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RELATIONSHIPS BETWEEN PHYSICAL AND BIOMECHANICAL PARAMETERS AND GOLF DRIVE PERFORMANCE: A FIELD-BASED STUDY

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ABSTRACT

A proficient golf swing is composed of a sequence of highly complex biomechanical movements and requires precisely timed and coordinated body movements to achieve great distance and accuracy. The aim of the current study was to identify the key physiological and biomechanical variables that relate to golf drive performance. Eighteen golfers (handicap 11±6 strokes, playing experience 18±15 years), volunteered to take part in the study. Drive distance and accuracy were measured directly. Balance was assessed using a modified stork test and hand-eye coordination was assessed using a 3D maze. Average balance duration of both legs (r= 0.563; p=0.015), left leg (r= 0.620; p=0.006) and right leg (r= 0.488; p=0.044) were all significantly correlated to drive distance. Hand-eye coordination was significantly negatively correlated to total drive distance (r=-0.600 p=0.008), but was not associated significantly with the centre of hit between the clubface and ball. Several parameters were found to have significant relationships to golf drive distance in a group of amateur golfers. Therefore, training regimes could include tasks that aim to improve hand-eye coordination and balance.

Key words: Co-ordination; Balance; Biomechanics; Golf; Performance.

INTRODUCTION

The game of golf requires players to strike a golf ball so that it travels long distances towards a small target (Hume *et al*., 2005). A proficient golf swing is composed of a sequence of highly complex biomechanical and coordinated body movements (Knight, 2004; Jagacinski *et al*., 2009; Wells *et al*., 2009; Keogh & Hume, 2012), which affect the distance and accuracy of the flight of the ball. To drive the golf ball effectively, a golfer needs to adopt various body positions throughout the swing, which requires well-developed postural control and balance (Smith, 2010). Sell *et al*. (2007) has suggested that finer balance, flexibility and coordination are all required to perform an effective golf swing.

It should be emphasised that the overall purpose of the golf swing is to develop a maximal amount of kinetic energy that is transferred directly to the golf ball (Nesbit & 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). Despite this, it should be noted that increasing the club head velocity alone might not result in an overall increase in the distance achieved during ball flight, because other factors, such as spin, may affect the accuracy and distance of the shot (Hume *et al*., 2005).

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

Weight transfer from one leg to another is as vital in achieving a successful golf swing (Hume *et al*., 2005) as a golfer's ability to control his/her balance (Smith, 2010). Additionally, a change in the position of the centre of gravity will allow a golfer to compensate for the position and momentum of the golf club (Burden *et al*., 1998). Proper 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).

Eye-hand-club coordination, the ability of a golfer to control their hand position, as well as the club, by using information received from the eyes, is also an important aspect of golf driving skill. Experienced golfers may be able to compensate for errors that may occur in the swing (Bradshaw *et al*., 2009). The ability to control the movements and position of the hands, based on information received from the eyes, is a highly complex task (Natarajan & Malliga, 2011).

Unlike other sport where hand-eye coordination is an important performance related component, the hand-eye coordination necessary for golf is compounded by properties, such as the length and loft of the golf club. 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). Although the effect of club type has been shown to alter the coordinative strategies of trained golfers' body segments (Shan *et al*., 2011), the interaction between the club itself and the hand-eye coordination of golfers has never been assessed.

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. Neumann and Thomas (2009) showed that experienced golfers had a lower heart rate than novice players just prior to putting, which indicates that experienced players are able to calm themselves before attempting the shot. The effect of an elevated heart rate on the performance of a golfer's drive shot is unclear.

PURPOSE OF STUDY

Despite anecdotal suggestions that hand-eye coordination is vitally important to a successful golf swing, quantified empirical proof that assesses the magnitude of the contribution that this variable makes to a successful golf swing is largely lacking. Therefore, there is a need to quantify the effects of balance and hand-eye coordination on the direct outcomes of the golf swing. It is hypothesised that the balance duration of a golfer should have a direct relationship to the drive distance achieved. Furthermore, it is expected that other physiological contributors, such as hand-eye coordination, and autonomic state (as measured by heart rate), will affect the drive performance of golfers. The results of this study may provide valuable insight into variables related to drive performance, which then might be incorporated into existing training programmes in order to improve golf drive performance.

