance (Hume *et al*., 2005). Movement in mediolateral centre of pressure was correlated to the club head velocity at contact, both in a group and individual assessment (Ball and Best 2012).

In the latter study Ball and Best (2012) demonstrated in an individual golfer that there was a greater range of weight shift between his two legs which required the golfer to assume a more stable position when executing the golf swing. The relationship between the mediolateral movement of the centre of pressure and the club head velocity was shown to be linear (Ball and Best, 2012). If the centre of pressure is shifted to a position that is outside of the stable base created by the feet, the golfer may find it difficult to maintain balance and transfer the optimal amount of energy. Best and Ball (2007a, 2007b, 2012) have extensively researched weight shift patterns during the golf swing. Their findings suggest that two main "weight shift" types exist namely: front foot and reverse. These two weight shifting types differ only in the way the centre of mass (COM) is moved during the swing. Front foot weight shift will have the COM position shifted toward the front foot at the time of ball contact, while the reverse weight shift group will have the COM position slightly toward the middle of the stance (Ball and Best, 2007a). The same authors suggest that these different styles of weight transfer may be another factor in the swing variation however the overall result of the shot was not shown to be different between the two styles as neither of them offered an advantage on increased club head velocity. (Ball and Best 2007a, 2007b). The overall range of weight transfer is important to the golf shot (Ball and Best, 2012) and the timing of the weight shift is more important than the per cent amount of weight shift to the outcome of the shot (Hume *et al*., 2005, Ball and Best, 2012).

1.3.3 Optimizing golf performance using biomechanics

Zheng and colleagues (2008) found that more skilled golfers had greater ranges of motion at the top of the backswing. Additionally these skilled golfers were able to maintain a higher X-factor value and had a greater left elbow flexion through the downswing phase (Zheng *et al*., 2008). These two swing optimizations may be efficient strategies that are used to transfer optimal energy during the downswing. A different biomechanical analysis by Chu, Sell and Lephart (2010) further emphasize the importance of the trunk rotation, the delayed action of the left arm and wrist uncocking during the swing. The role of these latter contributors to the kinetic energy used in the swing and their relation to ball velocity confirm the importance of the training regimes that aim to improve the muscle groups involved in the action of the golf swing (Chu *et al*., 2010). Chu and colleagues (2010) showed, using multiple step wise regression, that the forces developed in the golf swing begin from the contact of the feet with the ground, progress through the legs, trunk, and finally the arms. The important role of the lower limbs in the development of power appears especially true in the backswing position (Chu *et al*., 2010).

1.4 The effects of fatigue on golf biomechanics

A golf game continues for numerous hours and as such golfers need to have capacities to cope, both mentally and physically, with the demands that they may face. There is a need to remain focussed on the tasks at hand, when preparing for or executing a golf shot. Between shots, golfers can walk up to a total of eight km in distance however the literature surrounding the effects of walking or the effects of fatigue on golf performance is limited. To my knowledge only one study has been published regarding the effects of fatigue on the biomechanical action of golf swing performance. Higdon and colleagues (2012) showed a

reduction in club head velocity by 2% and 2.5% at the backswing and contact positions respectively associated with fatigue but demonstrated an improvement in shot accuracy following their fatigue protocol. The fatigue protocol developed by Higdon and colleagues (2012) required their participants to hit 20 golf balls and then walk a mile with a 20 pound load. Their procedure was repeated seven times on a single day. In total their participants would have hit 140 shots and would have walked seven miles. Clearly, more research is required to determine the effects of fatigue on golfers and their performance. Part of the current study is focussed on the evaluation of a far less arduous fatigue model, similar to what is experienced during a golf game.

1.5 Predictive model for golf drive distance

The preceding sections have displayed how the golf swing is multifaceted and how it requires a sequence of highly complex biomechanical movements along with well coordinated body movements and postural control. The relationships seen in the sections above cannot act in an isolated manner and must be as a result of many factors. The prediction of golf shot performance has been quantified using various components from biomechanical variables (Chu *et al*., 2010); a combination of physiological and biomechanical components (Bradshaw *et al*., 2009) to the contributing factors of physics occurring in the golf shot (Hellström, 2009). Smith (2010) proposed that not all physical attributes of the golfer that relate to golf performance have been identified. A multi regression or predictive model must be established to determine whether these factors exist in isolation or whether they are one of the many possible factors that together contribute to golf drive performance.

1.6 The outdoor setting

The majority of current studies that investigate the golf swing make use of indirect measuring techniques to determine the distance and accuracy of the ball based on the flight of the golf ball (Mitchell *et al*., 2003, Coleman and Anderson, 2007, Wallace *et al*., 2007) Wheat *et al*., 2007, Bradshaw et al., 2009, Chu *et al*., 2010, Horan *et al*., 2010). Although these same techniques are used commercially their true accuracy compared to the actual distance covered by the golf ball is questionable. Along with the indirect radar system, which calculates the speed and spin on the ball, most previous studies investigating the success of a golf swing have occurred indoors where the participants hit the ball into a net (Mitchell *et al*., 2003, Coleman and Anderson, 2007, Wallace *et al*., 2007, Wheat *et al*., 2007, Bradshaw *et al*., 2009, Chu *et al*., 2010, Horan *et al*., 2010). The effects of the outdoor setting on the golfer's ability and the validity of the results are questioned and not the accuracy of the measuring equipment. Evans and colleagues (2012) found no difference using an electromagnet system when comparing an indoor and outdoor setting. Despite this, when tested outdoors the golfer must be able to adapt to the conditions that they may face when on the golf course (Bradshaw *et al*., 2009). It is likely that an outdoor test will be more representative of a real golf setting, even though there are numerous environmental variables that must be noted.

1.7 Rationale:

Despite anecdotal suggestions that balance and coordination are vitally important to a successful golf swing, quantified empirical proof to assess the magnitude of the contribution that these variables make to a successful golf swing is largely lacking.

There is therefore a need to quantify the effects of balance and coordination on the golf shot, relative to the contribution of other known predictors of golf drive distance. In addition, it is possible that directly measured golf drive performance (as well as the measurement of drive performance candidate predictor variables) in an actual golf setting may more suitably assess the contribution of candidate variables to predicting drive distance and accuracy, compared to the more conventional laboratory based studies.

The idea that the physiological attributes contribute to the intricate biomechanical movement that is the golf swing is also a focus of the current dissertation. This idea follows from the studies by Tsang and Hui-Chang (2004 and 2010) where the proprioceptive abilities of older golfers were better than that of their non-golfing counterparts, and equivalent to the proprioception of non-golf playing healthy young adults. The relationship between physiological coordination and golf swing mechanics is likely to be evident where fine motor coordination in the hands of highly skilled golfers may enable them to eliminate any errors that could occur during the downswing. In the current dissertation the contribution of coordination as assessed by the ability to coordinate the club head is used (a measure of eye-hand-club coordination), a novel approach to the assessment of coordination in golfers. Although biomechanical and the physiological aspects of the golf swing have been independently investigated the comparison and interaction between biomechanical and physiological parameters are understudied.

A final reason for conducting the studies detailed in this dissertation is that the effects of short distance walking on the golf performance outcomes have never been investigated. Anecdotal evidence would suggest that walking could negatively affect the performance of the amateur golfer. This could arise from the perception of increased mental fatigue or a decline in the golfer's abilities to fully execute the needed shots. Despite this anecdotal suggestion, it is also possible that the physiological impact of walking may have positive effects on the golf swing where a minor aerobic warm-up may increase the alertness of the golfer or convey other benefits to the golfer.

1.7.1 Aims:

1. To identify the physiological and biomechanical variables that predict golf drive distance and accuracy.
2. To investigate and identify any physiological attributes of the golfers that may contribute to the biomechanical performance of the golf swing.
3. To determine the influence of walking induced fatigue on the golf drive and the biomechanical and physiological factors that determine golf drive performance.

1.7.2 Hypotheses:

I hypothesized that balance duration of a golfer should have a direct relationship to drive distance achieved by the golfer, when using a simplified field balance test. Furthermore I expected other physiological contributors such as hand-eye coordination and anthropometry would affect drive performance of golfers.

I expected physiological predictors, such as balance, hand-eye coordination and heart rate to affect the golfers' biomechanics during the golf swing. Centeredness of hit should be as a direct result of the golfer's ability to manipulate the golf club, identifying the importance of hand-eye coordination.

My hypothesis regarding the effect of walking on golf drive performance was that the walking would have little to no effect on the golfers' physiological and biomechanical abilities, since walking is an integral part of the game.

Chapter 2

Methods and Materials

2.1 Participants

Twenty-one right-handed male amateur golfers volunteered to take part in this study. All participants were recruited from a local golf practicing facility and were all injury free at the time of testing. Demographic data were collected from each participant which included: handicap, number of years playing, recent average scores, and the amount of golf rounds played annually. Participants were excluded if they failed to play less than 8 golf rounds a year or if they achieved in excess of 110 shots. Only right-handed amateur male golfers were considered for this study. Participants were included based on their ability to perform golf related tasks. General health indictors such as weight and smoking status did not exclude participants from the study as golf requires a relatively low level of fitness. Furthermore factors such as weight may dramatically influence the golfers' ability to perform.

2.1.1 Separation of golfers into two groups based on recent average scores

The golfers were divided into two groups based on their recent golf round scores (similar to Sell *et al*., 2007 and Zheng *et al*., 2008): those with scores of 88 or less were classed as more competitive golfers (MCG, n=13) and those having scores of 89 or higher as irregular social golfers (ISG, n=8). Furthermore the separation of golfers was justified by the difference in annual rounds of golf played (MCG: 60 ± 25 golf games per year compared to ISG: 9 ± 3 golf games per year).

2.2 Physiological measurements

2.2.1 Balance

Balance was determined by asking participants to raise one of their legs to create a 90° angle at both the knee and hip joints (modified stork test) (Figure 2.1). The balance was determined standing on each leg, and averaged with the participants' eyes open (EO). The balance tests were repeated with the participant's instructed to close their eyes once their individual legs were raised (EC). The time each participant could balance for was recorded to the nearest second. Each test lasted until balance was re-established or until 60 seconds. Participants wore their golf shoes during the balance procedures. The balance procedure was similar to that used by Wells and colleagues (2009). The decision to limit the balance test to 60 seconds was necessary to eliminate the testing of the golfers muscular fatigue limits (Vereeck *et al*., 2008).



Figure 2.1: The position of the participant during the balance procedures.

2.2.2 Hand-eye coordination

Hand and eye coordination was determined using a 3 dimensional maze constructed from brass tubing. A wire loop fitted to the end of a driver's shaft was used to complete the task. Participants were required to move a club through 360 degrees in both the horizontal and vertical planes (Figure 2.2). Golfers were instructed to complete the maze in the shortest possible time making as few contacts between the driver shaft and maze as possible. Errors (contacts between club and maze) and timing were tracked through an electric circuit which closed when an error was made. The maze circuit was connected to a Powerlab 26T system (ADI instruments, 26T, Australia), which allowed errors and maze duration to be recorded. Hand-eye-club coordination was quantified as the number of errors divided by the time taken to complete the task. Participants were instructed to hold the club shaft with the same grip they would a golf club. They were allowed to rotate their hands and move their arms and upper bodies while keeping their feet stationary. The maze was placed in the arc where the golfer would ordinarily make contact with the golf ball.



