Effect of Club Selection and Clubhead Speed on the Knee Joint during the Golf Swing

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Golf is a sport that can be played throughout one's lifetime providing an opportunity for competition, socialization, and improved physical activity. Golf is commonly recommended by physicians to those with knee ailments, under the assumption given that golf is considered a low impact sport. Previous research shows large forces and moments in the frontal plane of the knee, with magnitudes high enough to cause concern for injury and progression of overuse/degenerative conditions, especially with repeated exposure. In addition, changes to the golf swing across clubs have been seldom analyzed, while variations in clubhead speed using multiple clubs have yet to be investigated. Because shot ranges overlap between golf clubs, multiple clubs could be used for a given shot. A certain club's shot distance at given speed can also be achieved by using the next longest club in the set and swinging 6 mph slower. The purpose of this study was to determine if male golfers with a handicap below 18 can reduce their peak frontal plane moments by swinging 6 mph slower while using the next longest club in the set. It was hypothesized that swinging slower with a longer club, would reduce the peak adduction and abduction moments at the knee joint. Kinetics and kinematics of the lower body were analyzed from 11 intermediate to highly skilled participants (handicap: 10.1 ± 6.3) during the golf swing using 7 golf clubs (Driver, 4i, 5i, 6i, 7i, 8i, and 9i) and two participant-specific clubhead speeds (normal and slow). The normal speed was defined as the participant's self-selected clubhead speed, while the slow speed was set as 6 mph slower using the paired longer club. Normal (N) and slow (S) clubhead speed pairings of adjacent clubs were analyzed, including 5iN/4iS, 6iN/5iS, 7iN/6iS, 8iN/7iS, and 9iN/8iS. The shape of the moment waveforms were consistent within and between participants. Peak knee adduction moments ranged from 0.86-0.95 Nm/kg (N), and 0.84-0.9 Nm/kg (S). A two-way 'condition (2) x pair (5)' repeated measures analyses of variance was used to address the hypotheses. Peak abduction moments ranged from 0.58-0.77

Nm/kg (N), and 0.52-0.56 Nm/kg (S). There was a main effect of condition, but not of pair or an interaction for the peak abduction moments ($P<0.05$). There was no main effect, of condition or pair, or interaction for the peak adduction moments ($P>0.2$). While not statistically significant, peak adduction moments were lower with the slower swings. The magnitudes of these frontal plane moments are greater than those previously reported, potentially indicating differing swing mechanics compared to this study, resulting in altered kinetics of the lower limbs during the golf swing.

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I would like to say that this project was a bed of roses, however that would be far from the truth. Nothing came easy during this. There was too many heartaches, roadblocks, breakages, and downright nuisances to count. BUT, this process also brought me new friends, love, confidence, knowledge, passion, and hobbies that I would not have without doing this. So for all of those, this was worth it.

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On to the next obstacle…

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1 Thesis Overview

1.1 Introduction and Motivation

Golf is a sport that can be played throughout one's lifetime providing an opportunity for competition, socialization, and improved physical activity (Siegenthaler and O'Dell, 2003). Many golfers come from and/or play other sports such as hockey, baseball, tennis, jogging, or basketball, being widely considered more strenuous activities where players may have accumulated lingering injuries. Golf is recommended by doctors and clinicians as a safe sport to play after injury, joint disease, or surgery (Healy et al., 2001; Mallon and Callaghan, 1994, 1993). However, recent work has suggested that attention should be paid to the frontal plane moments at the knee joint during the golf swing (D'Lima et al., 2008; Hamai et al., 2008; Lynn and Noffal, 2010; Mundermann et al., 2008; Pfeiffer et al., 2014). The knee adduction moment is taken as a surrogate for medial knee joint loading, with a higher adduction moment being linked to the progression of knee osteoarthritis (OA) (Chehab et al., 2014; Creaby et al., 2010; Miyazaki et al., 2002; Sharma et al., 1998). Lynn and Noffal (2010) observed that knee adduction moments (straight foot (STR): 0.63±0.23Nm/kg; foot externally rotated 30° (EXT): 0.54±0.25 Nm/kg) during golf swings were greater than those Costigan et al. (2002) observed during gait (0.49±0.19 Nm/kg) or stair ascent (0.42± 0.15 Nm/kg). Knee abduction moments (STR: 0.7±0.12Nm/kg; EXT: 0.80±0.19 Nm/kg) were also found to be greater than abduction moments during drop-jump landings (0.74±0.46 Nm/kg), which has been identified as a measure to evaluate anterior cruciate ligament (ACL) injury risk (Hewett et al., 2005). Injuries to the ACL are often observed to occur during sporting activities (Hagino et al., 2015), at shallow knee flexion angles (less than 20° of flexion), and during periods of deceleration with multi-planar loading (Boden et al., 2000; McNair et al., 1990). Athletes who went on to injure their ACL in a subsequent season experienced similar magnitudes of abduction moments from the drop-jump task as what has been measured during the golf swing (Hewett et al., 2005; Lynn and Noffal, 2010). Therefore, the moments experienced by golfers may be sufficient to aggravate, or lead to, an injury.

The golf swing is a high-speed, asymmetrical, whole-body movement requiring coordination from all joints. The golf swing uses twisting of the torso, whip action of the arms and wrist, and power transfer from the legs and hips to the upper body (McNally et al., 2014; Thériault and Lachance, 1998). There are four general phases to the golf swing: Address (or set-up), Backswing, Downswing, and Follow-Through, and 2 transition points, Top of the Backswing and Ball Impact as outlined in Table 1.1 below (Gatt et al., 1998; Hume et al., 2005). The phases and transition points are labelled on the curve in Figure 1.1, which shows the hand height during the golf swing (adapted from Gatt et al., 1998). The swing is a very short and fast movement lasting roughly 1 second (not including the follow-through) where the backswing lasts roughly 0.76-0.86 seconds, while the downswing is much shorter, lasting between 0.23-0.33 seconds (Barrentine et al., 1994; Cochran and Stobbs, 2005; Egret et al., 2003; Sinclair et al., 2014).

Table 1.1 - General phases of the golf swing.

Phase	Description
Address/ Set-up	Feet are at comfortable width apart as to provide a solid base. Proper grip of the club will have the clubhead lie on the ground. The knees should slightly be flexed with the trunk flexed for a comfortable position to start the swing.
Backswing	Beginning of the swing; the club is pulled back from the ball, the body is rotated clockwise as the weight is transferred to the rear foot. The club rises over the head to a maximum point of rotation. The joints stretch and muscles begin to activate to initiate the downswing.
Top of Backswing	The transition point between the end of the backswing and start of the downswing.
Downswing	From the maximum point of rotation, the body is then rotated counter-clockwise, while the club is swung downward with high velocity to strike the golf ball. Weight is shifted from the rear foot forward onto the front foot.
Ball Impact	Instance when the clubhead makes contact with the ball, launching it in the air.
Follow-Through	After the golf ball is hit, the body rotation rapidly decelerates until the torso faces the direction of the shot. The club is swung through to rest over the head. The majority of the body's weight is supported by the front leg, as the pelvis pivots, and the back heel is lifted so that only the back toes are on the ground.

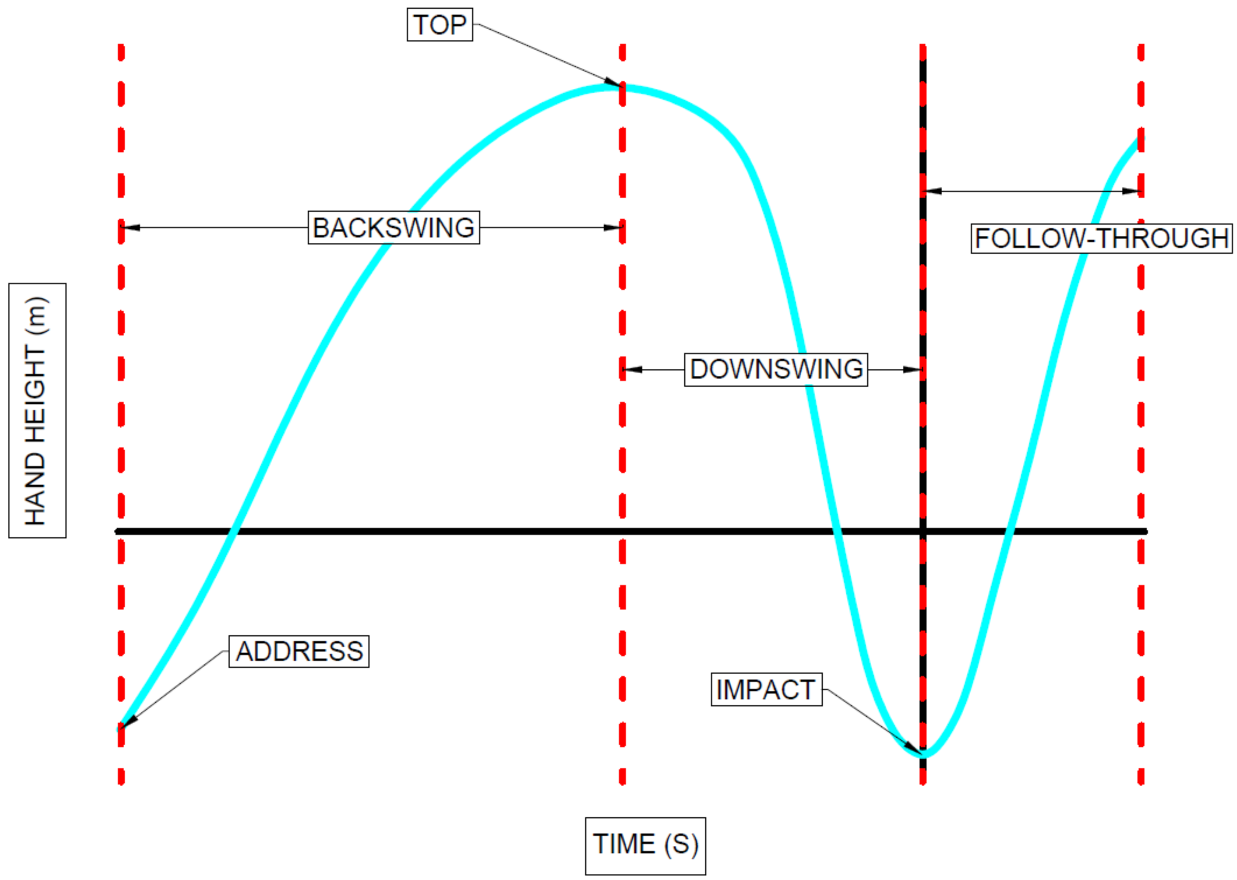


Figure 1.1 - Representative graph for the phases of the golf swing.

Golf coaches and players have largely transitioned golf swing styles from what is referred to as the *classic* (old) swing to the *modern* (current) swing to create a more consistent swing while also resulting in more distance. The modern swing involves rotation of the torso over a more rigid lower body, unlike the classic swing, which is less restrictive on lower body motion. In the modern swing, the front leg acts like a post/pivot from the end of the downswing (leading to ball impact) through the follow-through (after ball impact) (McHardy et al., 2006; Symes, 2014). The peak knee abduction moment occurs during the downswing while peak adduction moments are observed during the follow-through (Lynn and Noffal, 2010). This transition from the peak abduction to peak adduction moment occurs in a quick transition (approximately 200ms) (Lynn and Noffal, 2010). The follow-through phase involves rapid deceleration of the body from speeds generated from the down swing. Increasing the clubhead speed would require a more rapid deceleration from the higher velocity at ball contact to zero velocity at the end of the swing which may in turn affect the frontal plane moments experienced. To date, no study has explicitly controlled the swing style used. Based on the publication year, it is possible that Lynn and Noffal (2010) may have had a cohort which used the modern swing. However, they only studied kinematics and kinetics of the front limb with a single club.

Club selection is typically based on the desired shot distance. Lower numbered clubs are typically used to hit the ball farther. Their lower clubface loft (the angle of the clubface in relation to the shaft (in the frontal plane)) results in a lower ball flight, and longer length allows for high clubhead speeds. The higher numbered clubs (shorter length) have higher lofts making it easier to get the ball in the air, but result in shorter shot distance. Previous studies have postulated that players experience more knee pain when using longer clubs (Guten, 1996; Marshall and McNair, 2013). However, data across multiple clubs is limited since most studies have used a single club (see Appendix B). Shorter clubs allow for a narrower stance width and place the golfer closer to the ball, making ball contact easier, therefore it is common for players to favour shorter clubs. A narrower stance width is postulated to move the ground reaction force (GRF) vector closer to the knee joint center reducing its moment arm in the frontal plane and thus the frontal plane moments. It is also postulated that the ball will be placed closer to the front foot with the longer irons, meaning that more of the body weight could be shifted to the front foot around the time of impact. The frontal plane moment peaks typically occur just before impact (abduction) and at, or just after, impact (adduction) (Lynn and Noffal, 2010). If the ball is closer to the front foot and more of the participant's bodyweight is supported by that foot, then the GRF will be larger in cases where a longer club is used, making the frontal plane moments larger.

Each club has an intended range of shot distances, and variation in this distance is usually a result of technique, in particular control of clubhead speed (Figure 1.2). Clubhead speed at ball impact has been correlated to resultant ball distance (Fradkin et al., 2004). Therefore, a player who swings with a high clubhead speed can hit the ball the same distance with a shorter club than someone with a longer club and slower clubhead speed. A speed reduction of roughly 6 mph (2.75m/s) would result in an approximate 10 yard (9.14m) decrease in shot distance (Figure 1.2), roughly equivalent to the shot distance of the adjacent club (Figure 1.3).

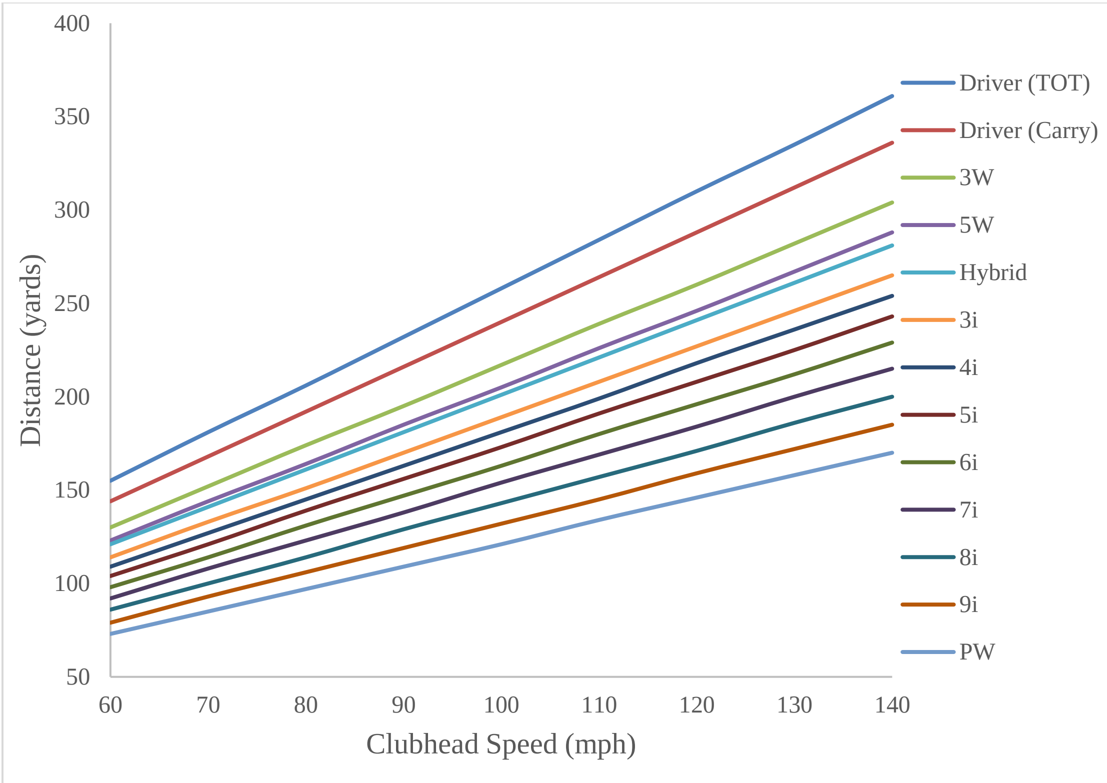


Figure 1.2 – Relationship between clubhead speed and ball distance for different clubs (data from Bowden (2013)). Carry is the ball flight in the air for the driver. Total (TOT) is the total distance the ball is hit (land and roll). (W- wood; i- iron; PW- pitching wedge).

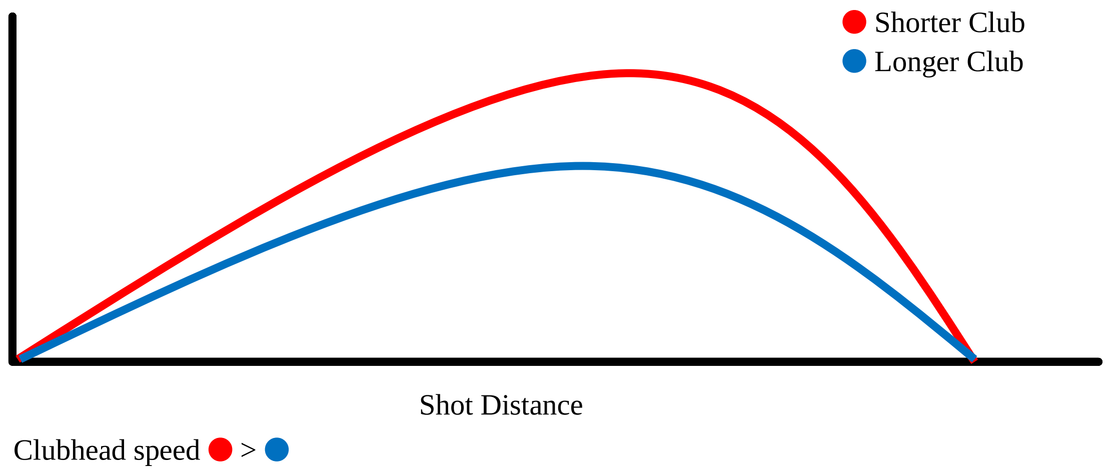


Figure 1.3 - An example of the ball flight of 2 different clubs being able to hit the same shot distance.

Swinging at a reduced speed will reduce the speed at which the body segments are moving, and is postulated to reduce the frontal plane moments. During gait it has been reported moving at a rate 15% slower than a participant's regular gait speed resulted in a lower peak adduction moment (Robbins and Maly, 2009). Although gait takes place in a different plane of movement than the golf swing, the findings from Robbins and Maly (2009) provide reason to postulate reduced frontal plane moments from a slower golf swing.

As mentioned previously, a longer club is expected to increase the frontal plane moments, with an increased stance width and change in ball position. However, the effect could be relatively small since the magnitude of the changes in stance width, being on the magnitude of a few centimeters or less, are limited by anatomy and comfort. Thus, the effect of swinging slower is proposed to outweigh the effect of greater length (Figure 1.4), ultimately resulting in decreased frontal plane moments. These expected outcomes motivated the hypotheses (Section 1.2) that swinging slower with a longer club, would reduce the frontal plane moments on the knee joint of the front leg.

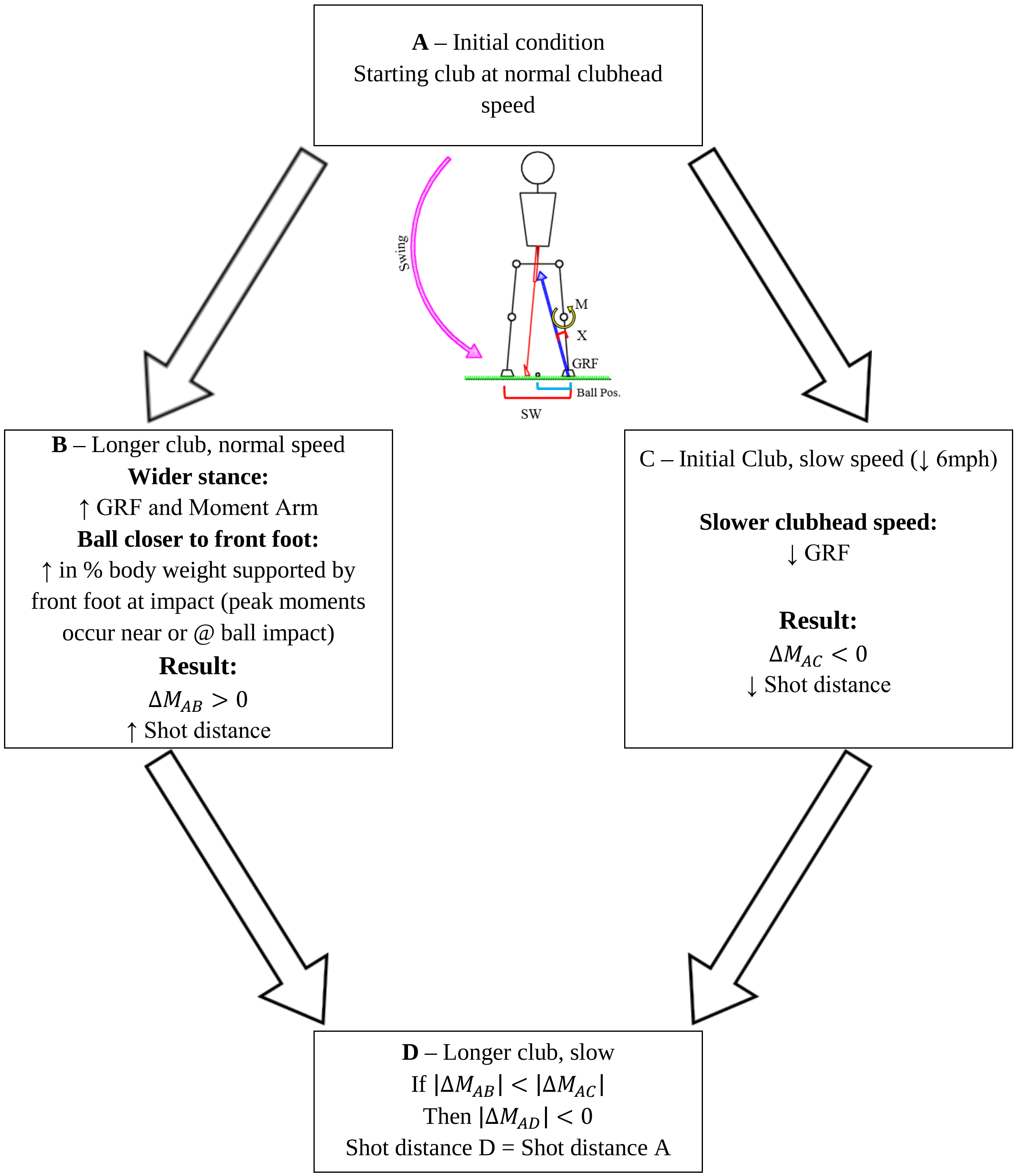


Figure 1.4 – Summary of the rationale for the study objective and hypotheses (see Section 1.2). The study was designed to test the change in moment between A and D (later referred to as the "initial condition" and the "modified condition" respectively.) (M- Moment; X- moment arm; SW- Stance Width, ΔM_{AB} indicates the change in moment from condition A to B).

