LOWER BODY MECHANICS OF GOLF SWING AND ITS ASSOCIATION WITH MAXIMUM CLUBHEAD SPEED IN SKILLED GOLFERS

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DEDICATION

I dedicate this dissertation to my mother in heaven, my father, and my two elder sisters for giving me love, blessings, and faith in countless ways.

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ABSTRACT

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The purpose of this study was to investigate the associations between peak clubhead speed and select kinematic and kinetic parameters of the lower extremity during the swing in skilled golfers. A total of 25 healthy, right-handed, male golfers with a posted handicap of 3 or better were recruited for this study. Peak orientation angles (OA) and ranges of the OA of the lower extremity joints (i.e., pelvis, hips, knees, and ankles) during the downswing, and normalized peak resultant joint moments (RJM) of the lower extremity joints (i.e., hips, knees, and ankles) were extracted for a correlation analysis to normalized peak clubhead speed (NPCS). Among OA parameters, only the pelvis right lateral tilted position (r = .510, .501, and .522 for driver, 5-iron, and pitching wedge, respectively) and the pelvis right tilting motion (r = .450, .409, and .493 for driver, 5-iron, and pitching wedge, respectively) were significantly correlated to NPCS across all the club conditions during the downswing. Therefore, the pelvis motion in the frontal plane was identified as the good consistent indicator of clubhead speed in skilled golfers. Among RJM parameters, the right hip extensor (r = .396, .667, and .732 for driver, 5-iron, and pitching wedge, respectively) and left knee extensor moments (r

= .451, .449, and .457 for driver, 5-iron, and pitching wedge, respectively) in the sagittal plane exhibited significant correlations to NPCS across all club conditions. The skilled golfers relied especially more on muscular effort from the right hip and left knee joints in the sagittal plane. Therefore, the right hip extensor and left knee extensor moments were considered as the good consistent indicator in generating higher clubhead speed in skilled golfers.

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CHAPTER I

INTRODUCTION

The PGA Tour average course length has increased consistently from 2003 to 2009 by over 40 yd (Golfpredictorcom, 2015). Average driving distance has also increased significantly every year from 1990 to 2005 on the PGA tour (Wiseman, Habibullah, & Yilmaz, 2007). There are two requisites for success with the full swing in golf: distance and accuracy (Kwon, Como, Singhal, Lee, & Han, 2012). Longer shot distance and higher accuracy are associated with better outcomes in terms of total score and ranking (Hale & Hale, 1990; Wiseman & Chatterjee, 2006). As the level of competition increases, shot distance becomes more important (Hellstrom, 2009). Clubhead speed at impact is known as the most important determinant of shot distance (Hume, Keogh, & Reid, 2005; Penner, 2003; Wallace, Otto, & Nevill, 2007) and emphasis has been placed on the movement patterns and swing motion characteristics that contribute to a higher impact clubhead speed. Some of these swing motion characteristics include the kinematic sequence (Burden, Grimshaw, & Wallace, 1998), X-factor (Myers et al., 2008), and delayed release (Sprigings & Mackenzie, 2002).

Recently, the interactions among the pelvis, upper body, arms and club (i.e., kinematic sequence) or between the pelvis and thorax (i.e., X-factor) have received significant attention in golf practice and research as key factors that affect peak clubhead speed. According to the principle of kinematic sequence, the downswing motion is initiated by the rotations of large proximal segments (e.g., pelvis and trunk) followed by those of smaller distal segments (e.g., arms, hands, and the club) in order to maximize the speed of the clubhead at the distal end of the body/club system (McTeigue, Lamb, Mottram, & Pirozzolo, 1994). The X-factor, the torsional separation between the pelvic and shoulder lines, has been reported to have a strong relationship with peak clubhead velocity (McLean, 1992; Myers et al., 2008; Zheng, Barrentine, Fleisig, & Andrews, 2008). In a recent study, however, X-factor parameters were not directly correlated to the clubhead speed in skilled golfers (Kwon, Han, Como, Lee, & Singhal, 2013).

The effect of delayed release (Sprigings & Mackenzie, 2002), also known as delayed uncocking of the wrist, has been analyzed using the double-pendulum model (e.g., Jorgensen, 1994; Milne & Davis, 1992; Pickering & Vickers, 1999; Sprigings & Neal, 2000). In this model, the golfer's arms and club were reduced to two rigid levers connected at the wrists with the arm and wrist motions being the primary contributors to clubhead speed. The movements of the trunk, arms, and club in the golfer/club system have therefore been emphasized more than those of the lower body. Consequently, the lower body motions have not received much research attention.

During a golf swing, the only external forces and moments that can be voluntarily manipulated by the golfer are the ground reaction forces and moments. The peak force moments generated through the foot-ground interaction during the early phase of downswing phase are significantly correlated to the peak clubhead speed (Han, Lee, & Kwon, 2014). The lower body (legs and pelvis) plays a critical role in promoting the foot-ground interaction: (1) the angular momentum generated through the foot-ground interaction is transferred to the upper body through the lower body; and (2) the unbalanced leg actions determine the quality of the foot-ground interaction such as weight shift and center-of-pressure (COP) excursion (Ball, & Best, 2007; Kawashima, Meshizuka, & Takeshita, 1998). Through the muscle actions in the lower body, the golfer controls the level and quality of the foot-ground interaction. Proper lower body mechanics, therefore, are a pre-requisite for a high clubhead speed at impact. Despite the importance of the mechanical role of the lower body, the direct biomechanical relationships between the lower body motions and the peak clubhead speed has not been established. This study, therefore, can offer valuable insights into the relationships between the key kinematic and kinetic factors of the lower body motions and peak clubhead speed.

Purpose of the Study

The purpose of this study was to investigate the associations between peak clubhead speed and select kinematic and kinetic parameters of the lower extremities during the swing in skilled golfers.

Hypotheses

1. Peak orientation angles (OA) and ranges of OA of the lower extremities (i.e., hips, knees, and ankles) and pelvis in three anatomical planes of motion

(i.e., sagittal, frontal, and transverse) would be significantly correlated to peak clubhead speed in skilled golfers.

2. Peak resultant joint moments (RJM) of the lower extremities in three anatomical planes of motion would be significantly correlated to peak clubhead speed in skilled golfers.

Assumptions

1. The body was a linked segment system with frictionless pin joints.
2. Each segment was a rigid body.
3. The mass, length, and moment of inertia of each segment about its center of mass (COM) remained constant throughout the golf swing.
4. The information provided by participants regarding their own skill level was accurate.

Delimitations

1. Participant handicap was restricted to 3 or less to reduce intra-golfer variability.
2. Participants were recruited from golfers of ages 19-40 to remove excessive age-related variability.
3. Only male golfers were recruited to remove gender differences in anthropometric characteristics, such as the amount of muscle.
4. Only lower body parameters were measured so that the kinetic data to the rest of the kinetic chain cannot be surmised.

Limitations

1. Swings were performed in an indoor laboratory.
2. Foam balls were used instead of real balls to minimize the effect at impact to the clubhead speed.
3. Balls were hit to the wall located 15 m from the ball plate.
4. The differences in the swing patterns and swing styles among the participants were not considered.

Definitions of Terms

Global reference frame: the laboratory coordinate system in which body marker coordinates are calculated

Ground reaction force (GRF): the force exerted by the ground acting on the body in contact with ground

Inverse dynamics: a method to compute resultant joint forces and moments based on the motion data of the body (kinematics) and the body's inertial properties and ground reaction force data

Kinematics: an area of mechanics which describe motion, including linear or angular body positions, velocities, and accelerations

Kinetics: an area of mechanics which explain the causes of motion, including force and moment

Local reference frame: the reference frame fixed to the moving body segments Orientation angles: the angles of the segments relative to their respective proximal segments about the axis in sequential order given by type of rotation chosen

Resultant joint force: sum of joint contact force (bone-on-bone force) and all muscle forces acting at the joint

Resultant joint moment: sum of all moments produced by the muscles acting at the joint

Weight shift: lateral motion of the weight center (center of mass) away from or toward the target during the swing

CHAPTER II

LITERATURE REVIEW

The literature review is divided into four main sections. The first three are related to the promotion of generating higher clubhead speed. Golf swing technique will be discussed first, including the concepts of kinematic sequence and kinetic energy transfer, X-factor, delayed release of wrist, and weight shift and foot-ground interaction. Physical conditioning will be discussed next, with a focus on strength and flexibility. Thirdly, the relationship between the condition of the club and clubhead speed will be presented. Finally, the history of golfer's body model used in the biomechanical research will be described.

Golf Swing Technique

Various movement patterns and characteristics of the swing motion result in a higher clubhead velocity at impact, which is proportional to driving distance (Shamus & Shamus, 2001) and to the skill level of golfers (Fradkin, Sherman, & Finch, 2004). The kinematic and kinetic parameters include: kinematic sequence and kinetic energy transfer; X-factor Parameters; delayed release of wrist, and; weight shift and foot-ground interaction.

Kinematic Sequence and Kinetic Energy Transfer

The term proximal-to-distal sequence (Bunn, 1972; Marshall & Elliott, 2000; Putnam, 1993; Robertson & Mosher, 1985) has been used in various sports and has been described using different nomenclature. It has been utilized in baseball (Hay, 1993), soccer (Putnam, 1993; Robertson & Mosher, 1985), and tennis (Marshall & Elliott, 2000), where it has been called "summation of speed principle" by Bunn (1972) or "kinetic link" principle by Kreighbaum and Barthels (1985). Since this principle, commonly known as kinematic sequence in golf, was first introduced by Cochran and Stobbs (1968), a substantial number of research studies have been conducted to find evidence of this principle (Burden et al., 1998; Callaway et al., 2012; Horan, Evans, Morris, & Kavanagh, 2010; Joyce, Burnett, & Ball, 2010; Lephart, Smouga, Myers, Sell, & Tsai, 2007; Neal & Dalgleish, 2008; Tinmark, Hellström, Halvorsen, & Thorstensson, 2010). The principle suggests that the body's motion should be initiated by the rotation of the body's larger proximal segments such as the pelvis and trunk and followed by the shoulders and then the smaller distal segments such as the arms, wrists, and hands. Therefore, the proper sequence of body segment motions from the larger proximal segments to the smaller distal segments can be associated with a higher speed of the clubhead at the distal end of the linked system when the energy is transferred to the golf club at impact.

An essential factor to improve clubhead speed in golf is to increase the amount of kinetic energy transferred from the body segments to the clubhead at impact. It has been reported that the kinematic sequence has an effect on energy transfer and power during the golf swing (McLaughlin & Best, 1994). Research following an 8-week golf-specific exercise program to improve physical characteristics, swing mechanics, and golf performance proposed that greater mechanical efficiency in transferring power to the club can result from the improvement of the kinematic sequence pattern (Lephart et al., 2007). In addition to proper kinematic sequencing during the golf swing, it is also important that the muscles contract with proper timing. For example, the thorax gains the energy accumulated after the deceleration of the pelvis. The pelvis in elite golfers decelerates earlier than that in recreational golfer, which leads to a more effective ball strike (Lynn et al., 2014). However, not all studies support the beneficial effect of the kinematic sequence in generating clubhead speed. One possible explanation could be that the direct contact of both hands creates a closed chain and, as a result, the typical kinematic sequence observed in other sports such as baseball pitching and tennis may be limited in its application to the golf swing.

X-Factor Parameters

Popular concepts in golf practice/research in recent years are the X-factor at the top of backswing and the X-factor stretch at the beginning of downswing. The X-factor is defined as the torsional separation between the shoulder and pelvis lines (Cheetham, Martin, Mottram, & St. Laurent, 2001; McLean, 1992). Several studies have reported that significant relationships between the X-factor and clubhead velocity were observed in a diverse group of golfers (Chu, Sell, & Lephart, 2010; Cole & Grimshaw, 2009; Myers et al., 2008; Zheng et al., 2008) and researchers have suggested that clubhead velocity could be increased by increasing the X-factor. However, Cheetham, Martin, Mottram, and St. Laurent (2001) reported that there was no significant difference in the X-factor between highly skilled (i.e., handicap less than 0 and one long drive champion) and less skilled golfers (i.e., handicap of 15+). The X-factor stretch, which comprises maximized increase in shoulder and pelvic separation at the initiation of the downswing, has been proposed to be more important to an effective swing than the X-factor at the top of backswing. An increase (i.e., X-factor stretch) in the skilled group (19%) was significantly greater than that in the less skilled group (13%). According to one study (Kwon et al., 2013), the potential relationship between the X-factor and clubhead velocity has often been explained with the X-factor stretch (Cheetham et al., 2001; Cole & Grimshaw, 2009) to include the stretch-shortening cycle (Hellstrom, 2009; Hume et al., 2005). In terms of the X-factor stretch, a study conducted by Cole and Grimshaw (2009) presented that the less skilled group exhibited a greater increase compared to the skilled group, in contrast to information presented by Cheetham et al. (2001). The possible reason for different results might be related to the methods used to define and compute X-factor parameters. In order to standardize and validate the methods used in computing the X-factor parameters, Kwon et al. (2013) have proposed a comparison of the various methods of computation. The first method is more conventional, which projects the hip and shoulder lines to the horizontal plane, then measures the angle between them. The second method includes the plane of motion of the golf swing, which is sloped, and thus uses a swing motion-oriented plane called the ‘functional swing plane’ (Kwon et al., 2013). The third method uses the directly computed relative orientation using a Cardan rotation sequence (Joyce et al., 2010). No direct relationship existed between X-factor parameters and the maximum clubhead speed in the trials of skilled golfers using a driver club (Joyce et al., 2010). In another study, the pelvic rotation was significantly associated with higher clubhead speed, rather than with the X-factor parameter (Lynn et al., 2014).