MATERIAL AND METHODS

Participants

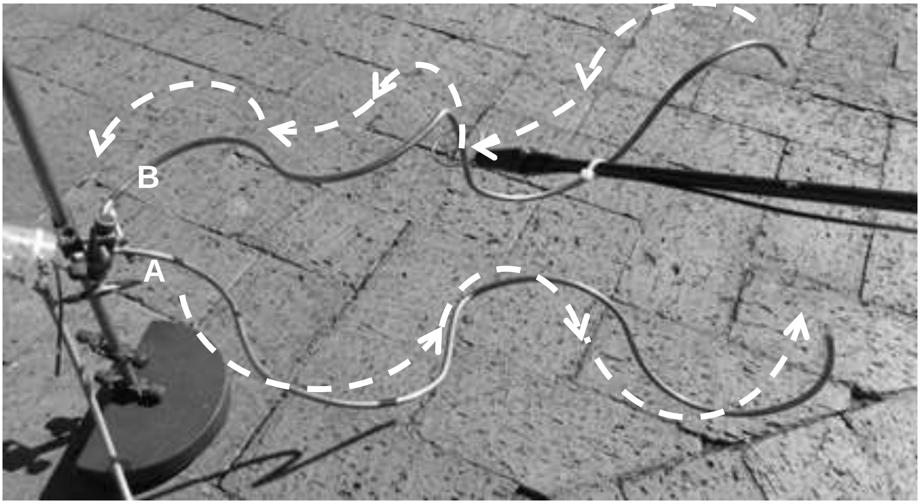
Eighteen right handed golfers (handicap 11±6 strokes, playing experience 18±15 years) with an average age of 36±13 years volunteered to take part in the study. The 18 golfers had an average height of 176.9±7.1 centimetres, body mass of 84.1±14.3 kilograms, lean body mass of 79.6±8.2% and heart rate of 74.4±15.1 beats/ minute. They had all played golf regularly in the past year (87±33 rounds a year) and were injury free at the time of testing. Ethical clearance was obtained from the Human Research Ethics Committee (Medical) of the University of the Witwatersrand (M110424) and written informed consent was obtained from all of the participants. All of the participants were recruited from a local practise facility.

Experimental procedures

In addition to participants being allowed to warm-up in their own accustomed manner, they were required to hit 5 practice balls under experimental conditions. Participants aimed their shots at a target, which was placed 260m from the tee at 1 end of a flat, grass, outdoor driving range. The accuracy was determined from the distance perpendicular from the tee-target axis to the resting position of the ball. Drive distances were determined from the intersection between the tee-target axis and the final position of the golf ball. The distance was measured, by using a retractable measuring line, as the distance between the final resting position of the ball and the tee. The participants hit 10 golf balls: 5 with their own driver and another 5 with a standard club. A standardised club was used to eliminate any manufacturer specific technologies that may have been present. All shots were hit from a standard tee. The centre of the clubface was identified by measuring the width and height. A piece of contact sensitive paper (70x35 mm) was placed over this position, so that the centres of the contact sheet and clubface overlapped, and was used to quantify the centeredness of hit for every shot.

Hand-eye coordination

Hand-eye coordination was determined by using a custom-made 3-dimensional maze constructed from brass tubing, which required a golfer to move a club through 360 degrees in both the horizontal and vertical planes (Figure 1). A wire loop fitted to the end of a driver's shaft was used to complete the task. 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 that closed when an error was made. The maze circuit was connected to a Powerlab 26T system (ADInstruments, Bella Vista, New South Wales, Australia), which allowed errors and maze duration to be recorded.



Participants were required to move the loop at the end of a driver shaft from starting point (A) to end point (B) as fast as possible without touching the maze itself. Dashed arrows identify the intended path.