The knee joint has often been overlooked during the study of golf swings, with more focus having been placed on the trunk and low back. Injury rates to the lower body range from 7-12% of total golfing injuries (Batt, 1992; Gosheger et al., 2003; McCarroll et al., 1990). Data has reported that the front (left) knee experiences greater loads and greater GRFs than the back (right) (D'Lima et al., 2008; Gatt et al., 1998; Worsfold et al., 2009, 2008), which may make it more susceptible to injury. Focus on the low back and trunk is most likely the result of how the golf swing is coached and executed for today's (modern) golfer, which puts more emphasis on the separation/angle between the shoulders and pelvis, termed the X-factor (Cheetham et al., 2000; Chu et al., 2010; Kwon et al., 2013). Due to the differences in swing styles, data from older studies, most likely measuring the classic swing, may not be representative for current golfers.

1.2 Objectives and Hypotheses

The primary objective of this study was to determine if male golfers with a handicap below 18 can reduce their peak frontal plane moments by swinging 6 mph slower while using the next longest club in the set. This objective was addressed following the notion that adjacent clubs can be used to hit the ball the same distance by simply adjusting clubhead speed (Figure 1.3). Knee mechanics were therefore analyzed during golf swings using multiple clubs (Driver, 4i, 5i, 6i, 7i, 8i, and 9i) at 2 controlled clubhead speeds (normal and slow). Five normal (N) and slow (S) clubhead speed pairings of adjacent clubs were analyzed, including 5iN/4iS, 6iN/5iS, 7iN/6iS, 8iN/7iS, and 9iN/8iS, where the normal speed was defined as the participant's self-selected (natural) clubhead speed and the slow speed was 6 mph slower using the paired longer club. It was hypothesized that swinging slower with a longer club would reduce both peak knee adduction and peak knee abduction moments on the front knee. These hypotheses were focused on the front (left) knee since previous literature indicated higher moment magnitudes for this leg compared to the back leg (Gatt et al., 1998). If these hypotheses were proven true, we would recommend that golfers use a longer club and a slower clubhead speed to better protect their knee joints.

Secondary analyses were completed to determine if some of the proposed mechanisms that motivated the primary hypotheses (Figure 1.4) and address potential confounding factors (ball position, stance width). Secondary objectives were:

A. To determine if moments decreased when clubhead speed decreased. It was hypothesized that swinging slower would decrease moments. Within-club speed pairs (normal and slow speed of same club) were tested to assess if speed affected the peak moment. It was hypothesized that a slower clubhead speed (without a change in club) would reduce the peak external knee adduction and abduction moments.

B. To determine if the ball was positioned closer to the front foot when using a longer club and slower clubhead speed. It was hypothesized that the ball would be closer to the front foot because of the use of a longer club.

C. To determine if stance width increased when using a longer club and slower clubhead speed. It was hypothesized that the stance width would be wider because of the use of the longer club.

The findings from this work can inform golfers on style of play with club use, for current golfer and/or those returning to play. They may also inform recommendations for those who might wish to take up golf after a previous injury or joint disease. The data could also be useful for coaches and professionals when recommending alterations to avoid cumulative injuries.

2 Background and Literature Review

Golf is considered a lifetime sport where participation can encompass early childhood into the late years of one's adult life. There are an estimated 60 million golfers worldwide (Golf Today, n.d.), including an estimated 24 million people in the US (National Golf Foundation, 2016), 4.4 million in Europe (Golf Advisory Practice in EMA, 2011) and 5.7 million in Canada (NAVICOM, 2012).

On the golf course, distances, lies, terrain, and obstacles change from shot to shot, requiring a variety of club types including: woods, hybrids, irons, wedges, and a putter, in order from longest to shortest. A player at any time is allowed 14 clubs in their bag, usually carrying three woods (1, 3, and 5), seven irons (3 to 9), a pitching wedge, a putter, and two clubs of the player's preference. Irons can be used for the first (tee) shot, and will most likely be used for remaining the majority of shots to reach the green, and are therefore the second most frequently used club type, next to the putter. It is therefore presumably quite important for the golfer to be able to use and control the irons. Due to the differences in iron lengths, each club requires its "own" swing type (swing plane (Coleman and Anderson, 2007), ball position relative to the body, etc.) in order to correctly strike the ball with the clubhead and attain the desired forward progression of the ball.

Conventional golf clubs use varying shaft lengths and clubhead lofts to allow players to attain many different shot distances. Shafts tend to be of incrementing lengths, usually increasing by roughly half an inch per club. Irons would typically range between 35.5 to 39 inches (0.9-0.99m). The loft will influence the trajectory of the golf ball; a high lofted club will result in a more vertical ball flight whereas low lofted clubs will be more horizontal. Additionally, weight of the clubheads tend to increase from the low numbered irons through the higher numbered irons. Due to the lighter clubhead weight, higher clubhead speeds are necessary with the low irons in order to increase the shot distance. This increased clubhead speed is typically achieved through a lengthening of the club shaft (clubhead velocity (v) = club length (r) multiplied by angular velocity (ω)). The length of the club changes the swing plane (angle to the horizontal axis), with longer clubs having a more shallow swing plane, becoming steeper as the club shortens (Coleman and Anderson, 2007).

The following sections will review the existing scientific analyses of the lower limb during the golf swing. Note that, when describing legs, the left leg is called the front leg, and the right leg is the back leg for a right handed golfer, meaning the right hand is lower hand when gripping a club (Sherman and Finch, 1999).

2.1 The Role of the Lower Limbs

The lower body is important for the golf swing and increasing shot distance (Rose, 2013). McNally et al. (2014) showed that total leg work is a predictor of clubhead speeds across age and skill levels (Partial R = 0.633). Both legs contribute, but the (total) front leg work (Partial R = 0.571) was shown to have a greater relationship to clubhead speed than the back (Partial R = 0.443). When analyzing the work of individual joints, the back knee work was the best predictor of clubhead speed (Partial R = 0.615). This finding indicates that primary contributions of the back leg to the development of clubhead speed come from the knee, whereas the front leg is a combined effort from all joints. These findings suggest therefore that the swing can be thought of as a "push off," transitioning from the back swing to downswing, or from back to front leg.

For most players, hitting the ball as far as possible, which requires increasing clubhead speeds, is a measure of success. Low handicap (better) players have been shown to have higher clubhead speeds than those with higher handicaps (Barrentine et al., 1994; Fradkin et al., 2004). Previous studies have shown that high clubhead speeds result from high, sequential trunk and shoulder/arm rotational velocities and weight transfer from the back to front legs (Cheetham et al., 2000; Hume et al., 2005; Kwon et al., 2013; Thériault and Lachance, 1998). The high rotational velocities of the upper body are driven by the lower limb's brace to the ground, creating high ground reaction forces (Barrentine et al., 1994; Hume et al., 2005). The swing creates forces that result in moments about the femur and tibia, which are then resisted by the ligaments and menisci of the knee. The compressive forces during the downswing are larger than those experienced during the backswing (Barrentine et al., 1994; Gatt et al., 1998; Marshall and McNair, 2013).

2.2 Susceptibility to Golf-Related Knee Injuries

Golf is rated as the fourth most frequently practiced leisure activity for older adults (Hughes et al., 2008) and has important social as well as health and fitness benefits (Siegenthaler and O'Dell, 2003). Golf is said to be a lifelong sport, but many golfers, professional or not, go for long durations with (minor) lingering injuries for which they do not take rest periods. Guten (1996) reported that in the practice of treating golf injuries, prevalence of knee injuries had increased and predicted that this prevalence would continue to increase in the future. To add to this, a number of individuals with a history of knee injuries or surgery have been found to adopt golfing as it is believed to be a less strenuous sport (Healy et al., 2001). Golf has been listed as a recommended activity after knee replacement (Healy et al., 2001; Mallon and Callaghan, 1994, 1993), due to its relatively "low impact", in this case meaning minimal wear and trauma to the weight-bearing joints (McGraw-Hill Concise Dictionary of Modern Medicine, 2002). Recently however, studies have begun to question the "low-impact" nature of golfing (D'Lima et al., 2008; Hamai et al., 2008; Mundermann et al., 2008; Pfeiffer et al., 2014).

Injuries to the lower body account for 7-12% of total golfing injuries (Batt, 1992; Gosheger et al., 2003; McCarroll et al., 1990); however limited information is available regarding their severity or type (Marshall and McNair, 2013). While different injury rates have been reported for the front and back legs (10% back and 7% front – Stover and Mallon (1992)), the front knee has been shown to be subjected to more complex motions and higher magnitudes of stress (D'Lima et al., 2008; Worsfold et al., 2009, 2008). Lower body injuries during golf have most commonly been attributed to overuse or errors in technique rather than acute trauma (Guten, 1996; Marshall and McNair, 2013).

With knee injuries being reported as an overuse injury one should consider that the golf swing can be viewed as a repetitive motion. It is common for player to constantly practice and execute the swing tens of thousands of times over a person's life. Repetitive loading reduces the failure strength of soft tissues (Schechtman and Bader, 1997; Sekiguchi et al., 1998; Thornton et al., 2007), and so the repetitive nature of the golf swing could increase its risk to the knee joint.

Injuries such as OA or ligament damage are considered to be the result of aggravation of pre-existing conditions (Parziale and Mallon, 2006). Many individuals who have had a total knee replacement (TKR) continue to play golf (Jackson et al., 2009), while it has been shown that the age of those undergoing the procedure is decreasing (Mundermann et al., 2008; NIH, 2003). Therefore the number of golfers with knee replacements is increasing, and they are playing for longer periods of time on these joint replacements. These populations are demanding increased performance from a TKR to continue their daily activities and sports (Bradbury et al., 1998; Healy et al., 2001; NIH, 2003). It has been demonstrated that having had a previous injury to the knee increases the risk of a subsequent injury (Fulton et al., 2014; Marshall and McNair, 2013; Murphy et al., 2003; Smith et al., 2012). Individuals with previous injuries, history of surgical interventions, or damage from joint disease such as OA, could therefore be more susceptible to joint pain or further injury due to cumulative exposures (Baker et al., 2017). This history of injuries to the knee have also been shown to lead to increased joint laxity (Murphy et al., 2003), which can alter the loading of the knee and other structures and increase the chance of meniscal damage (Baker et al., 2002). Therefore, there is a need to determine how golf-related injury/pain might be avoided in these vulnerable populations.

2.3 Modern vs Classic Swing

Swing technique has evolved over the past 30 years with the help of technology (golf club design, material advancements, motion analysis, etc.) and more biomechanical research of the golf swing (Kostis, 2016; Rose, 2014; Symes, 2014). The modern swing encompasses a more rigid stance, which increases power and torque production compared to the classic style (McHardy et al., 2006; Symes, 2014), resulting in less movement of the legs in comparison to during the modern style when compared to a classic swing. In addition, the modern swing is thought to promote a more consistent swing (Riggs and Chwasky, 2017). In comparison, the classic swing employs much more body movement in execution. Specific differences between each phase of the modern and classic swings are listed in and depicted in Figure 2.1 (McHardy et al., 2006; Symes, 2014).

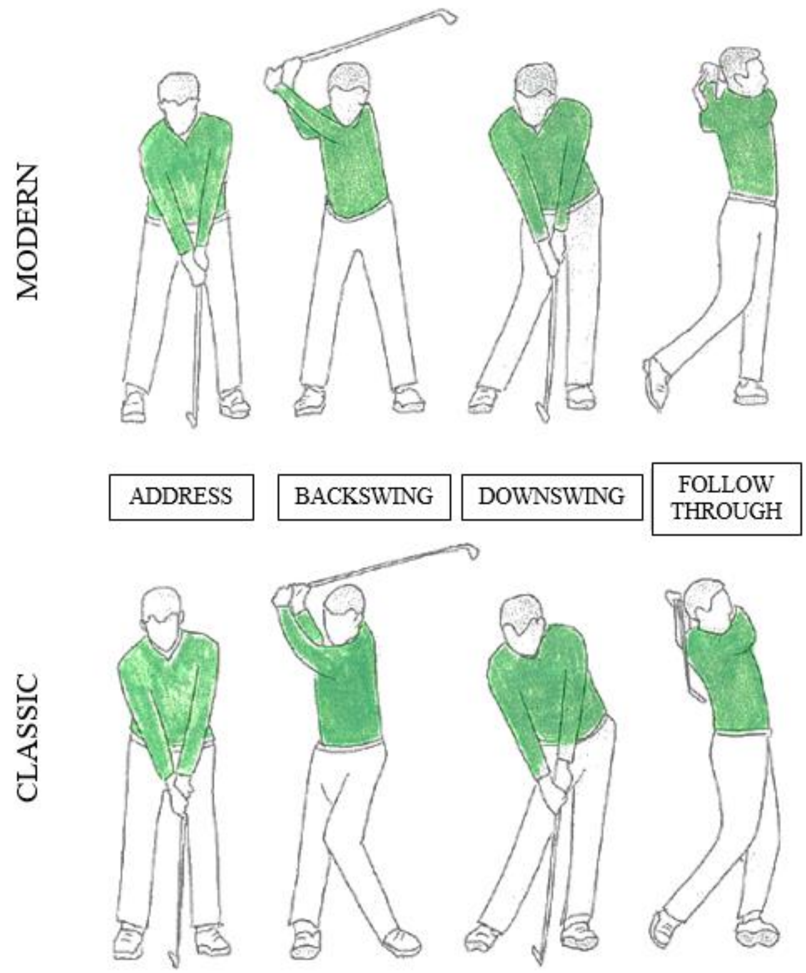


Figure 2.1 - Different swing phases of the modern (top) and classic (bottom) style golf swings.

While there are visible differences between the modern and classic swing styles, to date no kinetic or kinematic analyses have been performed in order to compare the biomechanical effects of either swing (McHardy et al., 2006).

Table 2.1 - Differences in the classic and modern style golf swings (McHardy et al., 2006; Symes, 2014).

Phase	Classic	Modern
Address/ Set-up	Feet are placed just slightly wider than shoulder-width. The feet are slightly splayed outward, with the front foot externally rotated 20-30° and the back just slightly externally rotated. Knees are slightly flexed as to have the club rest on the ground in a comfortable state.	Very similar to the classic style. Some players will opt for a wider stance with feet squared to the tee.
Backswing to Top	Shoulders start to rotate (clockwise), as does the pelvis. Center of mass (CoM) is shifted over the back foot and the back leg straightens. The front knee to moves medially and the heel comes off the ground, with only the toes touching the ground.	Shoulders start to rotate with the pelvis (clockwise). There is less body weight moved over the back foot therefore the back leg remains slightly flexed. The front leg holds its position, with the foot still planted on the ground. The large shoulder rotation compared to the pelvis (hips) (X-factor) creates a lot of muscular tension.
Downswing to Impact	Due to the large body movement in the backswing, the whole body moves in the downswing. The lower legs start moving right to left while the shoulders rotate equally with the hips.	Weight shifts from the back to front foot, movement is initiated by the hips. Hip rotation is ahead of the shoulders. The front hip stays in line with the front foot.
Follow-through	The momentum is directed forwards with the lower back in a relatively neutral position. Some players take a step forward due to the momentum.	After impact momentum is directed upwards, resulting in hyperextension in the lower back (C-shaped finish).

Previous literature has not explicitly stated which swing style the participants adopted. Given the years of publication, the Gatt et al. (1998) study could have had a mix of swings used by participants. The study by Lynn and Noffal (2010) could have been a study that used a cohort of participants (collegiate athletes) with a modern swing, however it was not explicitly stated. The current study involved only the modern swing technique.

2.4 Quantitative Studies of the Knee during the Golf Swing.

Few studies in the literature have similar outcome measures to this thesis. The findings of the previous studies will here be described and compared by outcome measure: knee joint kinematics, ground reaction forces, knee joint reaction forces, frontal plane knee joint moments (adduction and abduction), and knee joint contact forces. However, it is unclear which swing style was used in the previous studies.

2.4.1 Knee joint kinematics

Since the swing is asymmetrical, the kinematics and kinetics differ between limbs. Knee flexion is relatively low throughout the motion; however, the back knee flexes more than the front (Figure 2.2).

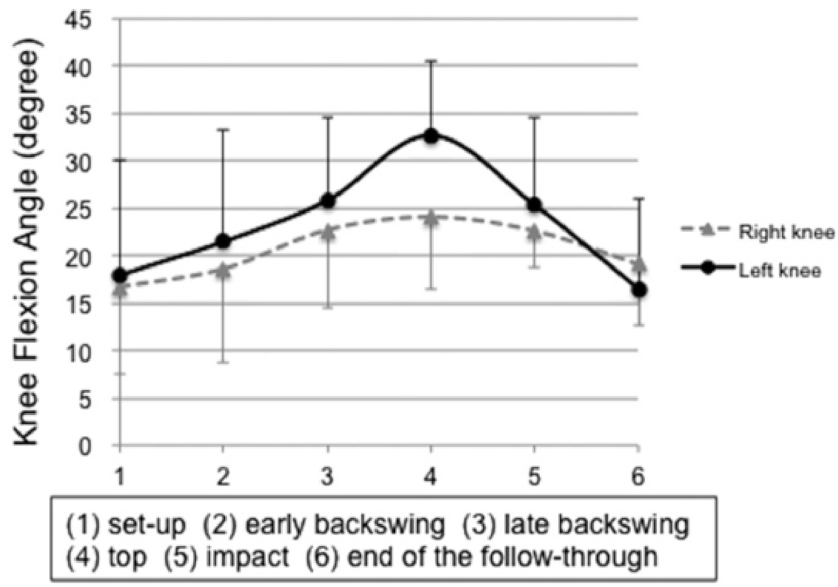


Figure 2.2 - Average knee flexion angle during the golf swing. Reprinted from The Knee, Vol 23, Koji Murakami, Satoshi Hamai, Ken Okazaki, Satoru Ikebe, Takeshi Shimoto, Daisuke Hara, Hideki Mizu-uchi, Hidehiko Higaki, and Yukihide Iwamoto, In vivo kinematics of healthy male knees during squat and golf swing using image-matching techniques, Pages 221-226, Copyright (2016), with permission from Elsevier.

At the end of the swing, 70-80% of the player's body weight is supported by the front leg (Ball and Best, 2007; Okuda et al., 2010), which is internally rotated.

2.4.2 Ground Reaction Forces and Center of Pressure (CoP)

At address, the golfer bends their knees slightly with the feet at or slightly wider than shoulder width depending on which club is being swung (Choi et al., 2015; Egret et al., 2003; Murakami et al., 2016). The distribution of weight on the front and back feet is about 60:40 % respectively at address. During the backswing, this distribution changes to 20:80 and is reversed from impact to the end of the swing to be 80:20 (Figure 2.3) (Ball and Best, 2007; Barrentine et al., 1994; Okuda et al., 2002; Worsfold et al., 2009). Impact produces forces greater than bodyweight for the front leg (Barrentine et al., 1994; Gatt et al., 1998; Worsfold, 2008; Worsfold et al., 2007). The front leg acts like a post or pivot about which the pelvis rotates.

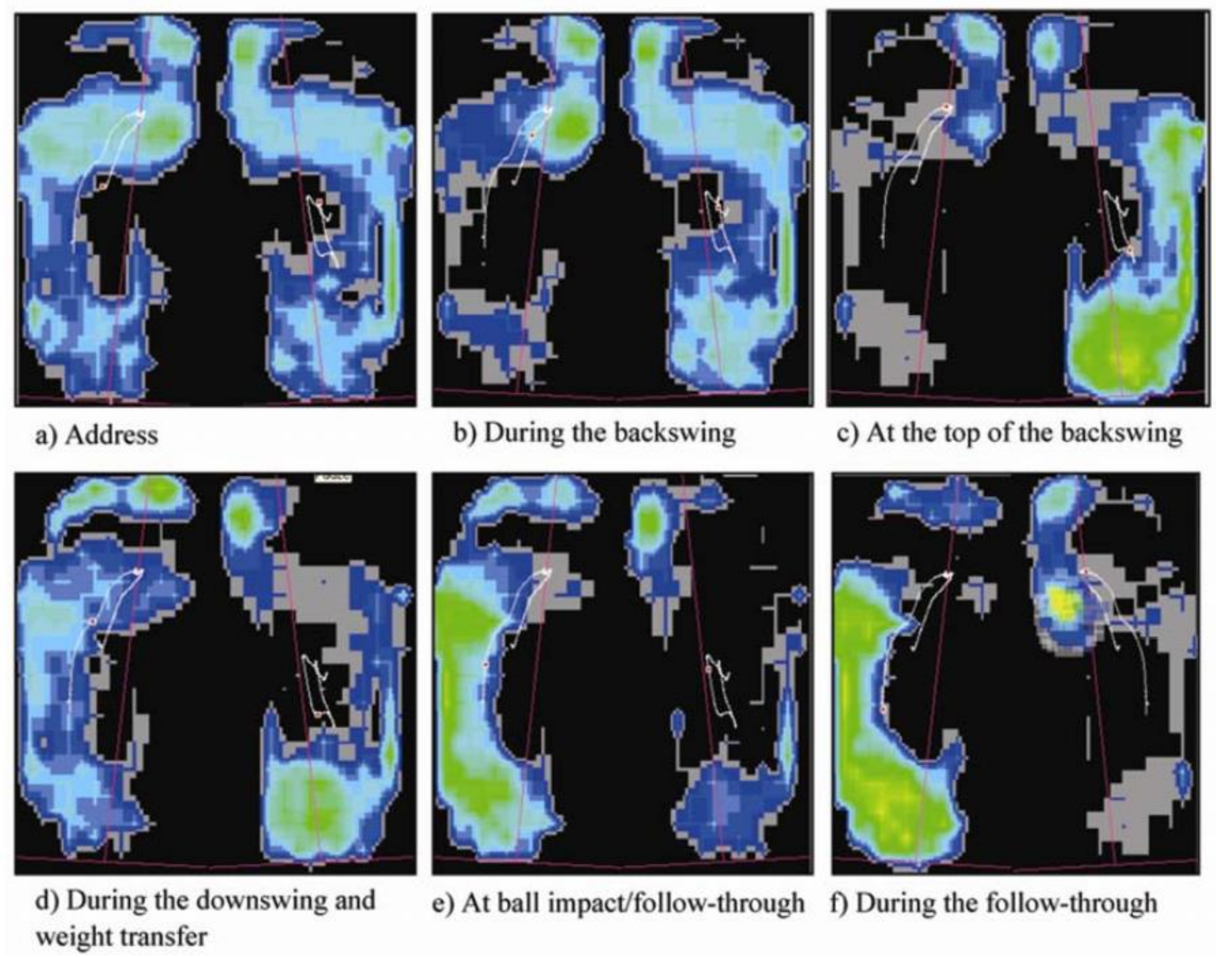


Figure 2.3 - Insole pressure scan during the golf swing (front being the left foot, and back being the right foot). Reprinted from Journal of Sports Science and Medicine, Vol 8, Paul Worsfold, Neal A. Smith and Rosemary J. Dyson, Kinetic assessment of golf shoe outer sole design feature, Pages 607-615, Copyright (2009), with permission from the JOURNAL OF SPORTS SCIENCE AND MEDICINE.

