

The Relationship of Club Handle Twist Velocity
to Selected Biomechanical Characteristics of the Golf Drive

by

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ABSTRACT

During the downswing all golfers must roll their forearms and twist the club handle in order to square the club face into impact. Anecdotally some instructors say that rapidly twisting the handle and quickly closing the club face is the best technique while others disagree and suggest the opposite. World class golfers have swings with a range of club handle twist velocities (HTV) from very slow to very fast and either method appears to create a successful swing. The purpose of this research was to discover the relationship between HTV at impact and selected body and club biomechanical characteristics during a driver swing. Three-dimensional motion analysis methods were used to capture the swings of 94 tour professionals. Pearson product-moment correlation was used to determine if a correlation existed between HTV and selected biomechanical characteristics. The total group was also divided into two sub-groups of 32, one group with the fastest HTV (Hi-HTV) and the other with the slowest HTV (Lo-HTV). Single factor ANOVAs were completed for HTV and each selected biomechanical parameter. No significant differences were found between the Hi-HTV and Lo-HTV groups for both clubhead speed and driving accuracy. Lead forearm supination velocity at impact was found to be significantly different between groups with the Hi-HTV group having a higher velocity. Lead wrist extension velocity at impact, while not being significantly different between groups was found to be positive in both groups, meaning that the lead wrist is extending at impact. Lead wrist ulnar deviation, lead wrist release and trail elbow extension velocities at maximum were not significantly different between groups. Pelvis rotation, thorax rotation, pelvis side bend and pelvis rotation at impact were all significantly different between groups, with the Lo-HTV group being more side bent to the trail side and more open at impact. These results suggest that world class golfers can successfully use either the low or high HTV technique for a successful swing. From an instructional perspective it is important to be aware of the body posture and wrist/forearm motion differences between the two techniques so as to be consistent when teaching either method.

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CHAPTER 1

GENERAL INTRODUCTION

To get a complete picture of the theoretical relationships between the various mechanical factors in the golf swing that contribute to the required result, it is helpful to use a process called deterministic modeling. This process was developed by Dr. James Hay (Hay & Reid, 1988). Deterministic modeling uses a top-down, block-style, flow chart to completely map out the mechanical parameters that determine the result of the performance of a motor skill. The mechanical parameters are shown as factors and sub-factors in the diagram. Figure 1 shows a section of a model for the golf swing, from ball displacement at landing, down to the club shaft and handle contributions. The complete model is presented in Appendix A.