Figure 2.2: The three-dimensional hand-eye coordination task completed using the shaft of a driver.

2.2.3 Heart rate

Heart rate was determined through the use of a heart rate monitor (Polar S610, Polar Electro Oy, Finland). Heart rate was recorded when the participants were seated after a short resting period (resting heart rate) and following a 500m walk.

2.2.4 Anthropometry

Height was measured using an upright measuring tape and body mass was measured using a Tanita scale (Tanita THD-308, Japan).Anthropometry, including lean body mass was determined through bioimpedence using BodyStat (BodyStat 1500, United Kingdom). Height, weight, age, gender and physical activity levels were used as input constraints by the device. The bioimpedance was measured at the same time of day (early evening) for each participant, but confounding factors such as hydration state were not recorded.

2.3 Measuring the golf shot outcomes

Participants aimed their shots at a target which was placed 260m from the tee at one end of a flat grass outdoor driving range. The accuracy was defined as the distance perpendicular from the tee-target axis. Drive distances were determined as the intersection between the tee-target axis and the previously described accuracy measurement axis. The exact distance from the axis was determined using a standard measuring tape (Figure 2.3).

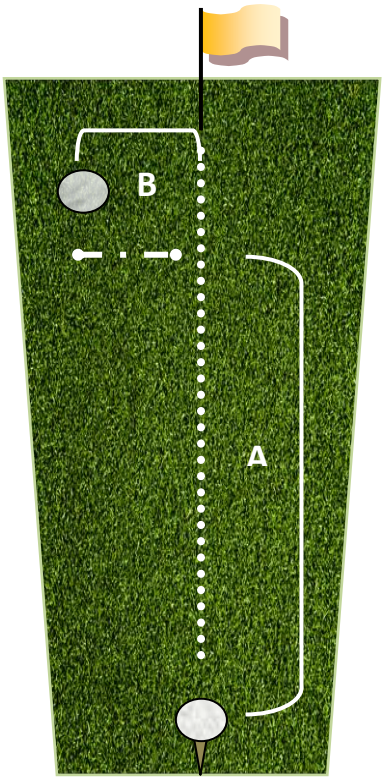


Figure 2.3: Schematic of the range and tee-target axis line, indicating how distance and accuracy was measured. A indicates the measurement of the distance up the target line, and B indicates the accuracy measurement to the target line.

The participants used Srixon AD333 golf balls. Each participant hit with their own driver and a standard club. The standard club was a 10.5° Adams Golf Speedline 9032LS, with an Alida Voodoo SNV6 stiff shaft. The shaft and loft of the participants' clubs were recorded along with their grip type. All shots were hit from an artificial grass mat with a rubber tee of a standard height. A small sheet of pressure sensitive paper (70x35mm) was placed on the club face over the defined "sweet-spot", and used to quantify the centeredness of hit for every shot (using the distance formula).A standard metallic ruler was used to determine the distance from the edge of the pressure sensitive paper to the ball centre.

$$\text{Distance} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

Where:

x_1 is the horizontal distance from the centre of the golf ball to the edge of the contact sheet.

x_2 is the horizontal distance from the centre of the golf ball to the edge of the golf club.

y_1 is the vertical distance from the centre of the golf ball to the edge of the contact sheet.

y_2 is the vertical distance from the centre of the golf ball to the edge of the golf club.

2.4 Biomechanics

The golf swing of the participants was captured using six Optitrack (NaturalPoint Oregon, USA) 250e high speed cameras. The videos were recorded through Arena (NaturalPoint Oregon, USA) at 250 frames per second. For each participant the cameras were calibrated using a three marker wand. Calibration of the recording system was only accepted when mean error for each camera was below0.145. Natural Point suggests the camera sensors are accurate to below a millimetre whereas independent researchers have found that similar Natural Point camera models (to those used here) to be as accurate as other well established brands (Thewlis *et al*., 2011). The recording for each swing lasted eight seconds. Retro-reflective markers were placed on the following anatomical landmarks: Jugular notch, xyphoid process, seventh cervical vertebrate, tenth thoracic vertebrate and sacrum. Bilaterally on the first finger, acrominum process, calf, thigh, anterior superior iliac spine (ASIS), first toe and heel. Bilateral markers place both medially and laterally on the wrists, elbows, ankles and knees and four markers on the head (Figure 2.4). An additional marker was place on the rubber tee, to determine when ball contact was made.

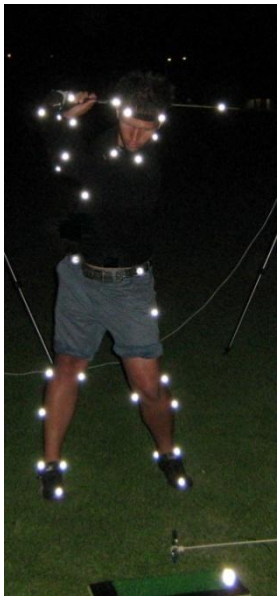


Figure 2.4: The position of the retro-reflective markers.

2.5 Procedure:

Participants had their anthropometric measurements taken and bioimpedance was performed. The participants performed the hand-eye coordination task and underwent the balance procedures. They were then allowed to warm up for their golf swing in their own accustomed manner. Retro-reflective markers were attached to the relevant anatomical landmarks; following which they were allowed to hit five practice balls under recording conditions.

For the experimental procedure, the participants hit 10 golf balls (five with a standard club and another five with their own club) towards a target 260m from the tee. Once these shots were complete they were instructed to walk to the 250m marker and back (a total of 500m), at the pace they would walk in between shots on the golf course. Their heart rates were recorded at this point. The protocol was repeated for five shots with their own club and the standard club. The coordination and balance tests were repeated following the completion of all shots.

2.6 Data analysis

The videos captured using Arena motion capture software were trajectorized and exported in c3d format. The c3d files were imported into MatLab (Mathworks, Natick, USA) using MatLab toolbox for c3dserver, version 2 (Walker and Rainbow, 2006) where further analysis was done. Body joint centres were calculated using mathematics similar to the Plugin Gait model (loosely based on Kadaba *et al*., 1990 and Gutierrez *et al*., 2003). MatLab scripts were specifically written to calculate the various body angles in 3-Dimensions as described hereafter. Swing variables were calculated at three specific events in the golf swing: the top of backswing, ball contact, and full follow-through position. An explanation of all calculated biomechanical variables are in Figure 2.5.

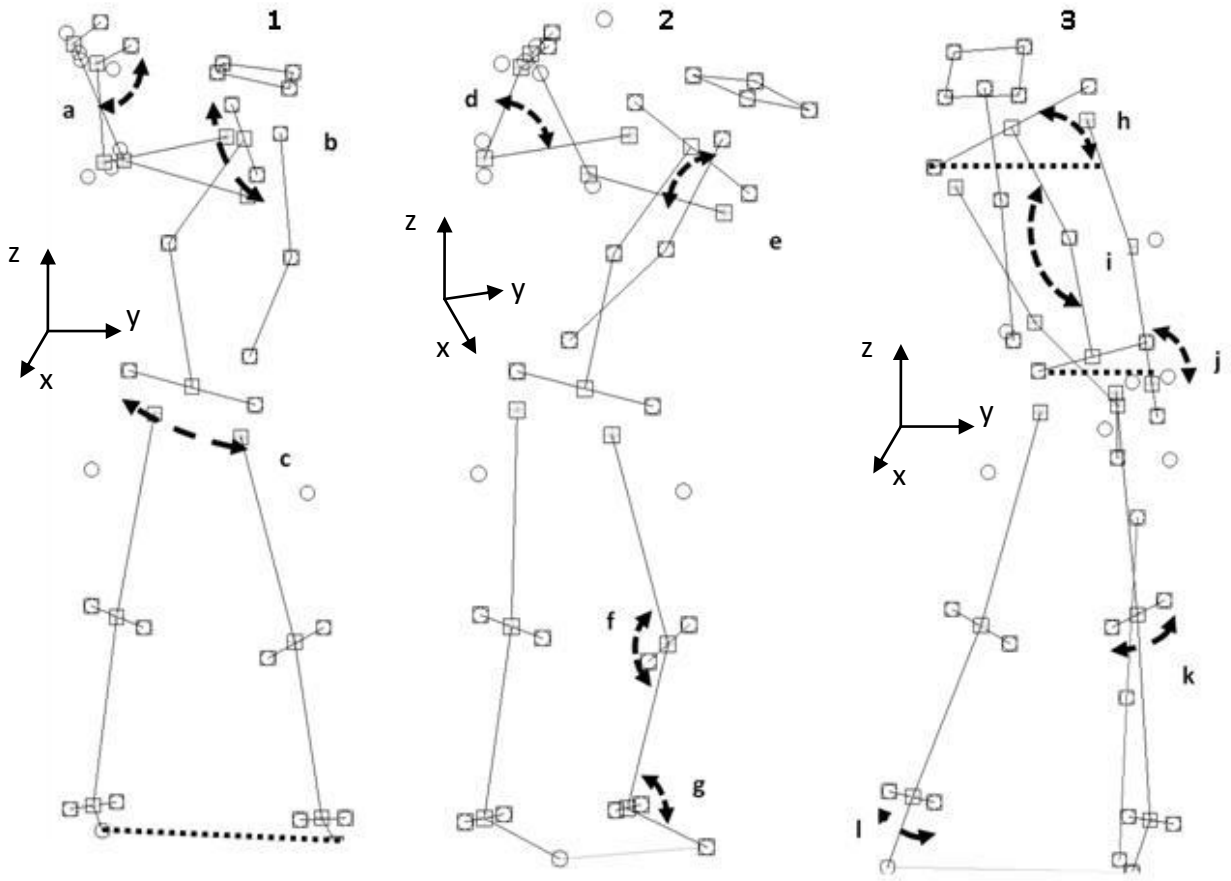


Figure 2.5: Biomechanical angle definitions: Position 1 and 2 are at full backswing, with position 3 at ball contact: The *xy* plane corresponds to the transverse plane and the *yz* plane corresponds to the coronal plane.

a. Wrist angles were defined by the vector line from the wrist joint centre to the first finger marker and the vector line from the wrist joint centre to the elbow joint centre. Calculated for both the right and left wrists.

b. Shoulder rotation and **c.** pelvis rotation were the angles created by translating the shoulder (left shoulder marker to right shoulder marker) and pelvic (Left anterior superior iliac marker to right anterior superior iliac marker) vector lines to the midpoint of the vector line established by the feet markers in the address position on the *xy* plane. X-Factor was calculated as the difference between the shoulder rotation and pelvis rotation.

d. Elbow angles were defined by the vector line from shoulder joint centre to elbow joint centre and the vector line from elbow joint centre to wrist joint centre.

e. The leading arm angle was calculated using atan2 function as the thorax vector (from left shoulder joint centre to mid shoulder point) and the upper left arm vector (from shoulder joint centre to elbow joint centre). This variable calculates the angle of upper arm extension from the shoulder joint.

f. Knee angles were defined as the vector line from hip joint centre to knee joint centre and the vector line from the knee joint centre to ankle joint centre.

g. Ankle angles were defined as the vector line from knee joint centre to ankle joint centre and the vector line from ankle joint centre to toe marker.

h. Shoulders and **j.** pelvis elevations were calculated using the vector lines transposed onto the *yz* plane and compared to feet vector line in the address position projected onto the same plane.

i. The lateral bend was the angle created between the thoracic and pelvic planes. The first plane was established between the mid-shoulder point, xyphoid process and the tenth thoracic vertebrate to define the upper segment. The lower trunk plane was established between the xyphoid process, mid anterior superior iliac spines and the sacral marker. The lateral bend angle was the angle created between the two planes.

k. Knee and **l.** ankle aspects were calculated using the vector lines from the middle of the joint to the lateral marker on the knee or ankle, and compared to the vector line created between the toes in the address position projected onto the *xy* plane.