FIGURE 1. **THREE-DIMENSIONAL MAZE TO DETERMINE HAND-EYE COORDINATION**

Participants were instructed to hold the club shaft with the same 2-handed grip (baseball, interlock or overlap), that they would use when holding a golf club. They were allowed to rotate their hands and move their arms and upper bodies while keeping their feet stationary, which would mimic the hand and arm movements that occur during the swing. Participants were instructed to complete the task as quickly as possible without incurring any errors. The maze was designed to test the rotational control of the wrists in both the horizontal and vertical planes while in a forwards and backwards motion, and was placed in a similar location to where golfer's would need to make corrections to their swing in order to strike the ball effectually.

Balance tests

Two balance tests were performed. The first test required the participants to raise one of their legs to create a 90-degree angle at both the knee and hip joints (Modified Stork test) (Hungerford *et al.*, 2007) with their hands positioned on their hips. The second test required the participants to stand on each of their legs in the same manner as before. Once the participants were in this position, they were instructed to close their eyes. The time that each participant could maintain balance was recorded to the nearest second for a maximum of 60 seconds. Each test lasted until balance had to be re-established by removing hands from hips, downward movement of raised leg or excessive lateral trunk movement. The time was recorded for each leg and the mean duration for both legs was calculated. Participants wore their golf shoes during the balance procedures.

Lean mass percentage was determined by bio-impedance using BodyStat 1500 (BodyStat, Douglas, Isle of Man, United Kingdom). Prior to the participants' warm-up, their sedentary ***heart rate*** was recorded after a seated period of 5 minutes using a heart rate monitor (Polar S610, Polar Electro Oy, Kempele, Finland).

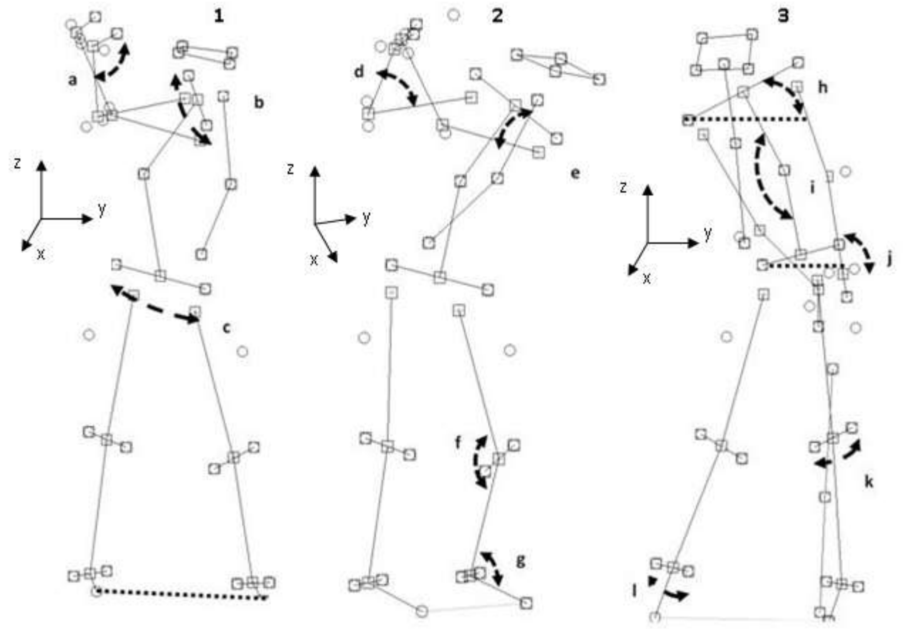
Biomechanical analysis

Biomechanical data was record at 250Hz using 6 Optitrack 250e (Natural Point Inc., Corvallis, Oregon, USA), high-speed cameras to capture all of the swings. All biomechanical data was analysed in MatLab 7 (Mathworks, Natick, Massachusetts, USA). The calibrated capture volume for trails was approximately ±32m^3, with volume calibration only being accepted when calibration residuals were less than 1mm. The *x*-axis corresponded to the anterior/posterior direction, *y*-axis to the medial/lateral direction, and *z*-axis to the superior/ inferior direction.