Delayed Release of Wrist

Although the relationship of delayed release to a high clubhead speed has been debated, the delayed release of wrist cocking during the downswing can significantly increase clubhead speed (McLaughlin & Best, 1994; Robinson, 1994; Sprigings & Neal, 2000). When the lead arm is parallel to the ground, professional golfers exhibited a significantly more cocked-wrist position than amateur golfers (McLaughlin & Best, 1994; Robinson, 1994). In an analysis using linear regression to assess 15 kinematic/kinetic swing variables, Robinson (1994) asserted that the degree of wrist-cocking was the most important determinant of the improvement in clubhead velocity. A computer simulation study conducted by Sprigings and Neal (2000) highlighted the importance of wrist torque applied to the club during the latter phases of the downswing for higher clubhead speed. A wrist-cocked swing generates an additional 9% increase in clubhead velocity at impact when the torques at impact were generated in proximal to distal sequence and the lead arm was placed approximately 30° below the horizontal.

Sprigings and Mackenzie (2002) found that the use of an active wrist torque following the delayed release was advantageous, as the main source of power transferred to the club originated from the passive joint forces generated at the wrist joint.

Weight Shift and Foot-Ground Interaction

One concept that has gained significant attention in recent golf studies regarding higher clubhead velocity at impact is weight shift, first introduced in Golf Digest by Nelson (1980). However, while the term is frequently discussed in golf research, a consensus on the definition of weight shift has remained elusive. Weight shift has been variously described as: bodyweight shift quantified by GRF (Barrentine, Fleisig, Johnson, & Woolley, 1994; Okuda, Gribble, & Amstrong, 2002; Williams & Cavanagh, 1983), COM movement (Burden et al., 1998) or foot pressure variation (Dowlan, Brown, Ball, Best, & Wrigley, 2001; Koenig, Tamres, & Mann, 1994; Wallace, Grimshaw, & Ashford, 1994; Williams & Cavanagh, 1983). The magnitude of weight shift during the full golf swing differs between amateur and elite golfers, as elite players significantly transferred more of their weight toward their trail foot during the backswing and toward their lead foot during the downswing (Koenig et al., 1994; Wallace, Graham, & Bleakley, 1990). To effectively utilize GRF, the timing and the magnitude of shifted GRF was more important than simply the magnitude of the GRF (Richards, Farrrell, Kent, and Kraft, 1985). However, not all studies have supported the importance of weight shift in the golf swing. It has been proposed that weight shift alone is not important but is necessary to allow the body to rotate optimally (Rae, Fairweather, & Sanders, 2001).

An important task in a golf swing is to generate a high clubhead speed through rotations of the body and club (Han et al., 2014). The rotational sequence of the downswing begins from the ground up with lower extremity movement being beneficial in producing higher clubhead speed at impact (Fujimoto-Kanatani, 1995). Maximum external moments of the lead knee have been shown to be higher than in the trail knee (27.7 Nm and 19.1 Nm, respectively) while maximum internal rotation torque of the lead knee was slightly lower than the trail knee (16.1 ± 4.8 and 19.6 ± 8.1 Nm, respectively) (Gatt, Pavol, Parker, & Grabiner, 1998). If the external resistance is created through foot ground interaction, the golfer is unable to add force to the golfer/club system and thus there is no change in moment. Limited research exists that investigates the moments generated by the foot-ground interaction. However, PGA professionals exhibited significantly more internal rotation torque about the lead foot than high handicappers (Barrentine et al., 1994). Worsfield, Smith, and Dyson (2008) reported that while using a driver, lower handicap golfers exhibited higher moments generated by the feet and increased internal rotation of the lead foot. The eccentric GRFs acting on the body due to foot-ground interactions generate force moments about the body's COM, promoting rotations of the body and club. It is the force moments that can contribute to the clubhead speed (Han et al., 2014). Moreover, the peak frontal-plane GRF moment and peak transverse-plane coupling moment showed significant correlations across all club conditions, concluding that moment parameters provided more significant associations with peak clubhead speed than forces (Han et al., 2014).

Physical Condition

The focus of past golf research has emphasized the technical, tactical, and mental aspects of golf-specific training. The focus of recent golf research has shifted to golf-specific strength and conditioning, and interventional training programs which may be able to improve golf performances such as high clubhead speed and long distance (Gordon, Moir, Davis, Witmer, & Cummings, 2009). The main purpose is to improve a combination of balance, functional strength and flexibility (Smith, 2010). It has been suggested that strength, muscle power, muscle balance, and aerobic conditioning are physical contributors to greater clubhead speed (Hume et al., 2005). Through the enhancement of specific physical conditioning, researchers have proposed that golfers could increase clubhead speed (Doan, Newton, Kwon, & Kraemer, 2006; Hetu, Christie, & Faigenbaum, 1998; Jones, 1999; Lennon, 1999; Lephart et al., 2007; Thompson, Myers, & Blackwell, 2007; Westcott, Dolan, & Cavicchi, 1996).

The core muscle groups of the lower back, pelvis, and hips are essential to the generation of a high rotational movement velocity during the golf swing. In a recent study conducted by Gordon, Moir, Davis, Witmer, and Cummings (2009) on 15 male golfers, total body rotational power, generated by throwing a medicine ball during a hip toss movement, was significantly correlated to club head speed. Skilled golfers typically demonstrate improved shoulder and core strength versus their less skilled counterparts (Sell, Tsai, Smoliga, Myers, & Lephart, 2007). A significant correlation between the strength of the gluteus medius and gluteus maximus muscles and clubhead velocity in low handicap golfers was observed by Callaway and colleagues (Callaway et al., 2012). This greater strength helped to transfer greater force to the golf ball. Keogh et al. (2009) compared the strength of two groups (i.e., low and high handicap golfers) with a 12% difference in clubhead speed. Participants performed a golf-specific rotational exercise (i.e., a golf swing-specific cable woodchop), which is very similar to the golf swing in terms of posture, range–of–motion, direction of force application and coordination patterns. Low handicap golfers had a significantly greater woodchop strength, bench press, and back squat strength, which were all statistically correlated to clubhead speed (Keogh et al., 2009). These exercises are greatly effective in generating more power from the whole body by mimicking the golf swing and may therefore improve the body segmental sequence pattern, resulting in a more efficient transfer of power (Lephart et al., 2007).

The relationship of strength and flexibility to clubhead speed of 15 male golfers' full swings was investigated by Gordon et al. (2009). Trunk strength significantly correlated to clubhead speed while rotational trunk flexibility did not. In another study, no significant correlation was observed between clubhead speed and any range–of–motion variables related to the flexibility of golfers (Keogh et al., 2009). Excessive muscular hypertrophy may be negative because of the restricted motions of the core muscles around the trunk and shoulder which could result in a decrement in golf performance (Keogh et al., 2009). According to Green (2012), it is necessary for golfers to acquire the ability to synergize the antagonistic effects of strength and flexibility in order to maximize the rotational power of the golf swing (Gordon et al., 2009). Such an improvement of muscle functionality while maintaining a high level of flexibility could be beneficial to golf swing performance.

Club Characteristics

The effect of different types or deformations of the golf club-shaft on golf shot outcomes have been examined in recent studies. An optimal shaft condition for transferring kinetic energy from clubhead to ball is one which is straight at impact, although the shaft flexibility can be observed throughout the downswing (Butler & Windield, 1994). In a study using computer simulation, the bending flexibility of the shaft involved the whipping effect, which contributes to a minor role in increasing clubhead speed (Brylawski, 1994; Milne & Davis, 1992). Miao, Watari, Kawaguchi, and Ikeda, (1999) conducted a correlation analysis between clubhead speed, grip speed, and shaft flexibility, utilizing both a swing machine and actual golfers. The authors concluded that the stiffness of the shaft and grip speed were significantly associated with clubhead speed, suggesting that the relationship between clubhead speed and grip speed is controlled partially by shaft flexibility and partially by the golfer's ability to adjust to the shaft's dynamics. Therefore, the ability to use the shaft-flexibility property appropriately is enhanced in skilled golfers when compared to less skilled golfers (Soriano, 1996).

Swing Model

The golf swing has been considered to be one of the most complex movements (Burden et al., 1998; McHardy & Pollard, 2005; Nesbit & Serrano, 2005) in all of sports. It would be of great value to create a model that would describe the golfer's motions in order to investigate the movement patterns of the entire body in detail during the swing. The double pendulum model proposed initially by Cochran and Stobbs (1968) was the first scientific model to describe the swing motion in golf biomechanical research. The first mathematical verification of the quantities used in the equations that describe the golf swing was a two dimensional double pendulum model. Introduced by Jorgensen in 1970, he proposed that a delay in the uncocking of the wrist would result in the improvement of clubhead speed. This model specifically served as a representative prototype over for 50 years, which helped to simplify complicated mechanical concepts related to the golf swing. In these models, segments consisted of only two levers: an upper (the arms) and a lower (the club) lever. There is a fixed pivot point (i.e., the wrist) for the moving segments, and those segments move in a single planar motion during the swing. Many researchers (e.g., Jorgensen, 1970; Miura, 2001; Pickering & Vickers, 1999; Sprigings & Neal, 2000) have, over several decades, analyzed the golf swing motion using planar multi-pendulum swing models. However, recent researchers have verified that the actual golf swing in the body and club systems during the downswing is not planar (Coleman & Anderson, 2007; Coleman & Rankin, 2005; Kwon et al., 2012; Neal & Wilson, 1985; Nesbit, 2005; Vaughan, 1981). In order to improve the early golf swing model, the triple pendulum model was introduced (Campbell & Reid, 1985; Sprigings & Mackenzie, 2002; Sprigings & Neal, 2000). In this model, there are three levers: the left clavicle, the lead arm, and the club. The club rotates around the pivot points of the hub at the top of the sternum and the wrists, respectively. The left clavicle pivots around the spine and the left arm moves independently from the rotation of the shoulders. With the development of technology in capturing and analyzing golf swing motions, the development of a full body, multi linked, three-dimensional biomechanical model is essential to gaining a more complete and valid understanding on the swing (Dillman & Lange, 1994). Nesbit (2005) created a computer simulation of the three-dimensional kinematics and kinetics of a golf swing using 84 male golfers and one female amateur golfer of various skill levels. The full-body model consisted of 16 segments including the club and 14 joints. Each joint was spherical, and could move in three dimensions.

Summary

A variety of factors contribute to a higher clubhead speed. These factors include kinematic sequence, kinetic energy transfer, X-factor, delayed release of wrist, weight shift, foot-ground interaction, muscular strength, flexibility, and shaft flexibility. The association between upper body motions, physical condition, and club conditioning to peak clubhead speed has been investigated thoroughly. There is very little research on the relationship between lower body motions and peak clubhead speed, possibly due to the popularity of the double pendulum model. This study can offer valuable insights to both the academic and the golf-practitioner communities by revealing key relationships between the biomechanical factors of the lower extremity motions and the peak clubhead speed.

CHAPTER III

METHODS

This chapter is divided into the following sections: participants, trial conditions, data collection, data reduction and processing, data analysis, and statistical analysis.

Participants

A total of 25 healthy, right-handed, male golfers with a posted handicap of 3 or better were recruited for this study (mass = 84.2 ± 9.0 kg; height = 182.3 ± 6.4 cm; age = 29.7 ± 7.9 years). The required sample size was estimated by using G*Power 3.1 software (effect size d = .8; significant level α = .05; power = .81). Golfers who were suffering from any major injuries that might prevent full-effort golf swings were excluded. The human participant research protocol was approved by the Institutional Review Board of Texas Woman's University and informed consents were obtained from the participants prior to data collection. The purpose and procedures of the study were explained to the participants prior to data collection.

Trial Conditions

Golfer performed swing trials with three different club conditions (i.e., driver, 5-iron, and pitching wedge) using their own clubs in an indoor setting at Texas Woman's University Biomechanics Laboratory. Foam balls were used instead of actual golf balls. Golfers chose their preferred tee heights.

Data Collection

A 250-Hz, 10-camera motion capture system (VICON, Centennial, CO, USA) was used to capture the motion trajectories of a total of 65 reflective markers attached to golfer's body, club, and the ball plate during data collection (Figure 1). The reflective markers were placed on the golfer's body only by the principal investigator to ensure consistency in marker placement across all participants. Golfers were required to wear black spandex shorts and a black swimming cap for motion capture purposes. Golfers wore their own gloves and shoes. Golfers were required to warm-up for at least 10 min prior to data collection. Sufficient practice shots were allowed for acclimatization and to find the optimal setup position and ball mat location for each golfer.

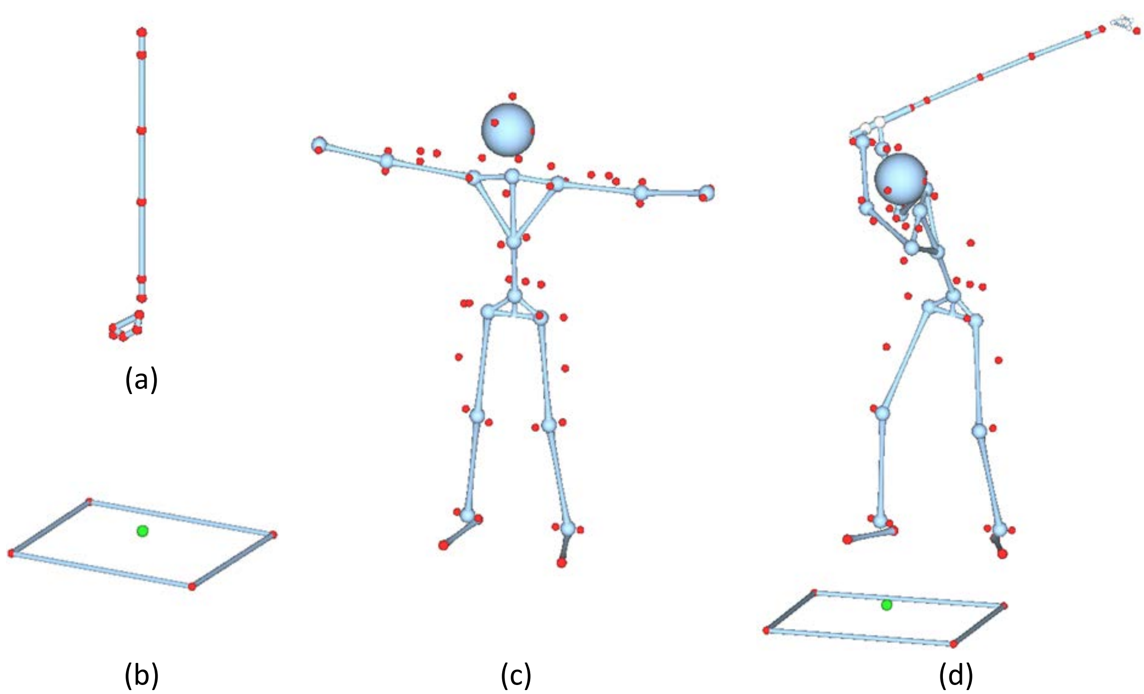


Figure 1. Trials: club (a), ball plate (b), static posture (c), motion trial (d).