2.7 Statistical analysis

All data are presented as mean ± standard deviation, unless specifically stated. All data were tested for normality using GraphPad Prism 5 (San Diego, USA) and further appropriate statistical tests were used based on the data distribution type. A Student's t-test was used to determine if there was any difference in the distance achieved using the two clubs. Paired t-tests were run to determine whether any variables changed due to the walking protocol. To determine the effects of walking on the changes in the various biomechanical and physiological factors, correlations were run on the change in values from before and after the walk. Either Spearman's or Pearson's correlations were selected based on the distribution of the data and along with the t-tests were run in GraphPad Prism 5 to determine the existence of any relationships with a significance level of $\alpha<0.05$. A stepwise multiple linear regression

was used to determine a model for drive distance using physiological and biomechanical variables in MatLab 7 (Mathworks, Natick, USA). Backwards stepwise multiple linear regression was used, whereby non-collinear variables were excluded if the level of significance was greater than 0.05. The resulting model would be the model which had highest R^2 value, with all contributing variables' significance levels below 0.05.

2.8 Ethics

Ethical approval was obtained from the Human Research Ethics Committee (Medical) of the University of the Witwatersrand (M110424) and written informed consent was obtained from all participants.

Chapter 3

Results

3.1 Subject demographics

The demographic data for the 21 golfers are shown in Table 3.1. All participants were right hand dominant. The participating golfers were regular players (42 ± 33 golf rounds per year) and had an average amount of playing experience of 17.6 ± 14.6 years. Of the 21 golfers tested only 18 had an official golf handicap (11 ± 6 strokes). The three golfers without handicaps were rated according to their average scores over recent rounds. Combined recent average scores was 87 ± 10 strokes.

Table 3.1: Anthropometric data of 21 right-handed male golfers

Age (years)	Height (cm)	Mass (kg)	BMI ($kg.m^{-2}$)	Lean Mass (%)
37.2±13.0	176.9±7.1	84.1±14.3	26.9±4.6	79.6±8.2

3.2 Golf shot outcomes

All the results presented are for those measured prior to the walk unless otherwise stated (see section3.8).

No difference was found between the standard and own club (p=0.820) therefore all correlations were run with the average distance achieved with the standard and the participants' club. The average drive distance for 10 shots before the 500m walk was 221.4 ± 37.5m with an accuracy (error) of 20.1 ± 6.2m. The centeredness of hit, the measure of the distance between the centre of the golf ball and the centre of the clubface or "sweet-spot", was 29 ± 7mm.

3.3 Balance

The balance duration with eyes open was not normally distributed, therefore the lower quartile, median and upper quartile for the right and left legs along with the average time are shown in Table 3.2.

Table 3.2: The lower quartile, median and upper quartile of balance time duration for 21 golfers.

	Left Leg (s)	Right Leg (s)	Average Balance(s)
Eyes open	41, 60, 60	44, 60, 60	41, 60, 60
Eyes closed	3.5, 10, 17	3.5, 8, 19	4.8, 10.5, 25.5

3.4 Hand-eye coordination

The time taken to complete the hand and eye coordination task was 27.9 ± 13.0s with an average of 65.3 ± 13.5 errors. The resulting score for the hand and eye coordination task was 2.8 ± 1.1 errors/second. The hand-eye coordination task and the distance from ball contact to the club sweet spot were not significantly correlated ($r = -0.135$; $p = 0.559$).

3.5 Physiological variables correlated to drive distance

Drive distance achieved over 10 golf shots was positively correlated to right leg balance (Spearman $r = 0.436$, $p = 0.048$), left leg balance (Spearman $r = 0.437$, $p = 0.048$), average balance (Spearman $r = 0.450$, $p = 0.041$), and the percentage of lean body mass ($r = 0.599$, $p = 0.004$).

The results from the correlation between the drive distance and the hand-eye coordination task indicate that golfers with finer motor skills required to complete the task were able to

drive the ball further (Figure 3.1). Further negative correlations were evident with drive distance and handicap (r= -0.577, p= 0.012) and recent average scores (r= -0.616, p= 0.003).No significant correlation was present between resting heart rate and drive distance (r= -0.04, p= 0.876).

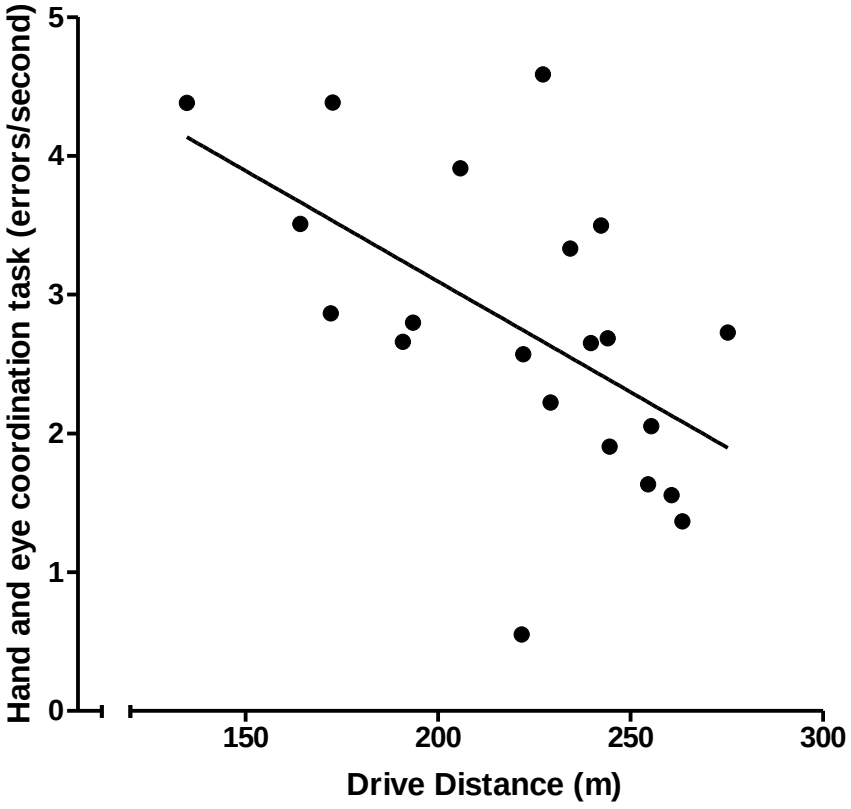


Figure 3.1: The correlation between drive distance (m) and the hand-eye coordination task (errors/second). (r= -0.563, p= 0.008).

3.6 Physiological model for distance

The resulting model for the physiology contributors of the drive distance show that age, lean body mass percentage and left leg balance are significant factors in achieving greater drive distances (Figure 3.2). Non-significant values excluded from the model were hand-eye

coordination and height. Comparisons between the univariate correlation models for drive distance and the multivariate regression for drive distance are shown in Table 3.3.

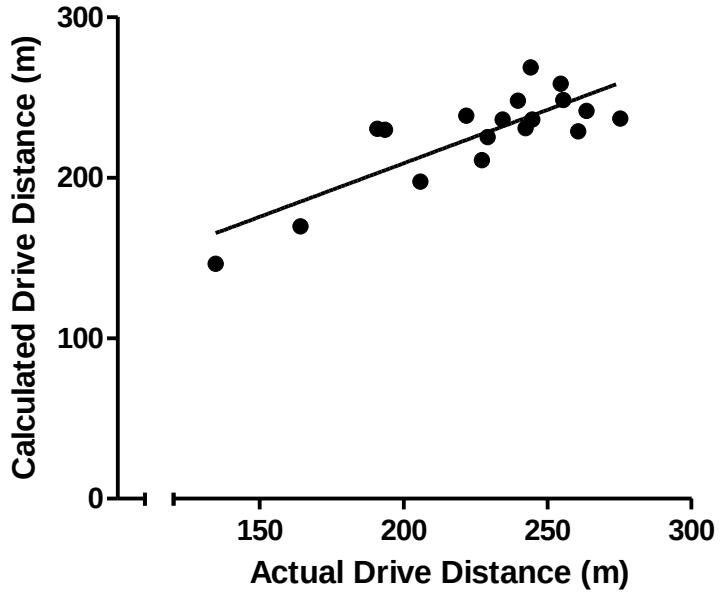


Figure 3.2: The physiological model for achieving drive distances. R^2 value is 0.667 (Adjusted R^2 0.595) p=0.001. Beta values: Age (years) 1.228* Lean Mass percentage 1.899* Left Leg Balance (seconds) 1.542†. * p< 0.05 † p < 0.01.

Table 3.3: The comparison between the univariate correlation models for drive distance and the multivariate regression for drive distance.

	r value	beta value
Right leg balance (s)*	0.436	
Left leg balance (s) *	0.437	1.542
Average balance (s) *	0.45	
Lean body mass (%)	0.599	1.899
Handicap (strokes)	-0.577	
Recent average scores (strokes)	-0.616	
Hand eye coordination (errors/s)	-0.563	
Age (years)	-0.241	1.228

* r value indicated is Spearman's r.

3.7 Biomechanical data

Only 7 of the participants video could be used for the biomechanical analysis as the retro reflective markers were obstructed during recording of the other participants rendering the video unusable. A further reduction in the sample size of seven during analysis of the biomechanical variables occurred as the calculation of the variable was reliant on the specific marker being visible. The results of the biomechanical analysis are shown in Table 3.4.

Table 3.4: Biomechanical variables collected for a sub-sample of the 21 male golfers before the 500m walk.

