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ARTICLE

Rotational Kinematics of the Pelvis During the Golf Swing: Skill Level Differences and Relationship to Club and Ball Impact Conditions

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It is known that proper proximal to distal sequencing of body rotations is important in the production of high club head velocities in the golf swing. Since these rotations originate at the pelvis, it is not clear how differences in pelvic kinematics are related to essential determinants of ball flight. One essential ball flight measure that has not been previously investigated is the ratio of club velocity before impact to ball velocity after impact, or smash factor. Therefore, this study investigated the differences in pelvic kinematics and ball flight determinants between golfers of different skill levels. It also determined the correlations between pelvic kinematic measures and these determinants of ball flight. Skilled golfers were found to have greater pelvic accelerations and a larger time between peak pelvic velocity and ball contact (peak to impact time). It was also discovered that pelvic acceleration correlated with the shot distance and with the smash factor. There

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was also a correlation between peak to impact time and smash factor. This is the first data to suggest that appropriate pelvic rotations is important in producing an efficient strike on ball so that the maximum amount of energy is transferred from the club to the ball.

Keywords: biomechanics, kinematic sequence, smash factor, ball speed

To achieve success in the sport of golf, one must have the ability to consistently produce golf shots that travel the intended distance in the desired direction. Extensive research has concentrated on measuring the speed of the golf club head before impact to determine the effectiveness of the golf swing (Fradkin, Sherman, & Finch, 2004b; Hetu, Christie, & Faigenbaum, 1998; Joyce, Burnett, Cochrane, & Ball, 2013; Leary et al., 2012; Read, Miller, & Turner, 2013). Although the speed of the club is important and has been correlated with golf handicap (Fradkin, Sherman, & Finch, 2004a), there are several other factors that will help determine the resulting path of the golf ball after it is struck (Wiren, 1990). One of these factors involves the efficiency of the strike, or the amount of energy that is transferred from the club to the ball during impact. This can be obtained using a Doppler Radar ball flight monitor to measure the speed of the golf ball after impact and dividing it by the speed of the club before impact (Lennard, 2010). This gives a unit-less ratio that has been termed the "smash factor" (SF). Since the combination of club head speed and ball speed (smash factor) is important to determining the success of a golf shot, research may be able to determine the mechanical characteristics of a golf swing that could consistently maximize these critical impact factors.

Recently, research investigating the efficiency of the golf swing has concentrated on examining the rotational movements of the body segments and the club during the downswing as the club approaches contact with the ball (*Cheetham* et al., 2008; Tinmark, Hellstrom, Halvorsen, & Thorstensson, 2010). As with other skills that involve maximizing the speed of the most distal segment in an open chain system, it is critical that these body rotations follow a proximal-to-distal sequencing pattern to achieve the most effective result possible (Putnam, 1993). This means that the most proximal segments should initiate the rotational movements by accelerating to reach peak speed before decelerating and transferring this energy to the next segment. The most effective sequencing during a golf shot involves first using large proximal muscles to accelerate and decelerate the pelvis segment before passing this energy on to more distal segments and ultimately the club (*Cheetham* et al., 2008; Tinmark et al., 2010). The movement of this most proximal segment is important, as it has been shown that skilled golfers have a higher peak angular velocity of the pelvis than less skilled golfers (Callaway et al., 2012; *Cheetham* et al., 2008); however, the relationship between pelvic kinematics and other factors, besides club head speed, that help determine the flight of the ball (i.e., ball speed, smash factor) have not been investigated. Therefore, this study will investigate the differences in pelvic kinematics and ball flight determinants between golfers of different skill levels. It will also determine the correlations between pelvic kinematic measures and these determinants of ball flight. We hypothesize that the skilled golfers will have higher peak pelvic angular velocities, average pelvic angular accelerations/decelerations, and a longer time from peak pelvic angular velocity to ball contact, as compared with the less skilled golfers. It can then be hypothesized that these pelvic kinematics will result in the skilled golfers producing higher club head speeds, ball speeds, and smash factors as compared with the beginner golfers.

Methods

Participants

Male golfers were recruited for two groups: 15 elite golfers and 14 recreational golfers (Table 1). Elite golfers were defined as having a USGA handicap lower than 3.0, while recreational golfers were defined as having a USGA golf handicap higher than 18.0. All participants signed a letter of informed consent approved by the University's Research Ethics Board before participation in the study.