Camera calibration was performed before data collection. The global Y-axis (laboratory reference frame) was aligned with the direction of shot toward the target and the vertical axis (upward) was used as the global Z-axis. The global X-axis, therefore, was the direction the right-handed golfers were facing at the setup (address) position. Two AMTI force plates (Model OR6; Advanced Mechanical Technology, Inc., Watertowwn, MA, USA) were used to measure the ground reaction force data.

Data Reduction and Processing

Captured three-dimensional marker coordinates were imported into Kwon3D Motion Analysis Suite (Version XP; Visol, Seoul, Korea) for subsequent processing and analysis. The marker coordinates were digitally filtered using a Butterworth 4^{th}-order zero phase lag low-pass filter. The cutoff frequency was set at 30 Hz for clubface points and at 15 Hz for the rest of the markers.

An 87-point body model (‘TWUGolfer’; Kwon et al., 2012) was used for the processing. In this model, 15 segments (i.e., pelvis, abdomen, thorax, head, hips, knees, feet, upper arms, right forearm, left radius, left ulna, and hands-club) were defined. Twenty-two additional points (including 13 joint centers) were computed based on the marker coordinates (Kwon et al., 2012). Zatsiorsky and Seluyanov’s body segment parameters (ratios) corrected by De Leva (1996) were used in locating the COM of the segments.

The segmental reference frame definitions, proximal-distal relationships among the segments, and the rotation sequences were used to compute the orientation angles

(Kwon et al., 2013). Twenty reference frames (i.e., pelvis, abdomen, thorax, shoulder girdles, head, hips, knees, feet, upper arms, right forearm, left ulna, left radius, hands-club, clubface, and functional swing plane) were defined. The X-axes of the segmental reference frames were aligned with the mediolateral axes of the segments, the Y-axes with the anteroposterior axes, and the Z-axes with the longitudinal axes. Thirteen degrees of freedom (joints/segments) were assigned to the golfer's lower body: pelvis (3), hip (3 each), knee (1 each), and ankle (1 each) (Table 1).

Data Analysis

Ten swing events were identified for the analysis (Figure 2): Address (AD), Mid Backswing (MB), Late Backswing (LB), and End of Pelvis Rotation (EPR) during the backswing; Top of Backswing (TB), Early Downswing Arm-based (EDA), Early Downswing (ED), Mid Downswing (MD), Ball Impact (BI), and Mid Follow-through (MF) during the downswing. EPR was used as the backswing to downswing transition event because the lower body motions including pelvis motions were analyzed in this study.

The maximum clubhead speed immediately before the impact was extracted. The OAs of the segments relative to their respective proximal segments and the RJM of the joints were computed for the analysis. The orientation angles of the pelvis segment and lower body joints were computed from the orientation matrices (Equations 1, 2, and 3).

Table 1.

Degrees of Freedom (Joint Motions) Assigned to Lower Body Joints

Joint/Segment	Axis	Orientation Angle		Joint/Segment Motion	
		Positive	**Negative**	**Increase**	**Decrease**
Pelvis	Z (Longitudinal)	Left rotated	Right rotated	Left rotation	Right rotation
	X (Mediolateral)	Posteriorly tilted	Anteriorly tilted	Posterior tilting	Anterior tilting
	Y (Anteroposterior)	Right tilted	Left tilted	Right tilting	Left tilting
R. Hip	X (Mediolateral)	Flexed	Hyperextended	Flexion	Hyperextension
	Y (Anteroposterior)	Adducted	Abducted	Adduction	Abduction
	Z (Longitudinal)	Internal rotated	External rotated	Internal rotation	External rotation
R. Knee	X (Mediolateral)	Hyperextended	Flexed	Hyperextension	Flexion
R. Ankle	X (Mediolateral)	Dorsi-flexed	Plantar-flexed	Dorsi-flexion	Plantar-flexion
L. Hip	X (Mediolateral)	Flexed	Hyperextended	Flexion	Hyperextension
	Y (Anteroposterior)	Abducted	Adducted	Abduction	Adduction
	Z (Longitudinal)	External rotated	Internal rotated	External rotation	Internal rotation
L. Knee	X (Mediolateral)	Hyperextended	Flexed	Hyperextension	Flexion
L. Ankle	X (Mediolateral)	Dorsi-flexed	Plantar-flexed	Dorsi-flexion	Plantar-flexion

Directional abbreviations: R – right and L – left.

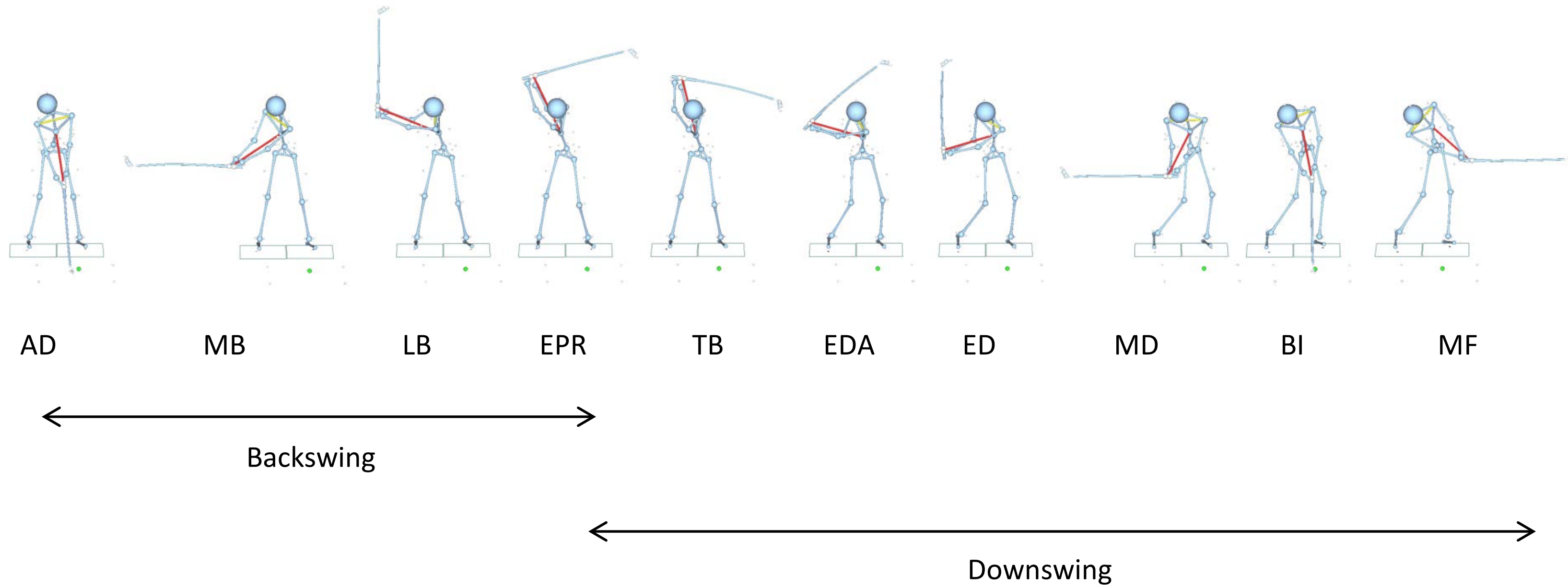


Figure 2. Ten events during the backswing and downswing. Abbreviations: AD – Address, MB – Mid Backswing, LB – Late Backswing, EPR – End of Pelvis Rotation, TB – Top of Backswing, EDA – Early Downswing, Arm-based, ED – Early Downswing, MD – Mid Downswing, BI – Ball Impact, and MF – Mid Follow-through.

The axis unit vectors of the segmental reference frames form the global orientation matrices (Kwon, 2008):

$$\mathbf{T}_{P/G} = \begin{bmatrix} \mathbf{i}_P \\ \mathbf{j}_P \\ \mathbf{k}_P \end{bmatrix} = \begin{bmatrix} t_{11P} & t_{12P} & t_{13P} \\ t_{21P} & t_{22P} & t_{23P} \\ t_{31P} & t_{32P} & t_{33P} \end{bmatrix}$$

$$\mathbf{T}_{D/G} = \begin{bmatrix} \mathbf{i}_D \\ \mathbf{j}_D \\ \mathbf{k}_D \end{bmatrix} = \begin{bmatrix} t_{11D} & t_{12D} & t_{13D} \\ t_{21D} & t_{22D} & t_{23D} \\ t_{31D} & t_{32D} & t_{33D} \end{bmatrix}, \qquad (1)$$

where $\mathbf{T}$ is the 3 × 3 orientation matrix, P is the proximal segment, D is the distal segment, G is the global reference frame, **i**, **j**, and **k** are the axis unit vectors of the segmental reference frame, and $t_{11} - t_{33}$ are the components of the axis unit vectors. The relative orientation matrix of the distal reference frame (frame D) to the proximal reference frame (frame P) was computed from the orientation matrices shown in Equation 1.

$$\mathbf{T}_{D/P} = \mathbf{T}_{D/G}\mathbf{T}_{P/G} = \mathbf{T}_{D/G}\,\mathbf{T}'_{P/G} \qquad (2)$$

where $\mathbf{T}_{D/P}$ is the relative orientation matrix of frame *D* to frame *P*, and $\mathbf{T}'$ is the transpose of $\mathbf{T}$. Relative orientation angles of the segments to their respective linked proximal segments were computed from relative orientation matrices using the mediolateral–anteroposterior–longitudinal (XYZ) rotation sequence:

$$\begin{bmatrix} C_2C_3 & S_1S_2C_3 + C_1S_3 & -C_1S_2C_3 + S_1S_3 \\ -C_2C_3 & -S_1S_2C_3 + C_1S_3 & C_1S_2C_3 + S_1S_3 \\ S_1 & -S_1C_2 & C_1C_2 \end{bmatrix} = \mathbf{T}_{D/P}\,, \qquad (3)$$

where C and S are $\cos\theta$ and $\sin\theta$, respectively, and $\theta_{1,}\theta_{2,}$and θ_3 are the relative orientation angles of the distal segment to the proximal segment forming the joint.

The kinetic data involving resultant joint moments for each joint was calculated using inverse dynamics (Equations 4 and 5; Figure 3) based on Newton's equation of motion:

$$\mathbf{F}_j = \mathbf{M}_j + \mathbf{J}_j = \sum_s \frac{d\mathbf{P}_s}{dt} - \sum_s \mathbf{W}_s - \mathbf{F}_E \quad (4)$$

$$\mathbf{N}_j = \mathbf{r}_j \times \mathbf{M}_j = \sum_s \left(\frac{d\mathbf{L}_s}{dt} + \mathbf{r}_{js} \times \frac{d\mathbf{P}_s}{dt}\right) - \sum_s\left(\mathbf{r}_{js} \times \mathbf{W}_s\right) - \left(\mathbf{r}_{jE} \times \mathbf{F}_E + \mathbf{N}_E\right) \quad (5)$$

where $\mathbf{F}_j$ is the resultant joint force acting at the joint, $\mathbf{M}_j$ is the muscle force not passing through the axis of rotation, $\mathbf{J}_j$ is the joint contact force passing through axis of rotation (bone-on-bone force), $\mathbf{P}_s$ is the linear momentum of the segment which is the same as the sum of inertial forces, $\mathbf{W}_s$ is the weight of the segments due to gravitational force, $\mathbf{F}_E$ is the ground reaction force which is the additional external force from the environment acting on the segment, $\mathbf{N}_j$ is the resultant joint moment acting at the joint, $\mathbf{r}_j$ is the relative position vector of muscle attachment to the joint, $\mathbf{L}_s$ is the local angular momentum of the segment due to the rotation of the segment about its own segmental COM, $\mathbf{r}_{js}$ is the relative position vector of each segment's COM to the joint, $\mathbf{r}_{jE}$ is the relative position vector of the joint to the point of the application of the additional external force, and $\mathbf{N}_E$ is the additional external moment.

The peak orientation angles were identified to describe the ranges of the orientation angles in each joint while performing the golf swing. The orientation angle and joint moment parameters used in this study are shown in Figures 4a and 4b.