	Backswing		Contact		Follow through
Angles (degrees)	n	Mean ± SD	n	Mean ± SD	n	Mean ±SD
Left Wrist	5	80.0±40.1	6	15.9±7.1	0	
Right Wrist	4	79.6±63.6	6	34.6±13.8	0	
Leading Arm	7	170.2±1.8	7	167.3±1.1	0	
Left Elbow	7	139.9±15.1	7	139.3±37.5	0	
Right Elbow	7	72.4±7.1	7	161.1±10.9	0	
Lateral Bend	7	43.7±7.5	7	11.7±2.5	0	
Hip rotation	7	66.4±35.2	7	23.3±12.4	7	93.1±10. 9
Shoulder rotation	7	100.4±26.8	7	14.1±11.5	5	122.2±11.3
X-Factor	7	34.0±32.3	7	-9.2±7.6	5	29.7±4.6
Pelvis elevation	7	-0.2±2.5	7	15.3±1.9	7	15.0±1.5
Shoulder elevation	7	-1.6±1.3	7	4.2±3.09	5	1.4±1.5
Left Knee	7	135.5±9.4	7	166.2±7.1	7	165.3±11.9
Right Knee	7	160.9±3.4	7	155.5±6.3	7	156.5±8.1
Left Ankle	6	99.1±9.5	7	77.5±7.7	7	80.6±7.7
Right Ankle	6	83.2±4.9	6	71.5±12.2	7	41.0±12.6
Left Femur aspect	7	8.0±9.1	7	30.4±6.6	7	42.8±5.8
Right Femur aspect	7	142.8±4.8	7	159.0±16.3	7	40.9±18.5
Left Ankle aspect	7	34.7±12.2	7	35.7±4.1	7	32.9±12.3
Right Ankle aspect	7	138.4±17.0	7	145.7±4.2	7	166.1±15.0

3.7.1 Biomechanical correlations

The only two biomechanical variables that were significantly correlated (Pearson's) to the drive distance were the left and right ankle aspect angles in the follow through position (Table 4). The biomechanical data were correlated to physiological measurements in an attempt to identify the physiological basis that results in the biomechanical movement. A relationship displayed in this data is the correlation (Pearson's) between the right leg balance with eyes closed and the right femur aspect angle in the contact position (Table 3.5).

Table 3.5: Pearson's correlation coefficient values of balance and drive distance and biomechanical angles in the golf swing sequence

Swing position	Variable	Biomechanical Angle	Pearson r	R^2
Contact	Balance Right Leg eyes closed	Right Femur Aspect	0.835*	0.698
Contact	Balance Right Leg eyes closed	Right Ankle Aspect	-0.038	0.001
Follow through	Drive Distance	Left Ankle Aspect	0.769*	0.592
Follow through	Drive Distance	Right Ankle Aspect	0.781*	0.610

n=7, * $p < 0.05$

3.7.2 Biomechanical model for distance

The outcome in the multiple stepwise regression for the biomechanical model of drive distance (Figure 3.3) shows that the leading arm angle, left elbow angle and the lateral bend are significantly involved in the drive distance achieved. The multiple regression model for distance using biomechanical factors accounts for 99.97% (Adjusted $R^2 = 0.9996$, $p= 0.025$) of the variation in a sub-group of five golfers. The greatest positive factor of variation for the biomechanical model for distance is leading arm angle (beta coefficient of 16.51). The two

variation factors that have a negative effect are the left elbow angle and the lateral bend angle (beta coefficient -0.27 and -1.3).

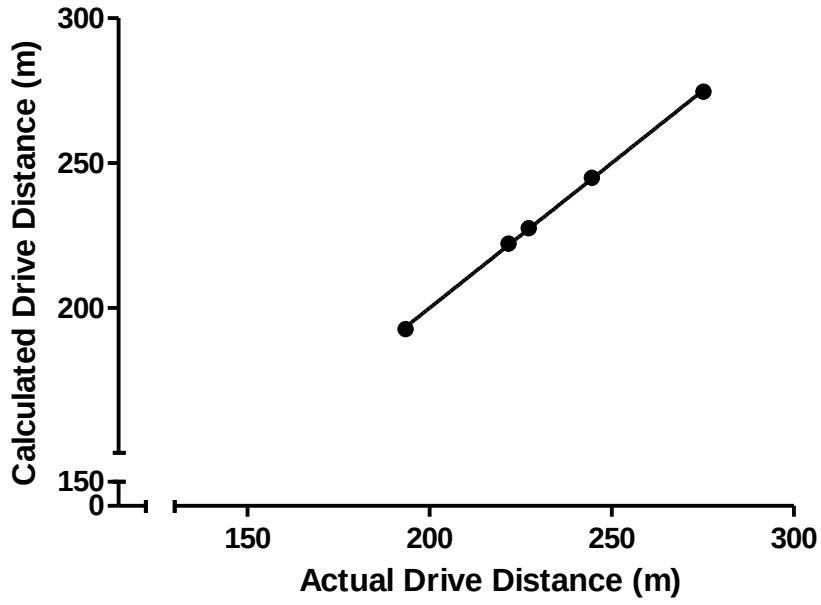


Figure 3.3: The Biomechanical model for achieving drive distances (n=5). Significant contributors include leading arm angle 16.51, left elbow angle -0.265, lateral bend -1,297. Intercept constant =207.05, R^2=0.9996, (Adjusted R^2 = 0.9985) Overall p value = 0.025

3.8 Walking differences

Prior to the 500m walk the 21 golfers had an average resting heart rate of 74 ± 15 beats per minute. Immediately after the walk the average heart rate for the 21 golfers was significantly elevated to 89 ± 16 beats per minute ($p< 0.001$).The change values noted in this dissertation are the differences between the before walking values and the after walking values. No

significant correlation was found between the changing in heart rate and the change in distance (r= 0.239, p= 0.297).

3.8.1 Changes in the shot outcomes

Following the 500m walk, the average drive distance for 10 shots was226.4 ± 40.0m with an accuracy of 18.6 ± 5.2m and centeredness of hit of 27 ± 7mm.The accuracy of the shots did not significantly improve following the walk, neither did the centeredness of ball strike on the club face.

3.8.2 Changes in balance

The results from the balance test are shown in Table 3.6.The balance tests show that there were no significant differences in the amount of time the participants could maintain their balance following the walk (Left leg eyes open: p=0.891 eyes closed: p=0.360; Right leg eyes open: p=0.325 eyes closed: p=0.841 (paired t test)).

Table 3.6: The lower quartile, median and upper quartile of balance time duration for 21 golfers following a 500m walk.

	Left Leg (s)	Right Leg (s)	Average Balance(s)
Eyes open	42.5, 60, 60	43, 60, 60	45, 60, 60
Eyes closed	5, 8, 26.5	5, 8, 18	5.5, 8.5,

3.8.3 Changes in hand-eye coordination

The average score for the hand-eye coordination task, following the 500m walk, was 2.4 ± 1.3 errors/second (53.5 ± 15.4 errors and 28.5 ± 15.8 seconds). The results from the paired t-test indicate that the golfers ability to perform the hand-eye coordination task improved following the walk ($p=0.045$, paired t-test). The time taken to complete the hand-eye coordination task was not significantly different following the walk ($p=0.652$) but the amount of errors was significantly lower ($p=0.004$).

Changes in drive distance did not significantly correlate with changes in balance with eyes open (right leg: $r= 0.364$, $p= 0.105$ left leg: $r= -0.03$, $p=0.888$), centeredness of strike($r= 0.026$ $p= 0.910$) or with changes in hand-eye coordination($r= 0.179$ $p= 0.437$).

3.8.4 Walking effects on the biomechanical action

The biomechanical variables following the 500m walk are reported in Table 3.7. Table 3.8 reports the change in angles, from the backswing position to contact position before and following the walk, with the differences brought about from the walk.

Table 3.7: Biomechanical variables collected for a sub-sample of the 21 male golfers after the 500m walk.

	Backswing		Contact		Follow through	
Angles (degrees)	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD
Left Wrist*	2	74.7 ± 4.4	7	15.8 ± 8.5	0	
Right Wrist	9	56.0 ± 17.0	10	25.7 ± 14.5	0	
Leading Arm	11	170.5 ± 1.3	11	167.1 ± 1.0	0	
Left Elbow	10	134.5 ± 20.1	10	154.8 ± 11.8	0	
Right Elbow	11	68.8 ± 10.6	11	151.1 ± 10.0	0	
Lateral Bend	10	39.3 ± 20.4	11	15.5 ± 6.2	0	
Hip rotation	11	52.9 ± 13.6	11	27.2 ± 12.2	11	88.6 ± 21.3
Shoulder rotation	11	93.5 ± 14.3	11	16.0 ± 10.1	11	125.1 ± 24.7
X-Factor	11	40.6 ± 13.4	11	-11.7 ± 13.7	11	36.4 ± 22.0
Pelvis elevation	11	-0.7± 2.6	11	14.5 ± 3.3	11	14.2 ± 1.9
Shoulder elevation	11	-1.8 ±1.8	11	4.1 ± 3.2	11	0.4 ± 3.2
Left Knee	11	134.5 ± 9.2	11	165.9 ± 6.3	11	166.3 ± 8.2
Right Knee	11	156.6 ± 7.1	10	154.0 ± 9.8	11	153.8 ± 9.0
Left Ankle	11	93.9 ± 6.2	11	78.7 ± 10.0	11	79.0 ± 7.2
Right Ankle	11	82.8 ± 4.3	10	73.5 ± 15.8	11	45.6 ± 20.4
Left Femur aspect	11	13.8 ± 12.0	11	35.4 ± 16.1	11	41.8 ± 9.0
Right Femur aspect	11	146.3 ± 9.9	10	157.2 ± 18.6	11	34.4 ± 19.8
Left Ankle aspect	11	36.6 ± 4.0	11	34.5 ± 7.0	11	38.4±10.5
Right Ankle aspect	11	142.4 ±4.7	11	145.1 ± 9.6	11	147.2 ±45.2

* Sample size for left wrist at backswing insufficient for appropriate statistical test.

Table 3.8: The change in biomechanical angles from backswing to contact position resulting from the 500m walk and the correlation with the change in the drive distance achieved.

Angles (°)	n	Before	After	Change	r
ASIS rotation	7	-43.11±43.75	-23.06±21.97	20.05±32.57	-0.115
Shoulder Rotation	7	-86.28±33.47	-74.38±19.46	11.90±17.93	-0.325
Left Knee	7	30.77±9.47	29.09±8.76	-1.69±7.17	-0.131
Right Knee	6	-5.40±5.03	-6.65±11.33	-0.98±7.73	-0.577
Left Femur Aspect	7	22.41±13.09	27.50±26.38	5.08±20.99	-0.510
Right Femur Aspect	6	16.19±16.11	13.69±21.28	-5.06±10.85	0.872*
Left Ankle	6	-20.71±15.31	-14.11±14.63	7.02±9.00	-0.500
Right Ankle	6	-11.70±14.14	-13.68±14.45	-1.97±4.49	-0.167
Left Ankle Aspect	7	1.07±9.57	-1.51±3.72	-2.58±11.63	0.140
Right Ankle Aspect	7	7.28±20.13	4.76±6.69	-2.51±14.13	0.289

* $p < 0.05$

In the contact position the change in right femur aspect also predicted the changes in drive distance (Table 3.8), but this same relationship is not seen at the level of the ankle. A significant reduction in the right ankle angle occurring in the contact position is evident following the walk ($p=0.04$) (Table 3.8). There was no obvious correlations between the changes in right leg balance with eyes closed and any leg aspects or leg angles.