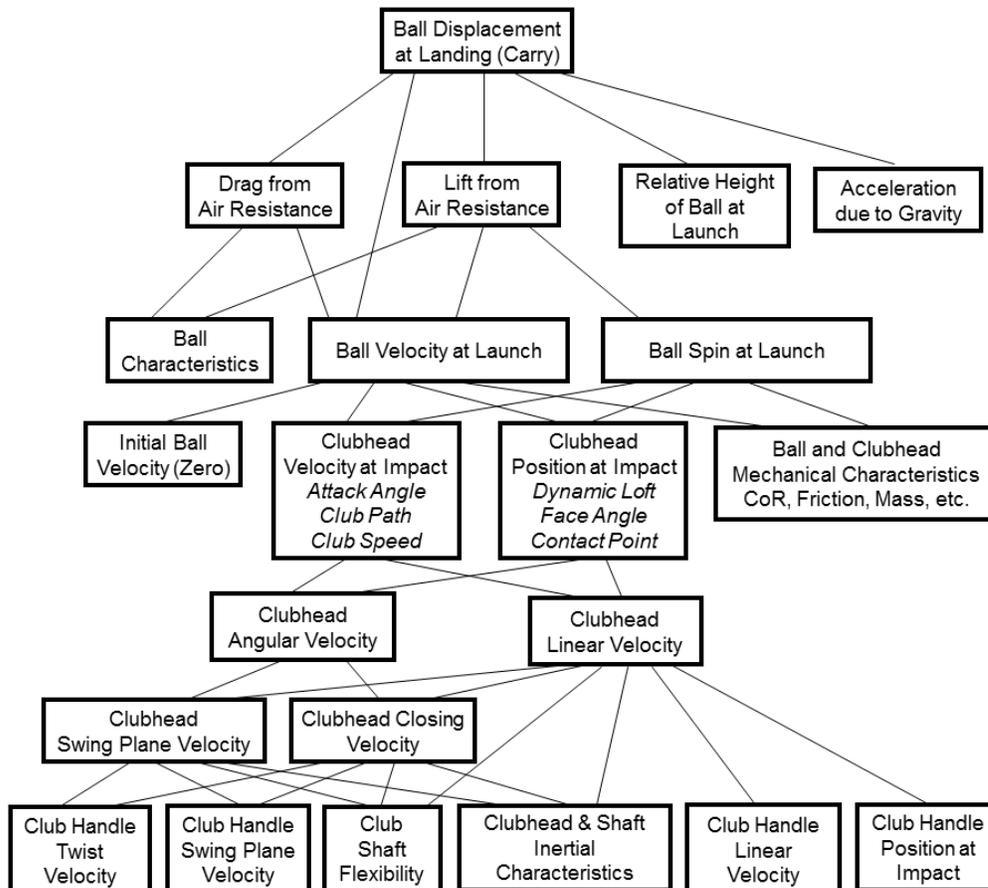


Figure 1. Deterministic Model from Ball Displacement at Landing to Club Handle

The goal of the drive is to propel the ball as far as possible in the required direction. An important result is the ball displacement at landing. This becomes the top level of this section of the model. Note though that here we are only looking at carry and are ignoring bounce and run, however Appendix A shows the complete model. Having defined the key factor we now break it down into the sub-factors by which it is directly determined. Acceleration due to gravity will directly affect the flight, as will air resistance. Air resistance has two major portions drag and lift. The displacement at landing will also be affected by the relative height of the ball at launch, that is, how high the tee-off point was relative to the landing point. Ball velocity at launch will also directly affect the carry because it includes the initial speed of the ball and its initial direction of flight. The ball velocity will interact with air resistance to affect drag and lift, as will the ball characteristics such as size and shape. At this level we also see ball spin which affects the lift of the ball. Launch is defined as the moment the ball leaves the club face. At the next level down, both ball velocity and spin are affected by the clubhead velocity and position at impact, plus the ball and clubhead characteristics such as coefficient of restitution, friction and mass. It is also important to include that the ball is initially stationary. Clubhead velocity at impact includes its speed and direction. Direction is the direction the club is traveling at impact, which can be partitioned into path, its horizontal direction at launch and attack angle, its vertical direction at launch. Clubhead position at impact includes the relative position of the clubhead and the ball. The parameters making up position at impact are dynamic loft, which is the number of degrees that the face is pointing up or down, face angle, which is the number of degrees that the face is pointing left or right, and contact point, which is where the ball contacts the club on the face and how far that is from the center of percussion. Continuing to the next sub-factors, the velocity and position of the clubhead at impact are determined by its linear and angular components. The linear velocity of a point in the middle of the clubface has x, y, and z component velocities, but of more interest to our discussion is the angular velocity of the club face which is composed of its velocity in the swing plane, that is, its angular velocity around a normal to the swing plane, and the velocity with which it is closing with respect to the ball, this is its angular velocity around a line vertical to the club face but local to the clubhead and moving with it during the swing. There may

also be angular motion in and out of the plane of the swing, but near the impact area this is very small because here the motion is primarily planar (Kwon, Como, Singhal, Lee, & Han, 2012). Now we step to the bottom level of the model. We will concentrate on the angular components because they are of importance to this research. Both clubhead swing plane velocity and closing velocity are affected by club handle twist velocity, club handle swing plane velocity, the inertial characteristics of the clubhead and shaft (moment of inertia, mass, etc.), and the shaft flexibility. With this outline as a basis, Study 1 focused on clubhead speed, driving accuracy, and handle twist velocity. More detail in wrist/forearm actions and body posture were investigated in Studies 2 and 3.

If we look at what physically happens during the downswing of a high speed swing, we find that the body undergoes strenuous motion that includes both rotation and translation. The pelvis moves toward the target during the downswing, while the thorax initially moves toward the target but then, just before impact, moves away from the target (Rose & Cheetham, 2006). Also during the downswing the pelvis and thorax rotate rapidly, first accelerating early in the downswing, then decelerating just before impact, in a sequential manner (Cheetham et al., 2008). While the torso is rotating and translating, the arms and club swing down in a manner that resembles the motion of a double pendulum (Jorgensen, 1999), gaining energy from the torso's motion and transmitting it to the clubhead. At impact the clubhead acts like a projectile as it transfers its kinetic energy to the ball (Cochran & Stobbs, 1968). The key goal of the drive in golf is to project the ball as far and as accurately as possible with the goal of landing it in the fairway as close to the pin as possible. In order for the ball to be driven a long way, the main factor is clubhead speed (Fletcher & Hartwell, 2004; Sprigings & Neal, 2000). In order for the ball flight to be accurate the biggest single factor is face angle at impact (Keogh & Hume, 2012). These relationships are also supported by the deterministic model already discussed and shown in Figure 1. There have been many studies on the golf swing to determine the keys to increased clubhead speed. The factors that have been found to relate to increased driving speed include the appropriate cocking and uncocking of the wrists (Dillman & Lange, 1994), delayed wrist release (Pickering & Vickers, 1999; Robinson, 1994), lateral shift of the shoulder (Jorgensen,