Instrumentation

Full body kinematic data were obtained from retro-reflective markers placed on the body, club and ball (Figure 1). For this current study, only the pelvic data were analyzed. Pelvic kinematic data were collected with 4 tracking markers attached to a rigid body strapped securely to the sacrum/pelvis along with individual markers attached bilaterally to the ASIS and the middle of the iliac crest directly vertical from the greater trochanter. All kinematic data were collected using a 9 camera Qualisys (Gothenburg, Sweden) Oqus 300 motion capture system. Marker data were simultaneously collected at 240 Hz using Qualisys Track Manager (QTM) software (Gothenburg, Sweden). Golf shot tracking data were collected using a Flight Scope 3D Doppler radar tracking device (Stellenbosch, South Africa).

Protocol

Each Participant was asked to hit 3 practice golf shots with a 5-iron into an indoor net that was 5 m in front of the golfer. Each participant was then asked to hit five regular golf shots with a 5-iron for recorded trials. All golfers were right handed for this study.

Golf Swing Data Processing

All kinematic data were processed using Visual3D software (C Motion Inc., Rockville, MD, USA). Pelvic raw marker positions were filtered at 6 Hz using a

Table 1 Age, Anthropometrics, and USGA Handicap for the Elite (*n* = 15) and Recreational (*n* = 14) Golfers

	Elite Golfers	Recreational Golfers
Age (years)	23.2 ± 5.3	27.1 ± 3.4
Height (m)	1.8 ± 0.1	1.8 ± 0.1
Weight (kg)	77.7 ± 6.8	79.9 ± 6.8
USGA Handicap	0.3 ± .9	20.7 ± 3.1