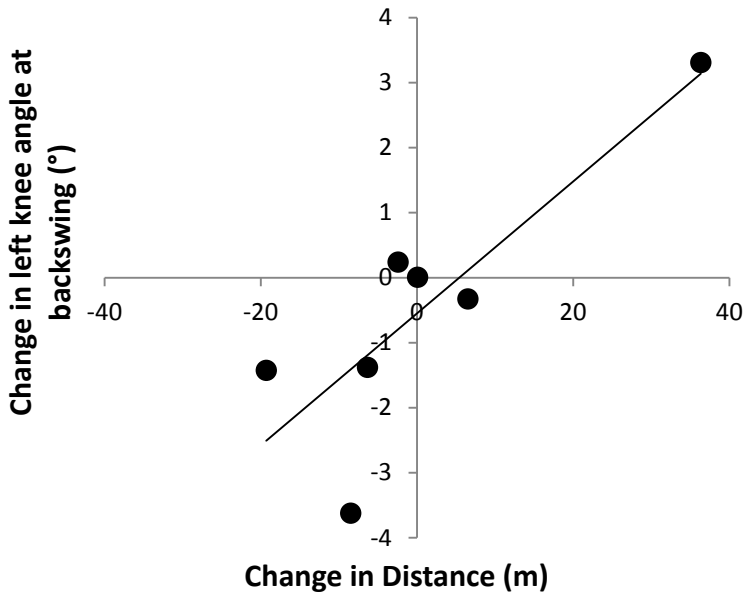


Figure 3.4: The correlation between the change in left knee angle at backswing (°) and the change in drive distance (m) in a sub-group of 7 golfers. R^2 = 0.712 r= 0.844 p=0.017.

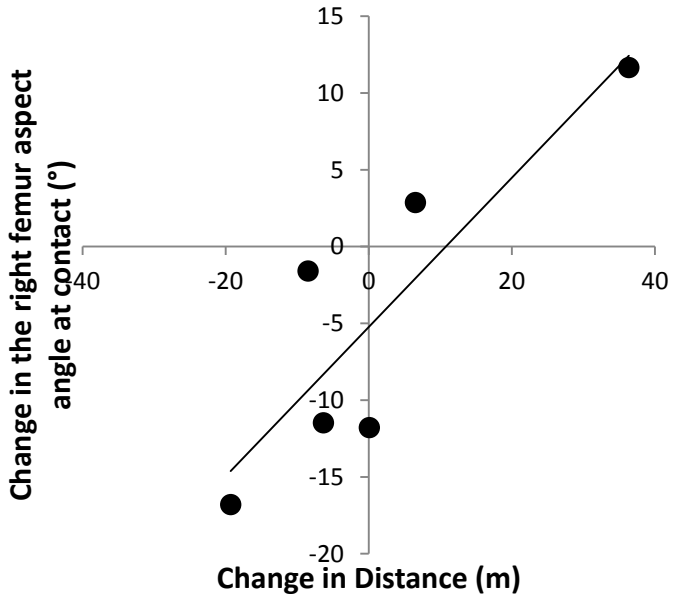


Figure 3.5: The correlation between the change in right femur aspect angle at contact (°) and the change in drive distance (m) in a sub-group of 6 golfers.R^2 = 0.751 r= 0.867 p=0.025.

Biomechanically, the change in drive distance was positively correlated to left knee angle change at backswing (Figure 3.4). In the contact position the change values in distance was correlated to the change in right femur aspect (Figure 3.5). The only relationship between movement variables describing the swing in our golfers (in a subgroup of six golfers where this analysis was possible) was where changes in right femur aspect from backswing to ball contact were significantly correlated to changes in pelvic rotation from backswing to ball contact ($r=0.872$ $R^2= 0.930$, $p= 0.002$).

3.8.5 Analysis of walking effects in two groups of golfers with different skill levels

All of the physiological results up to this point have been for the whole group of 21 golfers. To further investigate any changes that may result from the effects of a 500m walk the 21 golfers were divided into two groups based on their recent average scores. The More Competitive Group (MCG) had recent average scores of 88 or less and the Irregular Social Group (ISG) had scores of 89 or higher. The demographics, recent average scores and amount of annual rounds are reported in Table 3.8. Significant differences are observed between the two groups in the amount of annual rounds of golf and their recent average scores (Table 3.9).

Table 3.9: The demographics, recent average scores and amount of annual rounds of golf for the two groups of male golfers.

	More Competitive Group	Irregular Social Group	p
n	13	8	
Age (years)	39.2 ± 14.6	34.1 ± 9.8	0.402
Height (cm)	177.2 ± 8.2	176.4 ± 5.2	0.796
Mass (kg)	86.7 ± 14.3	79.9 ± 14.2	0.304
Average Score (strokes)	82 ± 4	97 ± 9	<0.001
Annual golf rounds	60 ± 25	9 ± 3	<0.001

The MCG improved their drive distance by an average of 10m (p= 0.018), whereas there was no significant change in drive distance in the group of ISG. Neither the accuracy of the shots nor the centeredness of the ball strike on the club face were significantly different following the walk for either group (Table 3.10). The results of the balance tests (Table 3.10) show that there was no significant differences following the walk in the amount of time the participants in either group could maintain their balance, under both conditions. Additionally, there was no change in the two groups regarding the hand-eye coordination task. Although the heart rates of both groups were significantly higher following the walk, these were not different between the groups. Changes in the ability to balance on the dominant leg with eyes closed was correlated to changes in drive distance (Figure 3.6 A), with a stronger relationship when isolating ISG (Figure 3.6 B).

Table 3.10: The effects of a 500m walk on two groups of golfers differentiated based on their average game scores.

	Before		After	
	MCG	ISG	MCG	ISG
Drive Distance (m) † ‡	237.6 ± 29.0	195 ± 35.9	247.1 ± 25.6	194.7 ± 31.2
Drive Accuracy (m)	19.7 ± 5.2	20.9 ± 7.9	19.6 ± 4.8	18.3 ± 6.6
Distance from centre of golf club (mm)	29.7 ± 8.1	26.8 ± 4.9	26.5 ± 6.6	27.2 ±7.0
Hand-eye Coordination task (errors/s)	2.6 ± 1.2	3.0 ± 0.9	2.3 ± 1.4	2.4 ± 1.2
Balance Left Leg Eyes open (s)	50.9 ± 14.8	49.9 ± 18.8	48 ± 20.7	55.4 ± 8.6
Balance Right Leg Eyes open (s)	52 ± 17.8	48.6 ± 17.2	47.7 ± 17.9	49 ± 19.2
Balance Average Eyes open (s)	51.5 ± 16.0	49.3 ± 15.2	47.8 ± 19.2	52.2 ± 12.9
Balance Left Leg Eyes closed (s)	14.5 ± 16.9	12.6 ± 10.3	14.8 ± 16.6	19.8 ± 19.1
Balance Right Leg Eyes closed (s)	10.8 ± 9.4	18 ± 20.7	9.8 ± 6.4	18.5 ± 17.3
Balance Average Eyes closed (s)	16.4 ± 15.4	15.3 ± 13.9	12.3 ± 11.1	19.1 ± 14.3
Heart Rate (beats/minute) *	72.1 ± 13.8	78.1 ± 17.5	89 ± 15.6	89.1 ± 18.5

* significant difference between before and after walk

† significant difference in More Competitive group between before and after walk

‡ significant difference between the More Competitive and Irregular Social groups

ISG= Irregular Social Group scores > 89.

MCG= More Competitive Group scores ≤ 88.

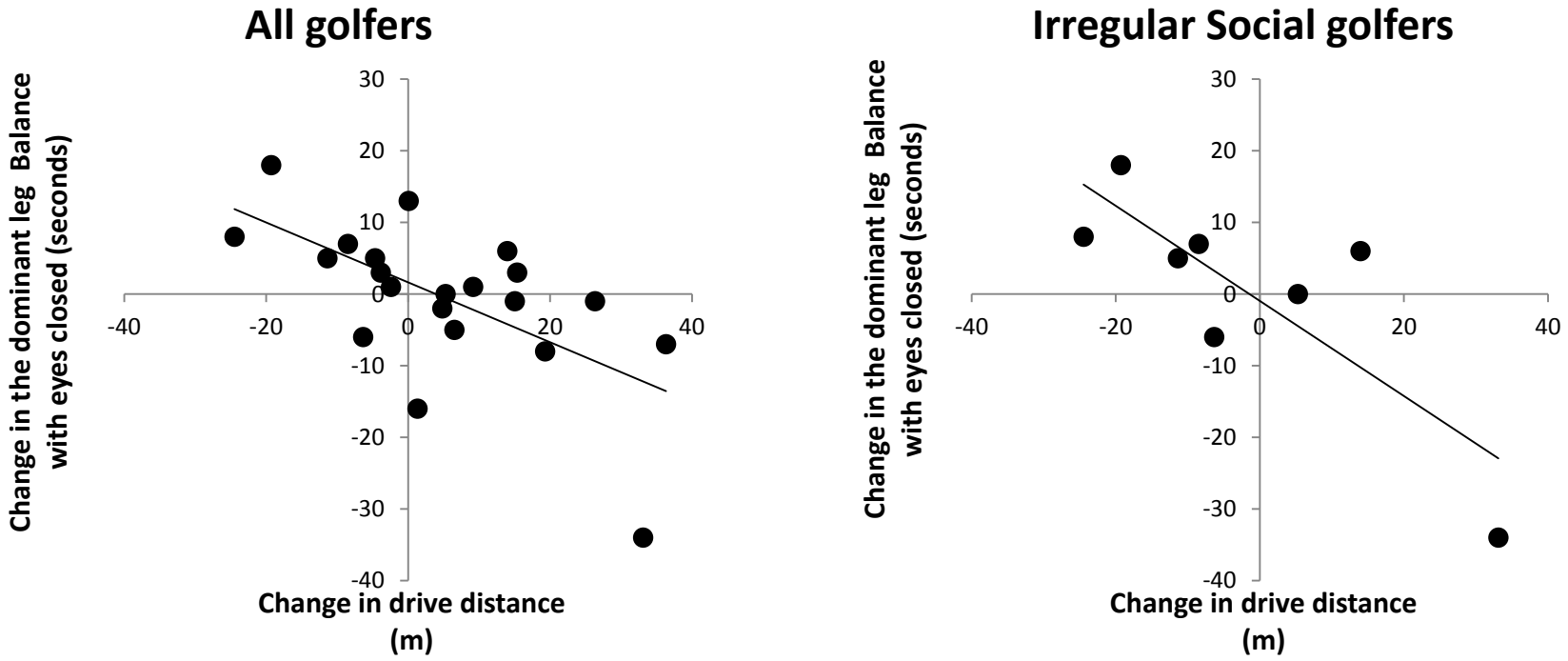


Figure 3.6 A and B: (A) The correlation between the change in balance in the dominant leg with eyes closed (seconds) and the change in drive distance (m) in a group of 21 golfers. $R^2 = 0.383$ r=-0.619 p=0.003, and (B) in a group of 8 golfers with scores greater than 89 strokes. $R^2 = 0.650$ r=-0.807 p=0.016.