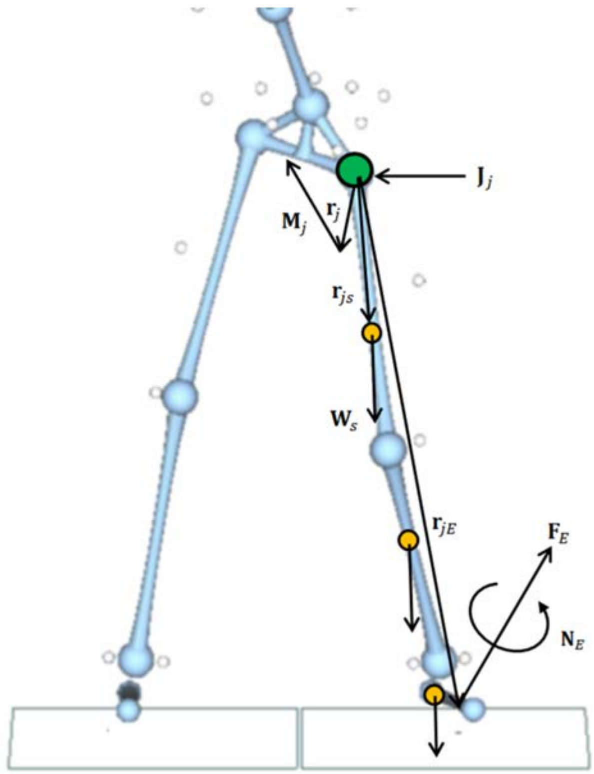
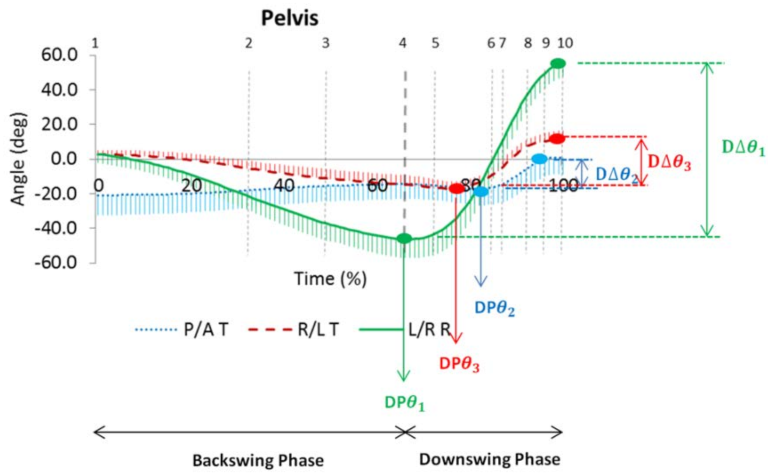
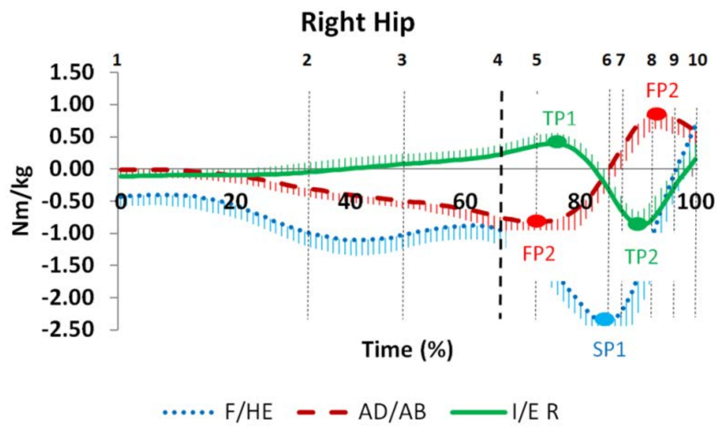


Figure 3. Free body diagram of left hip joint



(a)



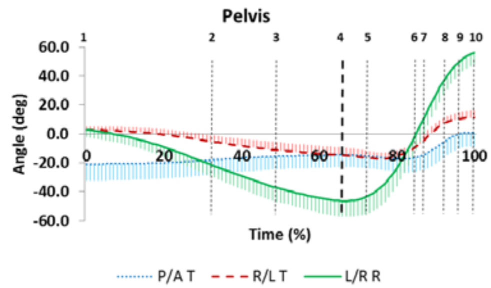
(b)

Figure 4. Exemplar OA (a) and RJM (b) parameters used during the downswing phase: (a) Pelvis defined as the longitudinal–mediolateral–anteroposterior–(ZXY) rotation sequence. $P\theta_{1,}P\theta_{2,}$ and, $P\theta_3$ were defined as peak orientation angles in the longitudinal, mediolateral, and anteroposterior axes, respectively. $\Delta\theta_{1,}\Delta\theta_{2,}$ and $\Delta\theta_3$ were defined as ranges of the orientation angles in the longitudinal, mediolateral, anteroposterior axes, respectively. (b) Peak resultant joint moments in the right hip joints. SP1 – peak joint moment in the sagittal plane, FP1 and FP2 – peak joint moments in the frontal plane, and TP1 and TP2 – peak joint moments in the transverse plane.

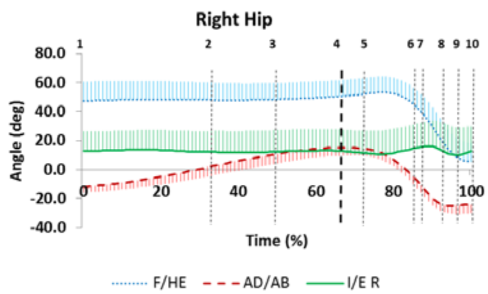
The ensemble average patterns of the OA and RJM during the golf swing were derived using AD to MF phases as 100% time. The ensemble average patterns of the OA parameters are presented in Figures 5, 6, and 7 for the driver, 5-iron, and the pitching wedge, respectively. All peak orientation angles occurred in the early downswing phase, during the transition from backswing to downswing (Figures 5, 6, and 7). Therefore, the OA parameters during the backswing were excluded from all subsequent analyses.

The ensemble average patterns of the RJM patterns of the lower extremity joints are presented in Figures 8, 9, and 10 for the driver, 5-iron, and the pitching wedge, respectively. During the downswing, two peaks were identified in the right hip joint are identified in the frontal and transverse planes. Two peaks were also identified in the left hip joint in the sagittal and transverse planes. Peak joint moments in the knees and ankles were observed in the early downswing phase.

Based on the ensemble average patterns of OA and RJM parameters, peak OA and ranges of the lower extremity joints (i.e., pelvis, hips, knees, and ankles) during the downswing, peak RJM of the lower extremity joints (i.e., hips, knees, and ankles), were extracted for a correlation analysis to normalized peak clubhead speed. The peak clubhead speeds and the RJM were normalized to golfer's body height (BH) and mass (BM), respectively, to eliminate the effect of body size.



(a)



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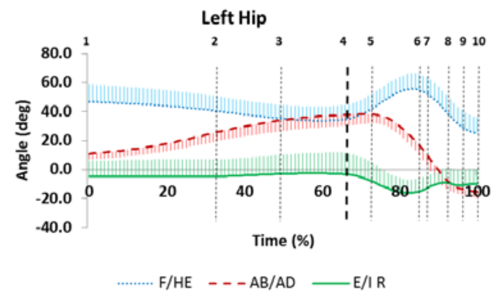

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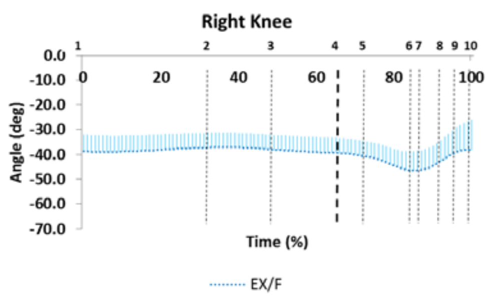

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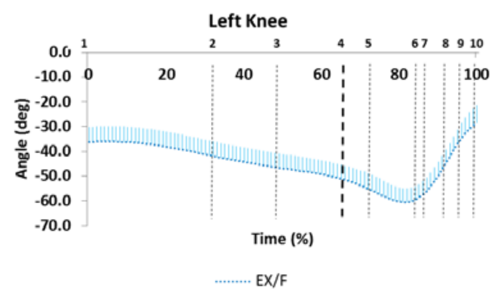

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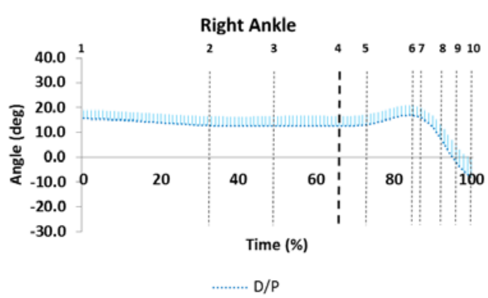

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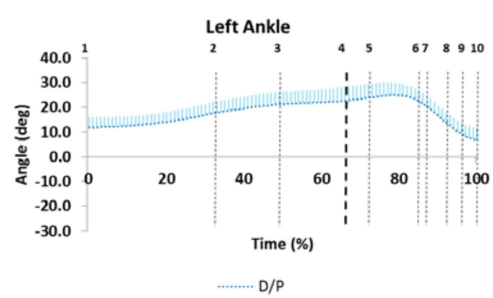


(g)

Figure 5. Ensemble-average patterns of OA in driver condition: Event: 1 – AD, 2 – MB, 3 – LB, 4 – EPR, 5 – TB, 6 – EDA, 7 – ED, 8 – MD, 9 – BI, and 10 – MF. The AD-MF phase was used as 100% time. Directional abbreviations: A – anterior, P – posterior, R – right, L – left, I – internal and E – external. Relative positions: T – tilted, R –rotated, F – flexed, HE – hyperextended, EX – extended, AD – adducted, AB – abducted, D – dorsi-flexed, and P – plantar-flexed.

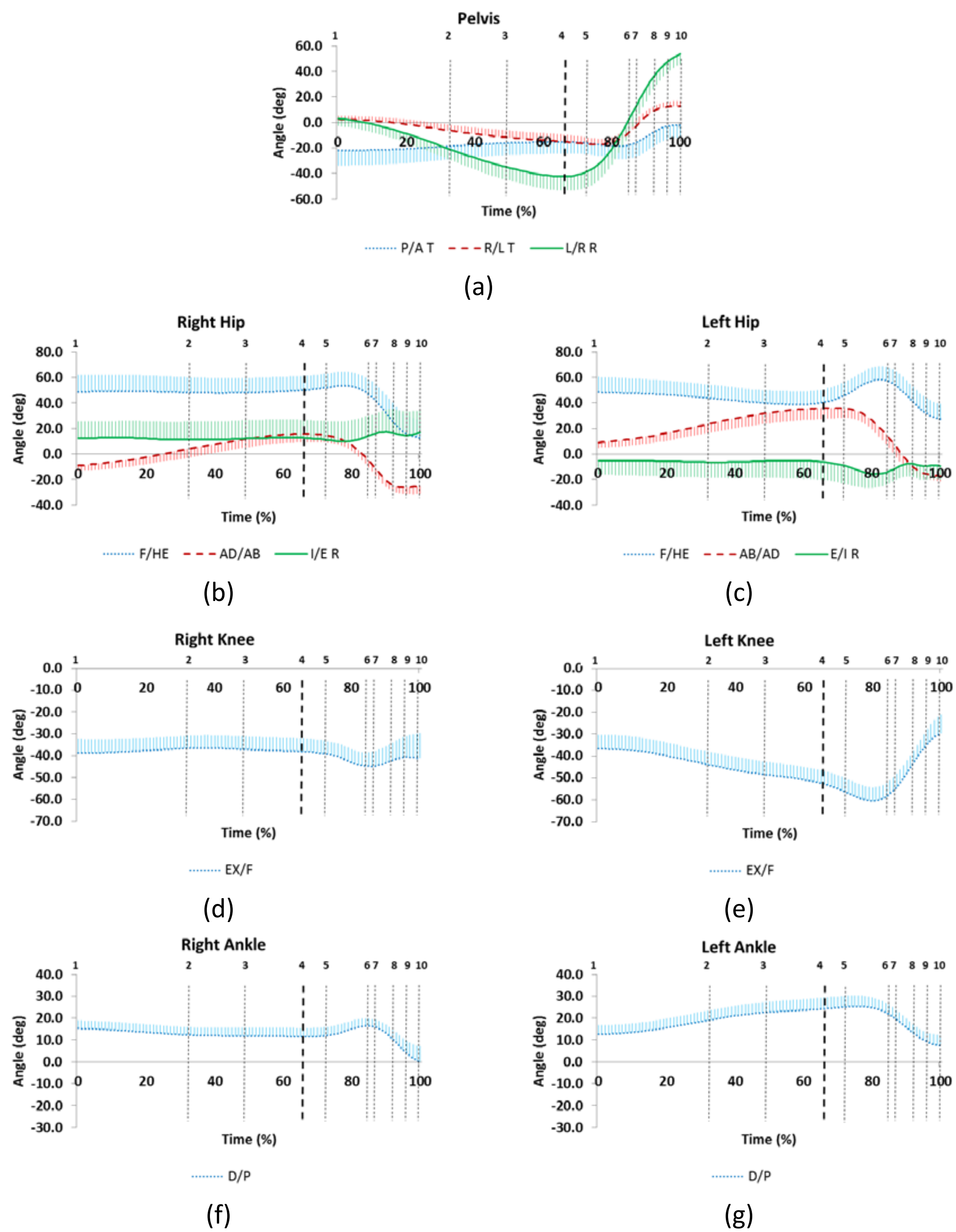
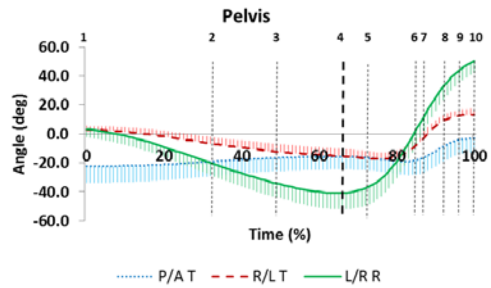
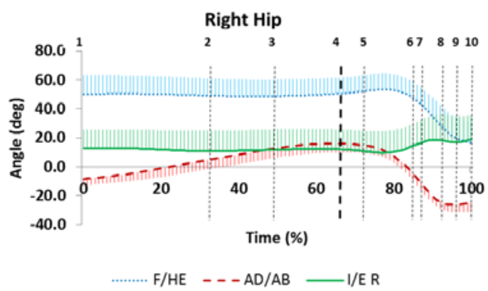


Figure 6. Ensemble-average patterns of OA in 5 - iron condition: Event: 1 – AD, 2 – MB, 3 – LB, 4 – EPR, 5 – TB, 6 – EDA, 7 – ED, 8 – MD, 9 – BI, and 10 – MF. Directional abbreviations: A – anterior, P – posterior, R – right, L – left, I – internal and E – external. Relative positions: T – tilted, R –rotated, F – flexed, HE – hyperextended, EX – extended, AD – adducted, AB – abducted, D – dorsi-flexed, and P – plantar-flexed.