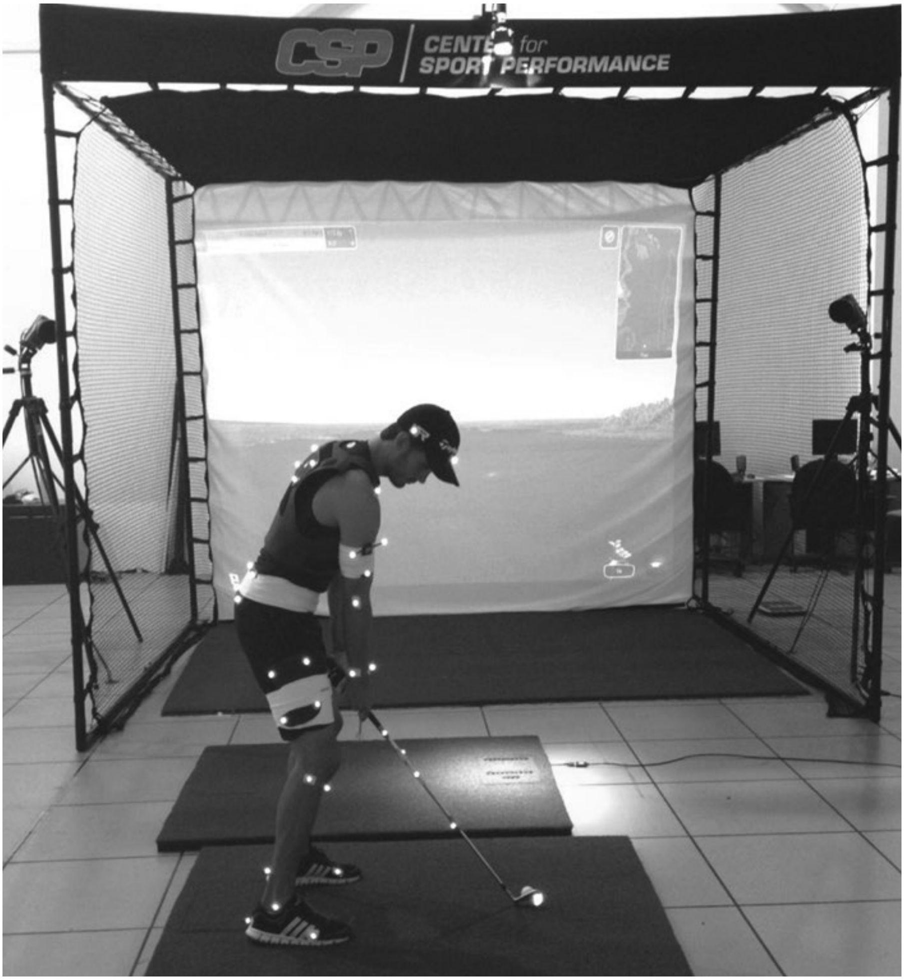

Figure 1 — Subject outfit with markers for data collection. The four markers attached to the plate which is strapped to his pelvis/sacrum were used to calculate pelvic kinematics.

low pass double-pass Butterworth filter. Visual3D software was used to analyze the downswing phase and calculate peak pelvic angular velocity, average pelvic angular acceleration, average pelvic angular deceleration and the time from peak pelvic angular velocity to ball impact (peak to impact time). The pelvic angular velocity was calculated about the vertical axis of the pelvic segment coordinate system. Average angular acceleration was the average slope of angular velocity curve from the club transition to the peak pelvic angular velocity, while average angular deceleration was the average slope of the angular velocity curve from the peak pelvic angular velocity until ball contact. Data from all five trials were averaged for each individual.

Ball Flight Data

Outcome measures collected by the FlightScope Doppler radar ball tracking device were club head speed, ball speed, smash factor, and shot distance. These data were collected for each swing and data from all 5 trials were averaged for each individual.

Statistics

All data were analyzed using the Predictive Analytics Software (PASW) Statistics version 20.0 (SPSS Inc., an IBM Company, Chicago, IL, USA). Independent Samples T-Tests were run to determine differences between the elite and recreational golfer groups for the four pelvic kinematic variables, ball speed, club head speed, smash factor, and distance. Pearson correlation coefficients were run using data from all participants (n = 29) to determine the relationship between pelvic kinematic variables and ball flight measures. Significance level was set at $p < .05$ for all statistical analyses.

Results

Independent Samples T-Tests revealed significantly greater Average Pelvic Angular Acceleration and peak to impact time in elite golfers compared with recreational golfers during the downswing phase (Table 2). Elite golfers also had higher average ball speed, smash factor, and shot distance as compared with the recreational golfers (Table 2).

Pearson correlation coefficients also revealed three significant correlations between pelvic kinematics and ball flight variables. These significant correlations

Table 2 Pelvic Kinematic Variables and Ball Flight Variables for the Elite (n = 15) and Recreational (n = 14) Golfers

	Elite Golfers	Recreational Golfers
Pelvic Kinematic Variables		
Peak Pelvic Angular Velocity (°/s)	427.8 ± 69.9	398.8 ± 69.4
Average Pelvic Angular Acceleration (°/s^2)‡	2166.5 ± 532.4	1707.4 ± 265.6
Average Pelvic Angular Deceleration (°/s^2)	-1771.8 ± 1007.4	-1604.3 ± 854.1
Peak time to impact (msec)‡	101.7 ± 18.0	79.6 ± 23.0
Ball Flight Variables		
Ball Speed (km/hour)‡	201.5 ± 12.0	179.6 ± 21.4
Club Head Speed (km/hour)	148.4 ± 9.0	141.1 ± 16.9
Smash Factor‡	1.36 ± 0.03	1.27 ± 0.04
Distance (m)‡	172.8 ± 9.1	144.5 ± 25.5

Note:—‡ = significant difference between the Elite and Recreational Golfers ($p < 0.05$).
Smash Factor = Ball Speed/Club Head Speed

Table 3 Pearson Correlation Coefficients Between the Pelvic Kinematic and Ball Flight Variables for All Subjects (*n* = 29)

	Distance	Club Head Speed	Ball Speed	Smash Factor
Peak Pelvic Angular Velocity	0.166	0.017	0.121	0.281
Average Pelvic Angular Acceleration	0.368‡	0.200	0.326	0.393‡
Average Pelvic Angular Deceleration	-0.252	-0.217	-0.199	-0.034
Peak to Impact	0.311	0.177	0.309	0.399‡

Note—‡ = statistically significant correlation between variables ($p < 0.05$)

were: (1) average pelvic angular acceleration and distance, (2) average pelvic angular acceleration and smash factor, and (3) peak to impact time and smash factor (Table 3).