Chapter 4

Discussion and Conclusions

4.1 Summary of main findings

The results presented in this dissertation indicate that to effectively execute a golf swing the golfer requires: a high level of fine motor control, as shown by in hand-eye coordination and the ability to balance. Variables that positively correlate to drive distance included: balance time and percentage lean mass. These variables, when combined with age were able to be statistically incorporated into a model that closely predicts drive distance. Other variables that correlated with drive distance included: the novel hand-eye coordination task, handicap and recent average scores. When considering biomechanical variables, the drive distance can be increased when the golfer acquires the relevant body segment positions which allow for greater transfer of energy to the ball. In particular the leading arm angle, the left elbow flexion angle and the lateral bend angle.

Walking is an essential component of the game of golf, however knowledge about the influence of walking on the biomechanical action of the golf shot is largely unknown. The results presented in this study would suggest that walking not only affects the physiology of the golfer, but can also alter the resulting golf swing mechanics.

The accuracy of the drive was not significantly correlated with any of the physiological or biomechanical predictors measured in this study. It is likely that accuracy is determined by other aspects of the golfers' anthropometry, physiology and human biomechanics and is likely to be predicted by variables more closely examining contact of the club face on the golf ball. Although the physiological predictor could not determine the accurate outcomes of the golf drive, many physiological attributes of a golfer were shown to be related to golf drive distance.

4.2 Balance

Balance is a multifaceted motor skill requiring integration of visual, vestibular and somatosensory information to produce postural actions [and stability] (Vereeck *et al*., 2008). More proficient athletes have been shown to have better balance than lesser skilled athletes (Hrysomallis 2011). The better balance in the more proficient athletes has been attributed to practising the motions of a particular activity, resulting in an improved ability to respond to proprioceptive and visual inputs (Hrysomallis, 2011). Furthermore, better golfers were shown to have superior postural control at different phases of the swing (Wrobel *et al*., 2012).

The important contribution that the ability to balance plays in golf performance is illustrated by the significant correlations between drive distance and the results of the stork test, as well as the inclusion of the left leg balance in the predictive physiological model from the current study, agrees with studies on older golfers (Tsang and Hui-Chan, 2010) and in a group of highly proficient golfers (Sell *et al*., 2007). My results demonstrate how drive distance is affected by the golfers' ability to balance. It is likely that non-dominant leg (usually left leg) balance is more important to achieving further drive distances. It is probable that the greater role that the non-dominant leg balance may play is attributable to the larger proportion of total body mass which is supported by the non-dominant leg in the follow through phase of the golf swing. The correlation with the dominant leg and drive distance in this study could indicate the weight transfer during the backswing phase where the body centre of mass is shifted towards the dominant leg (Wells *et al*., 2009).

Balance in golfers has been investigated by Sell and colleagues (2007) and their results indicated that balance was correlated to drive distance, however the indirect nature of this study does raise some uncertainty over the findings reported. The drive distances were self reported by their participants and not directly measured which could result in over or

underestimation of the distance measurements. In contrast to the Sell and colleagues study, Wells and colleagues (2009) failed to show a correlation between balance and drive distance, however non-dominant leg balance was shown to correlate with the amount of greens hit in regulation indicating a potential relationship between balance and accuracy. Wells and colleagues (2009) measured balance in a similar fashion to the procedures in this study. Similarly the balance protocol used by Wells and colleagues (2009) had no upper limit cut off. They subsequently did not find any significant relationship with the static balance and drive distance. An interesting note is the average balance time duration for their male participants and the participants in this study. The averages (repeated three times on each leg) of the balance protocol used by Wells and colleagues (2009) was: dominant leg average of 31.2 ± 14.5 seconds and non-dominant leg average of 32.2 ± 16.2 seconds, which are considerably lower when compared to the values in this dissertation (51 ± 15 non dominant leg and 53 ± 16 dominant leg).

Balance tested in the present study was a simplified field test and not the more precise force platform technique that was used by Sell and colleagues (2007). The latter balance tests allowed for the quantification of centre of pressure sway across the two axes quantifying the mediolateral and anterior-posterior sway along with the vertical ground reaction force. The sensitivity of the balance measurements increases when using a force platform to quantify balance (Era *et al*., 2006). Indeed, the minor sway of the body that is quantified when using a force platform will not be observed when using a simple balance test. The present tests were only terminated when the single observer could visually determine any movements to be considered loss in balance or that balance was needed to be regained. Although I have shown a significant correlation between balance duration and drive distance more sensitive methods may reveal more insightful mechanisms into the relationship between balance ability and drive distance.

The need for a stable base of support during the golf swing is well documented (Thompson *et al*., 2007, Worsfold *et al*., 2008, Jagacinski *et al*., 2009). A stable base of support with sufficient coverage for centre of mass movement allows for maximal trunk rotation and optimal weight transfer (Thompson *et al*., 2007, Worsfold *et al*., 2008, Gordon *et al*., 2009, Tsang and Hui-Chan, 2010). Furthermore, Best and Ball (2007b) suggested that in the front foot type of weight shifting golfers that have a widened stance may be beneficial to increasing club head velocity. Although neither the width of the stance or the weight shift type were quantified directly in these studies their important contribution to the golf shot is likely to have contributed to the biomechanical variables noted as well as the resulting drive distances.

The ability to control weight shift is a differentiating factor, allowing for the discrimination of good and average golfers (Oduka *et al*., 2010), and must be directly related to the ability to balance and proprioception of the golfers' lower limbs. This could be related to the flexion and aspect of the joints of the legs. The ability to maintain the body posture during the golf swing and dynamic control of the weight transfer is a direct measure of the dynamic balance of the golfer (Hrysomallis, 2011). However to quantify dynamic balance in a field test (as was the case here) is not always possible as it requires specialised equipment in a controlled setting.

The ability to balance may be affected by the interaction between the golfer and the surface on which they are being tested (Vereeck *et al*., 2008). This relationship may be compounded by the addition of golf spikes present under the sole of the golf shoe (Worsfold *et al*., 2009). These spikes may improve stability. Sell and colleagues (2007) along with Lephart and colleagues (2007) had their subjects perform balance procedures with eyes open and eyes closed and barefoot using force platforms, the studies found that balance differed between golfers of various skill level (Sell *et al* 2007) and improved following a training regime

(Lephart *et al* 2007). It is likely that the addition of golf shoes would be a true reflection of the golfers' ability to balance as they require these specifically designed shoes to play (Worsfold *et al*., 2008). Balance, in this study, was determined wearing golf shoes and on a level patch of grass, to emulate real golf situations. The decision to select a 60 second cut-off for balance is a potential limitation of this study, with a high percentage of golfers having the test terminated at this level. However the cut off was necessary to maintain the testing of the golfers balance and not the golfers' limits of fatigue (Vereeck *et al*., 2008). Despite this, the positive correlations shown testify to the obvious importance of balance ability for the golf drive.

4.3 Coordination

Conventional hand-eye coordination tasks tests the fine motor skill of the upper body segments and the interaction between segments, requiring motor control of arm segments and the hand to accurately perform the task. Hand-eye-club coordination was tested in this study using the three dimensional maze which was placed in a similar location to where a golfer would need to make corrections to their swing in order to effectually strike the ball. The maze was designed to test the rotational control of the wrists in both the horizontal and vertical planes while in a forward and backwards motion. The hand-eye coordination task used here not only tested the complexities of fine motor coordination as per Natarajan and Malliga (2011) but tested it including the ability to control a golf club. The negative correlation between drive distance and the hand-eye coordination task would suggest that the golfer's ability to control their hand and upper limbs would greatly affect their ability to strike the ball.

The relationship between the hand-eye coordination task and drive distance is supported by the findings of Grigore and colleagues (2012) who showed that participants from contact ball sports such as basketball show better hand-eye coordination than swimmers or gymnasts. Whole body coordination and proprioception are likely to affect drive distance (Knight, 2004, Neal *et al*., 2007, Keogh and Hume, 2012) which is more inclusive than the discreet measurements of fine hand-eye coordination made in the present study. The coordination of the upper body segments may be key factors when determining the timing of a good golf shot (Neal *et al*., 2007, Keogh and Hume, 2012). It is only when all of the different facets of the golf swing are combined that the shot will be well executed as multiple factors relate directly to the energy transfer via the kinetic chain (Penner, 2003). The golf club's position, speed and aspect of the face is vital to the performance outcome of the shot (Knight, 2004), yet this non physiological extension of the player (the club) has no way to convey sensory feedback to the golfer. This is further compounded by less experienced players being unable to determine errors in their swing sequence (Knight, 2004). The motions and feedback mechanisms require time to develop (Bradshaw *et al*., 2009). Furthermore, the "feel" of the swing or timing of the body segments during the swing is thought to relate to centeredness of hit (Neal *et al*., 2007, Jagacinski *et al*., 2009).

A major finding of my study is that there was no relationship between the hand-eye coordination task and the centeredness of hit. It was hypothesized that the centeredness of hit would be as direct result of the golfer's ability to manipulate the golf club. The effects of the golfer being able to maintain the perfect strike plane at contact might be the only factor that determines the centeredness of hit. MacKenzie (2012) suggested that maintaining the club along a single plane may reduce the striking error at ball contact. The golfers with better hand-eye coordination scores may be able to correct the position of their arms and hands to the optimal position while ensuring the correct strike angle of the club face. The lack of

relationship between the hand-eye coordination task and the centeredness of hit might be attributable to the advances in the designs of modern day drivers, which aims to improve ball strike by increasing the "sweet spot" area on the club face. Note that further aspects of whole body coordination and skill are addressed in the discussion of the biomechanical data.