(a)



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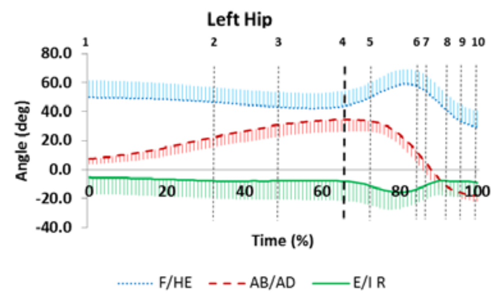

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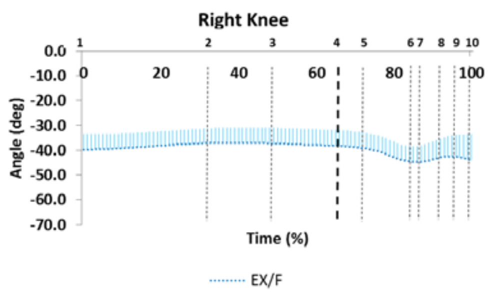

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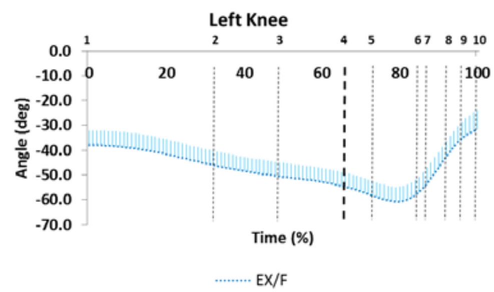

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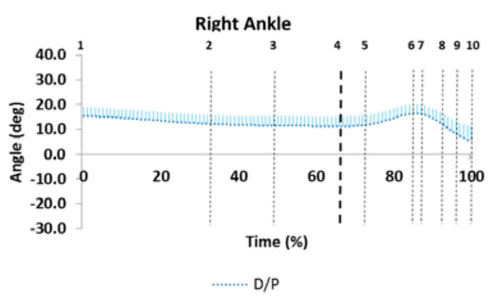

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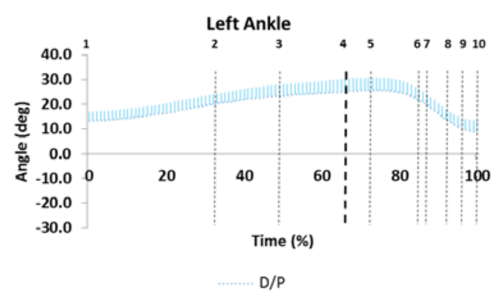


(g)

Figure 7. Ensemble-average patterns of OA in pitching wedge condition: Event: 1 – AD, 2 – MB, 3 – LB, 4 – EPR, 5 – TB, 6 – EDA, 7 – ED, 8 – MD, 9 – BI, and 10 – MF. Directional abbreviations: A – anterior, P – posterior, R – right, L – left, I – internal and E – external. Relative positions: T – tilted, R –rotated, F – flexed, HE – hyperextended, EX – extended, AD – adducted, AB – abducted, D – dorsi-flexed, and P – plantar-flexed.

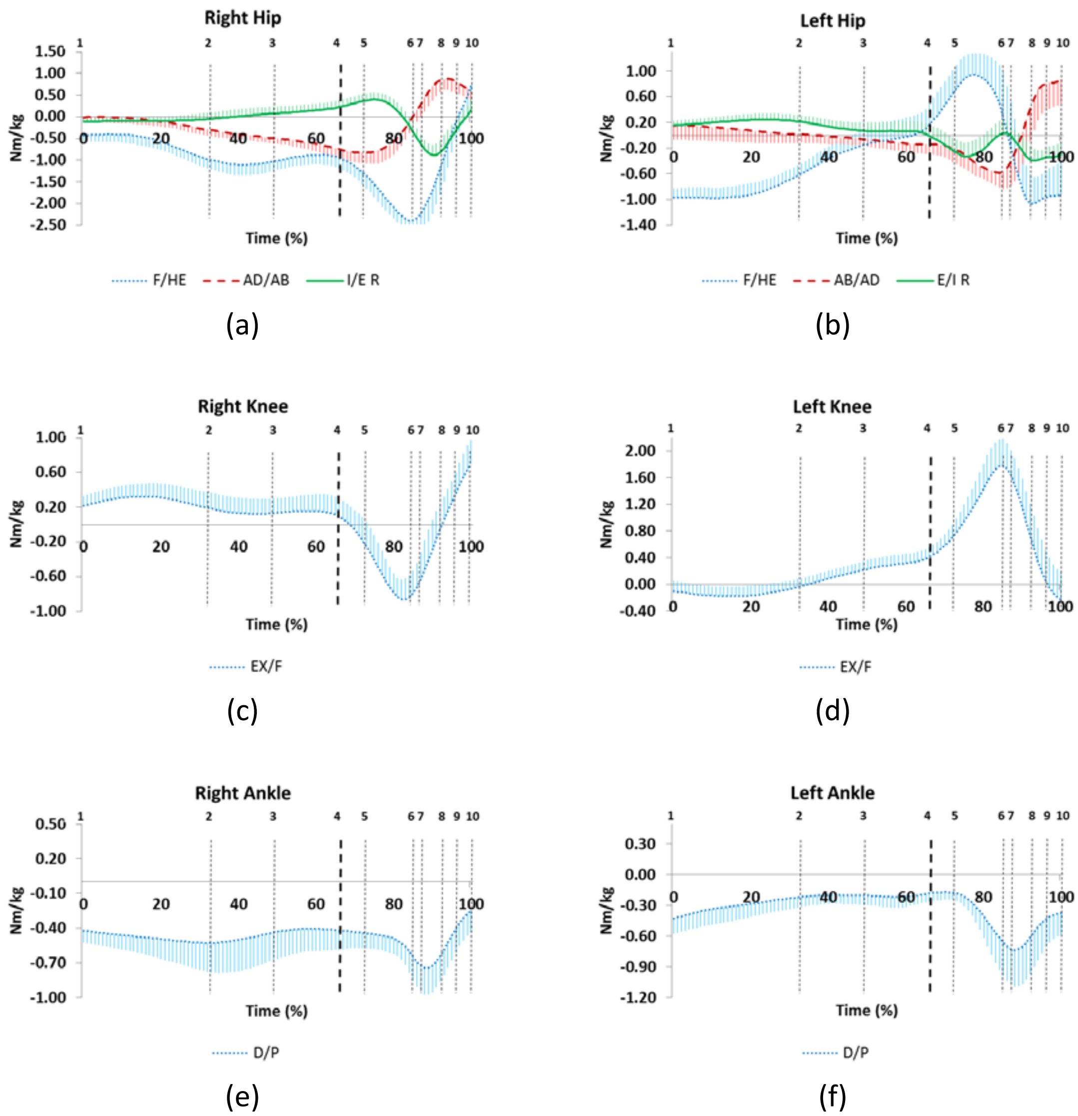


Figure 8. Ensemble-average patterns of normalized RJM in driver condition: Event: 1 – AD, 2 – MB, 3 – LB, 4 – EPR, 5 – TB, 6 – EDA, 7 – ED, 8 – MD, 9 – BI, and 10 – MF. The AD-MF phase was used as 100% time. Directional abbreviations: I – internal and E – external. Moment abbreviations: F – flexor, HE – hyperextensor EX – extensor, AD – adductor, AB – abductor, R – rotator, D – dorsi-flexor, and P – plantar-flexor.

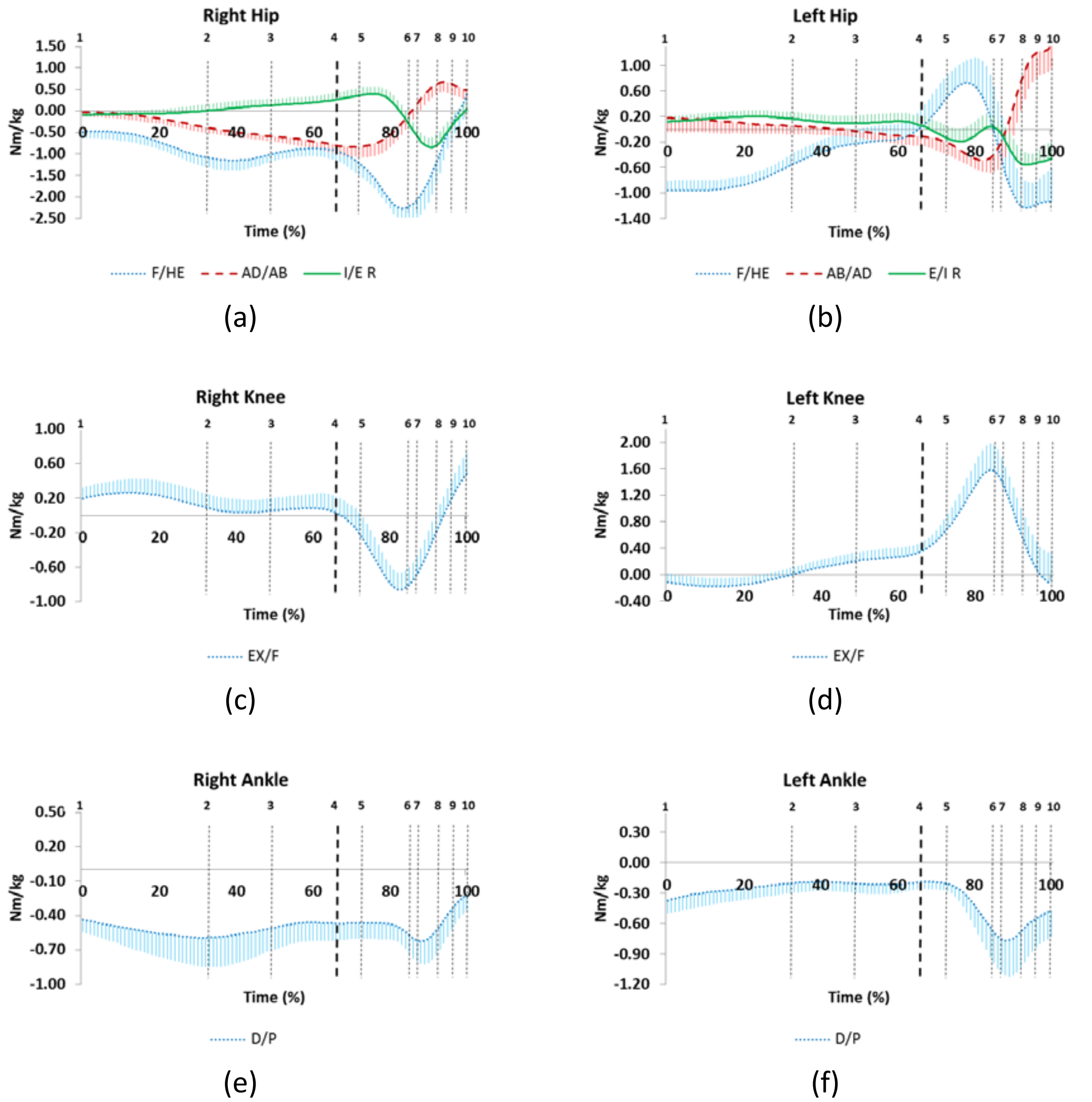


Figure 9. Ensemble-average patterns of normalized RJM in 5 - iron condition: Event: 1 – AD, 2 – MB, 3 – LB, 4 – EPR, 5 – TB, 6 – EDA, 7 – ED, 8 – MD, 9 – BI, and 10 – MF. The AD-MF phase was used as 100% time. Directional abbreviations: I – internal and E – external. Moment abbreviations: F – flexor, HE – hyperextensor EX – extensor, AD – adductor, AB – abductor, R – rotator, D – dorsi-flexor, and P – plantar-flexor.

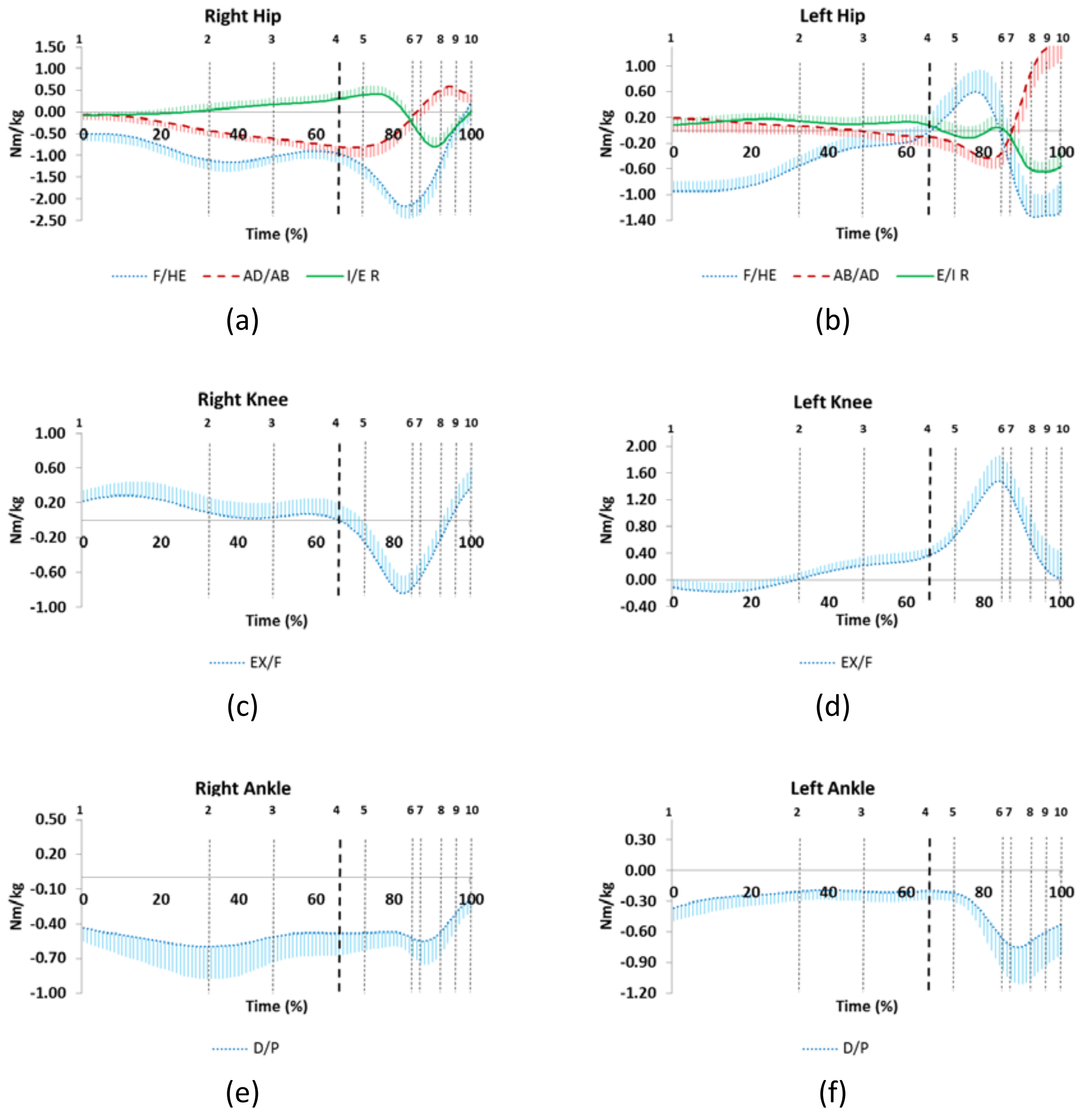


Figure 10. Ensemble-average patterns of normalized RJM in pitching-wedge condition: Event: 1 – AD, 2 – MB, 3 – LB, 4 – EPR, 5 – TB, 6 – EDA, 7 – ED, 8 – MD, 9 – BI, and 10 – MF. The AD-MF phase was used as 100% time. Directional abbreviations: I – internal and E – external. Moment abbreviations: F – flexor, HE – hyperextensor EX – extensor, AD – adductor, AB – abductor, R – rotator, D – dorsi-flexor, and P – plantar-flexor.