Discussion

The purpose of this study was to determine differences in pelvic kinematics and certain variables which help determine ball flight between a group of elite and recreational golfers. Correlations were also calculated between the measured pelvic kinematics and resulting ball flight variables.

One interesting finding was that the peak pelvic angular velocity was not different between our elite golfers and recreational golfers. This is contrary to previous work where skilled golfers have had higher pelvic angular velocities than less skilled golfers (Callaway et al., 2012; *Cheetham* et al., 2008). This could be due to several factors. First of all, our participants were hitting a five iron, while those in previous research were hitting a driver. In addition, the skilled players in previous research included professional golfers and ours were collegiate golfers. This is exemplified by the fact that our skilled group had a lower pelvic angular velocity (428°/sec) than the skilled group in the Callaway et al. (503°/sec) and Cheetham et al. (477°/sec) studies (Callaway et al., 2012; *Cheetham* et al., 2008). In addition, our recreational golfers were all relatively young and highly athletic individuals who had participated in several other sports throughout their lives. The age of the less skilled players in the previous research is unclear (Callaway et al., 2012; *Cheetham* et al., 2008); therefore these groups could include golfers who were older than our recreational player. This is supported by the fact that our recreational golfers did produce higher pelvic angular velocities as compared with the less skilled golfers in the other two studies (Callaway et al., 2012; *Cheetham* et al., 2008); however, the differences between studies were not as large as they were with the skilled groups. Since muscular strength has been related to peak pelvic angular velocity (Callaway et al., 2012) and it is known that muscle strength peaks in the 20s or early 30s and declines with age (Vandervoort, 2002), this could be part of the reason for our aberrant finding.

Another difference between our results and those of *Cheetham* et al., (2008) involves the time between peak pelvic angular velocity and impact. We found that our elite players had their pelvic angular velocity peak significantly sooner (before impact) than our recreational players, while *Cheetham* et al., (2008) did not find differences between golfers of different skill levels for this variable. It can be hypothesized that it would be advantageous to have the pelvis angular velocity peak well in advance of ball contact to allow more time for the energy to be passed distally in the appropriate sequence to the club. This hypothesis is also supported by previous research done in our laboratory investigating ground reaction force (GRF) patterns of skilled golfers as compared with beginner golfers (Lynn, Noffal, Wu, & Vandervoort, 2012). It was found that a higher skilled group of golfers transferred their weight to their front foot and initiated the rotational force couples created by the anterior-posterior GRFs much earlier before ball contact than a group of beginner golfers (Lynn et al., 2012).

It could also be hypothesized that there may be an optimal time between peak pelvic angular velocity and impact for each individual based on their anthropometrics, muscle fiber composition, and swing styles. This alternative hypothesis would propose that if this time is increased or decreased from optimal, the resulting swing would be less efficient. Clearly, future work needs to clarify the role of the time from peak angular velocity of the pelvis to impact; however, the results of this current work provide evidence that supports the first hypothesis.

Other kinematic variables that were measured had similar results to those of Cheetham et al. (2008). Both the current study and *Cheetham* et al., (2008) found that more skilled players had significantly higher pelvic accelerations but similar pelvic decelerations to the less skilled players. Although this is the case, *Cheetham* et al., (2008) reported that some of their less skilled golfers did not actually decelerate their pelvic velocity before impact, while all of the skilled golfers did. In the current study, all participants (elite and recreational golfers) did slow down or decelerate their pelvic angular velocity before the ball was struck. It seems that quickly accelerating the pelvis during the downswing is important to producing an efficient golf swing; however, the magnitude of the pelvic deceleration may not be as important, as long as the pelvic rotational velocity does in fact peak and then slow down before impact.

It was also extremely interesting that the club head speed of our recreational group was not significantly different from the elite golfers. Therefore, the recreational golfers were able to generate club head speeds that could have produced shots of similar distance to the elite golfers; however, the elite golfers shots went much farther (almost 30 m) than the recreational golfers due to hitting the ball much closer to the “sweet spot”, thus producing a much more efficient strike of the ball and an increased smash factor. Ultimately, producing high ball speeds is the goal of the golf swing, as a high club head speed is not of much use if it results in an off center hit, inefficient strike, and low ball speed. Therefore, it is extremely important to determine the swing kinematics that result in an efficient strike of the ball.