2.4.3 Kinetics: Joint Reaction Forces, Frontal Plane Moments and Joint Contact Forces

Knee joint kinetics have been reported by Gatt et al. (1998), where 13 participants used the same 5i club. The mean peak joint reaction forces on the proximal shank acting along the long axis of the shank were 756.3N and 540.4N for the front and back knees respectively. These peak values were reported to occur during the backswing for the back foot and the downswing for the front foot.

The knee adduction moment, which has been associated with the development and progression of knee OA (Chehab et al., 2014; Creaby et al., 2010; Maly, 2008; Miyazaki et al., 2002; Sharma et al., 1998), can be interpreted as a surrogate for relative medial knee loading (Zhao et al., 2007). Lynn and Noffal (2010) reported peak front knee adduction moments of 0.54±0.25 Nm/kg or 0.63±0.23 Nm/kg (depending on front foot position, EXT or STR respectively) (0.83±0.32 Nm/kg (Gatt et al., 1998)) during the golf swing was greater than those from gait (0.49±0.19 Nm/kg) and stair ascent (0.42±0.15 Nm/kg) (Costigan et al., 2002). It was also reported that the knee abduction moment of 0.70 ± 0.12 Nm/kg or 0.80±0.19 Nm/kg (depending on foot position) (0.32±0.14 Nm/kg (Gatt et al., 1998)) was similar to those measured during drop-jump landings (0.74±0.46 Nm/kg) from individuals who went on to sustain an ACL injury (Hewett et al., 2005).

Lynn and Noffal (2010) speculated that ACL tears are not frequently seen during golf due to different loading rates, with golfers reaching peak loads slower than the rate typically measured during a drop-jump. Mechanical loading of the knee joint is thought to be linked to the etiology of OA (Felson, 2013). Articular cartilage and subchondral bone are viscoelastic, which become less deformable under faster loading rates (Radin and Paul, 1971). Therefore, a golfer adjusting their regular swing could cause a difference in their loading rate or pattern and the tissue response.

Published data from Gatt et al. (1998) and Lynn and Noffal (2010) do not agree with one another, for the follow-through phase. Mean peak adduction moments in the front knee reported by Lynn and Noffal (2010) occur after impact, but Gatt et al. (1998) reported these same moments to occur prior to impact. The peak values for the frontal plane moments calculated were also reported to be of different magnitudes. Swing style was not explicitly stated in these studies but, given the 12-year gap between them, differences in swing technique may have contributed to this discrepancy in values.

Direct measurement of compressive loads on the knee are rare, due to the requirement of instrumented knee implants, so the external knee adduction moments, computed using inverse dynamics, are used as a surrogate measure for medial compartment loading (Zhao et al., 2007). Mundermann et al. (2008) and D'Lima et al. (2008) recorded *in vivo* knee joint contact forces during the golf swing with an instrumented knee replacement and were surprised by the high loads measured. Compressive knee joint contact forces of approximately 3 and 4 times body weight were measured for the back and front knees, respectively (D'Lima et al., 2008; Mundermann et al., 2008). These values are greater than what is typically experienced during gait (1.8-2.5 times body weight) (D'Lima et al., 2008).

3 Methods

3.1 Participants

Eleven male participants were recruited to participate in this study (age: 23.8 ± 4.5 years; weight: 77.4 ± 9.2 kg; height: 1.8 ± 0.1 m). Inclusion criteria for participants required that each be an intermediate to high skilled level golfer (handicap: 10.1 ± 6.3) who swung a golf club right handed (left hand above right hand when gripping the club) due to the clubs provided for this study. It has previously been reported that players with a lower handicap have better postural control and less CoM displacement (Choi et al., 2015; Wrobel et al., 2012) and increased tempo similarity (ratio of backswing to downswing durations) swing-to-swing, resulting in more consistent/reproducible trials than inexperienced golfers (Grober and Cholewicki, 2006). We also believed that these levels of golfers would be more likely to have received training on the modern style swing. Each participant's swings were visually assessed to ensure that modern style techniques were used (Table 2.1 and Figure 2.1). It was also expected that the more highly skilled recruited participants would be better able to adapt to the required changes in clubhead speed (from normal) for this study than unskilled golfers may have been. All participants were free from injury/pain that would have prevented golfing over the past year. All participants wore tight fitting athletic clothing and swung barefoot.

3.2 Instrumentation

3.2.1 Set-up

3.2.1.1 Calibration

The study was completed in the Biomechanics of Human Mobility (BOHM) Lab at the University of Waterloo. An Optotrak system (NDI, Waterloo, ON, Canada) was used for motion capture. The lab layout is shown in Figure 3.1, with 6 Optotrak camera banks (3 cameras per bank) and 4 AMTI force plates (OR6-7, AMTI, Watertown, MA, USA). Figure 3.1 also shows the set-up position of the participant for the trials, which is detailed in Section 3.3.2.

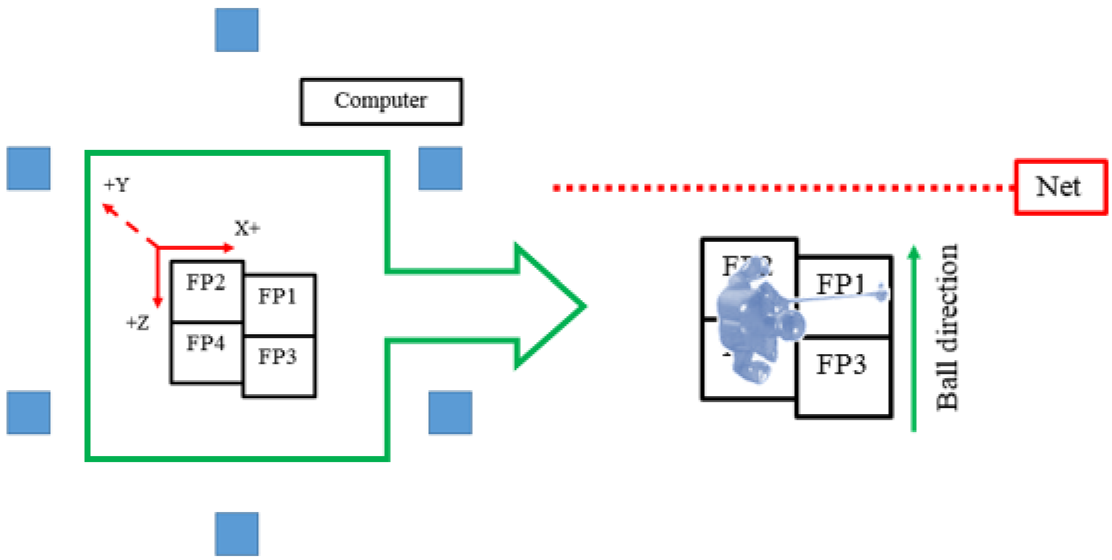


Figure 3.1 – (Left) Lab setup, global coordinate system (GCS) shown with +Y axis perpendicular to the ground. The solid blue squares represent the Optotrak cameras, and the squares denoted with *FP#* represent the force plates; (Right) participant positioning for the swing trials.

The collection volume was calibrated using a 240 second (4 minute) trial using a 16-marker rigid cube. Alignment of the global coordinate system (GCS) in the collection volume was completed using a 4-marker digitizing probe. To relate the positions of the force plates in the space, each corner of each force plate was digitized.

3.2.1.2 Clubs

Right handed 4i, 5i, 6i, 7i, 8i, and 9i clubs used for the study were V Series II Pro Grind Irons (Monark Golf, Walnut, CA, USA) and the driver was a TaylorMade Burner 420 (TaylorMade-Adidas Golf, Carlsbad, US). This selection of clubs encompassed the range of a modern iron set used by today's golfers.

3.2.1.3 Ball, Turf, and Netting

For each trial, participants swung a given golf club and made contact with a practice foam golf ball. To protect the equipment, as well the researcher, netting was strung from the lighting/ceiling of the lab in order to create a ball catching saftery barrier. To protect the force plates and club from damage, artificial turf was placed over top of FP1 and FP3; soft mats were also placed around surrounding areas to reduce ball bounce and potential ricochet. Setup in the lab is presented in Figure 3.2.

Figure 3.2 – Setup showing the turf overtop FP1 and FP3, surrounding mats, foam golf ball, and microphone. Golf netting used as a safety barrier to the equipment and study investigator (black mesh highlight in red).

3.2.1.4 Microphone

In order to detect ball impact, a microphone was used (Tenco Dynamic Range Microphone #9070 with Bigen amplifier Model C 10, Lear Siegler Inc, Paramus, NJ, USA). The microphone was placed close to the ball on the turf to get a clear soundwave from impact of the clubhead hitting the ball.

3.2.1.5 Clubhead Speed Calculation

Clubhead speed was measured using a commercially available sensor for swing analysis (SkyPro Golf Swing Analyzer, SkyHawke Technologies, Ridgeland, MS) having a resolution in the calculated clubhead speed of ± 1 mph. The clubhead speed output was tested for its accuracy as outlined in Appendix C. In comparison to a golf simulator (About Golf, Maumee, OH, USA), the SkyPro device was on average within 1.25 mph of the simulator measured speed. It connected via Bluetooth to a mobile/tablet device and attached to the shaft of the golf club just below the hand grip. The sensor requires calibration for each club used. Calibration was performed by attaching the sensor to the shaft, just below the hand grip, and holding the mobile/tablet device flat against the clubface. The position of the mobile/tablet device in relation to the shaft-mounted sensor was calculated through a process of levelling the phone/tablet and moving it side-to-side in order to register the sensor with the club. The sensor data was collected at 3200 Hz (SkyPro, 2018) from the time of the backswing to impact with the ball.

3.2.1.6 System Collection Parameters

Kinematic data (motion capture) was sampled at 85 Hz, with analog signals (force plates, and microphone) sampled at 2125 Hz. All channels were sampled synchronously with the use of an analog to digital breakout box collecting through NDI First Principles software (NDI, Waterloo, ON, Canada).

3.2.2 Motion Capture

3.2.2.1 Body

The lower body segments were tracked using rigid body marker clusters (4 markers per rigid body) on the left hand, pelvis, and both thighs, shanks and feet Table 3.1 and Figure 3.3). Local landmarks were then digitized to define the segment coordinate systems relative to the rigid bodies.

Table 3.1 – Anatomical placement and digitized landmark locations of rigid bodies.

Segment	Rigid Body Location	Digitized Landmarks
Left Hand	Centrally placed on the top of the hand	Club top of the grip Clubhead heel Clubhead bottom toe Clubhead top toe
Pelvis	Strapped around the participant's waist, and fixed over the sacrum.	L/R iliac crest L/R anterior superior iliac spine (ASIS) L/R posterior superior iliac spine (PSIS) Sacrum
Thigh	(Femur) Midpoint between the greater trochanter and medial/lateral epicondyles; on lateral side.	Greater trochanter Medial/Lateral epicondyles
Shank	(Tibia) Between the medial/lateral tibial epicondyles and medial/lateral malleoli. On lateral side or angled medially to the tibialis anterior muscle.	Medial/Lateral tibial epicondyles Medial/Lateral malleoli
Foot	Lateral side below lateral malleolus.	Medial/Lateral malleoli Heel $5^{th}/1^{st}$ metatarsal Toe

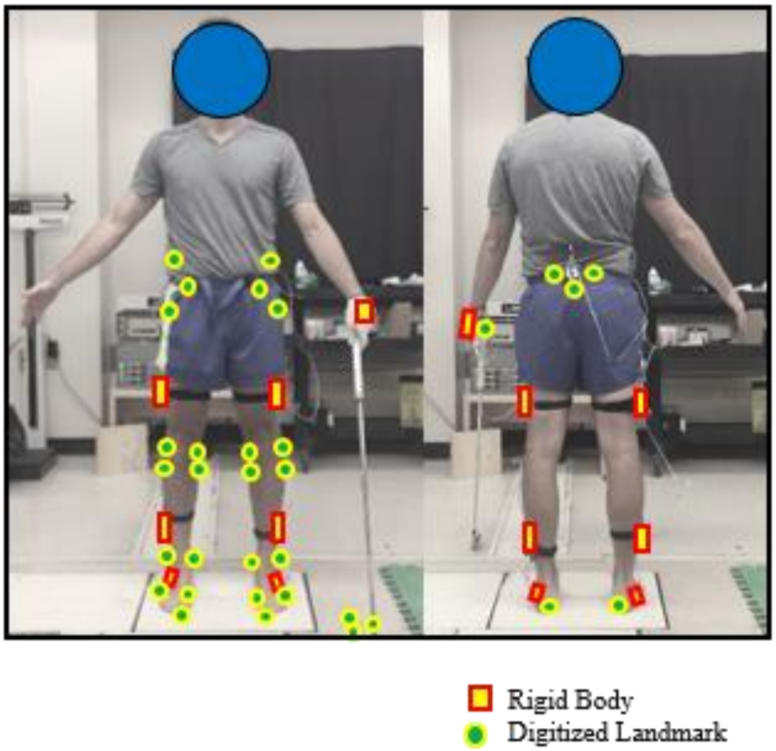


Figure 3.3 – Rigid body and digitized landmark locations on the body.

3.2.2.2 Club

Club digitization was completed as to locate the clubhead at the address position. The starting club was randomized, and was the only club that was digitized. Motion was related to the rigid body located on the top of the hand. In order to locate the clubheads of each club, vector math was completed translating the digitized points with relation to the club lengths (Section 3.3.7). The club was assumed to be rigid and flexing of the shaft was neglected. To ensure consistent digitized points on the club, small indentation marks on the clubface were made to position the tip of the digitizing probe. The wire connecting the rigid body to the strober was strung up the inside of the left arm over the shoulder and down the back, with extra slack as to prevent possible damage to the components and unplugging. A commercially available golfing device (SkyPro Swing Analyzer) was attached to the golf club shaft just below the grip.

3.3 Protocol

The study involved a single visit by the participant, with the protocol consisting of the consent process, motion tracking marker instrumentation and landmark digitization, performing the swing trials, and then removal of the equipment. The study protocol is outlined below in Figure 3.4.

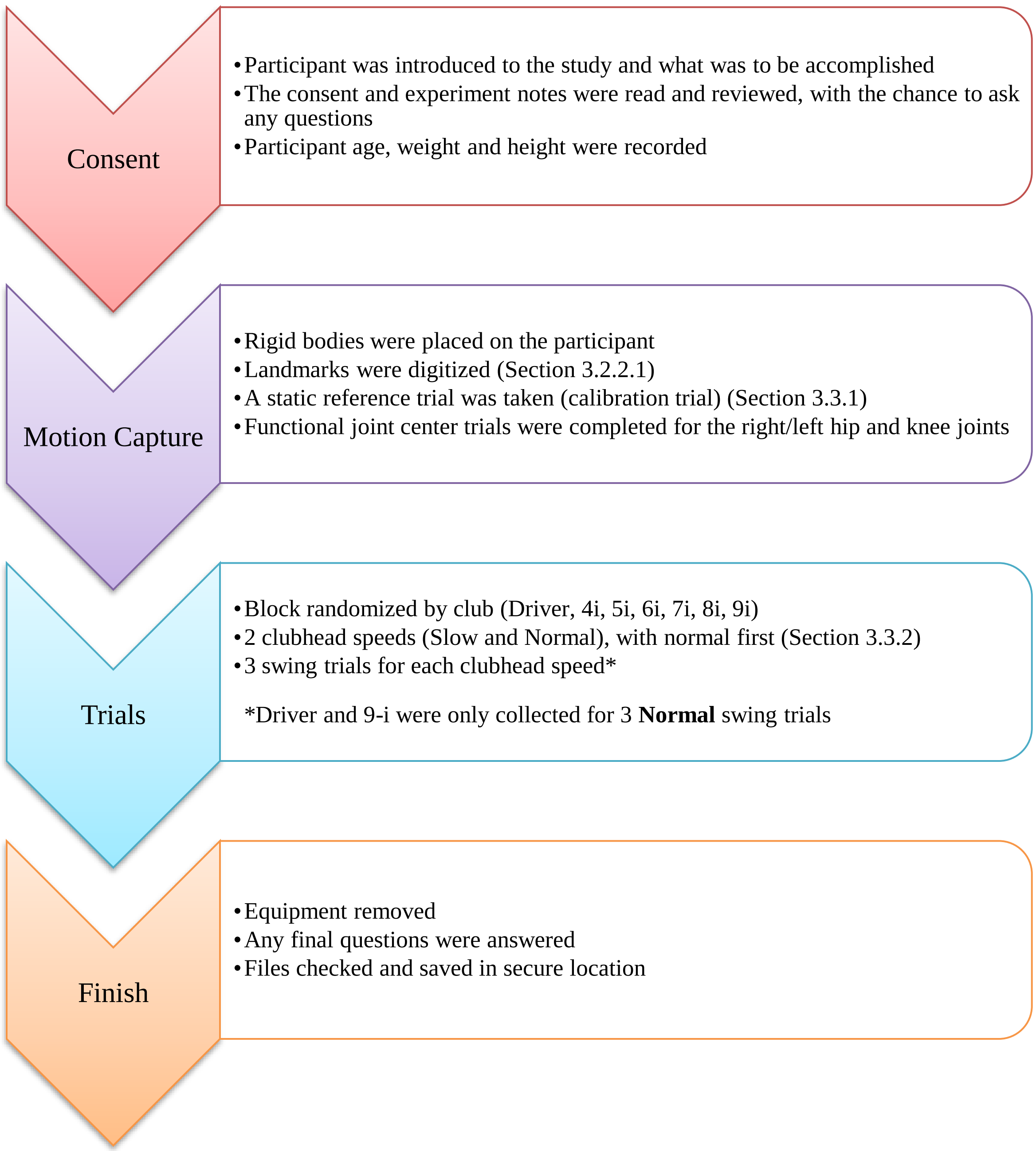


Figure 3.4 – Overview of the study protocol.

3.3.1 Static Calibration and Functional Joint Trials

To estimate the joint centers of the right and left hip and knee joints, 15-second functional joint trials were collected (Table 3.2). When needed for stability, a chair was placed on the opposite side of the testing leg to hold.

Table 3.2 - Function joint trial instructions.

Functional Joint	Instructed Motions
Hip	Standing upright, the participant flexed, extended, adducted, and abducted their hip followed by circumduction (Begon et al., 2007).
Knee	Standing upright, the participant flexed and extended their knee, from full extension (0°) to approximately 90° flexion). This was done while limiting the motion of the hip, keeping a stationary femur.

For model generation, following the functional joint trials, a 5 second static calibration trial was completed with the participant standing on FP2.

3.3.2 Trials

Participants stood barefoot in their typical, comfortable (self-selected) stance with the left foot on FP2 and their right foot on FP4, positioning the ball and club in their normal set-up position. The trials were block randomized by club; the participant finished all swing trials with the same club before changing to the next club, with the exception of the starting club. The starting club's slow swing was the last set of trials as no data from previous club was available at the start. The swing trials for each club always started with the normal swing and then were followed by the slow clubhead speed. For each of the 2 clubhead speeds (normal and slow), 3 trials were collected, equaling a total of 6 trials per club, except for the driver and the 9i which only had 3 swings of the participant's normal swing (36 swing trials total, listed in Figure 3.5, not necessarily in the order they were collected.).

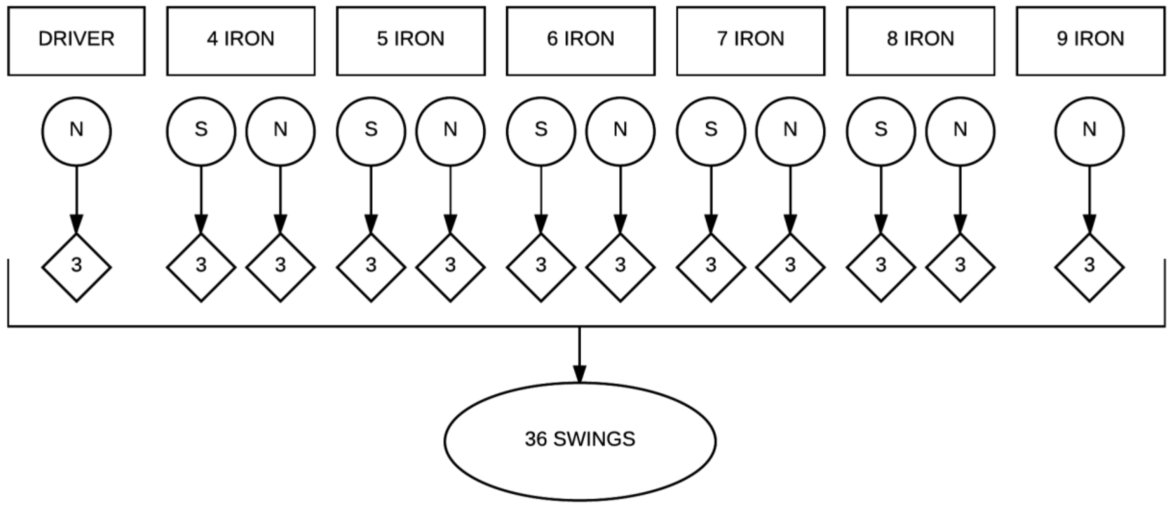


Figure 3.5 - Trial breakdown by club and swing (S - slow; N - normal).

Before the slow swing trials were collected for the current club, the speed was calculated based on the normal speed of the previous club. The slow speed was 6 mph slower than the previous club's normal speed; see Section 3.3.2.1 and Figure 3.6. In order to hit the target speed for the slow swings, the participant was allowed to alter their swing. Prior to performing the trials, participants were asked to warm-up and practice their swing to become comfortable with the current club.

After the total number of trials were completed for the given club, the preceding numbered club in the set was used, for example, if the participant finished with the 6i the next club would be the 5i. Although the 4i normal, and driver normal swings were collected, they were not necessary for comparisons related to the hypothesis, as there is no next club for which these speeds are required.

Each time the participant changed clubs, the SkyPro device was transferred to the next club and recalibrated. This allowed some rest time for the participant, and a check to make sure all instrumentation was still in the proper locations.

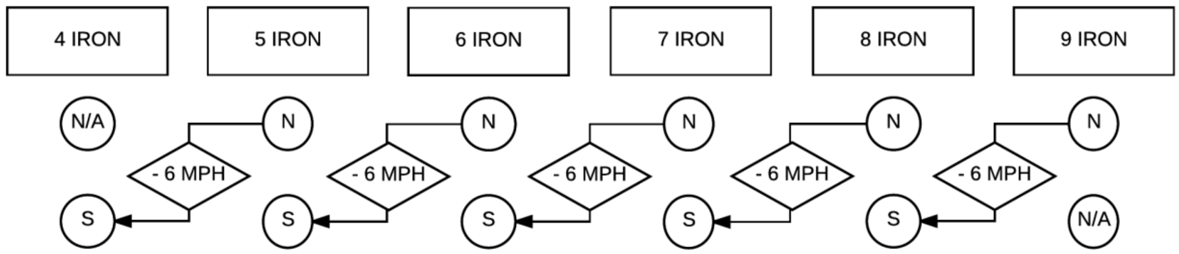


Figure 3.6 - Club clubhead speed relationships. Pairs joined by arrows are intended to produce equivalent shot distances.

3.3.2.1 Swing Instructions

A standard set of instructions was given to each participant in regards to the normal and slow swings that are outlined below.