Retro-reflective markers (10mm diameter) were placed on the following anatomical landmarks: jugular notch; xiphoid process; 7th cervical vertebra; 10th thoracic vertebra; and sacrum. Additional retro-reflective markers were placed bilaterally on the first finger, acromion process, mid-point on the lateral aspect of the calf and thigh, anterior superior iliac spine (ASIS), first toe and heel. Furthermore, markers were placed both medially and laterally on the wrists, elbows, ankles and knees, and 4 markers on the head. Additional markers were placed on the rubber tee and the club head, to determine when ball contact was made. Virtual markers for joint centres were found using mathematics similar to the Plugin Gait model (based on Kadaba *et al*., 1990 and Gutierrez *et al*., 2003). Joint centres for elbows, wrists, knees and ankles were defined as the midpoints of the respective lateral and medial markers.

The calculated biomechanical variables are shown in Figure 2. Shoulder and pelvis rotations were the angles created by translating the shoulder vector line (right shoulder marker to left shoulder marker), and the pelvic vector line (Right ASIS marker to left ASIS marker), to the midpoint of the vector line established by the toe markers in the address position on the *xy*-plane. X-Factor was the difference between the shoulder rotation and pelvis rotation. All rotation values were calculated to the vector line created by the toe markers in the address position indicating the intended direction of the golf shot. Positive rotation values indicated rotations to the right of the intended target line. The leading arm angle was calculated as the difference between an established thorax vector (thorax tilt as defined by the vector from right shoulder marker to left shoulder marker), and the upper left arm vector (left shoulder marker to the virtual marker at the centre of the left elbow joint), where 180 degrees indicated complete abduction of the left arm and 0 degrees indicated complete adduction.

Shoulders and pelvis elevations were calculated using the vector lines transposed on to the *yz*-plane and compared to the toe vector line in the address position. The lateral bend was the angle created by 2 planes in the trunk. The first plane was established between the mid-shoulder point, xiphoid process and the 10th thoracic vertebra. The lower trunk plane was established between the xiphoid process, mid-anterior superior iliac spines and the sacral marker. A positive angle indicated flexion of the upper thorax towards the lower trunk segment. Knee and ankle rotation angles were calculated using the vector lines from the middle of the joint to the lateral marker, and compared to the vector created from the toes in the address position.



Position **1** *&* **2**= Full backswing; *Position* **3**= Ball contact - Full backswing (frame before downswing started), ball contact and end of follow through (when club shaft is stationary behind shoulders)

X-axis: Anterior/posterior direction; *Y-axis*: Medial/lateral direction; *Z-axis*: Superior/inferior direction
a= Wrist flexion angle **b** & **c**= Shoulder & pelvis rotations **d**= Elbow flexion angle
e= Leading arm angle **f**= Knee flexion angle **g**= Ankle flexion angle
h & **j**= Shoulders & pelvis elevations **i**= Lateral bend **k** & **l**= Knee & ankle rotation angles

FIGURE 2. **DEFINITIONS OF BIOMECHANICAL ANGLES**

The biomechanical analysis was performed at 3 stages (Figure 2): full backswing (the frame before the downswing started - downward movement of the club head); ball contact; and at the end of the follow through (when the club shaft was stationary behind the shoulders). The contribution of the arms in the follow-through position was found to have a minimal effect on the outcome of the shot. The variables related to the arms were excluded, as they were likely to indicate the dissipation of energy. The nature of the golf swing and the method of outdoor data acquisition resulted in the loss of kinematic data (markers not being visible), and thus a subsample of 7 participants with complete data sets underwent biomechanical analysis.