Statistical Analysis

The select variables (Tables 2 and 3) used in the statistical analyses were peak OA and ranges of OA of the lower extremity joints (i.e., pelvis, hips, knees, and ankles) during the downswing, peak joint moments of the lower extremity joints (i.e., hips, knees, and ankles), and peak clubhead speed. The mean values of the five repeated trials were used in the statistical analyses. Pearson's product–moment correlation coefficients (r) were computed between the OA and RJM parameters and peak clubhead speed in each club condition. An alpha level of .05 was used in all tests. All statistical analyses were conducted using SPSS V. 19.0 (SPSS, Inc., Chicago, IL).

Table2.

OA Parameters for Data Analysis during Downswing

Plane	Joint	Peak Position	Joint Motion
Sagittal	Pelvis	Max Anteriorly tilted	Posterior Tilting
	R. Hip	Max Flexed	Extension
	L. Hip	Max Flexed	Extension
	R. Knee	Max Flexed	Extension
	L. Knee	Max Flexed	Extension
	R. Ankle	Max Dorsi-flexed	Extension
	L. Ankle	Max Dorsi-flexed	Extension
Frontal	Pelvis	Max left tilted	Right tilting
		Max Right tilted	
	R. Hip	Max Adducted	Abduction
		Max Abducted	
	L. Hip	Max Abducted	Adduction
		Max Adducted	
Transverse	Pelvis	Max Right rotated	Left Rotation
		Max Left rotated	
	R. Hip	Max Internal rotated	Internal rotation
	L. Hip	Max Internal rotated	Internal rotation

OA – Orientation angle. Directional abbreviations: R – right and L – left.

Table3.

RJM Parameters for Data Analysis

Plane	Joint	Dominant muscle of Peak RJM
Sagittal	R. Hip	Extensor
	L. Hip	Flexor (P1)
		Extensor (P2)
	R. Knee	Flexor
	L. Knee	Extensor
	R. Ankle	Plantar-flexor
	L. Ankle	Plantar-flexor
Frontal	R. Hip	Abductor (P1)
		Adductor (P2)
	L. Hip	Adductor
Transverse	R. Hip	Internal rotator (P1)
		External rotator (P2)
	L. Hip	Internal rotator (P1)
		Internal rotator (P2)

Directional abbreviations: R – right and L – left. P1 – first peak, and P2 – second peak.

CHAPTER IV

RESULTS

This chapter is divided into the following sections: orientation angle and resultant joint moment.

Orientation Angle

The mean maximum clubhead speeds at impact were 25.9 ± 1.1 BH/s (47.0 ± 2.0 m/s), 21.8 ± 1.0 BH/s (39.4 ± 1.8 m/s), and 19.7 ± 1.2 BH/s (35.9 ± 2.0 m/s) for driver, 5-iron, and pitching wedge, respectively. Correlation coefficients (r) of OA parameters to normalized peak clubhead speed (NPCS) are presented in Tables 4 and 5. Among the peak position values of OA, the maximum right tilted position values of the pelvis during the downswing revealed significant correlations to NPCS across all club conditions. The maximum adducted position of the left hip joint in pitching wedge condition exhibited a significant correlation to NPCS during the downswing. Among the ranges of OA, the pelvis right-tilting range during the downswing consistently yielded significant correlations to NPCS across all club conditions. Right hip extension range in pitching wedge condition, left hip adduction range in driver and pitching wedge conditions, and pelvis left rotation range in pitching wedge condition showed significant correlations to NPCS during the downswing.

Table 4.
Peak OA and Correlation Coefficients (r) to NPCS (in degree)

Plane	Joint	Peak Position	Driver		5-iron		Pitching Wedge	
			M ± SD	***r***	**M ± SD**	***r***	**M ± SD**	***r***
Sagittal	Pelvis	Anteriorly tilted	18.1 ± 9.0	-.051	19.3 ± 9.4	-.021	19.4 ± 9.3	-.038
	R. Hip	Flexed	54.0 ± 10.6	-.028	53.8 ± 10.7	-.051	54.0 ± 10.7	-.003
	L. Hip	Flexed	56.4 ± 10.7	.002	58.7 ± 10.5	-071	59.4 ± 10.2	-.030
	R. Knee	Flexed	-49.8 ± 7.1	.227	-48.5 ± 7.4	.182	-48.8 ± 7.3	.164
	L. Knee	Flexed	-61.1 ± 5.1	.119	-60.8 ± 5.7	.075	-61.1 ± 5.6	.055
	R. Ankle	Dorsi-flexed	17.3 ± 3.9	.060	16.7 ± 3.4	.227	16.9 ± 3.5	.170
	L. Ankle	Dorsi-flexed	25.2 ± 5.0	.016	25.7 ± 4.7	.006	26.1 ± 4.8	-.072
Frontal	Pelvis	left tilted	-17.7 ± 4.4	.017	-18.1 ± 4.5	-.020	-18.1 ± 4.7	-.143
		Right tilted	11.9 ± 4.8	.510*	13.3 ± 4.1	.501*	13.4 ± 4.0	.522*
	R. Hip	Adducted	15.3 ± 5.3	-.198	15.7 ± 5.8	.021	16.1 ± 6.0	.059
		Abducted	-27.0 ± 5.3	-.301	-28.0 ± 5.2	-.224	-27.8 ± 5.3	-.307
	L. Hip	Abducted	39.0 ± 6.8	.216	36.6 ± 7.8	.216	34.6 ± 8.0	.306
		Adducted	-16.0 ± 4.1	-.326	-18.1 ± 3.6	-.302	-18.4 ± 3.8	-.431*
Transverse	Pelvis	Right Rotated	56.1 ± 8.2	.198	53.6 ± 7.9	.109	50.3 ± 7.9	.389
		Left Rotated	-46.2 ± 10.6	-.188	-42.6 ± 10.7	-.241	-40.7 ± 10.9	-.189
	R. Hip	Internal Rotated	20.2 ±15.8	.169	21.4 ± 15.8	.090	21.6 ± 16.4	.087
	L. Hip	Internal Rotated	-18.2 ± 9.8	.170	-17.7 ± 10.8	-.014	-17.3 ± 11.1	-.097

NPCS – Normalized peak clubhead speed. Directional abbreviations: R – right and L – left. *p < .05.

Table 5.
Range of OA and Correlation Coefficients (r) to NPCS (in degree)

Plane	**Joint**	**Joint Motion**	**Driver**		**5-iron**		**Pitching Wedge**	
			M ± SD	***r***	**M ± SD**	***r***	**M ± SD**	***r***
Sagittal	Pelvis	Posterior Tilting	19.8 ± 4.5	-.251	18.1 ± 4.6	-.207	17.0 ± 4.3	-.094
	R. Hip	Extension	49.2 ± 8.5	.272	42.2 ± 8.2	.130	37.6 ± 8.8	.427*
	L. Hip	Extension	32.3 ± 9.1	-.141	31.4 ± 8.3	-.271	30.2 ± 7.9	-.066
	R. Knee	Extension	16.8 ± 8.2	.179	14.6 ± 7.8	.117	13.4 ± 7.7	.090
	L. Knee	Extension	32.7 ± 8.8	.119	31.0 ± 9.5	-.001	29.5 ± 8.2	.128
	R. Ankle	Plantar-flexion	25.4 ± 8.1	-.056	17.1 ± 7.8	-.049	13.0 ± 6.7	-.044
	L. Ankle	Plantar-flexion	18.4 ± 5.8	.217	18.4 ± 5.3	.120	17.7 ± 4.9	.186
Frontal	Pelvis	Right tilting	29.6 ± 5.3	.450*	31.4 ± 5.3	.409*	31.5 ± 5.6	.493*
	R. Hip	Abduction	42.3 ± 6.3	.086	43.8 ± 6.6	.194	43.8 ± 6.7	.292
	L. Hip	Adduction	55.0 ± 6.3	.444*	54.7 ± 7.2	.383	52.9 ± 7.9	.515*
Transverse	Pelvis	Left rotation	102.3 ± 9.9	.366	96.2 ± 9.2	.373	91.0 ± 11.1	.465*
	R. Hip	Internal rotation	15.1 ± 5.2	.169	14.7 ± 5.0	.085	14.8 ± 5.6	.159
	L. Hip	Internal rotation	17.2 ± 4.9	.125	15.7 ± 5.3	.051	14.6 ± 4.8	.090

NPCS – Normalized peak clubhead speed. Directional abbreviations: R – right and L – left. *$p < .05$.

Resultant Joint Moment

Table 6 shows the correlation coefficients (*r*) of the normalized RJM parameters to NPCS during the downswing. Right hip extensor, left hip flexor (P1), left knee extensor, and right ankle plantar-flexor moments in the sagittal plane and right hip adductor moment (P2) in the frontal plane exhibited significant correlations to NPCS across all club conditions. Right knee flexor moments in driver and pitching wedge conditions and left ankle plantar-flexor moment in driver condition showed significant correlations to NPCS in the sagittal plane. Left hip adductor moments in 5-iron and pitching wedge conditions showed significant correlations to NPCS in the frontal plane. Right hip external rotator moment in pitching wedge condition showed significant correlations to NPCS in the transverse plane.

Table 6.

RJM and Correlation Coefficients (r) to NPCS (in Nm/kg)

Plane	Joint	Dominant Muscle	Driver		5-iron		Pitching Wedge	
			M ± SD	***r***	**M ± SD**	***r***	**M ± SD**	***r***
Sagittal	R. Hip	Extensor	2.39 ± .25	.396*	2.26 ± .26	.667*	2.17 ± .28	.732*
	L. Hip	Flexor (P1)[§]	.94 ± .33	.424*	.73 ±.35	.544*	.60 ± .32	.597*
		Extensor (P2)[§]	1.06 ± .41	-.198	1.2 ± .40	-.222	1.34 ± .34	-.255
	R. Knee	Flexor	.86 ± .23	.527*	.85 ±.19	.383	.84 ± .20	.465*
	L. Knee	Extensor	1.90 ± .39	.451*	1.58 ± .39	.449*	1.48 ± .38	.457*
	R. Ankle	Plantar-flexor	.74 ± .23	.515*	.63 ± .19	.609*	.55 ± .19	.547*
	L. Ankle	Plantar-flexor	.76 ± .36	.447*	.76 ± .34	.183	.74 ± .36	.189
Frontal	R. Hip	Abductor(P1)[§]	.91 ± .13	.030	.83 ± .22	.142	.82 ± .22	.210
		Adductor(P2)[§]	1.0 ± .14	.456*	.67 ± .22	.585*	.58 ± .20	.502*
	L. Hip	Adductor	.58 ± .23	.384	.50 ± .16	.437*	.44 ± .14	.572*
Transverse	R. Hip	Internal rotator (P1)[§]	.45 ± .08	-.106	.40 ± .15	.075	.40 ± .18	.149
		External rotator (P2)[§]	.94 ± .16	.243	.84 ± .23	.375	.80 ± .21	.468*
	L. Hip	Internal rotator (P1)[§]	.33 ±. 21	-.077	.19 ± .20	-.265	.12 ± .18	-.260
		Internal rotator (P2)[§]	.38 ± .18	.194	.55 ± .19	-.071	.46 ± .21	.084

NPCS – Normalized peak clubhead speed. Directional abbreviations: R – right and L – left. P1 – first peak and P2 – second peak. [§] See Figures 8, 9, and 10 for the peaks. *p < .05.

CHAPTER V

DISCUSSION

This study investigated the associations between peak clubhead speed and select kinematic and kinetic parameters of the lower extremities in skilled golfers. Normalized peak clubhead speed and peak OA and ranges of the lower extremities joints (i.e., pelvis, hips, knees, and ankles) and normalized RJM parameters of the lower extremities joints (i.e., hips, knees, and ankles) were calculated in three anatomical planes of motion (i.e., sagittal, frontal, and transverse).