- **ALL SWINGS:** "Position yourself with your left foot fully on FP2 and your right foot fully on FP4. Place the club down on the ground with the ball positioned in the middle of the clubface to start your swing. I will give you a 3-2-1 countdown and you can proceed to start your swing after then. After you complete you swing try to hold your follow-through and not walk off the force plates, until I say the trial is over."
- **NORMAL**: "Use your regular swing as if there are no obstructions or obstacles to hit the ball."
- **SLOW**: The speed from the previous club was taken and the 6 mph change was told to the participants to aim for. *For example: "You are aiming to swing 80 mph with the 5 iron as the 6 iron speed was 86 mph."*

3.3.2.2 Feedback

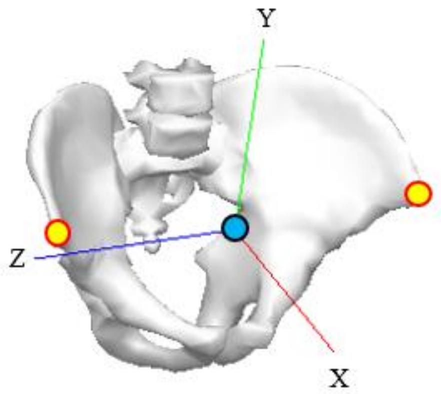
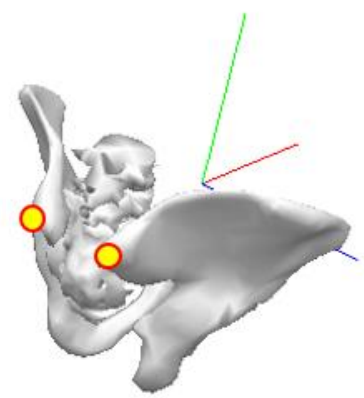
After each trial the participant was notified of the clubhead speed provided by the SkyPro device (SkyPro Golf Swing Analyzer, SkyHawke Technologies, Ridgeland, MS). This provided them with the knowledge if they were in the proper speed range or if they needed to increase/decrease the clubhead speed. Clubhead speed was required to be within ± 1 mph (0.45 m/s) range of the desired speed defined before trial collection began. For the 3 normal swings, a maximum difference of 2 mph (0.9 m/s) between swings was allowed, as these 3 swings were averaged and used to calculate the slow swing for the next club. If the clubhead speed for the swing trial was outside the bounds of the target speed, this trial was not analyzed and additional trials were collected. The speeds (mph) for each club and clubhead speed combinations of each participant are presented in Table D.6 in Appendix D.

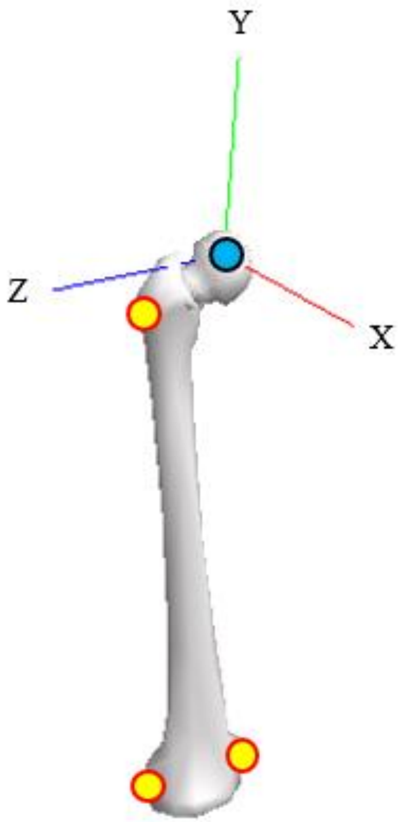
3.3.3 Rigid Link Segment Model

A rigid link model was constructed for the lower body using the pelvis, right and left thighs, shanks, and feet (Table 3.3) in accordance to ISB standards (Wu and Cavanagh, 1995). Functional knee and hip joint center trials were calculated in Visual3D (C-Motion, Germantown, MD, USA), using the Gilette algorithm, prior to segmental local coordinate system (LCS) definition (Schwartz and Rozumalski, 2005). This algorithm uses 2 adjacent segments which span the joint of interest. The axis of rotation between segment movements is computed (i.e. femur movement with the pelvis stationary), with the most likely intersection and orientation of all axes found. This intersection is the effective joint center (Schwartz and Rozumalski, 2005). Anatomically the Y-axis was defined as the superior/inferior axis, X-axis the anterior/posterior axis, and the Z-axis the medial/lateral axis. Flexion/extension was represented by the medial/lateral axis, abduction/adduction by the anterior/posterior, and internal/external rotation by the proximal/distal axis. The GCS was located off the corner of FP2 (Figure 3.1), positioning the GCS in this location meant that all markers had positive X, Y, and Z coordinates throughout the motion.

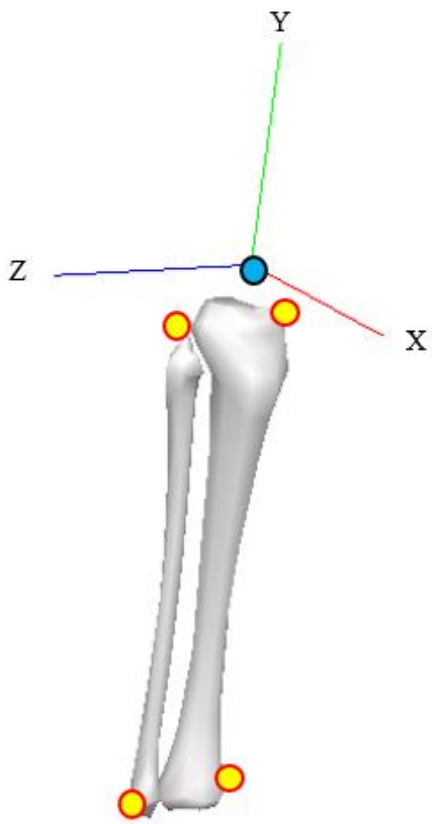
A 'CODA' pelvis was selected for creation of the pelvis segment and coordinate system because the anterior superior iliac spine (ASIS) and the posterior superior iliac spine (PSIS) are readily identifiable on healthy adults. The other methods for pelvis creation use the sacrum, pubis, and iliac crest landmarks, which can be more difficult to locate accurately due to soft tissue.

Table 3.3 – Local coordinate system definitions for pelvis, thigh, shank and foot.

Segment	Coordinate System
Pelvis (CODA)  	Origin: Midpoint between the left and right ASIS XZ Plane: Left and right ASIS and midpoint between left and right PSIS landmarks Y-axis: Perpendicular to the XZ-plane Z-axis: Vector from the origin to the right ASIS X-axis: Cross product of Y-by-Z

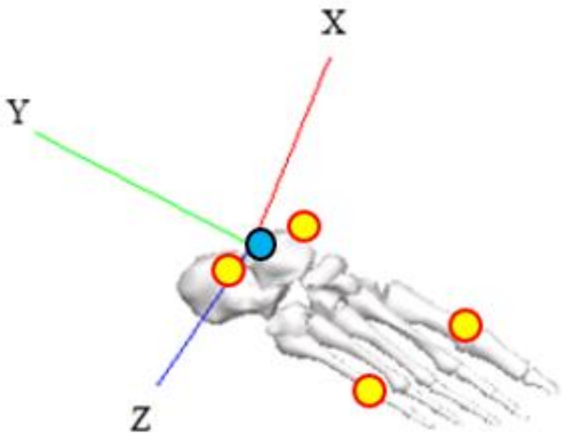
Thigh 	Origin: Functional hip joint center, defined during calibration YZ Plane: Greater trochanter, medial and lateral femoral epicondyles Y-axis: Vector between the hip joint center and the midpoint of the medial and lateral epicondyles of the femur X-axis: Perpendicular to the YZ plane (anteriorly) Z-axis: Cross product of X-by-Y

Shank



Origin:
The functional knee joint center, defined during calibration.
YZ Plane:
Lateral tibial condyle, and the medial and lateral malleoli
Y-axis:
Vector from the midpoint of the medial and lateral malleoli and the medial and lateral tibial plateau
X-axis:
Vector perpendicular to the YZ plane
Z-axis:
Cross product of X-by-Y

Foot



Origin:
Midpoint between medial and lateral malleoli
YZ Plane:
Medial and lateral malleoli and the 1st and 5th metatarsals
Y-axis:
Vector from the midpoint of the 1st and 5th metatarsals to the midpoint of the medial and lateral malleoli
X-axis:
Perpendicular to the YZ plane, projecting in the superior direction
Z-axis:
Cross product of X-by-Y

Note: All lines represent the positive (+) direction in the coordinate system. Circles represent points digitized on the segment (blue/black – origin/joint center, red/yellow – digitized landmark).

3.3.4 Kinematics

Kinematic data was filtered using a 2nd order dual low-pass Butterworth filter with a cutoff frequency of 10 Hz (Gatt et al., 1998). Missing data points were interpolated using a 3rd order cubic spline, up to 20 frames (approximately 0.2ms) (Howarth and Callaghan, 2010). For the body segments, the coordinate systems were defined in accordance to ISB standards (Wu and Cavanagh, 1995). Joint angles were calculated via Visual 3D using a *Z-X-Y* rotation sequence (Equation 4) corresponding to flexion/extension (θ), adduction/abduction (ϕ), and internal/external rotation (ψ).

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi & cos\phi \end{bmatrix} \quad \text{(Equation 1)}$$

$$R_y = \begin{bmatrix} cos\psi & 0 & sin\psi \\ 0 & 1 & 0 \\ -sin\psi & 0 & cos\psi \end{bmatrix} \quad \text{(Equation 2)}$$

$$R_z = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{(Equation 3)}$$

$$R_{zxy} = [R_y][R_x][R_z]$$

$$R_{zxy} = \begin{bmatrix} cos\psi cos\theta - sin\phi sin\psi sin\theta & -cos\phi sin\theta & cos\theta sin\psi + cos\psi sin\phi sin\theta \\ cos\theta sin\phi sin\psi + cos\psi sin\theta & cos\phi cos\theta & -cos\psi cos\theta sin\phi + sin\psi sin\theta \\ -cos\phi sin\psi & sin\phi & cos\phi cos\psi \end{bmatrix} \quad \text{(Equation 4)}$$

LCS made as stated in Table 3.3. Unit vector axes are as shown in Equation 5-7:

$$\hat{\imath} = \frac{\vec{\imath}}{\|\vec{\imath}\|} = \begin{bmatrix} ix \\ iy \\ iz \end{bmatrix}, \hat{\jmath} = \frac{\vec{\jmath}}{\|\vec{\jmath}\|} = \begin{bmatrix} jx \\ jy \\ jz \end{bmatrix}, \hat{k} = \frac{\vec{k}}{\|\vec{k}\|} = \begin{bmatrix} kx \\ ky \\ kz \end{bmatrix} \quad \text{(Equation 5-7)}$$

<u>For Thigh:</u>

$$[R]_T = \begin{bmatrix} ix & jx & kx \\ iy & jy & ky \\ iz & jz & kz \end{bmatrix}_T \text{(Local to Global)} \quad \text{(Equation 8)}$$

<u>For Shank:</u>

$$[R]_S = \begin{bmatrix} ix & jx & kx \\ iy & jy & ky \\ iz & jz & kz \end{bmatrix}_S \text{(Local to Global)} \quad \text{(Equation 9)}$$

The knee joint angle is expressed as the angle of shank relative to the thigh.

$$[R]_{Knee} = [R]_S[R]_T^T \qquad \text{(Equation 10)}$$

Where, $[R]_{Knee} = [Local\ to\ Global]_S[Global\ to\ Local]_T$

The $[R]_{zxy}$ matrix (Equation 4) is decomposed to compute the angles ($[R]_{zxy} = [R]_{Knee}$), representing the shank relative to the thigh.

3.3.5 Kinetics (Moments)

Force plate forces and moments were collected at 2125 Hz and were filtered using a 2nd order dual low-pass Butterworth filter with a cutoff frequency of 55 Hz (Gatt et al., 1998). External knee moments were calculated using a bottom-up inverse dynamics based approach (Visual 3D, C-Motion, Germantown, MD, USA) and resolved in the shank (tibia) coordinate system (Mündermann et al., 2004). Knee moments were normalized to participant body mass (Nm/kg). Moment peaks were identified as the maximum value on the moment curve. The peak abduction moments and peak abduction moments for each club/clubhead speed combination were identified by averaging the peaks of each of 3 trials (the driver and 9i were collected at only a single (normal) clubhead speed). In each trial, the peak abduction moment was identified prior to ball contact and the peak adduction moment was identified after ball impact (during follow-through).

3.3.6 Golf Swing Window

A 6 second trial time was used for collection of each swing, and the trials were cut to a 3 second window: 2 seconds prior and 1 second post-impact (prior: address, backswing, and downswing; post-impact: follow-through). Impact was identified using the peak sound (voltage) amplitude recorded by the microphone. The spike from the microphone allowed to line each swing up at impact, with data prior being the backswing/downswing, and after being the follow-through.

3.3.7 Address Position

Since the only club digitized was the first club used (randomized), to locate the clubhead locations of all other clubs vector math was completed (Figure 3.7). Club lengths (Table 3.4) were used to translate the digitized points to the club being used (Equation 11 to 17). The club length is calculated from the top of the grip to the bottom of the clubhead heel (digitized landmarks).

Table 3.4 - Club lengths for the clubs used. Values expressed in inches (meters).

Club	Length
Driver	44.75 (1.137)
4i	38.5 (0.978)
5i	38 (0.965)
6i	37.5 (0.953)
7i	37 (0.94)
8i	36.5 (0.927)
9i	36 (0.915)

The placement of the ball at address may be a confounding factor, as this position ultimately lines the golfer up to the location of impact. The frontal plane moments are of most concern from the downswing to follow-through phases with impact being within them. The ball placed closer to the front foot, or closer to the midline of the body may affect the GRF vector orientation in regards to the knee joint center.

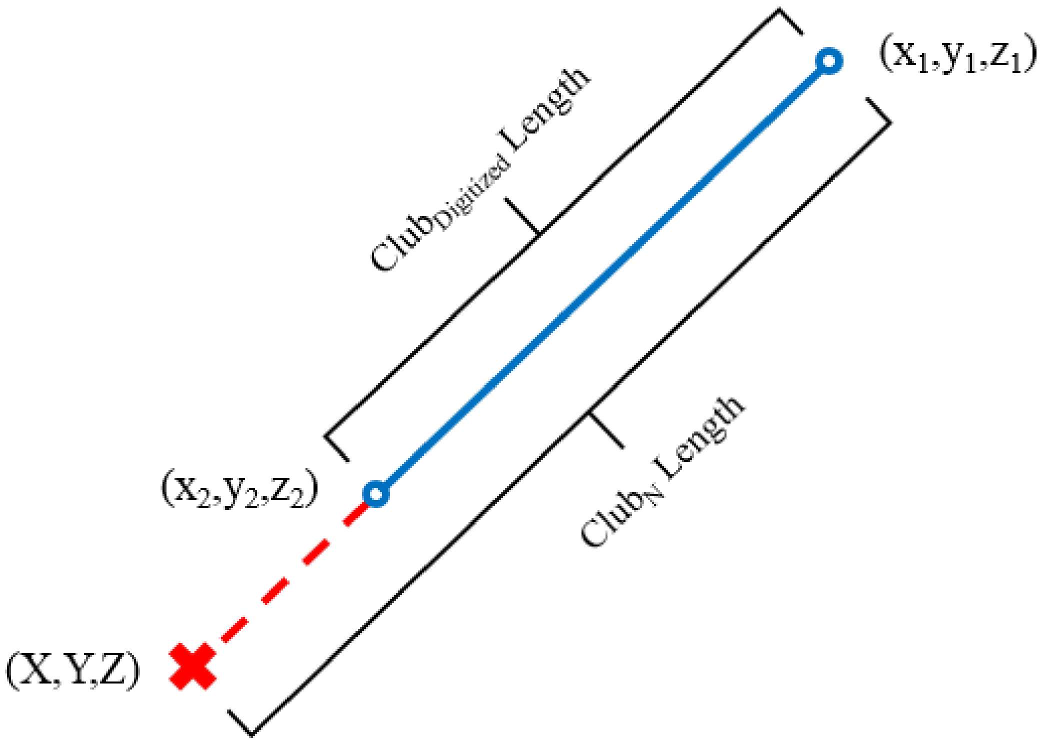


Figure 3.7 - Visual representation of translating the digitized clubhead markers to another club (N).

$\langle v_x, v_y, v_z \rangle = \langle x_2 - x_1, y_2 - y_1, z_2 - z_1 \rangle$ (Equation 11)

$(x_1, y_1, z_1) =$ x, y, z of the top of the grip digitized landmark

$(x_2, y_2, z_2) =$ x, y, z of the clubhead heel digitized landmark

$|\vec{v}| = \text{Club}_{\text{Digitized}}\ Length$

Unit vectors: $\hat{v}_x = \frac{v_x}{|\vec{v}|}, \hat{v}_y = \frac{v_y}{|\vec{v}|}, \hat{v}_z = \frac{v_z}{|\vec{v}|}$ (Equation 12-14)

Club_N Length $= |\text{Club}_N|$ (Table 3.4)

$X = (|\text{Club}_N| * \hat{v}_x) + x_1$ (Eqaution 15)

$Y = (|\text{Club}_N| * \hat{v}_y) + y_1$ (Eqaution 16)

$Z = (|\text{Club}_N| * \hat{v}_z) + z_1$ (Equation 17)

The calculated location of the heel marker on the clubhead was assumed to be the location of the ball during the address position, as the player will setup with the clubhead resting just behind the ball. The position of the feet at address were taken as the centroid of the 4 digitized landmarks on the feet (medial and lateral malleoli, and the 1st and 5th metatarsals) to create a single point. These points were averaged across the 3 trials to provide a plot for each club and swing. The left (front) foot rotation was calculated by finding the angle between the vector created from the midpoint of the ankle (medial and lateral malleoli) and midpoint of the forefoot (1st and 5th metatarsals), and the anterior-posterior axis.

3.4 Statistics

The peak abduction moment and peak adduction moment from each of the 3 swing trials for each club and clubhead speed was averaged by subject. Although kinematic and kinetic data was collected from both legs, statistical analyses were run on the front leg alone because hypotheses focused on the front knee solely. There were two parameters being investigated in this study (clubhead speed and club length). Because the research question dictated a specific combination of changes in these variables (a longer club with a slower speed), these parameters were treated as a single independent variable, which could be thought of as "condition" where the initial condition was a given club at normal speed and the modified condition was the longer club at a slower clubhead speed. It was hypothesized that swinging slower with a longer club would reduce both peak knee adduction and peak knee abduction moments on the front knee. There were 5 initial/modified condition pairs tested: 5iN/4iS, 6iN/5iS, 7iN/6iS, 8iN/7iS, and 9iN/8iS. Two-way 'condition (2) x pair (5)' repeated measures analyses of variance (ANOVAs, MATLAB, MathWorks, Natick, MA, USA) were used to address the primary hypotheses. To determine if speed alone decreased the frontal plane moments (secondary objective A), two-way 'clubhead speed (2) x club (5)' repeated measures ANOVAs were used. (The 4-iron through 8-iron were used for this analysis as there were no slow clubhead speed trials for the 9-iron). These pairings do not have specific clubhead speed reductions. The normal clubhead speed varied from participant to participant, and the difference between the normal and slow speed within a given club is not consistent, (see – Clubhead Speeds During Collection). The relationship between clubhead speed and peak frontal plane knee moments were plotted for each club to assess whether there was a linear relationship between clubhead speed and peak moments across all participants. To determine if the ball was positioned closer to the front foot and if the stance width increased in the modified condition (secondary objectives B and C), two-way ‘condition (2) x pair (5)’ repeated measures ANOVAs were run on the ball position and stance width respectively. In all ANOVAs, a significant main effect or interaction was indicated by $p<0.05$ ($\alpha=0.05$).

4 Results

This section is divided into two subsections. The first section (4.1) provides data that is specifically related to the primary objective (comparing peak frontal plane moments between the initial and modified conditions; slower clubhead speed, longer club). The second section (4.2) addresses the secondary objectives. Full moment data for the purpose of comparing the right and left legs and for comparison with previous literature is found in Appendix A. Inclusion of this section is complementary and provides a more thorough description of frontal plane moments, since, without it, the back leg would be neglected entirely.

4.1 The Effect of Clubhead Speed and Club Length on Left (Front) Leg Peak Moments

Generally, the frontal plane moments were smaller for the slow speed/longer club swings than the paired normal speed/shorter club swings (Table 4.1**)**. The magnitudes of both peak frontal plane moments were relatively consistent (as evidenced by the relatively small standard deviations) for each club. The left (front) knee moment waveforms (Figure 4.1) were consistent for each club and clubhead speed, as well as across subjects (as shown by the small standard deviations). The peak abduction moments occurred during the downswing just prior to ball impact, and peak adduction moments occurred at, or just after, ball impact. For the adduction moments, there were no main effects and no interactions (

Table 4.2). For the abduction moments, there was a main effect of condition but no main effect of pair and no interaction (Table 4.3).

Table 4.1 - Peak frontal plane moments for the 5 club pairings. Values are expressed in Nm/kg ± standard deviation.

Pair	Adduction		Abduction	
	Normal	Slow	Normal	Slow
5iN/4iS	0.93 ± 0.08	0.85 ± 0.06	0.67 ± 0.05	0.56 ± 0.04
6iN/5iS	0.95 ± 0.08	0.84 ± 0.08	0.65 ± 0.02	0.53 ± 0.04
7iN/6iS	0.96 ± 0.06	0.90 ± 0.09	0.64 ± 0.04	0.55 ± 0.05
8iN/7iS	0.93 ± 0.06	0.86 ± 0.07	0.63 ± 0.03	0.53 ± 0.04
9iN/8iS	0.94 ± 0.07	0.87 ± 0.05	0.58 ± 0.04	0.52 ± 0.03

Table 4.2 - ANOVA outputs for adduction moments (condition (2) x pair (5); N=11) (α=0.05).

Source	SS	df	MS	F	P-Value
Pair	0.022	4	0.005	0.05	0.995
Condition	0.166	1	0.166	1.58	0.212
Interaction	0.009	4	0.002	0.02	0.999
Error	10.532	100	0.105		
Total	10.728	109			

Table 4.3 - ANOVA outputs for abduction moments (condition (2) x pair (5); N=11) (α=0.05; significance indicated by *).