Statistical analysis

All data was tested for normality in Prism 5 (GraphPad, San Diego, California, USA) and presented as a mean±the standard deviation unless stated otherwise. Either Spearman's or Pearson's correlations were performed based on the distribution of the variables using the automated algorithms of Prism 5 (GraphPad, San Diego, California, USA), to determine the existence of any relationships with a significance level of $p<0.05$. A student's t-test was used to determine if there was any difference in the distance achieved when using each of the clubs.

RESULTS

No difference was found between the standard and the participant's club ($p=0.820$). All correlations were assessed with the average distance being calculated based on the combined distance values recorded for the standard and participants' clubs. The average drive distance over 10 shots was 227±37m with an accuracy of 21±6m from the intended target. The accuracy of the drive was not correlated significantly with any of the physiological or biomechanical variables measured in this study. The average distance from the club centre to the ball strike position was 2±7mm. The time taken to complete the hand-eye coordination task was 29±13 seconds with an average of 66±14 errors. The resulting score for the hand-eye coordination task was 2.7±1.1 errors/ seconds. The values for the balance test with eyes open were right leg 52.7±16.0 seconds and left leg 51.1±15.6 seconds (average balance 51.9±15.4 seconds). The values for the balance test with eyes closed were right leg 15±15 seconds and left leg 15±15 seconds (average balance 15±15 seconds).

TABLE 1. **CORRELATION COEFFICIENT VALUES OF DRIVE DISTANCE AND VARIABLES (n=18)**

Variables	r	p-values
Lean body mass (%) #	0.599	0.004*
Average balance (seconds) #	0.563	0.005*
Right leg (seconds) #	0.620	0.015*
Left leg (seconds) #	0.480	0.002*
Hand-eye coordination (errors/second) †	-0.600	0.024*
Handicap (strokes) †	-0.577	0.012*
Resting heart rate (beats/minute) †	-0.102	0.688
Playing experience (years) †	0.012	0.962
Golf rounds per year †	0.276	0.268

Spearman's correlation coefficient † Pearson's correlation coefficient
* Significance= $p<0.05$ Mean drive distance= 226.76±36.61m

Drive distance was correlated negatively to the hand-eye coordination task (Table 1) and correlated positively to balance as defined by an average duration for the balance task, both legs with eyes open. The correlation between the balance task duration for the left leg was greater than that of the right leg. No significant correlation was found between drive distance and balance with eyes closed. The distance from ball contact to the club's 'sweet spot' and the hand-eye coordination task was not significantly correlated (r=-0.428; p=0.07, Pearson's correlation). Further correlations of drive distance are recorded in Table 1, which shows the relationship between lower handicaps and greater drive distances.

TABLE 2. **BIOMECHANICAL VARIABLES AND PEARSON'S CORRELATION COEFFICIENT VALUES OF BALANCE AND DRIVE DISTANCE**

Variables (Angles in degrees)	**Backswing** n	 Mean±SD	**Contact** n	 Mean±SD	**Follow through** n	 Mean±SD
Left wrist	5	80.0±40.1	6	15.9±7.1		n.a.
Right wrist	4	79.6±63.6	6	34.6±13.8		n.a.
Leading arm	7	170.2±1.8	7	167.3±1.1		n.a.
Left elbow	6	139.9±15.1	7	139.3±37.5		n.a.
Right elbow	7	72.4±7.1	7	161.1±10.9		n.a.
Lateral bend	6	43.7±7.5	7	11.7±2.5		n.a.
Hip rotation	7	66.4±35.2	7	23.3±12.4	7	-86.9±10.9
Shoulder rotation	7	100.4±26.8	7	14.1±11.5	5	-57.8±11.3
X-Factor	7	34.0±32.3	7	-9.2±7.6	5	29.1±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 knee rotation	7	8.0±9.1	7	30.4±6.6	7	42.8±5.8
Right knee rotation	7	142.8±4.8	7	159.0±16.3†	7	40.9±18.5
Left ankle rotation	7	34.7±12.2	7	35.7±4.1	7	32.9±12.3*
Right ankle rotation	7	138.4±17.0	7	145.7±4.2	7	166.1±15.0*

* Correlated to drive distance (p<0.05) † Correlated to right leg balance, eyes closed (p<0.05)
n.a. = Arms at follow through not analysed

Note: Sample size (N=18) varies depending on visibility of reflective markers, which dictated ability to analyse data. Full backswing (frame before downswing started), ball contact and end of follow through (when club shaft was stationary behind the shoulders).