1999), inward pull the handle (Miura, 2001; Nesbit, 2005), and increased backswing angle (Reyes & Mittendorf, 1998). There have been fewer research studies that have looked at accuracy factors (Keogh & Hume, 2012), but there have been some important instructional articles (Cochran & Stobbs, 1968; Suttie, 2011). One of the accuracy factors that is discussed by these authors is the closing rotation rate of the clubface at impact. This rotation rate is necessarily affected by the rate at which the golfer twists the handle of the club into impact. It has been suggested that the higher the rate of handle twist and club face closure at impact the lower the chances for accuracy and consistency (Cochran & Stobbs, 1968). This is based on the logical conclusion that if the club face angle is changing rapidly then the timing to make contact with the ball at exactly the best angle will be more difficult than if the angle is changing more slowly. This handle twisting velocity is referred to by Nesbit (2005) as gamma motion and he states that the most important function of this motion is to square up the club face for impact. MacKenzie and Sprigings (2009a) include in their three-dimensional model, long axis rotation of the leading arm, to simulate the ability of the lead arm to externally rotate during the latter part of the downswing. This action twists the club shaft and brings the clubface square at impact.

Regarding clubhead speed, it is believed by the author that arm rotation velocity (roll) and shaft rotation velocity (twist) will also help increase clubhead speed. In racket sports it has been long established that internal rotation of the upper arm, pronation of the forearm and consequent long-axis rotation of the racket are important to racket head speed (Gowitzke & Waddell, 1979; Marshall & Elliott, 2000; Sprigings, Marshall, Elliott, & Jennings, 1994; Tang, Abe, Katoh, & Ae, 1995; van Gheluwe, de Ruyscher, & Craenhals, 1987). This principle may apply to the golf swing as well. The simple formula that relates linear velocity to angular velocity, $v = \omega r$, dictates that if there is rotation around an axis then the motion of a point around that axis will have a linear velocity proportional to the angular velocity and its perpendicular distance away from the axis. A point on the club face is a few centimeters away from the axis of the shaft. If a point on the end of the shaft where it joins to the club head (called the hosel) is translating and rotating then a point on the face will also be translating and rotating. That point, however, will be translating slightly faster than the hosel because of its rotation about, and offset from, the hosel. In a racket

there is no offset similar to that in a golf club, but if we move up to the wrist, then the angle caused by the wrist, as the forearm rotates around its long axis, will increase racket speed in a similar manner.

Older two-dimensional pendulum models (Budney & Bellow, 1979; Campbell & Reid, 1985; Cochran & Stobbs, 1968; Jorgensen, 1999; Lampsas, 1975; Milne & Davis, 1992; Pickering & Vickers, 1999; Sprigings & Neal, 2000; Sprigings & MacKenzie, 2002; Williams, 1967) were unable to include this principle because they were constrained to swinging in a single plane and did not account for any twist of the arm or club. They effectively only modeled ulnar deviation as the release mechanism but ignored lead forearm supination and handle twist. Newer three-dimensional models (MacKenzie & Sprigings, 2009a; Nesbit, 2007) have corroborated the idea of handle twist helping to increase club head speed. Nesbit (2005) explains that for a scratch golfer with a typical driver swing, the twist angular velocity of the clubhead mass center will generate an additional 1.5 m/s of linear speed at that point.

We know that world class players on the PGA Tour have a wide variation in handle twist velocities. This is one of the parameters that was captured during the last 10 years at the Titleist Performance Institute (TPI) in Oceanside, California using the AMM 3D Golf Motion Analysis System (AMM3D), by Advanced Motion Measurement, Inc., Phoenix, Arizona. The AMM3D software ("AMM 3D-Golf," 2008) supports full body motion capture and the TPI 3D database facilitates comparisons of biomechanical parameters within groups of selected professional swings. In the TPI 3D database handle twist velocity is called handle axial velocity but they are the same parameter. The database also includes information about wrist angles, velocities and torso positions and rotations.