4.4 A physiological model for drive distance

In the present study, the factors affecting the variation in drive distance included age, lean body mass percentage and left leg balance, as seen in the stepwise multiple regression analysis for the physiological factors (figure 3.2). According to established statistical convention, a stepwise regression only included variables that contribute to a model's predictability of the independent variable (Wormgoor *et al*., 2010). The resulting variables that are therefore included in the statistical model must describe different distinct predictive aspects of a model (and not be themselves, correlated). The strong evidence for balance as a correlate of drive distance is once again shown in the inclusion of non-dominant leg balance into the physiological regression model, which accounts for 67% of the distance variation. Other significant contributors in the physiological model included lean mass percentage and age. Lean mass percentage was expected to contribute to drive distance as muscle strength of the chest has been shown to correlate to club head speed (Gordon *et al*., 2009). Similarly, Wells *et al*. (2009) showed that power performance and muscle strength were both significantly correlated to drive distance. The inclusion of age in the physiological model must be taken with caution as age increasing the distance achieved will not continue to be linear as other age related factors will begin to contribute. It is likely that in this sample the age relationship is an indication of years of playing. The more years of experience a golfer has increases the likelihood that their coordination and timing sequence of body segments

will be well defined. Other known correlates of drive distance include flexibility (Gordon *et al*., 2009) and trunk rotational strength (Keogh e*t al*., 2009). By including flexibility and trunk rotational strength to the physiological factors it is likely that the physiological regression model could be improved further. The lack of inclusion of the hand-eye coordination task in the physiological model would suggest that whole body coordination instead of fine motor coordination is more important to the golf swing.

4.5 Biomechanics

When investigating physiological variables that result in kinematic descriptors of the golf swing, it was found that the relationship exists between the right leg balance (eyes closed) and the right femur aspect angle at ball contact. In the ball contact position, it is essential that the golfer maintains a functional level of balance, while the greatest momentum shift possible from leg to leg is used to transfer kinetic energy to the club and ball (Chu *et al*., 2010). In the previously mentioned correlation balance duration was determined with closed eyes biasing the likely sensory inputs for balance towards the vestibular, mechanoreceptive and muscular proprioception sense. A similar relationship was seen with the changes in the dominant leg balance with the eyes closed and the change in the drive distance following a 500m walk. This latter relationship will be discussed in more detail with the effects of the walk later.

This balance function was particularly evident when the golfers are divided into two groups, where the Irregular Social golfer, may not have refined the ability to process proprioception that the golf drive demands to the extent that more accomplished golfers can. Knight (2004) noted that novice golfers are often unable to determine what they have done correctly, which might be attributed to poor sensory-motor feedback. In addition, Tsang and Hui-Chang(2004) noted that the physical demands of golf, both walking and the biomechanical action of the

swing, may explain the differences between elderly golfer and young non golfers and their abilities to control balance, centre of pressure and the proprioception around the knee joint. The weight shift around the knee joint could be similar when the balance is tested to that during the swing. The data in this study showed that the relationship seems to occur at the level of the knee and not lower at the ankle joint, since a significant correlation between the change in drive distance and the change in knee rotation aspect, and not the change in ankle rotation aspect. Furthermore the relationship between the right knee rotation aspect at ball contact and the ability to balance with eyes closed may provide some insight into the physiological mechanisms that are responsible for balance control during the golf swing.

In the follow through position the left and right ankle aspect were correlated to the drive distance achieved, which may imply that the rotation around the ankles are related to the weight shift. In the discussion that follows, reference to left and right limbs as they appeared in this study (with all subjects being right side dominant). Note that in left side dominant golfers the opposite orientation would be appropriate. The greatest proportion of weight is usually supported by the left leg at the follow through stage of the swing (Worsfold *et al*., 2009). Ankle rotation allows for this weight shift to occur whilst maintaining a stable base of support for the large rotations of the pelvic (Knight, 2004) and shoulder girdles (Gordon *et al*., 2009). Movement of the ankle does not itself contribute greatly to weight shift at this stage of the swing (Worsfold *et al*., 2009). Rotation of the right ankle does however, contribute more to whole body rotation than the left ankle because of the completion of the weight transfer from the right leg at the backswing position to the left leg in the follow through position. Although Knight (2004) suggested that an open left toe (orientation of the left foot rotated towards and not perpendicular to the direction of target) at the follow through phase of the swing would allow for a greater pelvic rotation. Note that no such relationship was found here. During the swing itself the golfer attempts to keep their feet stationary and

free from unnecessary rotational movement that may lead to their feet being lifted off the ground which could cause loss of balance and power (Adlington, 1996). The development of upward momentum towards the end of the swing is most effective when the golfer can generate and maintain that power within their stable base (Hume *et al*., 2005, Worsfold *et al*., 2008). The rotation of the foot at the ankle joint, (in this study, defined as ankle aspect) may be detrimental to the development of power, which may be lost in an attempt to remain balanced.

In contrast to ankle rotation, rotation occurring at the level of the knee may facilitate the rotation of the pelvis. This rotation of the knee occurs dynamically during the swing and would not require the golfer to change their address position or to move their feet during the swing. It allows the feet to maintain the balance while the transfer of power can continue.

4.6 A Biomechanical model for drive distance

The multiple regression model of distance which included biomechanical factors accounted for 99.97% of the variation in a sub-group of five golfers (the number of subjects where analysis was possible). The greatest contributory factor accounting for the largest proportion of variation in drive distance in the latter biomechanical model was leading arm angle (beta coefficient of 16.5). The transfer of energy from the shoulders to the arms via the wrists to the club head using the kinetic chain model utilises the wrists to produce final addition of velocity to the club head (Hume *et al*., 2005). The leading arm angle in this study identifies the importance of the velocity transfer from the shoulder to the arm.

The two factors that had negative beta coefficient in the predictive model were the left elbow angle and the lateral bend angle (beta coefficient -0.27 and -1.3, respectively). An increase in

both of these angles may reduce the optimal amount of energy being transferred to the club. Previous research where left elbow angle was incorporated into optimizing models (Sharp, 2009) suggested that a fully extended elbow enables transfer of the most amount of kinetic energy to the club head and in turn the ball. However a fully extended elbow may not be the optimal method for achieving greater drive distance. The extent of lateral bend may affect the power generated around the central hub and could reduce the initial amount of energy of the golf swing. The lateral bend in this study was calculated in a (purposefully) different manner than the lateral bend calculated in other studies where the lateral bend is calculated as the movement of the torso relative to its address position (Chu *et al*., 2010) or as the angle between the shoulder and pelvic girdle (Zheng *et al*., 2008). The lateral bend measurement in the present study was the angle created between the thoracic and pelvic planes. This angle is likely to give a representation of the lean or bend that occurs in the body instead of a plane projection. The lack of flexion between the thoracic and pelvic planes may reduce the upwards generation of power in the whole body kinetic chain complex. By optimizing the upper plane (thoracic segment) flexion relative to the lower (pelvic plane) may assist in the weight shift, whereby the momentum of the body is most favourable at ball contact. One must be cautious when assessing the biomechanical model for distance for the angles used in the predictive model are not instantaneous angles from a specific position in the golf swing, but rather the change in angle from the backswing to ball contact. Therefore these numbers are an indication of the entire downswing and not event specific. The biomechanical model for drive distance in this study highlights the importance of the upper body segments kinematics during the swing. Furthermore it identifies the interactions between the left shoulder and elbow along with the extent of lateral flexion between torso segments in predicting total drive distance.

4.7 The effects of walking

Heart rate was significantly elevated following the 500m walk. Walking during a game of golf has been shown to elevate the golfers' heart rates to an average of 94.8±12.3 beats.min^{-1} (Hayes *et al*., 2009), which is similar to the average post walking heart rates observed here (89±16 beats.min^{-1}). Smith and colleagues (2012) alluded to the association between fatigue and a perceived decline in ability, in dehydrated golfers, identifying that the perceived effort of the task may increase. Lane and Jarrett (2005) showed that a change in mood states occurred following a round of golf in senior players who perceived their mood as fatigued. These two studies, testify to the known demands that a golfer must contend with during the average golf game. It is interesting to note that the changes heart rate was not significantly correlated to the changes in drive distance. This is likely due to the method used to measure heart rate. In this study heart rate was measured twice, once as resting and the other immediately after the walk. It is likely that a continuous measure of the heart's activity would identify the golfers' ability or lack of ability to reduce sympathetic tone prior to taking the shot.

In the present study, the only variable that statistically significantly improved for the combined group (both ISG and MCG) following the walk was hand-eye coordination. It is likely that this improved ability to perform the hand-eye coordination task should be viewed with caution however that is, although the results may suggest that their hand-eye coordination may have improved following the walk, when the participant did the task prior to the walk they were naïve to the task and as such the fine motor skill needed to achieve minimal errors was not as refined. Following the walk they were more aware of the necessary movements they had to fulfil to complete the task. It is therefore possible that these results reflect a learning effect. It is possible that further evidence for a learning effect is bared out by the fact that the time taken to complete the task before and after the walk was not

significantly different, however the number of errors incurred were significantly lower. The lack of relationship between the changes in centeredness of ball strike on the clubface and changes in drive distance could be testament to the advances in current golf club technology. That is to say, that the modern club head (as used in this study) is insensitive to small changes that may be present in centeredness of ball strike.

After separating the golfers based on their recent average scores, the group of more competitive golfers (MCG) improved their drive distance by 10m while the irregular social group (ISG) showed no improvement in drive distance following the walk. It is important to note that an obvious difference between these groups of golfers is that that MCG group plays far more golf. Note also that, Fradkin and colleagues (2004) noted an increase in club head speed in a group of golfers that underwent a full body aerobic warm-up. The addition of an aerobic warm up may be beneficial when incorporated into the preparation of recreational golfers, as many golfers do not warm up adequately prior to the first shot of the golf round (Fradkin *et al*., 2001).It is possible that the increase in distance seen in the group of More Competitive golfers could be attributed to the effects of an aerobic warm-up. It is likely that the MCG took less time to aerobically warm up than the ISG, being more accustomed to doing so. Note that following a warm up segment coordination may have improved resulting in better ball striking and greater distances (Knight, 2004, Neal *et al*., 2007, Keogh and Hume, 2012), through the summation of forces (Gergley, 2010).

Changes in the ability to balance on the dominant leg with eyes closed were correlated to changes in drive distance following the walk with a stronger relationship when isolating the irregular social group. This relationship further highlights the importance of balance in the golf swing. This correlation may reflect how proprioception or vestibulocerebellar processing as used for balance when the eyes are closed, are important contributors to an effective golf swing. This function is particularly evident in irregular social golfers, where the

proprioceptive capacity needed for the golf drive may not be as refined as it is in the more competitive group of golfers and so might be more easily confounded by walking, which may in turn, lead changes in drive distance, less evident in the MCG.