A subsample of the participants underwent full body biomechanical analysis. These variables are represented in Table 2. This sample (5 to 7 participants) was affected by the visibility of the markers at each phase of the swing. The only correlation (Pearson's) between the biomechanical variables at the contact position and the physiological variables was right knee rotation angle and balance duration with closed eyes (r= 0.835; p<0.05). Right ankle rotation angle (r= 0.781; p<0.05) and left ankle rotation angle (r= 0.769; p<0.05), at the follow-through position were shown to have a significant correlation with drive distance.

DISCUSSION

The results presented in this study indicate that the ability to achieve longer drive distances may be related to a high level of motor control, as shown during the hand-eye coordination task, as well as a level of balance control. Variables that correlated positively with drive distance included: balance time; and percentage of lean mass. Other variables that correlated with drive distance included the hand-eye coordination task and handicap. The accuracy of the drive did not correlate significantly with any of the physiological or biomechanical variables measured in this study. It is likely that accuracy is determined by other aspects of the golfer's anthropometry, physiology and human biomechanics and is likely to be related to variables more closely associated with the contact of the clubface with the golf ball. As expected and previously shown by Fradkin *et al.* (2004), the negative correlation between handicaps and total drive distance (club head velocity in the case of Fradkin *et al.*, 2004), was present in this study.

The important contribution that the ability to balance plays in golf performance, as shown in the data, agrees with studies done on older golfers (Tsang & Hui-Chan, 2010), and highly proficient golfers (Sell *et al.*, 2007). Data from the present study shows that drive distance was affected by the ability to balance. Balance in golfers was investigated previously by Sell *et al.* (2007) and their results indicate that balance was correlated to drive distance, however, the drive distances were self-reported by their participants and not directly measured. Wells *et al.* (2009) failed to show a correlation between balance and drive distance, however, non-dominant leg balance was shown to correlate with the number of greens hit in regulation. It is likely that left leg balance is more important in achieving greater drive distances as the follow-through phase of the golf swing results in a larger proportion of the total body mass being supported by the left leg (Wells *et al.*, 2009). Better balance in the follow-through phase may allow for a greater transfer of kinetic energy to the ball during the swing phase, with the body's momentum being compensated for during the follow-through. The correlation with the right leg could indicate the weight transfer during the backswing phase where the body mass is shifted towards the right leg (Wells *et al.*, 2009).

Sell *et al.* (2007) along with Lephart *et al.* (2007) had their subjects perform balance procedures barefoot with their eyes open and then closed. Although they made use of a different protocol to that used in the current study, they found that balance differed between golfers of various skill levels, which could be improved following a training regime. It is likely that the addition of golf shoes would be a true reflection of the ability to balance by the golfers, as they require these specifically designed shoes to play (Worsfold *et al.*, 2008). Balance, in the current study, was determined while participants wore golf shoes and stood on a level patch of grass, which mimicked real golf situations. The decision to select a 60-second cut-off for balance was a limitation of this study, with a high percentage of the golfers having the test terminated at this level. Despite this, the positive correlation shown testifies to the importance of balance ability for the golf drive.

A rough indication of the players' autonomic state as recorded by their resting heart rate showed no relationship with the drive distance. It is likely that a more detailed evaluation of the physiological state is required to identify the specific or the combined parameters that contribute towards achieving a competent golf drive.