In our study it was of interest to formally compare the club handle twist velocity in the driver swing to selected biomechanical body and club parameters in a newly compiled 3D motion database of 94 world class PGA and European tour professionals. The database was also divided into two groups, those with high handle twist velocity and those with low handle twist

velocity. The research was divided into three studies that investigated the swing characteristics and differences between golfers that use the high handle twist velocity technique to those that use the low handle twist velocity technique. Study 1 investigated the relationship of handle twist velocity to clubhead speed and driving accuracy. Study 2 looked at the relationship of handle twist velocity to wrist and forearm angular velocities. Study 3 researched the relationship of handle twist velocity to torso angles at impact, including pelvis and thorax, rotation and side bend. The hypotheses relevant to each study are explained in each study.

The results of this dissertation will be helpful to golf instructors in deciding whether to use the technique of high handle twist velocity and increased forearm roll or conversely to employ the method of low handle twist velocity and lesser forearm roll. The results of this study will give guidance on which wrist/forearm characteristics are most important and what the body posture at impact should be in order to remain consistent within the chosen technique.

CHAPTER 2

GENERAL METHODS

All the swings used in this study were from professional players that have competed in either USA or European PGA tour events. The data were captured at the Titleist Performance Institute using the AMM 3D Golf Motion Analysis system and software ("AMM 3D-Golf," 2008). AMM3D employs Polhemus, Liberty hardware. This is electromagnetic technology from Polhemus Inc., Colchester, Vermont. It captures six-degree-of-freedom motion of each body segment and the club at 240 Hz. The Liberty hardware and similar electromagnetic technologies have been used successfully in several studies of the golf swing (Cheetham et al., 2008; Cheetham, Martin, Mottram, & St. Laurent, 2001; Evans, Horan, Neal, Barrett, & Mills, 2012; Neal, Lumsden, Holland, & Mason, 2007; Tinmark, Hellström, Halvorsen, & Thorstensson, 2010). The static accuracy of the Liberty system, as quoted by Polhemus is 0.03 inches, 0.15 degrees RMS. This electromagnetic technology has been found to be accurate for quantification of human motion in many different applications (An, Jacobsen, Berglund, & Chao, 1988; Bull, Berkshire, & Amis, 1998; Johnson & Anderson, 1990; Mannon, Anderson, Cheetham, Cornwall, & McPoil, 1997). The tracking system works on an electromagnetic sensing principle (Raab, Blood, Steiner, & Jones, 1979). It uses a four-inch cubic transmitter that has three perpendicular coils of wire. Each coil transmits an electromagnetic signal. This transmitter is the global reference frame; the (0,0,0) reference point. Each half-inch cubic sensor also has three coils and each coil receives the corresponding signal from the transmitter and computes the position and orientation of each sensor in real-time. This is termed six-degrees-of-freedom of motion; three linear and three angular. Each sensor creates a local reference frame for the segment to which it is attached and tracks the segment's full six-degrees-of-freedom of motion, with respect to the transmitter, for the entire swing. The golfer's body is transparent to the electromagnetic field so there are never any missing data samples.

In the AMM3D full body system, twelve sensors are placed strategically to create a full body model including the club. Eleven sensors are placed on the body segments of the golfer using Velcro stretch straps; thorax, pelvis, upper arms, hands, shins, feet, and club as shown in Figure 2.



Figure 2. The AMM3D Golf Full Body Motion Analysis System

Sensor number 12 is attached to a plastic pointer with a known tip offset, as shown in Figure 3. The pointer is used to align the sensor reference frames to the anatomical reference frames, by digitizing at least three anatomical landmarks on each segment, in a manner similar to, Cappozzo, Catani, Della Croce, and Leardini (1995). This method creates local coordinate systems based in anatomically relevant positions with the axes aligned to each body segment. The transformation between the sensor and the anatomical coordinate system is stored and used in real-time to automatically output the anatomical reference frame instead of the raw sensor data. The assumption is made that the sensors do not move with respect to the body during the swing. This is an assumption that is made in any three-dimensional motion analysis procedure

that uses markers or sensors attached to the body and is standard practice in biomechanics research. After the segments are digitized, the pointer sensor is removed and placed on the golfer's head using a Velcro strap. The head is aligned manually by positioning it straight and aligning the sensor with the global reference frame.



Figure 3. Digitizing the Body Segments to Create Anatomical Reference Frames

From these sensor measurements a virtual-reality, three-dimensional model of the golfer is displayed on the computer screen (Figure 4) and during a golf swing capture the dynamics are calculated, including segment and joint positions, angles, velocities, and accelerations.