Source	SS	df	MS	F	P-Value
Pair	0.051	4	0.013	0.29	0.887
Condition	0.255	1	0.255	5.73	0.019*
Interaction	0.011	4	0.003	0.06	0.993
Error	4.453	100	0.045		
Total	4.771	109			

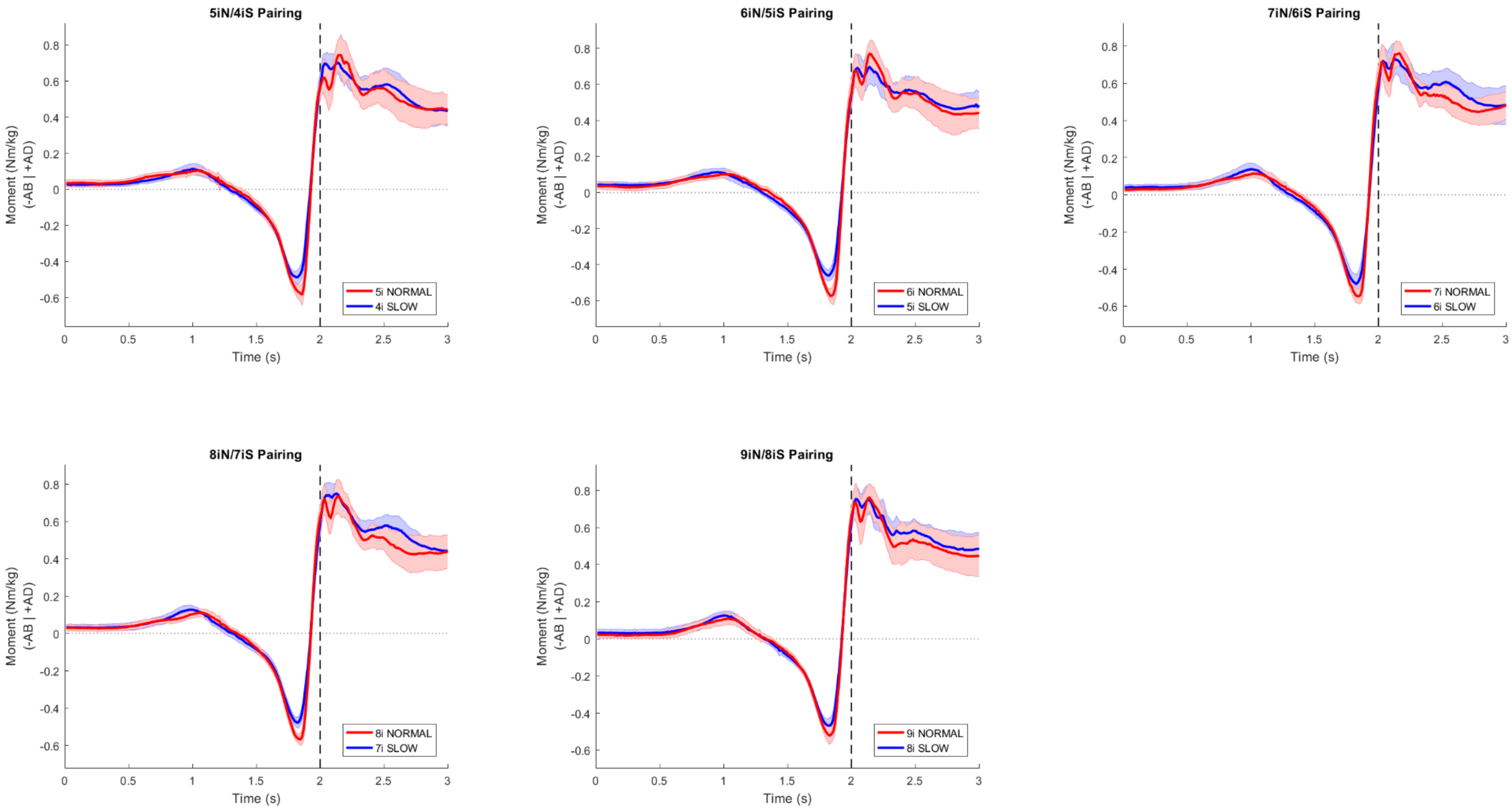


Figure 4.1 – Left knee frontal plane moment waveforms for each club pairing. Dotted line at 2 seconds represents ball impact.

4.2 Secondary Objectives

Within-club, moments tended to decrease for the slower clubhead speed (Table 4.4). Secondary objective A was to determine the effect of speed in the absence of a club change. There were no main effects or interactions for the adduction moments. There was a main effect of clubhead speed but no main effect of club and no interaction for the abduction moments. The relationships between clubhead speed and peak knee moments for each club across participants are plotted in Appendix E. For all clubs, the linear relationship between clubhead speed and peak moment and peak moment (abduction or adduction) were quite weak (all R^2<0.114).

Table 4.4 - Peak frontal plane moments within-club clubhead speed. Values are expressed in Nm/kg ± standard deviation.

Pair	Adduction		Abduction	
	Normal	Slow	Normal	Slow
4iN/4iS	0.93 ± 0.10	0.85 ± 0.06	0.70 ± 0.05	0.56 ± 0.04
5iN/5iS	0.93 ± 0.08	0.84 ± 0.08	0.67 ± 0.05	0.53 ± 0.04
6iN/6iS	0.95 ± 0.08	0.90 ± 0.09	0.65 ± 0.02	0.55 ± 0.05
7iN/7iS	0.95 ± 0.06	0.86 ± 0.07	0.64 ± 0.04	0.53 ± 0.04
8iN/8iS	0.93 ± 0.06	0.87 ± 0.05	0.63 ± 0.03	0.52 ± 0.03

Table 4.5 - ANOVA outputs for within-club adduction moment comparisons (clubhead speed (2) x club (5); N=11) (α=0.05).

Source	SS	df	MS	F	P-Value
Club	0.021	4	0.005	0.05	0.995
Clubhead speed	0.162	1	0.162	1.59	0.211
Interaction	0.010	4	0.003	0.02	0.999
Error	10.228	100	0.102		
Total	10.421	109			

Table 4.6 - ANOVA outputs for within-club abduction moment comparisons (clubhead speed (2) x club (5); N=11) (α=0.05; significance indicated by *).

Source	SS	df	MS	F	P-Value
Club	0.041	4	0.010	0.22	0.926
Clubhead speed	0.391	1	0.391	8.42	0.005*
Interaction	0.007	4	0.002	0.04	0.998
Error	4.637	100	0.046		
Total	5.075	109			

The address positions of each pair (Figure 4.2) were analyzed to determine if the ball position (secondary objective B) or the stance width (secondary objective C) changed between the initial and modified condition. The 3 points (left and right feet, and ball location) of each club in the pairing were overlaid on each other by aligning to the front foot of the normal swing (i.e. the positioning of the three points relative to each other remained the same, while all points were shifted to align with the position of the front foot during the normal swing for the pairing). For the ball position (Table 4.8) and stance width (Table 4.10) comparisons there were no main effects or interactions.

Table 4.7 – Ball distance from the front foot at address (N=11). Values are expressed in meters ± standard deviation.

Pair	Normal	Slow
5iN/4iS	0.21 ± 0.04	0.17 ± 0.03
6iN/5iS	0.18 ± 0.03	0.18 ± 0.03
7iN/6iS	0.23 ± 0.12	0.20 ± 0.06
8iN/7iS	0.23 ± 0.07	0.22 ± 0.08
9iN/8iS	0.19 ± 0.03	0.21 ± 0.08

Table 4.8 – ANOVA outputs for ball position at address (condition (2) x pair (5); N=11) (α=0.05).

Source	SS	df	MS	F	P-Value
Pair	0.024	4	0.006	0.86	0.489
Condition	0.001	1	0.001	0.15	0.695
Interaction	0.010	4	0.002	0.36	0.836
Error	0.687	100	0.007		
Total	0.724	109			

Table 4.9 – Stance width at address (N=11). Values are expressed in meters ± standard deviation.

Pair	Normal	Slow
5iN/4iS	0.49 ± 0.01	0.49 ± 0.01
6iN/5iS	0.48 ± 0.01	0.48 ± 0.01
7iN/6iS	0.52 ± 0.09	0.48 ± 0.01
8iN/7iS	0.49 ± 0.05	0.50 ± 0.05
9iN/8iS	0.45 ± 0.01	0.48 ± 0.05

Table 4.10 - ANOVA outputs for stance width at address (condition (2) x pair (5); N=11) (α=0.05).

Source	SS	df	MS	F	P-Value
Pair	0.015	4	0.004	0.5	0.735
Condition	<0.001	1	<0.001	0	0.945
Interaction	0.015	4	0.004	0.51	0.727
Error	0.732	100	0.007		
Total	0.761	109			

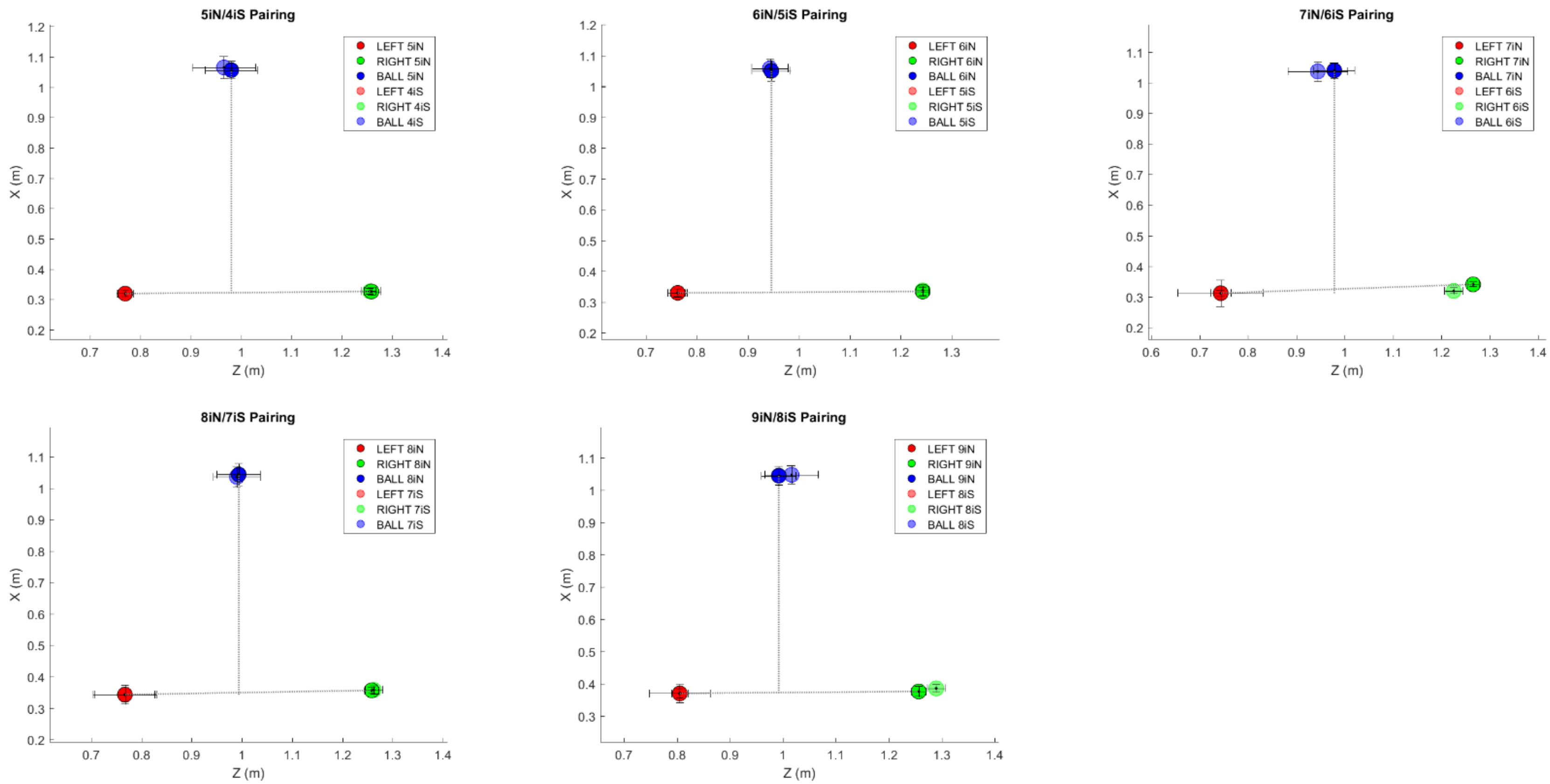


Figure 4.2 - Address position (left, right, and ball location) of each club pairing. Positions are aligned to the front foot of the normal swing, with standard deviations shown.

5 Discussion

5.1 Primary Objective and Hypotheses

The objective of this study was to determine if male golfers with a handicap below 18 can reduce their peak frontal plane moments by swinging 6 mph slower while using the next longest club in the set. To date, limited work has been conducted to analyze the knee during the golf swing making it difficult for coaches and medical practitioners to provide informed advice related to the sport.

Both adduction and abduction moments tended to be lower in the modified condition but testing the hypotheses that swinging slower with a longer club would reduce the peak knee adduction and abduction moments found a main effect of condition on the abduction moments only. It was hypothesized that swinging slower with a longer club would reduce both peak knee adduction and peak knee abduction moments on the front knee. This hypothesis is rejected for the adduction moments and accepted for the abduction moments. The magnitudes of these abduction moments (mean magnitudes of 0.52-0.67 Nm/kg) are lower than values measured when assessing ACL injury risk through drop-jump landing (0.74 ± 0.46 Nm/kg) (Hewett et al., 2005) and side-cutting (1.2 ± 0.40 Nm/kg) (Sigward and Powers, 2007). Therefore, despite reductions in the abduction moments, even the highest measured abduction moments (in the normal condition) do not appear to be of clinical concern.

5.2 Secondary Objectives and Hypotheses

Secondary objective A was to determine if moments decreased when clubhead speed decreased. It was hypothesized that swinging slower would decrease moments. There was a main effect of clubhead speed for the peak abduction moments only. It was hypothesized that a slower clubhead speed (without a change in club) would reduce the peak external knee adduction and abduction moments. Similar to the primary hypothesis, this hypothesis is rejected for the adduction moments and accepted for the abduction moments.

Recall, that the knee abduction moments were significantly reduced in the modified condition: swings slower with a longer club (Table 4.3). The results of the clubhead speed x club ANOVA (Table 4.6) provided insight into the relative roles that the change in clubhead speed and change in club (length) played in reducing the peak knee abduction moments, between the initial and modified conditions. Since there was a main effect of clubhead speed, but not for club (Table 4.6) we can conclude that the reduction in peak abduction moments between the initial and modified conditions (Table 4.3) is largely a result of the reduction in clubhead speed, with the increase in club length having a minimal effect. The lower abduction values at slower clubhead speeds could be due to how the participants executed their swing. In some cases, participants or used a half/check swing, this limits the distance the club travels in the backswing/downswing phases to limit the amount of clubhead speed generated.

Although plotting the clubhead speed versus frontal plane moments produces weak linear relationships with R^2 values (Appendix E), those plots were across all participants, within participant comparisons showed a significant reduction in abduction moments with a reduction in clubhead speed. Therefore, although abduction moments decrease in most cases when swinging slower for a particular person, the relationship between clubhead speed and peak moment is not linear across participants. The small correlations across participants for the abduction moments could be due to variations in the execution of the swing from participant to participant due to differences in anthropometrics and subtle adjustments in their joint motion. Some participants were able to reach higher clubhead speeds and have moment values similar in magnitude to those moments of another participant at lower speeds.

Secondary objective B was to determine if the ball was positioned closer to the front foot when using a longer club and slower clubhead speed. The address position was analyzed as this position is the starting point of the backswing and end point of the downswing (immediately before impact) and the relative position of the ball and feet at impact could confound the effects of clubhead speed and club length. Moving the ball forward or back, or side-to-side, and having a wider or narrower stance width was postulated to change the frontal plane waveforms and peaks. The position of the ball in relation to the front foot was relatively consistent with a range across participants of 0.05m for the normal and slow swings across participants (normal: 0.18-0.23m; slow: 0.17-0.22m) (Figure 4.2 and Table 4.7). The standard deviation bars on Figure 4.2 showed the most variability in ball position for the 6i, 7i, and 8i. This could be due to personal preference of the participant or due to the use of standard sized clubs which may not be best suited for their anthropometrics. It was hypothesized that the ball would be closer to the front foot because of the use of a longer club. The theory was proved false; there was no condition main effect on ball position (Table 4.8).

Secondary objective C was to determine if the stance width increased when using a longer club and slower clubhead speed. The stance width was postulated to change the frontal plane waveforms and peaks, by adjusting the moment arm between the GRF vector and the knee. However, stance width did not vary greatly (normal: 0.45-0.52 m; slow: 0.48-0.50m) (Figure 4.2 and Table 4.9) and there was no condition main effect (Table 4.10). Continuing with the 6i, 7i, and 8i showing the greatest standard deviation bars on Figure 4.2 can be due to personal preference of the participant. The theory of having a wider stance was proven false and the slow swing did not result in a significantly decreased stance width (Table 4.9).

It was theorized that changes in the peak external frontal plane knee adduction moments could be due to changes in ball position and stance width (Figure 1.4). This theory is supported by the lack of condition main effects for ball position and stance width, and the lack of club main effect for abduction moments in spite of a condition main effect.

5.3 Comparison to Previous Literature

Data from this study was compared to the frontal plane knee moment data from Lynn and Noffal (2010) and Gatt et al. (1998) (Table 5.1). These studies used only the 5i for their analyses, so the 5i normal swing from the current study was used to compare to these studies. Gatt et al. (1998) did not explicitly state whether they were measuring internal or external moments but, based on the description of their analysis, it appears that they reported internal moments. Therefore, their data were negated to be expressed as external moments for comparisons. These two previous studies and the current study expressed moments in the tibial coordinate system. Comparing data from this study to the others may be challenging, as the participants in this study used the modern swing whereas previous studies did not explicitly state or control for the style of swing.

Table 5.1 – External frontal plane knee moment data comparison (values expressed in Nm/ kg ± standard deviation).

Study	# of Participants	Adduction	Abduction
Current	11	0.93 ± 0.08	0.67 ± 0.05
Lynn and Noffal (2010)	5	0.63 ± 0.23*	0.70 ± 0.12
		0.54 ± 0.25‡	0.80 ± 0.19
Gatt et al. (1998)	13	0.83 ± 0.32	0.32 ± 0.14

* Use of a straight front foot position (STR)
‡ Front foot externally rotated 30° (EXT)

The adduction moment values from the current study are greater than both previous studies. Adduction moments (normalized to body mass) are 48-72% greater than those in the Lynn and Noffal (2010) study, and 12% greater than the study by Gatt et al. (1998). The abduction values are 4-16% less than Lynn and Noffal (2010) and 109% greater than Gatt et al. (1998). It should be noted that the standard deviations from the current study are smaller for both adduction and abduction moments (Table 5.1). The peak adduction moments of the current study were of similar magnitudes for all clubs used. The data does not support the possibility that decreased knee adduction moments are responsible for the anecdotally reported decreased pain with shorter irons (Guten, 1996; Marshall and McNair, 2013). The abduction moments show a decreasing trend from longer clubs to shorter clubs.

The values reported from Lynn and Noffal (2010) may not be completely representative of the participant's natural swing as both conditions enforced a set stance. For the current study, participants were free to position the front foot however they felt comfortable. On average, the front foot was externally rotated about 15° (Table 5.2) (relative to the anterior-posterior axis/ X-axis), which is mid-way between the two conditions studied by Lynn and Noffal (2010).

Table 5.2 - Front foot rotation at setup. Values are stated in degrees ± standard deviation. Positive values indicates an external rotation.

Club	Normal	Slow
Driver	16.0 ± 6.4	--
4i	15.1 ± 7.1	15.5 ± 7.6
5i	15.5 ± 6.1	15.4 ± 6.7
6i	14.7 ± 6.4	16.2 ± 6.9
7i	14.9 ± 6.9	14.6 ± 7.2
8i	14.3 ± 7.0	15.7 ± 7.0
9i	15.1 ± 6.1	--

Astephen-Wilson et al. (2011) studied patients with mild to moderate knee OA during gait. They reported a peak knee adduction moment of approximately 0.7 Nm/kg during the gait cycle (approximately 15% gait cycle). This value is of similar magnitude to that found in the current golf study. Those with OA can be found to have pain in their knee while walking and during activities of daily life (O'Connell et al., 2016; Thorp et al., 2007). O'Connell et al. (2016) analyzed gait related knee pain for those with knee OA and reported a peak knee adduction moment value of 0.62 Nm/kg for those with moderate to severe knee pain. The average peak adduction moment magnitude for the current study was 0.93 Nm/kg, therefore, the golf swing could cause discomfort in those with knee OA. Multiple studies report that an increase in the adduction moment predicts signs of OA progression (Chehab et al., 2014; Creaby et al., 2010; Miyazaki et al., 2002; Sharma et al., 1998). Amin et al. (2004) reported that greater knee adduction moments during activities contributes to future chronic knee pain. Thus, it is possible that avid golfers with existing knee OA (diagnosed or not) could start to feel more pain or experience more knee OA progression due to the knee joint moments at the level of those measured in this study.

5.4 Comparison Between Legs

The data for both knees can be found in Appendix A. When the front leg experiences an abduction moment prior to ball impact the back knee experiences an adduction moment, and then adduction and abduction after impact, respectively. Peak adduction moments for the left are markedly greater (0.86-0.95 Nm/kg), than those for the right knee (0.41-0.44 Nm/kg). The peak abduction moments are of similar magnitudes for the left and right knees (0.58-0.77Nm/kg and 0.55-0.67 Nm/kg, respectively). The ending positions of the legs at the end of the swing are different to one another; the back leg rotates finishing up on the toes as the pelvis and torso face the shot direction, whereas the front leg bears the majority of the body weight and acts like a post, about which the body pivots.

5.5 Limitations

There are some identified limitations to the study regarding the experimental setup and interpretation of the results. The motion tracking system used was cumbersome as rigid bodies with wiring was required for connection to the system. The system uses active markers. Unlike a passive system, the active markers retain the rigid body shape. There is no confusion in the system as to which marker is which, as these are explicitly stated during the experimental setup. The use of this system limited the maximum sampling frequency that could be used. The sampling frequency is dependent on the number of markers in the study (Equation 11).

$$Max\ Sampling\ Frequency = \frac{3500}{(N+2.3)}\ (where\ N = \#\ of\ markers) \qquad \text{(Equation 11)}$$

Because of the limited sampling rate, clubhead speed could not be calculated based on marker data. Instead, clubhead speed was calculated using a commercially available IMU device (SkyPro) with a sampling rate of 3200Hz. Raw data is unable to be taken from the device, therefore the reported clubhead speeds are the result of unknown built-in algorithms for speed calculation. However, the device was tested against a golf simulator (taken as the gold standard), and the speeds were sufficiently accurate. The 6 mph decrease in speed for the slow swings was based on theoretical calculations by Bowden (2013) to produce equivalent shot distance, and not taking into account environmental discrepancies which may occur during play. Ball motion was not tracked, so no resulting launch parameters or shot distances could be estimated. Shot outcome performance was based solely on clubhead speed, so it was also assumed that all swings at the correct speed would have produced a favourable resulting shot. This assumption was mitigated by using higher skill-level golfers, who would generally produce good shots.

The clubs used in the study were of standard size and length. Additional parameters such as club masses and moment of inertias, make the clubs feel and swing different than others. Therefore, participants were swinging clubs they were unaccustomed which may have altered performance. To mitigate the effect of unfamiliar equipment, all participants were allowed to warm-up and take practice swings to feel more comfortable.

There was more "trial and error" in the participants being able to achieve the desired clubhead speed for the slow swings. This resulted in more unused trials for the slow swings. However, once they achieved the target clubhead speed, they were able to consistently repeat 2 more swings. This initial difficulty in making a speed adjustment may be because, during play, players make adjustments to their swing based on the distance to their target rather than focusing solely on changing the clubhead speed.