Looking at the kinematic changes in values before and after the walk, the change in drive distance was positively correlated to left knee angle change at backswing and in the contact position to the change in right femur aspect. The direct correlation between the change in left knee angle at backswing and the change in drive distance is supported by Higdon and colleagues (2012) who recently confirmed the relationship between the effects of fatigue and the left knee angle at backswing using pathway analysis. They continued to show that the change in the left knee angle at backswing could be responsible for the changes in consistency and club head velocity (Higdon *et al*., 2012). The left leg in the backswing phase should have very little weight bearing effect as most of the weight at this point should be shifted to the right leg (Worsfold *et al*., 2009). The extension of the left knee should mediate a more pronounced transfer of weight to the right leg resulting in a greater drive distance. Chu *et al*. (2010) suggested that the flexion of the knee could assist in the facilitation of pelvic rotation. This idea is in agreement with the idea of the power of the kinetic chain being generated from the ground up (Hellström, 2009). The correlation between the change in drive distance and the change in right femur aspect angle at contact lends itself to the idea of the weight being transferred during the swing sequence. The right knee aspect seems to act in a similar fashion to the rotation angle of the foot. When the right foot is abducted it allows for a greater pelvic rotation at full backswing (Knight, 2004). This greater pelvic rotation allows for more energy to be built up and stored, to be released during the down swing (Hume *et al*., 2005). In this dissertation it was shown that there was a relationship between the changes in the delta values for the right femur and the changes in the delta values for pelvic rotation. The delta angles are the change in angle from the backswing position to the contact position and

how these delta values changed from before to after the walk. Therefore it seems that not only does the rotation of the pelvis require the correct flexion of the knee but will also require the knees rotation angles to assist in the generation and transfer of power.

Higdon and colleagues (2012) mention their study limitation regarding the number of swing that each golfer took and the distance that each walked. It is likely that the latter protocol could have induced a high level of fatigue that may not be observed in a normal game or would only reflect the long term fatigue that would only take effect later on during the golf game. They showed a reduction in club head velocity and accuracy after simulated golf fatigue. However in my study there was no significant change in the shot accuracy following the 500m walk. Additionally Higdon and colleagues (2012) mentioned that an indoor study further confounded the results found through the collection of data in a highly artificial setting. The present study was conducted at an outdoor driving range, where distance and accuracy could be directly determined. The participants' accuracy was determined by the perpendicular distance from the tee-target axis line, enabling the participants to select any shot that they were comfortable performing (fade or draw) in attempting to reach the target. During practice a golfer may need to adapt their swing in times of varying circumstances such as fatigue and the position of their feet on the various playing surfaces (Bradshaw *et al*., 2009). The number of shots taken with the driver was substantially less in this study than those in the Higdon *et al*. (2012) study. Participants in this study hit a maximum of 25 shots which even though is more than they would hit with the driver during a round, it would not likely have nearly as fatiguing an effect as the 140 completed golf swings of the latter study.

It must be noted that in this study we only simulated the effects of walking by making the participants walk 500m once off, and not multiple shorter distances that would be experienced on the golf course. Furthermore the study only evaluated the outcomes of one club, being the driver. In reality the golfer would select the driver to attain maximal distance

off the tee, and would rarely be used on consecutive shots. The very nature of the golf game makes it difficult to simulate the effects as the same shot will not have the same outcome on the golf course thereby changing the distance and aim to the next target.

4.8 Limitations

The 500m walk was done at the pace of that the participant was comfortable with and would reflect the pace they would normally walk on the golf course. However the variation in pace between the golfers was not noted and the walking pace would have a direct effect on the heart. Another limitation of this study is that the 3D maze has not been validated and needs to be tested against a standardised hand-eye coordination test using both control and experimental groups. Furthermore the participants were not allowed to practice the task before the commencement of testing.

The limitations of the biomechanical data were caused by the limited number (six) of high speed cameras and compounded further by the unnatural biomechanical movement that occurs during the golf swing. The biomechanical data were selected based on the quality of the video, being the videos that had the most visible markers. However the calculation of the variables requires certain markers to act as “zero” point when establishing local coordinate points. Without the established local coordinate points it is impossible to calculate the relevant variable. Furthermore the reduced sample size of the biomechanical data and the differences in the swing patterns of the participants have resulted in the high standard deviation values seen in this study.

This study is limited further by the type of equipment used such as bioimpedance, which is dependent on the physiological state of the participant and prone to errors from minor physiological disturbances.

4.9 Future studies

There is a need to determine the coordinative abilities of the golfer and their ability to ensure momentum transfer between the centre of the club face and the golf ball. The coordinative abilities may be the coordination of individual body segments, coordination between the body segments, fine motor coordination, whole body coordination or the efficacy of the entire coordination system, involving the proprioceptive, somatic, vestibular and central nervous system as well as all of the above.

The large variation of handicaps shown by golfers in the present study may have facilitated the significant correlations between drive performance and balance and coordination. Future studies could exclude less experienced golfers to only focus on a narrower range of handicaps to see if these relationships remain or whether other variables become more important in more distinct groups of golfers of similar abilities. The limit for the balance protocol of 60 seconds could be extended indefinitely until the golfer needs to regain balance, although this suggestion would need to occur in addition to (and not replacing) the type of measurements made in the present study so that the fatigue threshold of the individual legs does not confound coordination data. Whole body centre of mass sway during quiet standing and during the golf swing should be quantified to assess whether a relationship exists. Note that the latter recommendation would require a large number (recommend 18 or more) of high speed kinematic cameras.

More studies are required to investigate the interaction between leg rotations and weight distribution throughout the golf swing. This study is limited by the sample sized used to

determine the biomechanical relationships. However the statistical significance of the biomechanical variables here regardless of the small sample size would bear witness to the importance of upper body kinetic linkage and the stability of the lower limbs to the golf swing. This is particularly true for the lateral bend variable which was developed here to quantify the lean in the trunk. This new variable may add new insight into the kinetic chain and how the energy is developed and transferred between body segments.

4.10 Conclusion

In conclusion I have identified several factors that predict golf drive distance in a group of golfers ranging in ability from social players to more competitive golfers. I have done this by demonstrating that the combination of the components shown in the regression models as well as the individual or a combination of individual variables may result in greater drive distances. The regression models have indicated that physiological factors such as age, balance and lean mass percentage play a role in the achieved drive distances. Furthermore many of these physiological factors can independently predict the outcomes of the golf shot. I have also shown that individual leg balance is an important factor to a successful golf drive. In addition I have shown hand-eye coordination to be a determinant of golf drive performance as well as the ankle rotations in the swing sequence. However in contrast to the original hypothesis centeredness of hit had no relationship with the golfer's ability to manipulate the golf club through the 3D maze. The biomechanical predictive model indicates the importance of the upper body in the kinetic chain. Of particular interest was that no biomechanical or physiological variables were found to predict drive accuracy. It is likely that the accuracy of the golf drive is a combination of many physiological and biomechanical components and is not restricted to the variables tested in this study.

The idea that the physiological attributes contribute to the biomechanical action of the golf swing was a focus of the current dissertation. When identifying physiological attributes that can affect the golfers' biomechanical abilities it was shown that a relationship exists between the rotation angle of the right femur and balance ability. This idea combined with the relationships between the change in balance and the change in drive distance along with the change in right femur aspect and the change in drive distance highlight the importance of the underlying physiological control in the golf swing.

In the current investigation of the effects of walking on the golf drive and its candidate biomechanical and physiological predictor variables I have shown that the effects of walking on the golf swing are likely to include a warm up effect which is beneficial to a group of more competitive golfers. This is in contrast to the original hypothesis that the effect of walking on golf drive performance is that the walking will have little to no effect on the golfers' physiological and biomechanical abilities. The idea that walking may be beneficial during the early stages of the golf game was shown for the first time in this dissertation. A second important novelty of the studies described here is that improving the proprioceptive ability of irregular social golfers may improve their drive distances. Finally data supporting the importance of right knee rotation facilitating pelvic rotation was shown for the first time.

The data from the present dissertation have added to current understanding of the optimization of golf performance by illustrating the relevance of physiological ability and the upper body kinetics in predicting golf drive distance that directly or indirectly contribute to the highly complex biomechanical and coordinated body movements that make up the golf swing.

Chapter 5

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Chapter 6

Appendices

Appendix 1: Ethics Clearance Certificate

M110424

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG
Division of the Deputy Registrar (Research)

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
R14/49 Mr Andrew Green

CLEARANCE CERTIFICATE	**M110424**
PROJECT	The Biomechanical and Physiological Predicators of Golf Swing Performance
INVESTIGATORS	Mr Andrew Green.
DEPARTMENT	School of Physiology
DATE CONSIDERED	06/05/2011
DECISION OF THE COMMITTEE*	Approved unconditionally

Unless otherwise specified this ethical clearance is valid for 5 years and may be renewed upon application.

DATE 06/05/2011 **CHAIRPERSON** .....
(Professor PE Cleaton-Jones)

*Guidelines for written 'informed consent' attached where applicable
cc: Supervisor : Warrick McKinon

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10004, 10th Floor, Senate House, University.
I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. **I agree to a completion of a yearly progress report.**
PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES...

Appendix 2: Submission of a manuscript to the journal: Kinesiology

Kinesiology journal_preliminary evaluation results_article 968

From : Kinesiology Journal <kinesiology@kif.hr> Mon, 03 Dec, 2012 14:07

Subject : Kinesiology journal_preliminary evaluation results_article 968

To : 'Andrew Green' <Andrew.Green@students.wits.ac.za>

Editorial Office of
"KINESIOLOGY "
FACULTY OF KINESIOLOGY
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http://hrcak.srce.hr/index.php?lang=en&show=casopis&id_casopis=72

Dear Dr. Green,

This is to inform you that your manuscript No 968 has undergone preliminary evaluation procedure. As the results were positive, the manuscript has immediately been sent to regular peer review procedure. You will be contacted with the results of the evaluation as soon as possible.

With best regards,

On the behalf of Editor-in-Chief

Prof.DraganMilanović, PhD

Daniel Bok, MagEd, Junior Editor

The Physiological and Biomechanical Predictors of Golf Drive Performance

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Running title: Predicting golf drive performance

Intended Journal: Kinesiology

Key words: Co-ordination, balance, biomechanics

Appendix 3: Submission of a manuscript to the journal: South African Journal of Sports Medicine.

Re: [SAJSM] The effects of walking on golf drive performance in two groups of golfers with different skill levels.

From : Mike Lambert <Mike.Lambert@uct.ac.za> Wed, 14 Nov, 2012 10:03

Subject : Re: [SAJSM] The effects of walking on golf drive performance in two groups of golfers with different skill levels.

To : Andrew Green <Andrew.Green@students.wits.ac.za>

Thank you Andrew. I have received it and will get it started with the review process.

regards
Mike Lambert

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The effects of walking on golf drive performance in two groups of golfers with different skill levels.

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Running title: Walking: the effects it has on drive performance

Intended Journal: South African Journal of Sports Medicine

Appendix 4: Papers published during the candidature of this dissertation

Dafkin C, Green A, Kerr S, Veliotes D, McKinon W. (2013). A comparison between subjective assessment of the patellar reflex by neurologists, general practitioners and medical students; and objective kinematic measurements. Muscle & Nerve. *In press*.

Dafkin C, Green A, Kerr S, McKinon W. (2012). The Patella Reflex: Does activity of quadriceps femoris muscles reflect leg movement? *Neurological Research* **34**(6): 623-626.

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