This is the first study to correlate body segment kinematics with critical ball impact variables. Our findings of a significant correlation between pelvic acceleration and smash factor as well as shot distance, along with the correlation between peak velocity to impact time and smash factor are extremely interesting. This is first work to suggest that a proper kinematic sequence may not only be beneficial in producing high club head speeds, but may also be beneficial in producing an efficient strike on the ball. It appears that using the large proximal musculature to accelerate the pelvis quickly so that it reaches peak velocity well in advance of ball contact is related to how solidly the ball is struck and hence, how far it travels. It can be hypothesized that using the appropriate kinematic sequence, where the angular velocity is initiated from the ground up to the pelvis and then passed down the chain to the club, results in a more solid strike of the ball as it may decrease the dependence on the relatively smaller distal musculature. It may be that if the golfer attempts to achieve a high club head velocity with the smaller distal musculature, the path of the club may be less consistent on the downswing, resulting in a less efficient strike of the ball.

This could be related to the recently proposed Leading Joint Hypothesis (Dounskaia, 2010). If the pelvis is used correctly as the "leading joint", the distal subordinate joints (i.e., shoulder, wrist) can execute their appropriate function of controlling interactive torques, while guiding the direction and accuracy of the club. If the sequence is not optimal and these subordinate joints are given more of a "leading joint" role, their effectiveness in guiding the direction and accuracy of the club may be compromised. Similarly, a motor control perspective would relate this to a constraints-based approach which would suggest that the position and velocity of the pelvis "constrain" or position the shoulders and wrists in a manner that allow for a more efficient strike of the ball (Magill, 2011). Specifically, more efficient movement of the pelvis allows the shoulders and wrists to get in a better position.

Despite the control theory used to explain the findings of this study, the means in which the results of this study are applied into instructional environments is critical. Two primary areas within motor control and learning that should be considered are focus of attention and part/whole practice. Based on the work of Porter, Wu, and Partridge (2010) and Wu, Porter, Partridge, Young, and Newman (2012), elite level practitioners, generally, fail to use evidence-based approaches to practice. Popular among practitioners is to provide verbal instructions that reference the body or limb segments. While this may seem like a logical approach, the motor control and learning literature provides an overwhelming body of evidence that demonstrates significant decrements in performance when performers are instructed to focus on specific body segments (Wulf, 2013). For example, instead of telling golfers to fire their hips and keep their hands back, instructors should tell golfers to move their belt buckle first and fast, and have the clubface come through last. From a whole/part practice perspective, instructors should avoid devoting significant practice time to breaking the downswing into components (i.e., focusing on pelvic motions). According to Magill (2011), a skill should only be broken into parts when it is comprised of components that are independent to one another. Utilizing the results of this study, instructors should create drills that include movements of the pelvis and upper body sequentially rather than as 2 independent drills for each body segment. Because of the sequencing and timing requirements of the downswing, the movements of the downswing are interdependent of one another and should be practiced together.

Although this study discovered many interesting findings related to the connection between pelvic kinematics during the golf swing and ball impact variables, there were also some limitations. Firstly, all data were collected in an indoor biomechanics laboratory where the participants hit the ball into a net. Future research should examine the differences in golf swing kinematics between hitting balls indoors into a net and hitting balls outdoors under more realistic golfing conditions. In addition, all testing was done using a 5-iron, while much of the current literature used a driver for testing. The differences in swing kinematics between clubs designed more for accuracy and those designed more for distance should be investigated in future studies. This study also focused only on the kinematics required to produce an effective golf swing, without considerations of the stresses being applied to the golfer's body. Future research should investigate how to produce an effective and safe golf swing that will allow the golfer to maximize performance while minimizing the stress on the musculoskeletal system.

The findings of this study provide valuable insight to the role of pelvic movement kinematics during the golf swing and outcome performance. The results of this study demonstrate the critical relationship between pelvic movement sequencing, club head velocity, and how efficiently the ball is struck. While it's important to identify critical features of the swing, future research needs to identify evidence-based learning tools that help to integrate these findings into optimal performance on the course.

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