Golf is played on a natural surface, and the lab setup placed participants barefoot overtop of force plates. Rigid bodies were placed directly on skin of the foot, so more representative foot motion was collected than a rigid body on a shoe. A shoe could limit the collection of actual foot motion, as the foot can roll and move inside, with the shoe showing minimal deflection or motion (Arnold and Bishop, 2013). Golf is played on a natural grass or artificial turf surface, which the laboratory setting does not provide. Turf could have been securely adhered to the tops of force plates for participants to stand on with golf shoes. However, with multiple studies occurring in lab, this was not feasible. Non-rigidly securing the turf would be troublesome to keep it aligned due to the twisting motions produced during the golf swing. Also, not all golfers wear spiked shoes while playing.

The statistical findings in this study indicate that speed is a much bigger factor in reducing knee abduction moments than club selection. While a club x clubhead speed ANOVA found a main effect of speed, this main effect is difficult to interpret on its own in practical terms. Although it indicates that swinging slower significantly reduces the peak abduction moment, how much slower is not specifically defined in this analysis since the difference in speed between the normal and slow swings, within a given club, is not a constant. However, because there was no main effect of club on abduction moment (part of the analysis in secondary objective A), but there was a main effect of condition (from the analysis for the primary objective), we can confidently say that the 6mph decrease between conditions is largely responsible for the significant decrease in abduction moments.

Although golf is a popular sport, finding intermediate to highly skilled golfers was challenging. The University of Waterloo golf team would have a roster of these golfers, but unlike other varsity team sports where players commonly interact with one another, golf is an individual sport and the onus is on the players themselves to keep their level of play high to maintain their spot on the team. Players practice on their own time, usually not as a team. Therefore, the potential for recruitment through word-of-mouth between players or through coaches was low.

5.6 Summary

The golf swing is not a completely standardized motion varying from golfer to golfer, unlike a highly standardized and repeatable motion to study like gait. However, a golfer will have their own consistent swing, defined, at least in part, by a player's anthropometrics, teaching, equipment, and on-course conditions. Using different clubs on-course is a guaranteed reality during a round of golf to be able to hit the ball varying differences, requiring changes in stance and swing. The findings from this study indicated that swinging slower with a longer club did not result in a significant decrease in the peak knee adduction moments. Significant reductions in the peak knee abduction moments were observed, however the magnitudes of these values are not large enough for clinical concern. The peak knee abduction moments showed a main effect of speed, indicating that clubhead speed influences the moment values. However, the peak knee adduction moments showed no main effects for condition or pair with no interactions, indicating that the peak knee adduction moments are not influenced by the club used or clubhead speed. The moments found in this study were of different magnitudes than those previously reported in the literature, the peak adduction moments were greater than previous literature, where the peak abduction moments were smaller than Lynn and Noffal (2010), but greater than Gatt et al. (1998). This data provides up to date data for the modern swing to better assist those in recommending golf to someone with a knee injury or degenerative disease, or a TKR.

5.7 Contributions

This thesis adds the following unique contributions to the scientific golf literature. Most previous studies use a single club or a select few, with the popular choices being the driver or mid iron club. Of 34 studies reviewed for this study (see Appendix B), 23 used only a single club; and 11 of these studied lower body kinetics. The current study spans the range of a set by using a variety of clubs. Previous studies have not explicitly stated if their participants were using one style or the other. Since the lower body in the modern style is different than the classic style, variables from previous research may not be representative of the modern swing. The current study explicitly analyzed the modern swing, which is what is currently taught and used. Club selection and swing type vary throughout a round of golf. The current study is the first to perturb the normal swing or control for club selection in order to determine effect on the lower limb and on performance. Data attained from this study can provide input data for modelling purposes. Finite element analysis and modelling software such as OpenSim allow for the input of motion capture, and force plate data to run simulations that can predict knee joint contact forces for healthy, injured or diseased knees. Additional, work into analyzing muscle activity (EMG) of the lower limbs during the golf swing is warranted to aid in computer simulation models.

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Appendix A – Additional Data

This section showcases additional findings from the study that were not statistically tested and supplementary in its contribution. Data from the driver is included, however no slow swing condition was used as this club is used for maximum shot distance, so a slower swing is not representative of what a player would do during play. The peak frontal plane moments for all 7 clubs used for the left knee is presented in Table A.1, and Table A.2 for the right knee. For the adduction moment, the max value was 0.95 Nm/kg using the 6i and 7i, the max abduction moment was 0.77 Nm/kg using the Driver.

Table A.1 – Left (front) knee peak frontal plane moments for each club and clubhead speed (N=11). All values are expressed in Nm/kg ± standard deviation.

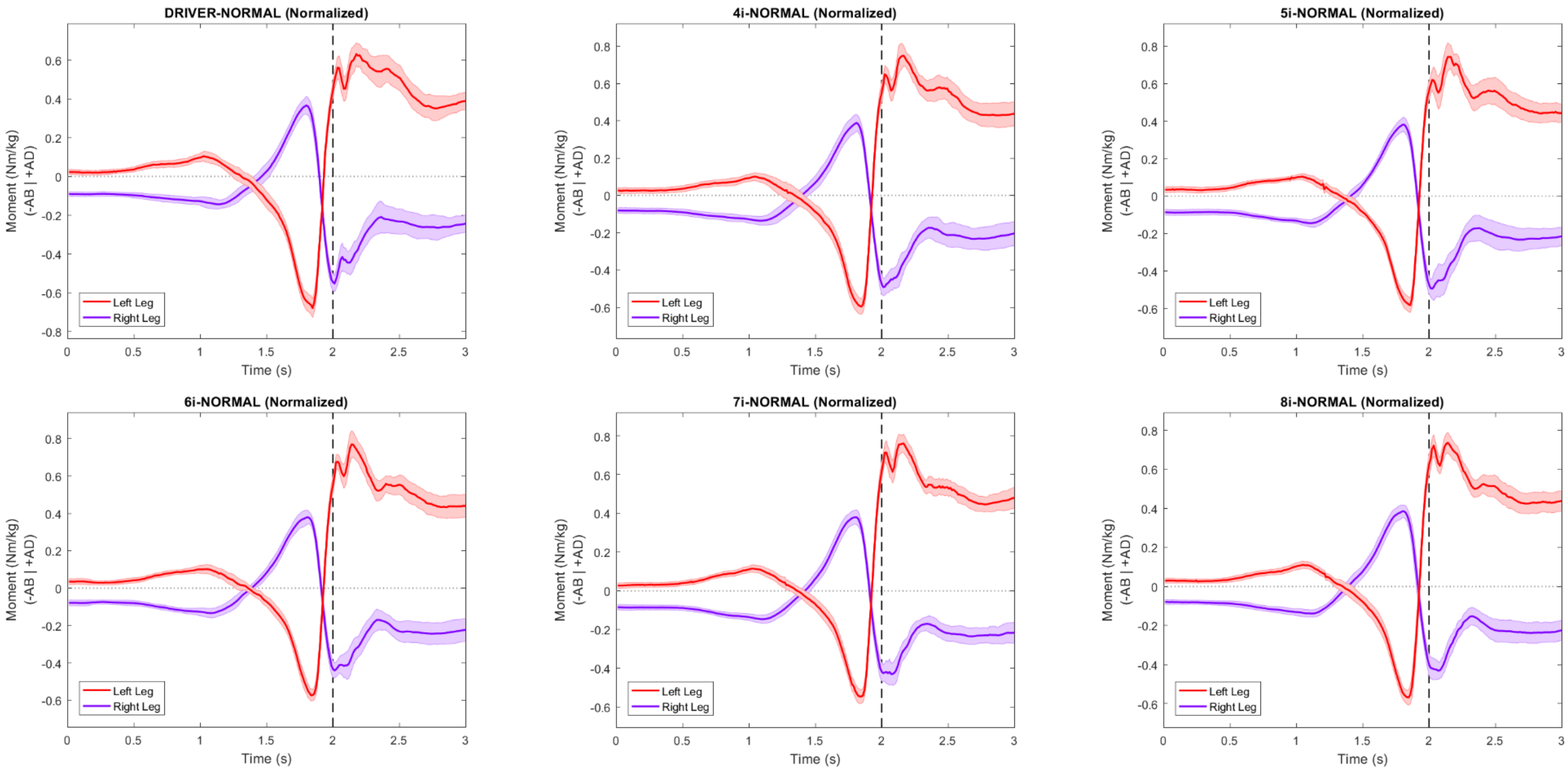
Club	Adduction		Abduction	
	Normal	Slow	Normal	Slow
Driver	0.86 ± 0.06	--	0.77 ± 0.05	--
4i	0.93 ± 0.10	0.85 ± 0.06	0.70 ± 0.05	0.56 ± 0.04
5i	0.93 ± 0.08	0.84 ± 0.07	0.67 ± 0.05	0.53 ± 0.04
6i	0.95 ± 0.08	0.90 ± 0.09	0.65 ± 0.02	0.55 ± 0.05
7i	0.95 ± 0.06	0.85 ± 0.07	0.64 ± 0.04	0.53 ± 0.04
8i	0.93 ± 0.06	0.87 ± 0.05	0.63 ± 0.03	0.52 ± 0.03
9i	0.94 ± 0.07	--	0.58 ± 0.04	--

Table A.2 - Right knee peak frontal plane moments for each club and clubhead speed (N=11). All values are expressed in Nm/kg ± standard deviation.

Club	Adduction		Abduction	
	Normal	Slow	Normal	Slow
Driver	0.41 ± 0.03	--	0.67 ± 0.04	--
4i	0.43 ± 0.05	0.34 ± 0.06	0.62 ± 0.04	0.52 ± 0.03
5i	0.43 ± 0.06	0.33 ± 0.04	0.63 ± 0.04	0.47 ± 0.04
6i	0.44 ± 0.04	0.35 ± 0.04	0.58 ± 0.03	0.48 ± 0.04
7i	0.43 ± 0.05	0.33 ± 0.04	0.57 ± 0.04	0.47 ± 0.03
8i	0.44 ± 0.05	0.35 ± 0.04	0.57 ± 0.05	0.44 ± 0.03
9i	0.42 ± 0.07	--	0.55 ± 0.04	--

The adduction moment values for the right leg are markedly less than those of the left leg; however the abduction moment values are similar for both legs. The waveforms for both the left and right legs were consistent for club and speed (Figure A.1 and Figure A.2).

The peak adduction moment is experienced at or just after ball impact for the front knee, and during the downswing to impact for the back knee. The peak abduction moment for the front knee occurs during the downswing, and at or just after impact for the back knee.



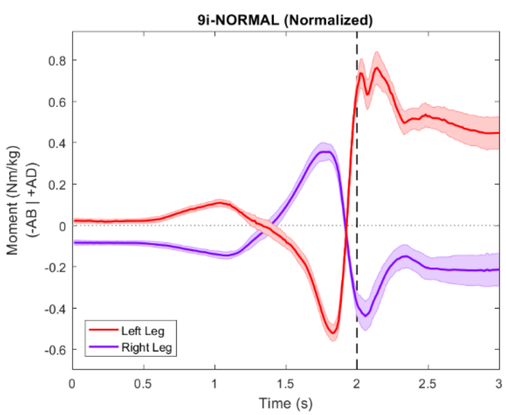


Figure A.1 – Frontal plane knee moment waveforms of both legs for the normal swing of each club. Shaded regions indicate the standard deviation.

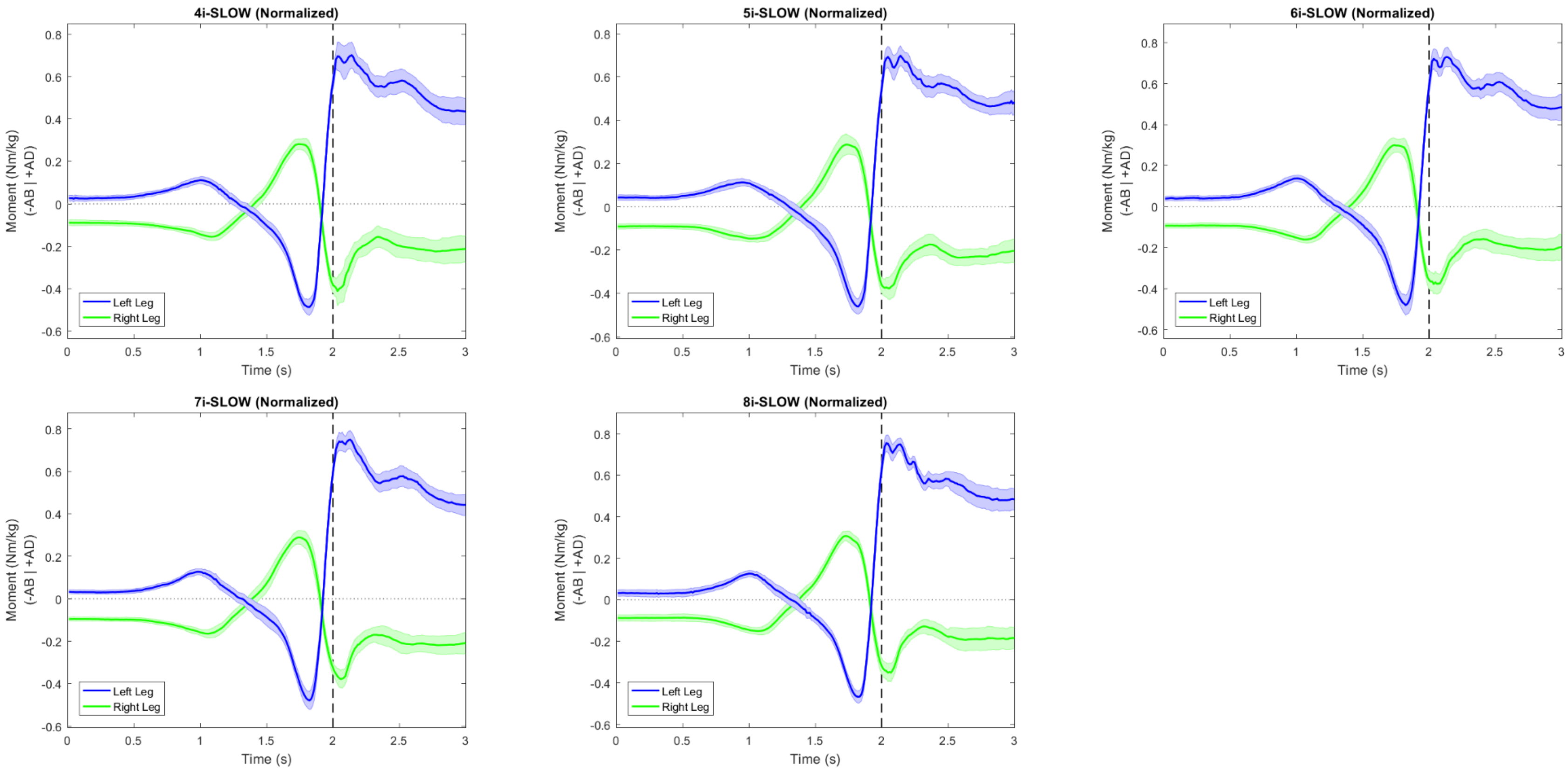
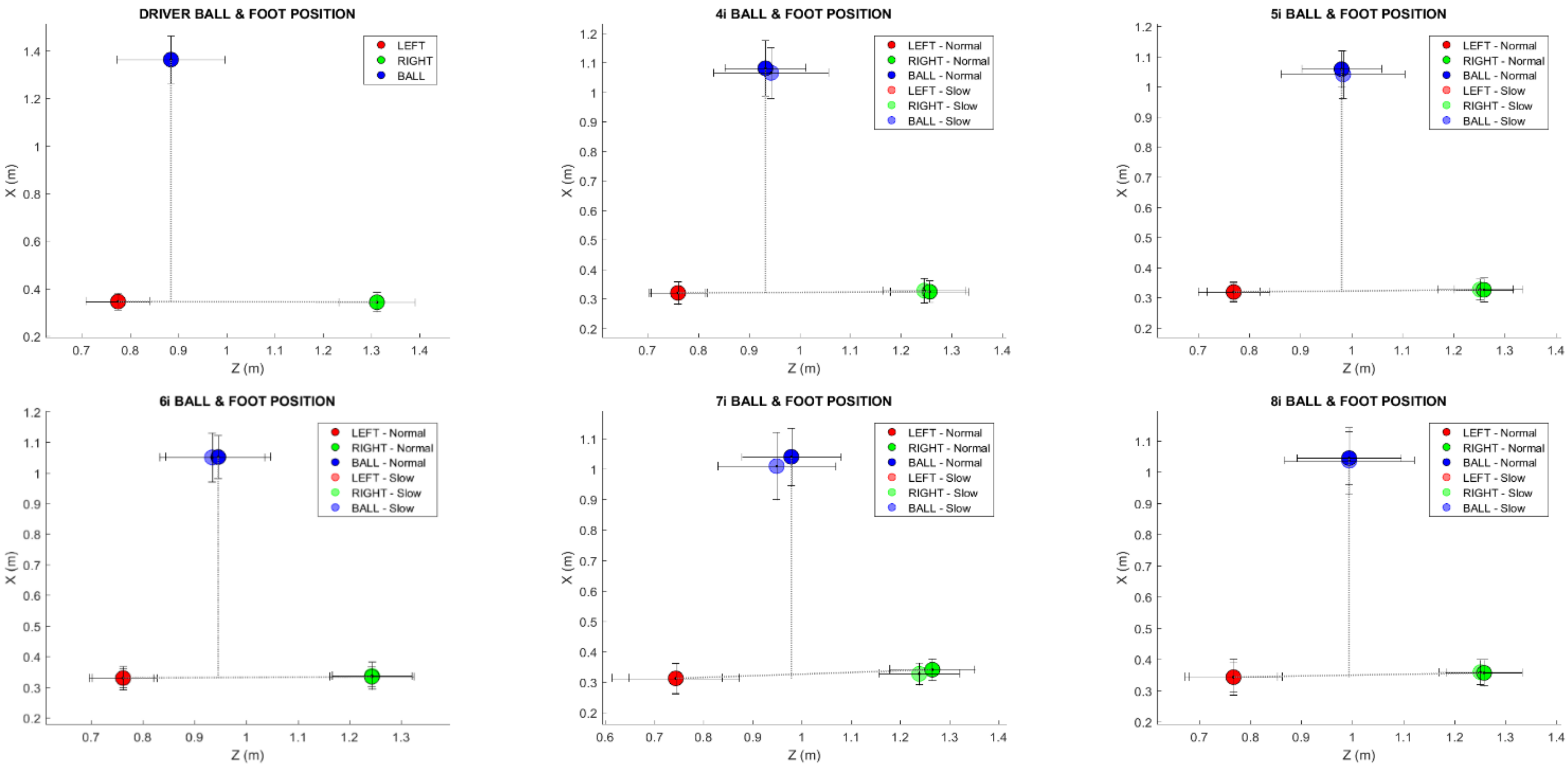


Figure A.2 - Frontal plane knee moment waveforms of both legs for the slow swing of each club. Shaded regions indicate the standard deviation.

Considering club only, the feet were relatively square (not staggered; in the anterior-posterior direction) at address for all clubs, with the ball positioned closer to the front foot for the driver and more middle for the 9i. The address positions for the normal and slow swings of each club show minor fluctuations in the stance (Figure A.3).

Table A.3 - Stance width at address (distance between the left and right feet). Values are expressed in meters ± standard deviation.

Club	Normal	Slow
Driver	0.54 ± 0.01	--
4i	0.50 ± 0.01	0.49 ± 0.01
5i	0.49 ± 0.01	0.48 ± 0.01
6i	0.48 ± 0.01	0.48 ± 0.01
7i	0.52 ± 0.09	0.50 ± 0.05
8i	0.49 ± 0.05	0.48 ± 0.05
9i	0.45 ± 0.01	--



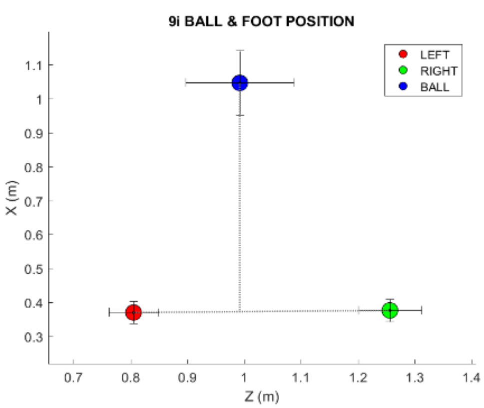


Figure A.3 – Address position (left and right feet, and ball location) of the normal and slow swings of each club. The calculated location of the heel marker on the clubhead was assumed to be the location of the ball during the address position,

Appendix B – Golfing Literature

Table B.4 - Overview of previous golf studies.