Orientation Angle

During the downswing, the pelvis motions were characterized by an initial anterior tilt and a left lateral tilt followed by a posterior tilt and a right lateral tilt. The pelvis exhibited continuous right rotation (Figures 5a, 6a, and 7a). The right hip joint motions revealed a transition from adduction to abduction and consistent flexed and internal-rotated positions (Figures 5b, 6b, and 7b). The left hip joint motions were demonstrated by transitions from flexion and abduction to extension and adduction, and consistent flexed and right-rotated positions (Figures 5c, 6c, 7c). The right and left knee were observed with continuous flexed positions throughout the downswing. The right and left knees were characterized by a transition of flexion to extension (Figures 5d, 6d, 7d, 5e, 6e, and 7e). The right ankle motion was characterized by a transition from dorsi-flexion to plantar-flexion (Figures 5f, 6f, and 7f). The left ankle exhibited a consistent flexed position and was transferred from dorsi-flexion to plantar-flexion (Figure 5g, 6g, 7g). Similar patterns in terms of OA parameters were observed in all club conditions.

Among the peak OA variables, only the right lateral tilted position of the pelvis was significantly correlated to NPCS across all the club conditions during the downswing (Table 4). Additionally, among the ranges of OA, only the right tilting motion range of the pelvis showed significant correlations to NPCS across all club conditions during the downswing (Table 5). Therefore, the pelvis motion in the frontal plane could be the good consistent indicator of clubhead speed.

Among OAs during the downswing, the left rotation of the pelvis exhibited the largest motion range (102.3, 96.2, and 91.0° for driver, 5-iron, and pitching wedge, respectively), followed by the left hip adduction (55, 54.7, and 52.9° for driver, 5-iron, and pitching wedge, respectively) and the right hip extension (49.2, 42.2, and 37.6° for driver, 5-iron, and pitching wedge, respectively). Also, the pelvis right tilting (29.6, 31.4, and 31.5° for driver, 5-iron, and pitching wedge, respectively) and the left hip extension (32.3, 31.4, and 30.2° for driver, 5-iron, and pitching wedge, respectively) revealed substantial motion ranges (Table 5). One of the most controversial aspects of the recent golf swing has been whether the limited motion ranges of pelvis and hip is more effective in generating higher clubhead speed. The findings from this study indicated the pelvis in the transverse and frontal planes and the right and left hips in the sagittal and frontal planes demonstrated sufficient motion ranges during the downswing. Additionally, among OAs during the downswing, significant correlations to NPCS were observed in pelvis and right/left hip joint motions while no significant correlations to NPCS in knee and ankle joint motions were observed (Table 5). Therefore, as long as the motion ranges of the pelvis and the right/left hip joints are placed within the base of support, the motions of pelvis and hip joints should be not limited in generating higher clubhead speed during the downswing.

Resultant Joint Moment

The RJM patterns of lower extremity joints are presented in Figures 8, 9, and 10. The sagittal plane component of the right hip joint moment showed a continuous dominance of the flexor moment with one peak. The frontal plane component was characterized by the initial adductor dominant phase followed by the abductor dominant phase with each peak (e.g., adductor peak and abductor peak). The transverse plane component presented the initial internal rotator dominant phase followed by the external rotator dominant phase with two peaks (e.g., internal rotator peak and external rotator peak) (Figures 8a, 9a, and 10a). The sagittal plane component of the left hip joint moment exhibited the initial flexor dominant phase followed by extensor dominant phase with two peaks (e.g., flexor peak and extensor peak). The frontal plane component was characterized by the initial adductor dominant phase followed by the abductor dominant phase with one peak (e.g., adductor peak). The transverse plane component showed internal rotator dominant phase with two peaks (e.g., two internal rotator peaks) (Figures 8b, 9b, and 10b). The right knee was characterized by the dominance of initial extensor moment followed by flexor moment and another extensor moment with one peak (e.g., flexor peak). The left knee was characterized by the dominance of initial extensor moment followed by flexor moment with one peak (e.g., extensor peak) (Figures 8c, 9c, 10c, 8d, 9d, and 10d). The plantar-flexor moments of right and left ankles were consistently dominant throughout the downswing with one peak each (e.g., plantar-flexor peak) (Figure 8e, 9e, 10e, 8f, 9f, and 10f). Similar patterns in terms of the peak RJM parameters were observed in all club conditions.

Among the club conditions, RJM parameters with the driver and pitching wedge conditions revealed the greatest number of significant correlations to NPCS (Table 6). The RJM parameters in the sagittal, frontal, and transverse planes included in Table 6 explain 76, 55, 8% of the significant correlations to NPCS, respectively, suggesting the RJMs in the sagittal plane are affecting the peak clubhead speed the most.

Among the RJM parameters, the right hip extensor moment revealed the largest RJM value, followed by the left knee extensor moment (Table 6). Among hip joint moments, the largest right hip extensor moment was consistent with the outcome of a previous study (Foxworth et al., 2013), which compared the three dimensional hip joint moments between the right and left legs. This result was also supported by the finding of another study in which the gluteus maximus of the right leg, which serves as the right hip extensor, was the most active hip muscle and drove the flexed hip into extension during the downswing (Gatt et al., 1998). With regard to knee joint moments, the finding in this study was consistent with a previous study conducted by Gatt et al., in 1998. Among knee RJMs, the maximal left knee extensor moment occurred in the sagittal plane. Also, the right hip extensor and left knee extensor moments in the sagittal plane exhibited significant correlations to NPCS across all club conditions. Based on these results, the skilled golfers relied on more muscular effort of the right hip and left knee joints in the sagittal plane to generate higher clubhead speed.

As mentioned previously, during the downswing the largest values for RJM occurred in the right hip and left knee joints in the sagittal plane. This is explained by the technique used in a golf swing motion to generate the large peak joint moments. This was identified from the external moment components such as moment arm (MA) and ground reaction force (GRF) (Figure 11). The timings of peak right hip joint and left knee joint moments in the sagittal plane were relatively consistent across all participants while differences were identified with the timings of the maximum GRF and maximum MA. In Figures 12a, b, and c, type 1 (n = 11 and 2 in right hip and left knee, respectively) is the peak hip joint moment value at the instant the MA was longest in the sagittal plane. Type 2 (n = 5 and 2 in right hip and left knee, respectively) is the peak value occurred in the maximum GRF magnitude. Type 3 (n = 9 and 21 in right hip and left knee, respectively) is the best combination of both MA and GRF magnitude. This indicates that the skilled golfers more relied on type 1 style to generate the peak right hip extensor moment while type 3 style to generate the peak left knee extensor moment.

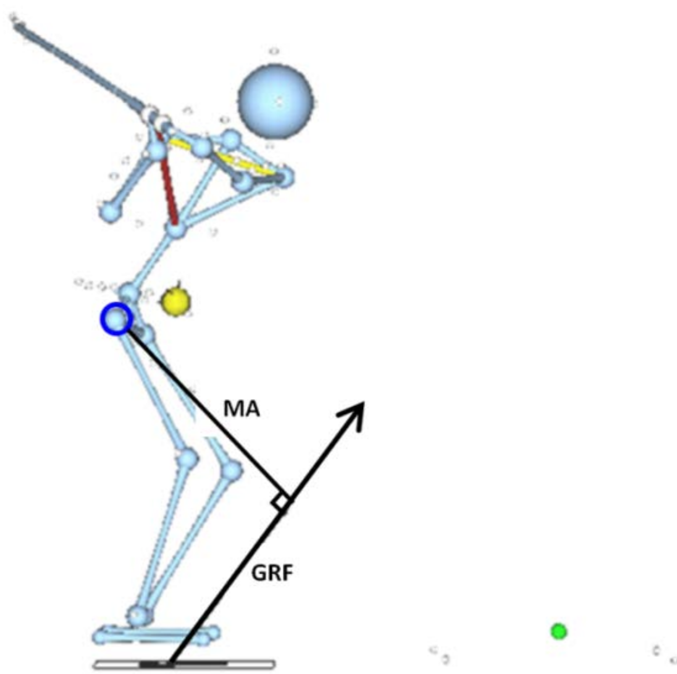
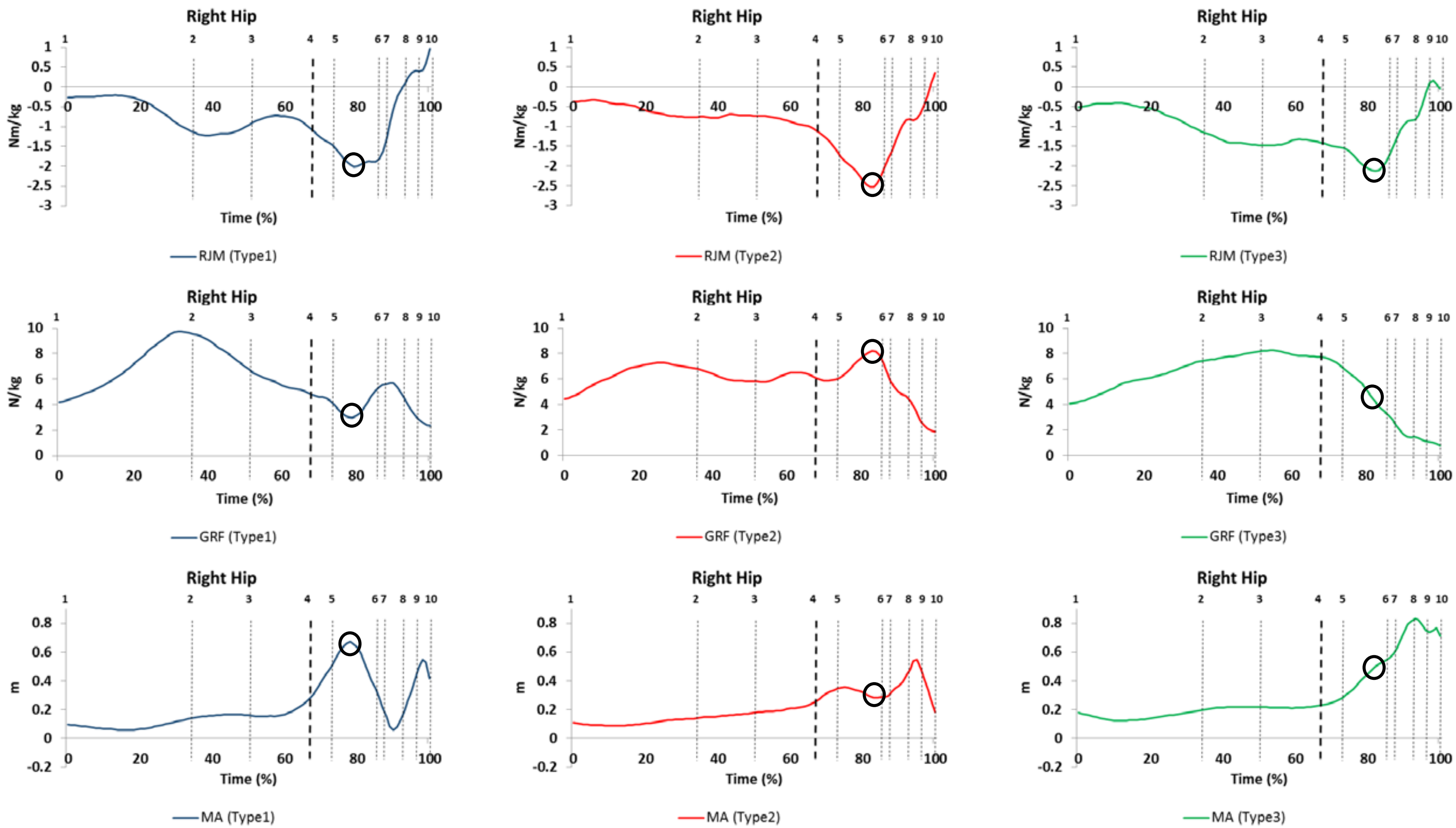


Figure 11. Exemplar moment arm from the line of action of the GRF vector to each joint and the magnitude of GRF at the instant of peak right hip RJM in the sagittal plane.



(a) Type 1 (b) Type 2 (c) Type 3

Figure12. Exemplar MA and GRF patterns at the instant of peak right hip RJM in the sagittal plane. Type 1 (max MA; a), Type2 (max GRF; b), and Type3 (combination of MA and GRF; c).

Different dominant muscles were used between the right hip extensor and left hip flexor moments (P1), the right knee flexor and left knee extensor moments, and the right hip abductor (P1) and left hip adductor moments at the instant of peak RJM (Tables 6, 7, and 8). This could be explained by the discrepancy in the direction of the GRF vector to each hip and knee joint center between the two legs. For example, in the sagittal plane, the directions of the GRF vector to each joint center were counterclockwise (+) in the right hip and knee while clockwise (–) in the left hip and knee. As a result, the moments in the hip and knee joints between the two legs were produced by the dominant muscles in the opposite direction (e.g., the right hip extensor [–] and left hip flexor [+] moments and the right knee flexor [–] and left knee extensor [+] moments).

Different types of muscle contractions occurred at the instant of peak RJMs (Table 7). Based upon OA and RJM results, the type of muscle contractions can be obtained. If the OA and the RJM results are in the same direction, a concentric contraction occurred in that muscle group. If the results are in opposite directions, an eccentric contraction occurred. In the transverse plane, for example, the right hip muscles in the first peak (P1) exhibited an eccentric internal rotator contraction while the right hip muscles in the second peak (P2) showed a concentric external rotator contraction due to different RJM directions. The right /left hip, knee, ankle joints exhibited the types of concentric contractions in three motion planes except for the right hip eccentric contraction of the second peak (P2) in the transverse plane.

Therefore, the muscle contractions of the lower extremities that occurred at the instant of peak RJMs are primarily concentric contractions.

Table7.
Type of Muscle Contraction at Peak RJM

Plane	Joint	Dominant Muscle	Joint Motion	Type of Contraction
Sagittal	R. Hip	Extensor	Extension	CON
	L. Hip	Flexor (P1)§	Flexion	CON
		Extensor (P2)§	Extension	CON
	R. Knee	Flexor	Flexion	CON
	L. Knee	Extensor	Extension	CON
	R. Ankle	Plantar-flexor	Plantar-flexion	CON
	R. Ankle	Plantar-flexor	Plantar-flexion	CON
Frontal	R. Hip	Abductor (P1)§	Abduction	CON
		Adductor (P2)§	Adduction	CON
	L. Hip	Adductor	Adduction	CON
Transverse	R. Hip	Internal rotator (P1)§	External-rotation	ECC
		External rotator (P2)§	External-rotation	CON
	L. Hip	Internal rotator (P1)§	Internal-rotation	CON
		Internal rotator (P2)§	Internal-rotation	CON

Directional abbreviations: R –right and L – left. Contraction abbreviations: CON – concentric and ECC – eccentric. P1 – first peak and P2 – second peak. § See Figures 8, 9, and 10 for the peaks.