The hand-eye coordination task used here not only tested the complexities of fine motor coordination as per Natarajan and Malliga (2011), but also tested the ability to control a golf club. The negative correlation between drive distance and the hand-eye coordination task would suggest that the golfers' ability to control their hands and upper limbs would greatly affect their ability to strike the ball. It is interesting that the hand-eye coordination task did not have a significant correlation with the ball strike distance from the centre of the club or drive accuracy. However, this result may prove to be significant in an increased sample size (p=0.07, N=18) and be attributable to the advances in the designs of modern day drivers, which aim to improve ball strike by increasing the 'sweet spot' area on the clubface. Although the speed at which the test was conducted does not match the speeds of a golf shot, the test was designed to quantify the golfer's ability to manipulate the golf club as an extension of the kinetic chain, as well as the coordinative ability required to do so. It needs to be noted that whole body coordination and proprioception are likely to affect the drive distance (Knight, 2004; Neal *et al*., 2007; Keogh & Hume, 2012), which may form part of a more inclusive future study than the discrete measurements made in the present study.

When determining relationships between physiological components and the biomechanical movement, it was found that a relationship exists between the right leg balance with eyes closed and the right knee rotation-angle in the contact position. In the ball contact position of the golf swing, it is essential that the golfer maintain a functional level of balance, while still transferring a vast proportion of their body weight (Chu *et al*., 2010). The data showed that the right knee rotation-angle correlates with the right leg balance. The fact that the latter balance measurement was made with closed eyes biased the possible sensory inputs for balance towards the vestibular, mechanoreceptive and muscular sense, whilst also ensuring that balance could not be maintained for long durations. The weight shift around the knee joint could be similar, when the balance is tested, to that during the swing. The results in this study show that the relationship seems to occur at the level of the knee and not lower at the ankle joint.

In the follow-through position, the left and right ankle rotation angles correlated with the drive distance achieved, which would suggest that the rotation around the ankles is related to the shift in weight. The greatest proportion of weight would be on the left leg at the follow-through stage of the swing (Worsfold *et al*., 2009). The ankle needs to rotate in order to allow the weight shift to occur and to establish a firm base for the large rotations of the pelvic (Knight, 2004) and shoulder girdle (Gordon *et al*., 2009). The right ankle, which is not part of the major weight shift at this stage of the swing (Worsfold *et al*., 2009), would have a greater rotation value 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) suggests that an open left toe at the follow-through phase of the swing would allow for greater pelvic rotation, this relationship was not found to be present in this study. Weight shift was not measured in the current study; therefore, the relationship between ankle rotation angles and weight shift is speculative and requires further research.

Only the left ankle rotation value in the follow-through position was correlated to drive distance. This value may be related indirectly to the weight transfer occurring during the golf swing (Worsfold *et al*., 2009). The small sample of biomechanical data may exclude any relationships present in previous studies (Chu *et al*., 2010).

The large variation of handicaps, shown by golfers in the present study, facilitated the significant correlations between drive performance and balance or coordination. Future studies could exclude less experienced golfers to focus on a narrower range of handicaps for ascertaining if these relationships remain or whether other variables become more important. The limit for the balance protocol of 60 seconds could be extended until the golfer needs to regain balance, although this may then be testing the fatigue threshold of the individual legs rather than balance. Instead of a field balance test, whole body centre of gravity sway during quiet standing and during the golf swing could be quantified also. There is a need to determine the coordinative abilities of the golfer and their ability to ensure momentum transfer between the centre of the clubface and the golf ball. The coordinative abilities may not be limited to hand-eye coordination, but rather 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 (Shan *et al*., 2011), involving the proprioceptive, somatic, vestibular and central nervous system. These coordinative aspects require further investigation to assess whether any relationships exist. Biomechanically, more studies are required to investigate the interaction between leg rotations and weight distribution throughout the golf swing.

CONCLUSION

In conclusion, several parameters related to golf drive distance were identified in a group of amateur golfers. This was done by demonstrating that the combination of the components shown in the individual variables may result in greater drive distances. Individual leg balance ability was shown to be an important contributor to a successful golf drive. Additionally, hand-eye coordination, as tested by the golfers' ability to manipulate the golf club through a three-dimensional maze, was shown to be a determinant of golf drive performance. Therefore, it may be beneficial for a golfer to include tasks that improve hand-eye coordination and balance in their practice and training regimes.

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