Study	Purpose	Club	Motion Capture	Gender & Age	Skill (Handicap)
McNally et al., 2014	Work of the lower extremities during the downswing.	Driver	Vicon	Male (N=36) 36.3 ± 17.3 years	0 to 30
Lynn and Noffal, 2010	Frontal plane moments of the front knee during the golf swing.	5i	Optotrak	Male (N=5) Female (N=2) 21.3 ± 3.1 years	2.9 ± 3.6; 2.7 to 8.1
Kwon et al., 2013	Examine the X-Factor and how it relates to clubhead velocity (upper body).	Driver	Vicon	Male (N=18) 31.7 ± 10.4 years	-0.6 ± 2.1
Healy et al., 2011	Identify kinematical differences between high and low launch speed groups (upper body).	5i (personal)	Vicon	Male (N=40 recruited; N=30 used) 33 ± 15 years	High launch speed -4.3 ± 4.1; Low launch speed -11.3 ± 4.6
Gatt et al., 1998	Magnitudes of peak forces/ moments and kinematics of both legs during the golf swing with 2 different shoe conditions.	5i	Motion Analysis	Male (N=13) 35 ± 14.2 years	4 to 18

Study	Purpose	Club	Motion Capture	Gender & Age	Skill (Handicap)
Egret et al., 2003	Kinematic Pattern of the golf swing with 3 different clubs.	Driver, 5i, and PW	Vicon	Male (N=7) 17 to 34 years	0.4 ± 1.1
Choi et al., 2015	Evaluated quasi-stiffness based on moment-angle coupling of the knee.	Driver (personal)	Vicon	Male (N=30) Female (N=11) Skilled (N=18; 28.6 ± 8.3 years) Unskilled (N=23; 42.8 ± 10.1)	Skilled ~0; Unskilled 18.5 ± 7.4
Bechler et al., 1995	Describe muscle activity of hip and knee muscles for both legs during the golf swing.	Driver	High speed camera	Male (N=13) Female (N=3) 27 to 59 years (mean 36)	<5
Ball and Best, 2007	Determine if different weight transfer styles exist in the golf swing using cluster analysis.	Driver (personal)	High-speed camera)	Male (N=62) 34 ± 14 years	11 ± 8
Ball and Best, 2011	(Builds on 2007a) Determine if different weight transfer styles are seen with different clubs.	Driver, 3i, and 7i	^^ ^^	Male (N=46) 34 ± 14 years	^^ ^^
Worsfold et al., 2007	Looking at GRFs differences while wearing three different styles of footwear, using three different clubs.	Driver, 5i, and 7i (personal)	High speed camera	Male (N=24) Age not stated	0 to 26
Worsfold et al., 2008	To determine the torque at the shoe-grass interface using three different clubs, three	^^ ^^	N/A	^^ ^^	^^ ^^

Study	Purpose	Club	Motion Capture	Gender & Age	Skill (Handicap)
	different footwear conditions and effect they have on handicap.				
Sinclair et al., 2014	Determine differences in (full body) 3-D swing kinematics using three different clubs	Driver, 6i, and 9i	Qualysis	Male (N=35) 30.3 ± 4.5 years	9.4 ± 3.2
Cheetham et al., 2000	Test the X-factors during the downswing, between high and low skilled golfers.	5i	Polhemus	N/A (N=19)	High (<15) Low (>15)
Wrobel et al., 2012	Analyze dynamic postural control of the CoM for varying skill levels	Driver	Vicon	Male (N=18)	Advance: 9-14 Intermediate: 15-19 Novice: none registered
Chu et al., 2010	Identify and validate factors to driving performance.	Driver	Peak Motus (passive)	Male (N=266) Female (N=42)	8.4 ± 8.4; 2.7 to 8.1
D'Lima et al., 2008	Measure knee forces during exercise, to help define safe activities to patients with knee arthroplasty.	Driver	N/A	N=3	N/A
Fradkin et al., 2004	Investigate the relationship between clubhead speed and handicap.	5i	High speed camera	Male (N=45)	High (2-10) Mid (11-20) Low (21-27)
Grober, 2010	Measure tempo, rhythm, timing and torques during the golf swing.	5 or 6i	N/A	N=25	High to low skill

Study	Purpose	Club	Motion Capture	Gender & Age	Skill (Handicap)
Grober and Cholewicki, 2006	Test the tempo during the golf swing.	5i	N/A	N=43	Pro Amateurs Average
Hamai et al., 2008	Clarify in vivo kinematics during the golf swing and cycling after TKA using radiographic imaging	N/A (simulated)	Radiographic	Male (N=3) Female (N=1)	N/A
Jagacinski et al., 1997	Assess difference in older and younger golfers.	8i	N/A	Male: Older (N=12) Younger (N=12)	High and low
Mundermann et al., 2008	In vivo knee loading for activities with an instrumented knee replacement	N/A	Qualysis	Male (N=1)	N/A
Murakami et al., 2016	To investigate dynamic knee kinematics during the squat and golf swing with image matching.	N/A (simulated)	Radiographic	Male (N=5)	N/A
Okuda et al., 2002	To examine the factors of a professional level golfer.	Driver	Video camera	Male (N=1)	Pro
Okuda et al., 2010	Examine trunk patterns of high and low skilled players.	Driver	Motion Analysis (passive)	N=30	High (<5) Low (20-36)
Zheng et al., 2008	Compare swing kinematics between male and female pro players	Driver	Motion Analysis	Male (N=25) Female (N=25)	Pro

Study	Purpose	Club	Motion Capture	Gender & Age	Skill (Handicap)
Abernethy et al., 1990	See if there is temporal proportionality during the golf swing.	7i, 9i, and PW	N/A	Male (N=10)	Expert and Novice
Barrentine et al., 1994	Quantify the ground reaction forces and torques during the golf swing.	Driver, 5i	High speed camera	Male (N=60)	High (0-15) Low (>16)
Coleman and Anderson, 2007	Asses the planar nature of the golf swing.	Driver, 5i, and wedge	Motion Analysis	N=10	High (<5)
Koenig et al., 1994	Analyze the kinematics and kinetics of the shoe-ground interface.	Driver, 3i, 7i	Selspot II	N=14	High (0-7) Mid (8-14) Low (>15)
Neal et al., 1990	How club length and shot distance affect temporal characteristics of the golf swing in expert and novice golfers	7i, 9i, and PW	High speed camera	Male (N=10)	Expert and Novice
Worsfold, 2008	Determine torque at the ground interface with different clubs and handicap.	Driver, 3i, 7i	N/A	Male (N=24)	High (0-7) Mid (8-14) Low (>15)
Pfeiffer et al., 2014	Compare older men knee biomechanics of golf and bowling to other activities	Driver	Vicon	Male (N=11 golfers)	N/A

Appendix C – IMU Clubhead Speed

C.1 IMU Clubhead speed validation

In order to calculate the speed of the clubhead for each trial it was originally planned to use the digitized landmarks on the clubhead at the Optotrak sampling frequency (85Hz). However, this sampling frequency was too low of a sampling frequency and aliasing of the signal was apparent. Thus, another means of collection was needed. Three commercially available golf IMU devices were tested against a professionally installed golf simulator (About Golf, Maumee, OH, USA) at the University of Waterloo (located in MC-2037), which was taken as the gold standard.

C.1.1 Golf Simulator

The golf simulator uses multiple cameras and a reflective tape fixed to the clubhead to calculate club metrics. A camera was fixed to the ceiling looking down to the ground and a strip of reflective tape was placed on the top of the clubhead. When the club was swung through the camera's view, light would be reflected from the piece of tape, from which the camera would then calculate the clubhead speed and display onscreen.

C.1.2 IMU Devices

The 3 IMU devices tested were: Zepp Golf 2 (Zepp, San Jose, CA, USA), SkyPro Swing Analyzer (SkyHawke Technologies, Ridgeland, MS), and the Garmin TruSwing (Garmin International Inc., Olathe, KS, USA) (Figure C.1). The SkyPro and TurSwing devices attached to the club shaft just below the end of the hand grip. The Zepp Golf 2 device was attached to the back (or top) of the top hand on the grip (left hand for those that swing right handed).

Figure C.1 - The 3 IMU devices tested: SkyPro (left), Garmin TruSwing (middle), and the Zepp Golf 2 (right).

Testing was done using 4 clubs: the driver, 4i, 6i and 9i, where 20 trials per IMU device were used to assess the clubhead speed reliability. The speed outputs from each IMU device were compared to the speed from the golf simulator. Any trial that had a speed difference 5 mph or more in comparison to the simulator were omitted from the analysis. Such trials could have been resulted from a bad shot, club-ground interaction, light interference, or swinging before system was fully ready. With the 20 trials per IMU, a random number function was used as an identifier (being a number from 0-1), and then the trials were ranked from smallest identifier to the greatest. Pairs were made by grouping the adjacent trial in the new rankings (Pair_1 = Trial_1/Trial_2 to Pair_10 = Trial_19/Trial_20). The differences in speed outputs from the IMU and simulator were determined, and then the difference between the pairing was calculated. The total (absolute) difference from the pairs was added and this was used as a score to compare the 3 devices (Table C.1, Table C.2, and Table C.3). The difference between clubhead speeds was more important as to maintain the desired 6mph difference in the paired clubs.

Table C.1 - SkyPro VS Simulator clubhead speed comparison.

Grouping	SkyPro (mph)	Simulator (mph)	Random Assigned #	Absolute Difference	Absolute Pair Difference
1	102	100	0.0769	2	1
	105	104	0.1384	1	
2	88	92	0.1763	4	2
	83	85	0.2557	2	
3	86	85	0.2804	1	1
	91	91	0.3160	0	
4	81	82	0.3220	1	1
	76	76	0.4066	0	
5	90	89	0.4561	1	2
	85	88	0.5004	3	
6	94	95	0.5020	1	1
	78	78	0.5537	0	
7	85	85	0.6070	0	2
	103	101	0.6220	2	
8	105	105	0.6715	0	0
	88	88	0.7471	0	
9	84	84	0.9165	0	0
	87	87	0.9390	0	
10	75	79	0.9398	4	1
	100	103	0.9809	3	
				Total	11

Table C.2 - Garmin TruSwing VS. Simulator clubhead speed comparison (mph).

Grouping	Garmin (mph)	Simulator (mph)	Random Assigned #	Absolute Difference	Absolute Pair Difference
1	102	105	0.1203	3	0
	83	86	0.1360	3	
2	89	91	0.1458	2	1
	87	86	0.1804	1	
3	102	103	0.1824	1	1
	84	82	0.2253	2	
4	83	83	0.3591	0	0
	84	84	0.3753	0	
5	99	104	0.3754	5	2
	80	83	0.3785	3	
6	91	92	0.3840	1	0
	90	89	0.3862	1	
7	104	107	0.3909	3	3
	80	80	0.5082	0	
8	79	78	0.6762	1	4
	80	85	0.7431	5	
9	79	76	0.7481	3	1
	72	76	0.8576	4	
10	78	77	0.9513	1	0
	80	81	0.9871	1	
				Total	12

Table C.3 - Zepp Golf VS Simulator clubhead speed comparison (mph).

Grouping	Zepp (mph)	Simulator (mph)	Random Assigned #	Absolute Difference	Absolute Pair Difference
1	87	84	0.0049	3	1
	74	72	0.0740	2	
2	82	84	0.0951	2	0
	82	80	0.1364	2	
3	85	87	0.1509	2	1
	89	88	0.1569	1	
4	85	87	0.2731	2	1
	100	103	0.2995	3	
5	90	92	0.3568	2	1
	103	106	0.3648	3	
6	76	78	0.3675	2	1
	87	90	0.3777	3	
7	88	86	0.4104	2	1
	89	88	0.4591	1	
8	97	100	0.5647	3	1
	77	81	0.5997	4	
9	88	92	0.6199	4	3
	84	85	0.6238	1	
10	89	90	0.6566	1	1
	103	105	0.6854	2	
				Total	11

Looking at the total (absolute pair difference) values for the SkyPro (11), TruSwing (12), and Zepp (11), all IMU devices produce similar results in comparison to the golf simulator. There was a max difference of 5 mph between pairings Table C.2 for the Garmin TruSwing). Since the study protocol used a rigid body on the hand, integrating the Zepp device would have been difficult. The TruSwing did not employ a calibration for each club used similar to the SkyPro (Section 3.2.1.5), but rather used fixed club lengths for each club. Lining the device up on the shaft with the clubhead and swing direction was also more important due to the lack of calibration. The calibration with the SkyPro device allowed for non-perfect alignment due to its calibration stage. Finally, the SkyPro was selected because of ease of use and compatibility with the methods and protocol of the system.

C.2 Doppler device testing

Prior to testing IMU devices a low cost (simple) Doppler speed measuring device was tested (Swing Speed Radar, Sports Sensors, Cincinnati, OH, USA). The Doppler speed measuring device did not attach to the club or interface with the system, but rather was placed on the ground and pointed at a 45 degree angle to the club swing path (Figure C.2).

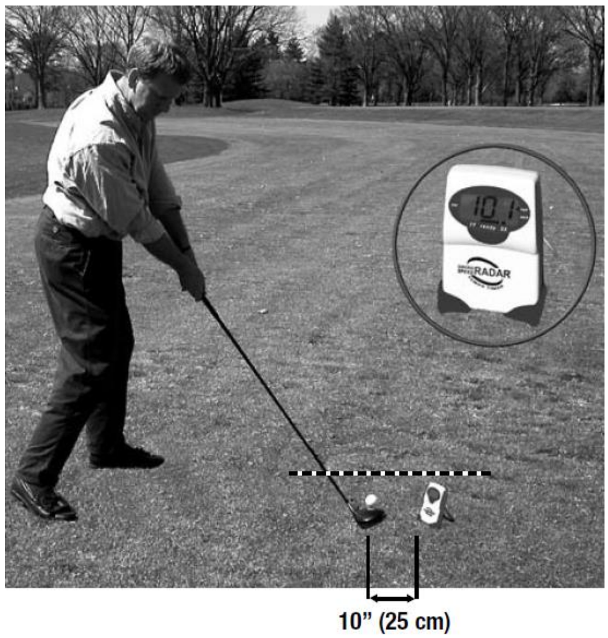


Figure C.2 - Swing Speed Radar sensor setup (Sports Sensors Inc., 2009).

This device did not require any system calibration and was fully mobile to adjust for new clubs (plug and play operations). The clubhead speed calculation was tested to that of a high speed camera (HS Cam) with a sampling rate of 9000Hz (S-PRI, AOS Technologies, Cheshire, CT, USA), and the golf simulator. This device was found to be the most finicky and non-reliable. Multiple testing sessions were conducted and successful trials from 3 clubs were attained (5i, 8i, and 9i) (Table C.4 and Table C.5).

Table C.4 - Doppler VS High Speed (mph) Camera clubhead speed comparison.

Grouping	Doppler (mph)	Simulator (mph)	Random Assigned #	Absolute Difference	Absolute Pair Difference
1	73	78.4	0.928	5	1
	78	83.9	0.130	6	
2	68	73.4	0.497	5	0
	74	79.6	0.141	6	
3	65	77	0.686	12	11
	81	80.1	0.102	1	
4	82	87.4	0.176	5	1
	76	82.3	0.295	6	
5	69	72.5	0.822	4	1
	72	76.8	0.670	5	
6	75	82.1	0.739	7	4
	69	72	0.092	3	
7	70	76.1	0.186	6	1
	69	76	0.838	7	
8	71	79.4	0.293	8	7
	74	75.4	0.476	1	
9	88	71.3	0.834	17	15
	85	83.3	0.040	2	
				Total	41

Table C.5 - Doppler VS Simulator clubhead speed (mph) comparison.

Grouping	Doppler (mph)	Simulator (mph)	Random Assigned #	Absolute Difference	Absolute Pair Difference
1	64	69	0.010	5	2
	82	85	0.075	3	
2	66	75	0.145	9	7
	80	78	0.195	2	
3	82	96	0.216	14	0
	67	81	0.316	14	
4	72	82	0.362	10	8
	65	67	0.443	2	
5	81	91	0.447	10	5
	72	77	0.465	5	
6	88	87	0.479	1	5
	66	72	0.633	6	
7	70	80	0.639	10	5
	91	86	0.744	5	
8	68	65	0.757	3	9
	76	88	0.764	12	
9	89	90	0.864	1	3
	80	84	0.981	4	
				Total	44

The data showed large (consistent) differences in the speed output with a max difference of 16.7 mph. Such large differences indicated that this device was not very reliable to be used in the study, prompting the investigation of three IMU devices.

Appendix D – Clubhead Speeds During Collection

Table D.6 - Average clubhead speed (mph) for each club, as measured by the SkyPro device, for the normal and slow clubhead speeds of all participants (N=11).

	Club											
Participant	Driver	4i		5i		6i		7i		8i		9i
	Normal	Normal	Slow	Normal	Slow	Normal	Slow	Normal	Slow	Normal	Slow	Normal
1	103.7	84.7	78	83.7	78.3	83.7	76.3	82.7	73	80	71	77.3
3	100	82	75.3	80.7	73.7	79.7	76.7	82	71.3	77.7	70.7	76.7
4	106.7	89.7	83.3	89	84.7	91	85	90.7	82	87.7	81.7	87
6	108.3	93.7	86.7	92	84.7	90.3	83.3	90.3	82	88	81.7	87
7	117.3	96.7	88.3	95.3	85	91.3	87	93	85.3	90.7	84	90.3
8	106.7	91	86	93	83	88	81.3	86.7	78.3	84	75	80.3
9	88.7	76	70.7	76.7	70	75	70	74.7	69	73.7	66	71
11	110.3	90.3	85	90.7	81	88.3	78.7	85	78.3	84	77.7	84.3
12	113.7	94.7	87.3	93.7	85	91.7	85.7	90.7	82	89.3	81.3	87.7
13	105	86.3	78.7	84.3	80.7	87	77.7	84	74.7	80.7	75	80.7
14	106	91.7	80.7	87	81.7	87.7	81	86.7	79.7	84.7	77.7	82

Table D.7 - Average speed (mph) for each club pairing of all participants (N=11). Note the slow swing being a reduction of 6 ± 1 mph to the normal clubhead speed.

Participant	Pair									
	5iN/4iS		6iN/5iS		7iN/6iS		8iN/7iS		9iN/8iS	
	Normal	Slow	Normal	Slow	Normal	Slow	Normal	Slow	Normal	Slow
1	83.7	78	83.7	78.3	82.7	76.3	80	73	77.3	71
3	80.7	75.3	79.7	73.7	82	76.7	77.7	71.3	76.7	70.7
4	89	83.3	91	84.7	90.7	85	87.7	82	87	81.7
6	92	86.7	90.3	84.7	90.3	83.3	88	82	87	81.7
7	95.3	88.3	91.3	85	93	87	90.7	85.3	90.3	84
8	93	86	88	83	86.7	81.3	84	78.3	80.3	75
9	76.7	70.7	75	70	74.7	70	73.7	69	71	66
11	90.7	85	88.3	81	85	78.7	84	78.3	84.3	77.7
12	93.7	87.3	91.7	85	90.7	85.7	89.3	82	87.7	81.3
13	84.3	78.7	87	80.7	84	77.7	80.7	74.7	80.7	75
14	87	80.7	87.7	81.7	86.7	81	84.7	79.7	82	77.7

Appendix E – Clubhead Speed VS. Frontal Plane Moment Regression Analysis

To see if there was an effect of the clubhead speed and peak frontal plane moments across participants, these 2 variables for all swings and participants were plotted against each other for the adduction moments (Figure E.3 & Figure E.4).

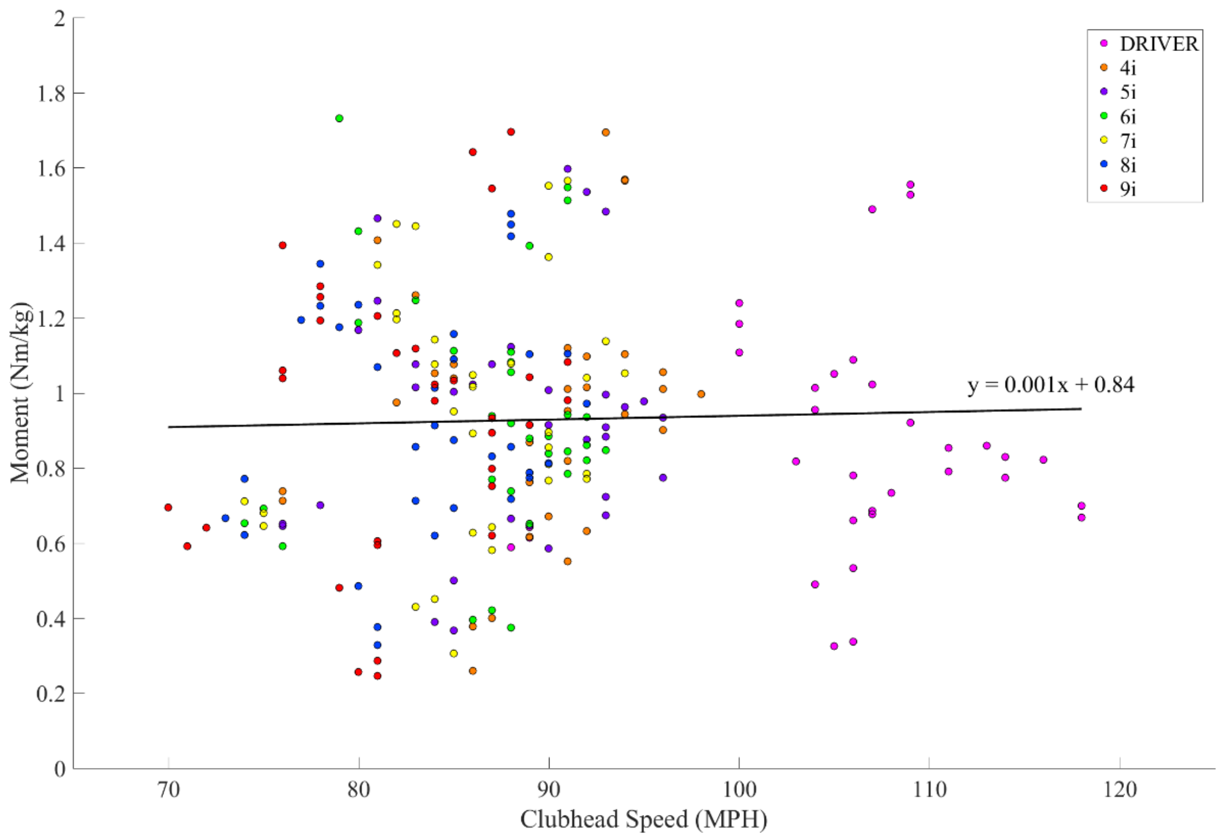


Figure E.3 – Clubhead speed VS. Peak left knee adduction moments for the normal swing.

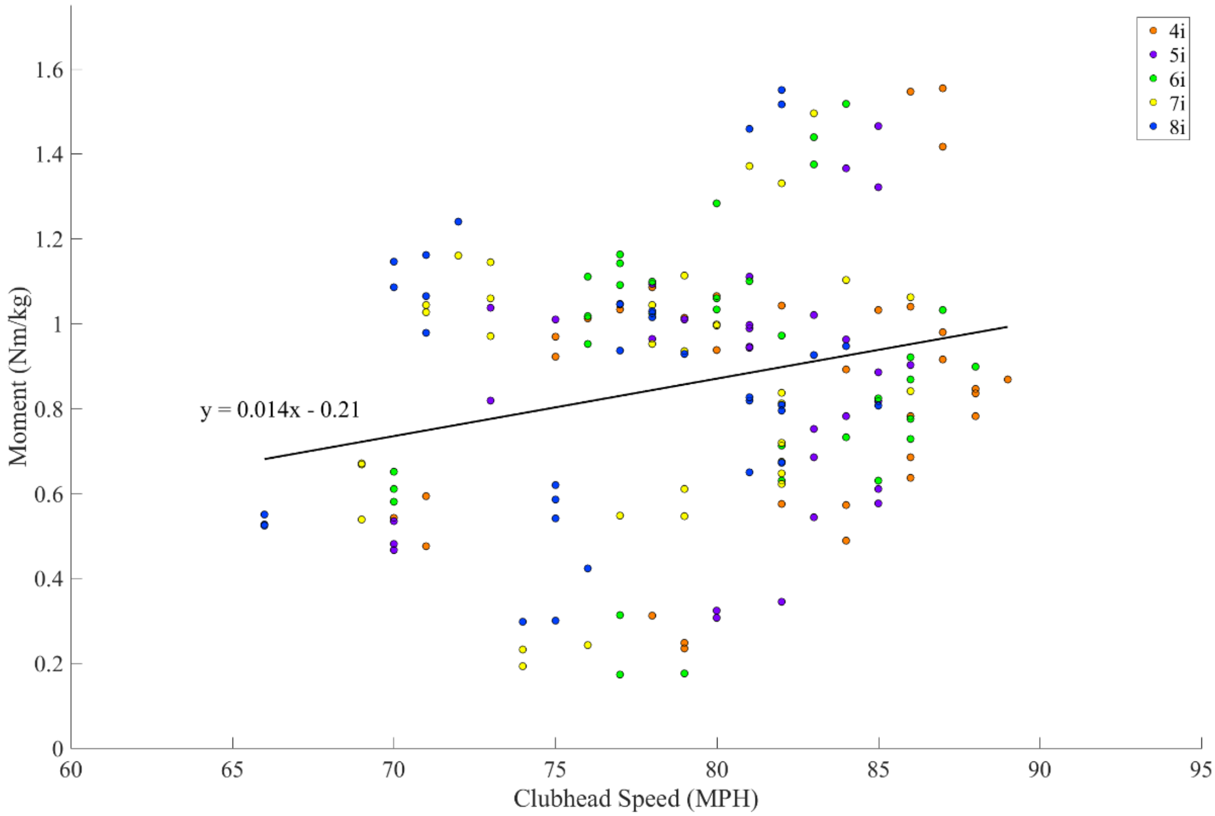


Figure E.4 – Clubhead speed VS. Peak left knee adduction moment for the slow swing.