The hip joint (between TB and EDA event; early downswing phase) reached the fastest peak joint moments followed by the knee joint (around EDA event) and the ankle joint (around ED event) (Table 8; Figures 8, 9, and 10). It is important to reach peak RJM values early in lower extremity joints so the golfer has enough time to accelerate the upper body and clubhead to obtain a higher clubhead speed. These findings can help explain the different roles exhibited by the lower body, which dominates the early downswing movement. The upper body controls or leads the mid-downswing movement. After EDA or ED, each lower extremity joint's RJM started to reduce, indicating a reduction in the moment applied to rotate the pelvis (Table 8; Figures 8, 9, and 10). The angular momentum generated through the foot-ground interaction and muscle actions is transferred to the upper body and the clubhead through the lower body. These results complement the findings in previous studies that describe the kinetic chain during a golf swing (Burden et al., 1998; Callaway et al., 2012; Horan et al., 2010; Joyce et al., 2010; Lephart et al., 2007; Neal & Dalgleish, 2008; Tinmark et al., 2010).

Table 8.
Peak RJM Timing (%)

Plane	Joint	Dominant Muscle	Driver	5-iron	Pitching Wedge
			Timing (%)	Timing (%)	Timing (%)
Sagittal	R. Hip	Extensor	83	83	83
	L. Hip	Flexor (P1)§	77	78	78
		Extensor (P2)§	94	94	94
	R. Knee	Flexor	83	83	83
	L. Knee	Extensor	85	84	84
	R. Ankle	Plantar-flexor	87	87	87
	L. Ankle	Plantar-flexor	87	87	89
Frontal	R. Hip	Abductor(P1)§	73	70	70
		Adductor(P2)§	94	94	94
	L. Hip	Adductor	83	83	83
Transverse	R. Hip	Internal rotator (P1)§	75	75	74
		External rotator (P2)§	93	93	93
	L. Hip	Internal rotator (P1)§	77	77	77
		Internal rotator (P2)§	95	94	93

NPCS – Normalized peak clubhead speed. Directional abbreviations: R – right and L – left. P1 – first peak and P2 – second peak. § See Figures 8, 9, and 10 for the peaks. Event timings during the downswing phase: EPR (69), TB (71), EDA (84), ED (87), MD (92), BI (95), and MF (100).

Conclusion

This proposed study offers valuable insights into the relationships between the key kinematic and kinetic factors of the lower extremity motions and peak clubhead speed. It was hypothesized that (1) Peak OA and ranges of OA of the lower extremity joints (i.e., hips, knees, and ankles) and pelvis in three anatomical planes of motion (sagittal**,** frontal, and transverse) would be significantly correlated to NPCS in skilled golfers and (2) Peak RJM of the lower extremity joints (hip, knee, and ankle) would be significantly correlated to NPCS in skilled golfers.

Based on the results in this study, it was concluded that:

- Among OA parameters, only the pelvis right lateral tilted position and the pelvis right tilting motion were significantly correlated to NPCS across all the club conditions during the downswing. The pelvis motion in the frontal plane was identified as the good consistent indicator of clubhead speed in skilled golfers. Therefore, strong association between the pelvis motions in the frontal plane and clubhead speed suggests that skilled golfers maneuver pelvic motion in the frontal plane in generating higher clubhead speed during the downswing.
- Among RJM parameters, the right hip extensor and left knee extensor moments in the sagittal plane exhibited significant correlations to NPCS across all club conditions. The skilled golfers relied especially more on muscular effort from the right hip and left knee joints in the sagittal plane. The right hip extensor and left knee extensor moments were considered as the good consistent indicator in

generating higher clubhead speed in skilled golfers. Therefore, it is important to develop a swing pattern that maximizes right hip extensor moment and left knee extensor moment during the early downswing phase to generate a high clubhead speed.

Recommendation for Future Study

The difference in the swing styles utilized by each individual who participated in this study was not considered. In order to generate angular effect, some of the golfers may be lower extremity dominant i.e. foot-ground interaction, or upper body dominant, i.e. mid-trunk muscular effort. As shown in the equation of the RJM (Equation 5), the RJM in the mid-trunk can be computed from inertial, gravitational, and external components. The external moment is a result of the participant being in contact with the ground. Without a firm connection with the ground (external term), golfers cannot maximize the moment generated by the muscle. If the external moment value is small, the only way to increase the moment is to rely more on the inertial moment by accelerating the lower body angularly. This study did not shed light on the angular effect from the mid-trunk as it comes from the inertial moment or the external moment through good foot ground interaction. Therefore, the next study will be to scrutinize the distinct characteristics and relationships among the inertial, gravitational, and external moment terms about the RJM produced from the mid-trunk joint.

In order to obtain the resultant joint moment, the inverse dynamics approach was that only combined moment of muscle forces was computed. Thus, this approach gives a fair idea about the overall muscle activity at the joint while the insight about specific muscles and their role in joint movement cannot be obtained. In order to solve this problem, musculoskeletal modeling would be used to estimate the amount of force muscles around the joint should produce. Therefore, a future study would combine kinematic, kinetic, Electromyography, and 3-D data with musculoskeletal modeling to estimate individual muscular efforts in the lower extremity joints during a golf swing.

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APPEMDIX A

INFORMED CONSENT FORM

TEXAS WOMAN'S UNIVERSITY

CONSENT TO PARTICIPATE IN RESEARCH

Title: Lower body mechanics in golf and its association with maximum clubhead speed in skilled golfers

Principal Investigator: Ki Hoon Han ………………………………. khan@twu.edu (940) 595-6191
Advisor: Young-Hoo Kwon, Ph.D. ……………………………… ykwon@ twu.edu (940) 898-2598

<u>Explanation and Purpose of the Research</u>

One of the most important determinants of success in golf is clubhead speed as it primarily determines the ball carry distance. Therefore, the emphasis has been placed on finding movement patterns and characteristics of the swing that result in higher clubhead speed at impact.

A substantial number of previous studies have been conducted based on the so-called double-pendulum model and its triple-pendulum sibling in which the golfer arms and club were reduced to two rigid levers connected at the wrists. In this model, only the arm and wrist motions were considered as the main contributor to the clubhead speed. As a result, the importance of lower extremity motions has practically been ignored in golf researches.

The purpose of this study is to investigate the associations between peak clubhead speed and select kinematic and kinetic parameters of the lower extremity motions during the golf swing.

Hypotheses:

1. Peak orientation angles of the lower extremities (ankle, knee, and hip) and pelvis in three different planes of motion (sagittal**,** frontal, and transverse) would be significantly correlated to peak clubhead speed in skilled golfers.

2. Peak joint moments of the lower extremities (ankle, knee, and hip) in three different planes of motion (sagittal**,** frontal, and transverse) would be significantly correlated to peak clubhead speed in skilled golfers.

<u>Research Procedures</u>

Once you agree to participate in the study and sign this Informed Consent Form, you will be asked to perform the following:

You will enter the Motion Analysis Laboratory on Texas Woman's University-Denton Campus (Pioneer Hall 124). You will be then asked to change into clothing specific to biomechanical research (close fitting dark spandex shorts and shirt) in the participant preparation room and will also be outfitted with reflective markers (up to seventy reflective markers) over specific anatomical landmarks (Figure 1). The clothing and reflective markers will be supplied by the Biomechanics Laboratory, unless you feel more comfortable in your own spandex. The anatomical landmarks will consist of but not limited to 5 pelvis markers, 11 trunk markers , 4 head markers, 20 arm markers, 16 leg markers , 9 club markers, and 5 ball-plate markers.

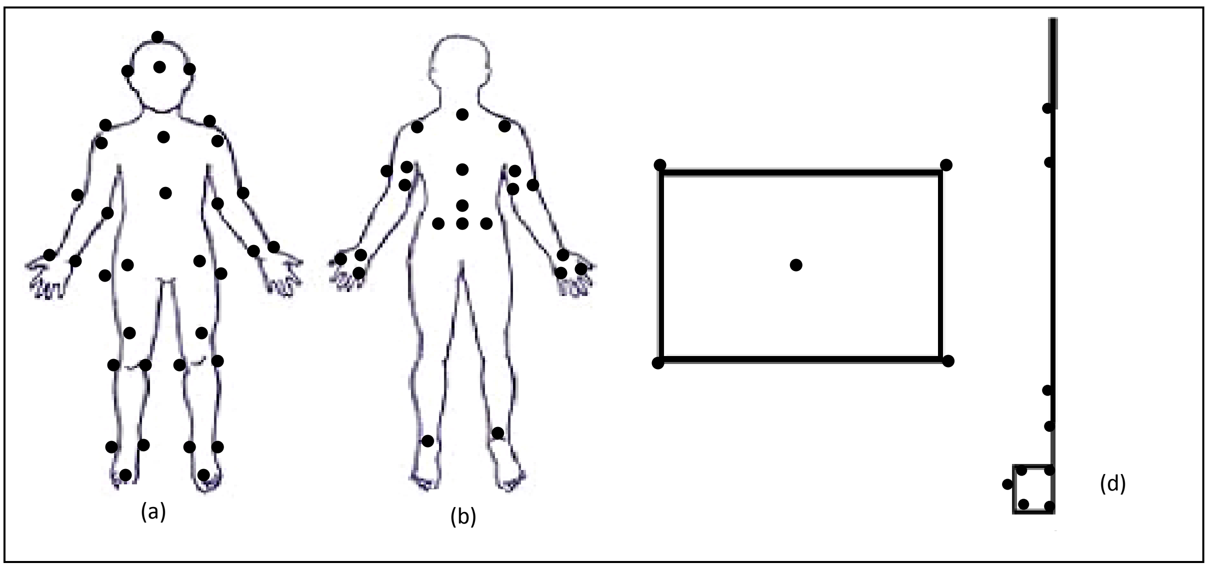

Figure 1. Marker locations: front (a), back (b), ball-plate (c), and club (d).

A warm-up and familiarization period will be allotted to make certain you have adequate time to raise your core temperature warming the connective tissue, thus reducing the possibility of injury and ensuring quality of movement.

A static trial (in T-pose) will be collected and used to determine a reflective marker relationship and calculate the secondary points (i.e. joint centers) of your body. In addition, a static trial allows for certain markers to be removed in the swing trials to minimize the negative influence of the markers on your movement during data collection.

Three different golf club conditions (driver, 5 iron, and pitching wedge) will be used. Five "good" swing trials will be collected per each golf club condition. Prior to collecting data under a new condition you will be allocated undetermined amount of time to re-familiarize yourself with the golf club being used to ensure quality movement. A "good" dynamic trial constitutes a swing that produces both a quality ball flight and normal "feel" to you.

This project involves single-session data collection. It will take approximately one and half hours in completing all procedures (explaining the consent form, attaching markers on your body, and conducting data collection).

Potential Risks

Loss of Confidentiality: The participant's name and contact information will be collected.

You as a participant will be identified by a unique participants ID code. All computer files associated with a given participant will be identified solely by this code and will not contain any identifying information. The master cross-reference list will be kept separate from all other data collected and will be accessible only to the principal investigator and research team. No other identifying information will be collected. Upon completion of data collection sessions, the master cross-reference list will be destroyed by shredding. As computer files will not contain any identifying information, erasure of computer files is not considered necessary to protect confidentiality after destruction of the master-cross reference list. All captured motion files are stored directly to the computer; therefore, will be erased from the computer three years from the conclusion of the study. There is a potential risk of loss of confidentiality in all email, downloading and internet transactions. Confidentiality will be protected to the extent that is allowed by the law.

Coercion: Participation in the current study is strictly voluntary, and you may withdraw at any time at your discretion.

Embarrassment: Reflective markers will be attached on your body by a male principal investigator after the approval from you. The researchers will try to prevent any problems associated to the embarrassment.

Irritation from skin preparation: This step is necessary to ensure good skin-to-reflective marker adhesion during static and motion trials. Erroneous results can occur if this step is not taken. Care will be taken in skin preparation to minimize risk by cleansing the area of contact. If you are sensitive to such treatment you will not be recruited or asked not to participate in the current research.

Possibility of Injury: The potential for injury will be minimized by allowing you adequate time to warm-up and adjust to the both conditions of the laboratory and the golf club being used per each trial. If you feel uncomfortable during the data collection with any of the testing conditions, you are free to discontinue your involvement in this research project.

Fatigue: You will be allowed to rest in between the testing session if you feel tired.

Loss of Time: There is a risk of loss of time to you. The loss of time will involve time of data collection and travel time to the Lab and back. There will not be any compensation for the loss of time.

The researchers will try to prevent any problems that could happen because of this research. You should let the researchers know at once if there is a problem and they will help you. However, TWU does not provide medical services or financial assistance for injuries that might happen because you are taking part in this research.

Participation and Benefits

Your involvement in this research study is completely voluntary, and you may discontinue your participation in the study at any time. The only direct benefit of this study to you is that at the completion of the study a summary of the results will be mailed to you upon request. Upon receiving the results of the research, if you happen to have any further questions you are welcome to contact the principal investigator and set-up an appointment for a private consultation to discuss your individual results. The time, date, and location will be determined at the time of contact.

Questions Regarding this Research Study

If you have any questions about the research study you may ask the researchers, their phone numbers are at the top of this form. If you have questions about your rights as a participant in this research or the way this study has been conducted, you may contact the Texas Woman's University Office of Research and Sponsored Programs at 940-898-3378 or via e-mail at IRB@twu.edu. You will be given a copy of this signed and dated consent form to keep.

_______________________________________ ___________________

Signature of Participant Date

If you would like to receive a copy of the published results of this research study, please provide the following contact information:

____

Full Name

____

Mailing Address

____

City, State and Zip Code

____

Email address (If you prefer to receive the published results via email)