There was small relation of the 2 variables with R=0.032 (R^2 =0.001) for the normal swing and R=0.237 (R^2 =0.056) for the slow swing relations. Regression analysis for the adduction moments for the normal (Figure E.5) and slow (Figure E.6) speeds was done for each club individually. The R and R^2 values were minimal outlined in Table E.8.

Table E.8 – Adduction moment regression values for each club and clubhead speed.

Club	R_{Normal}	R^2_{Normal}	R_{Slow}	R^2_{Slow}
Driver	0.089	0.008	--	--
4i	0.285	0.081	0.338	0.114
5i	0.135	0.018	0.264	0.070
6i	0.020	0.0004	0.210	0.044
7i	0.181	0.033	0.239	0.057
8i	0.188	0.036	0.252	0.064
9i	0.245	0.060	--	--

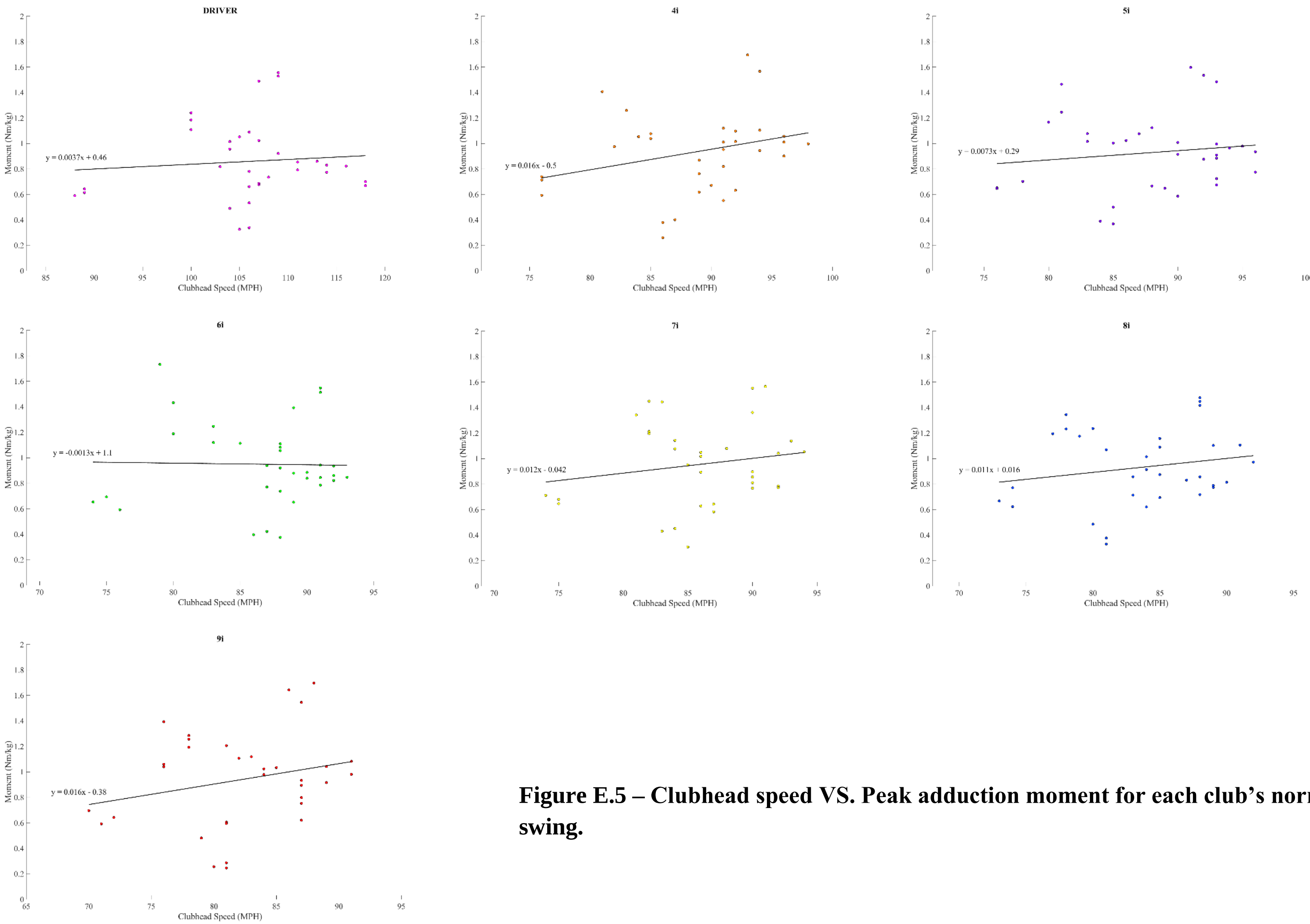


Figure E.5 – Clubhead speed VS. Peak adduction moment for each club's normal swing.

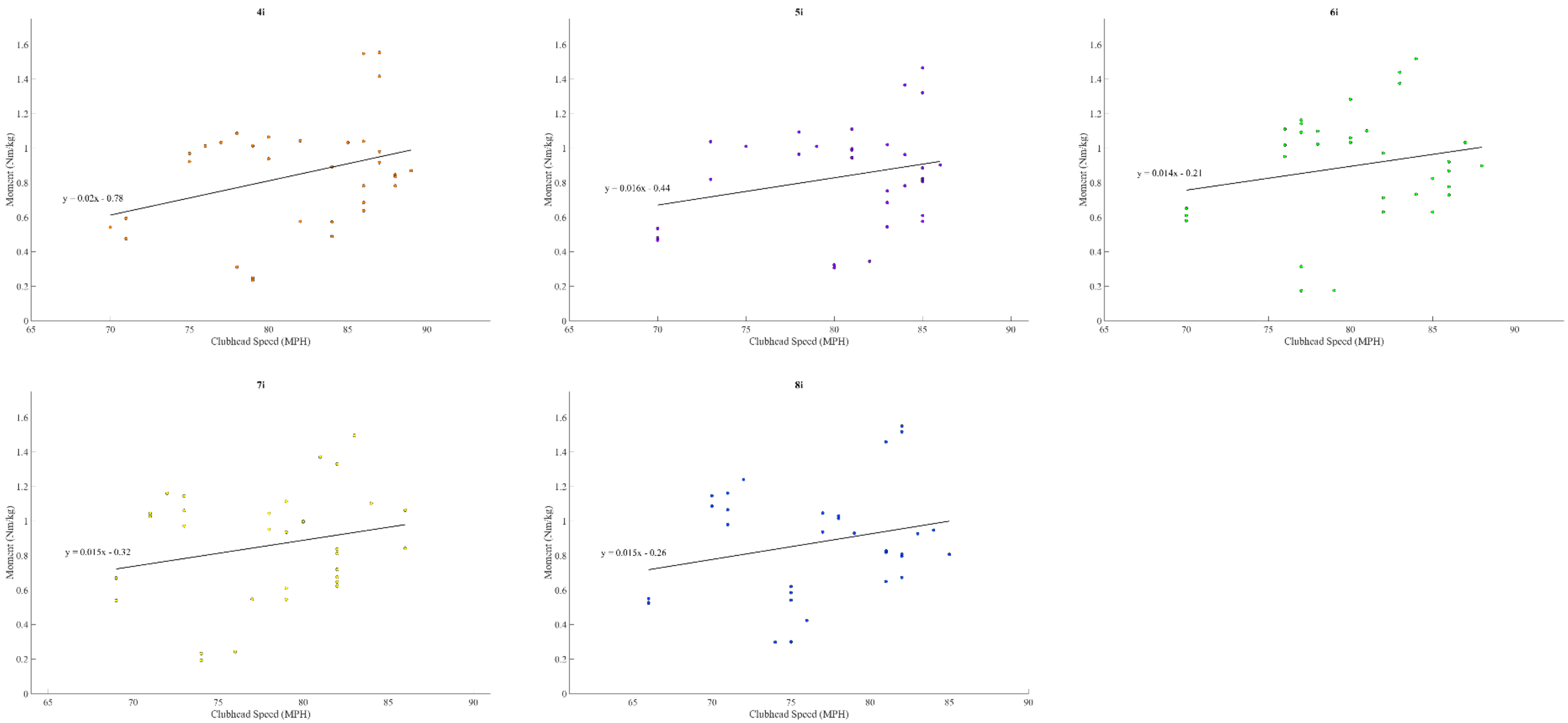


Figure E.6 - Clubhead speed VS. Peak adduction moment for each club's slow swing.

The plots for the abduction moments resulted in R=0.242 (R^2=0.059) for the normal swing (Figure E.7) and R=0.2 (R^2=0.04) for the slow swing (Figure E.8).

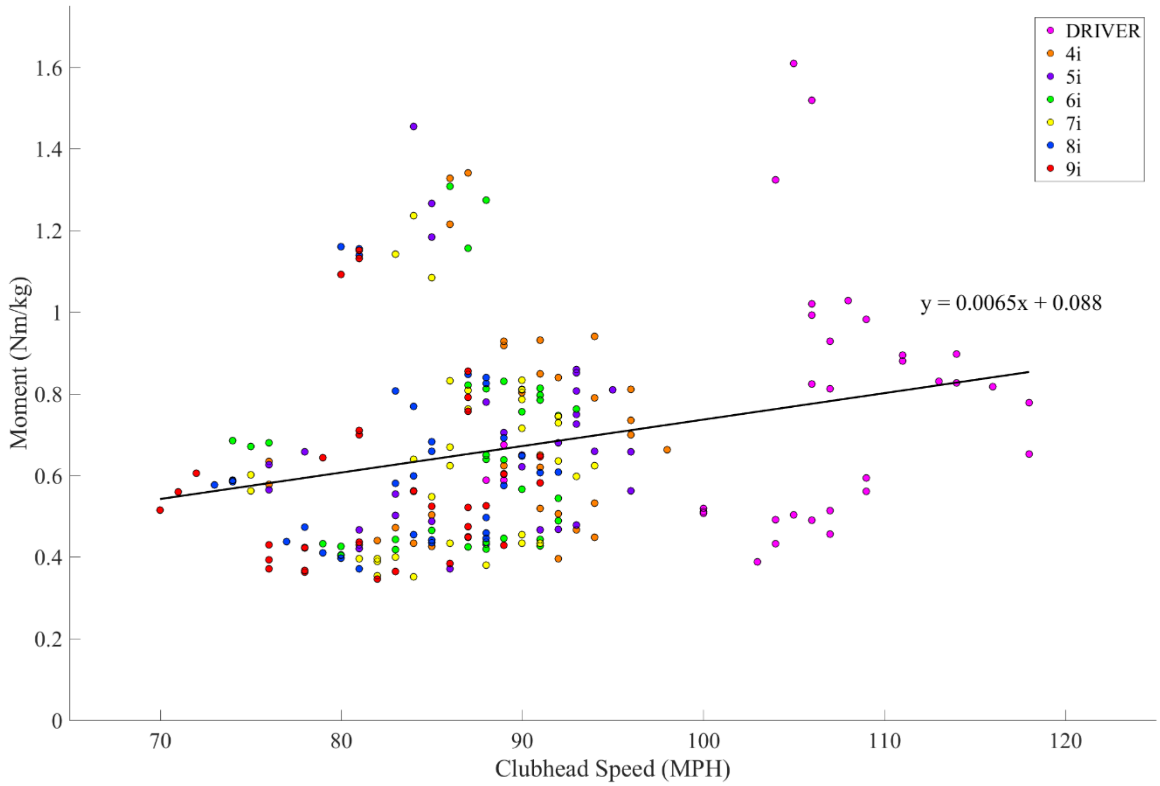


Figure E.7 – Clubhead speed VS. Peak left knee abduction moment for the normal swing.

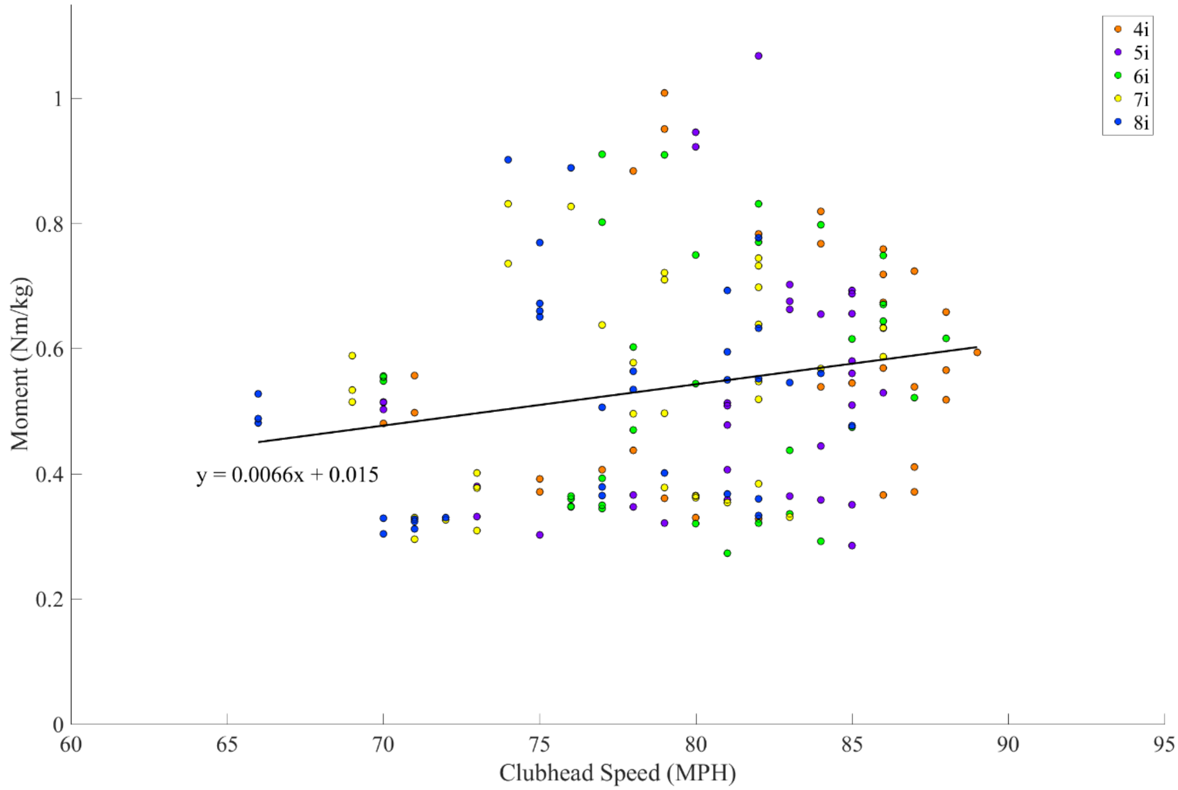


Figure E.8 – Clubhead speed VS. Peak left knee abduction moment for the slow swing.

Regression analysis for the abduction moments for the normal (Figure E.9) and slow (Figure E.10) speeds was done for each club individually. The R and R^2 values were minimal outlined in Table E.9.

Table E.9 – Abduction moment regression values for each club and clubhead speed.

Club	R_{Normal}	R^2_{Normal}	R_{Slow}	R^2_{Slow}
Driver	0.217	0.047	--	--
4i	0.133	0.018	0.178	0.032
5i	0.099	0.010	0.218	0.047
6i	0.142	0.020	0.143	0.020
7i	0.126	0.016	0.205	0.042
8i	0.060	0.004	0.201	0.040
9i	0.099	0.010	--	--

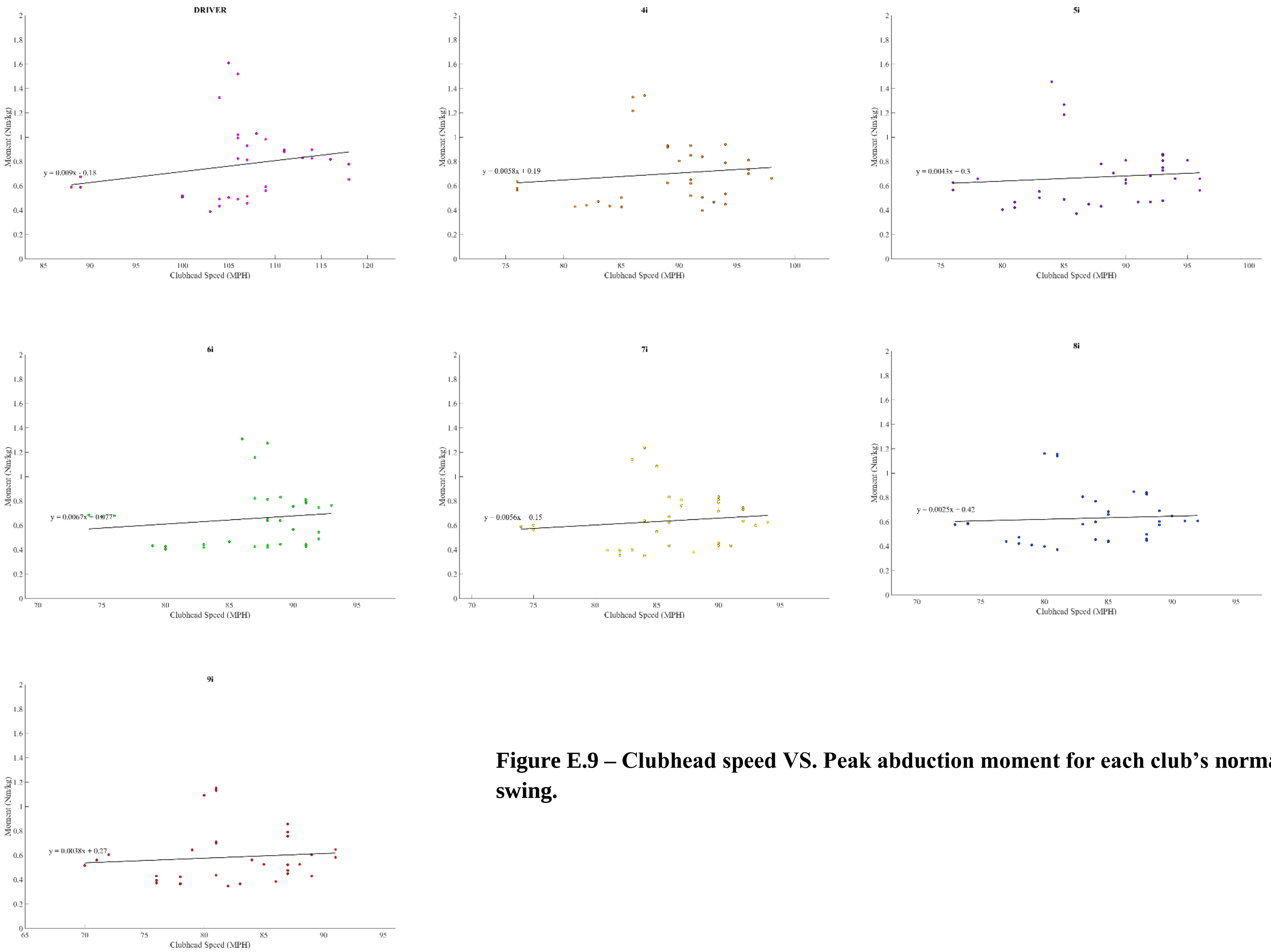


Figure E.9 – Clubhead speed VS. Peak abduction moment for each club's normal swing.

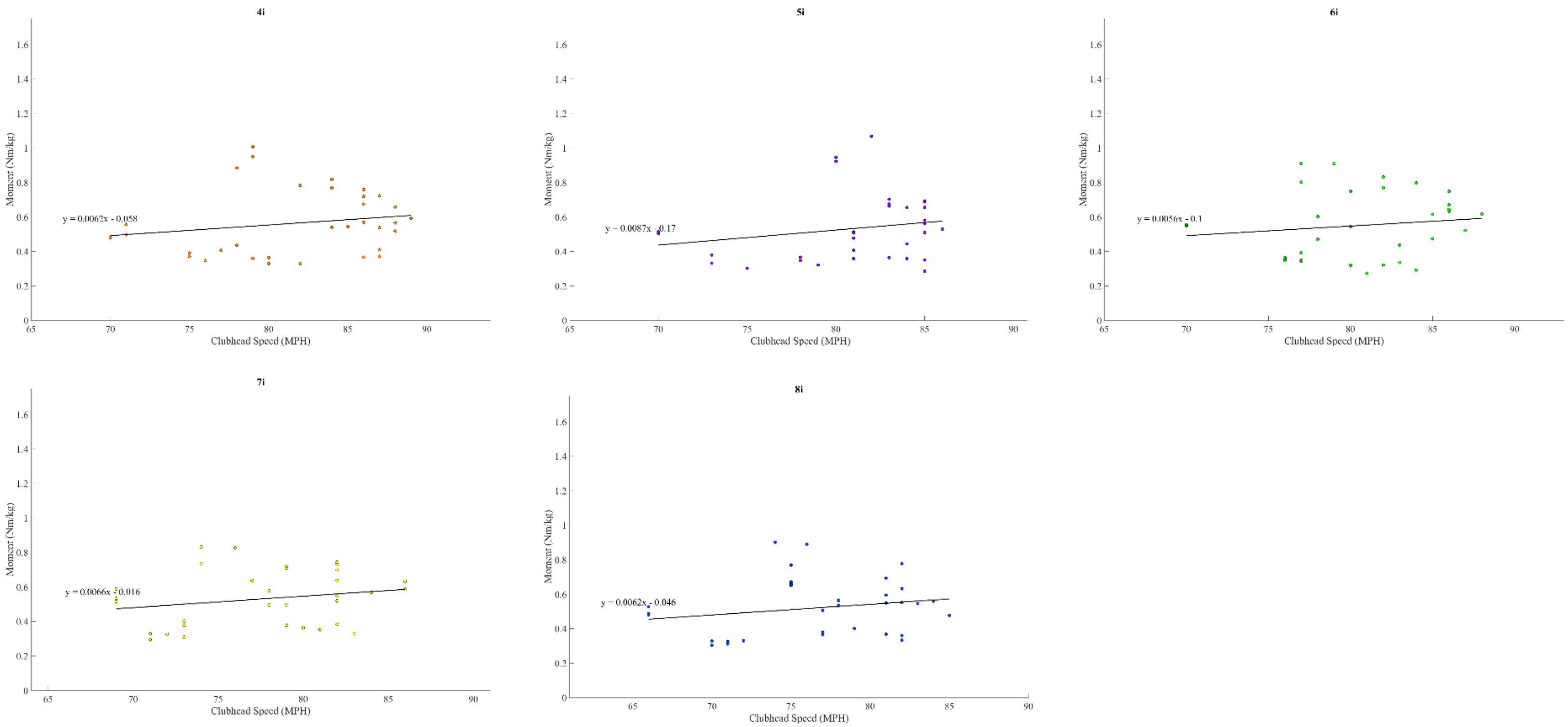


Figure E.10 - Clubhead speed VS. Peak abduction moment for each club's slow swing.