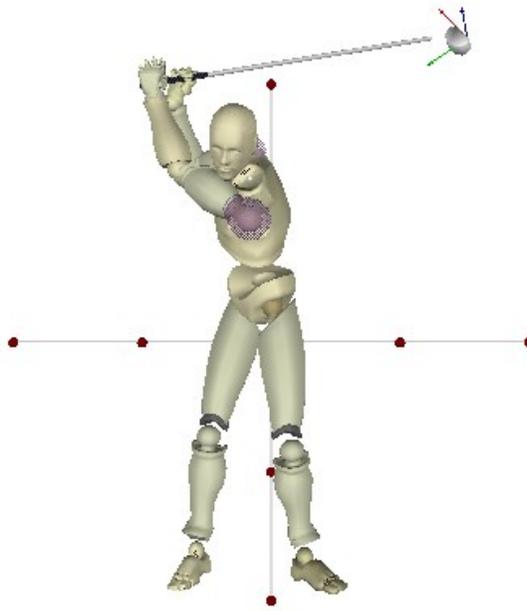


Figure 4. The TPI 3D Full Body Avatar of a Golfer

The AMM3D system allows one to build databases of any swings chosen. Once the swings are selected the system creates a database for all the kinematic parameters calculated on each body segment, joint, and the club. The means and standard deviations are calculated and a comparison table is created with all the kinematic variables and their values at seven key points, address, halfway back, top of backswing, halfway down, impact, halfway in follow through, and finish. The halfway points are defined as the sample at which the club shaft is parallel to the ground. Address is the sample just before the clubhead moves away from the ball. Top is the sample at which the club changes direction from backswing to downswing. Finish is the sample when the club stops its motion after the follow through. The impact sample is defined as the immediate sample prior to when the clubhead reaches the horizontal position equivalent to where it was at address. This sample is also cross-validated by reviewing the velocity curve graph from the AMM3D system (“AMM 3D-Golf,” 2008) and noting that the impact point is the sample before the clubhead velocity drops rapidly due to contact with the ball (Figure 5).

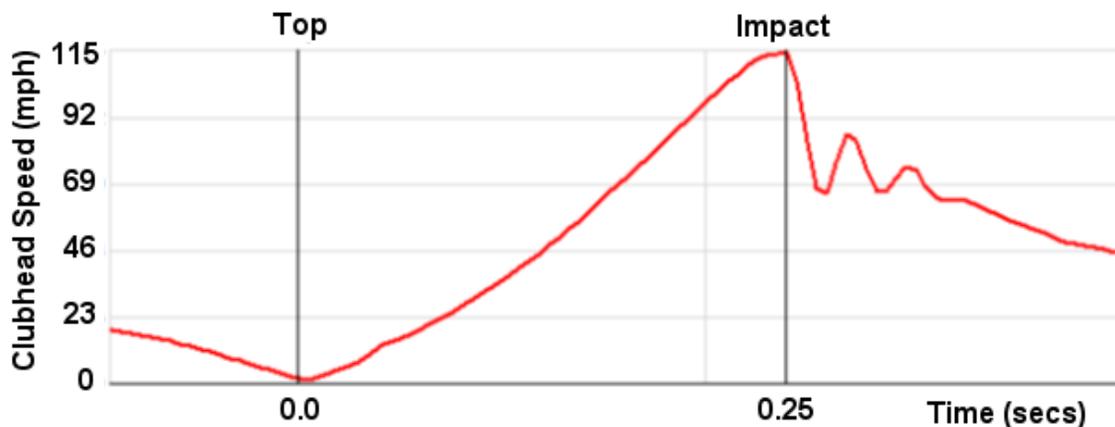


Figure 5. Immediately after Impact a Rapid Drop in Clubhead Speed is Evident

Values in the comparison table are shown in red if their magnitude for the current swing is greater or less than one standard deviation from the mean. The values are green if they are less than one standard deviation away from the mean.

HTV is the angular velocity of the club handle around its long axis. The AMM3D system computes this velocity by having a sensor secured to the golf club immediately below the grip on the shaft of the club. Points are digitized on the shaft and clubhead to produce a new local coordinate system with origin in the middle of the handle at the mid-hands level and with axes along the shaft, and in line with the heel of the clubhead. A fixed transformation matrix is created to compute this local coordinate system with respect to the sensor coordinate system. The origin and unit vectors of this coordinate system are stored for every sample during the swing. The local angular velocity is then calculated by first finding the global angular velocity vector of the handle reference frame with respect to the transmitter and then resolving this into the local coordinate system of the handle. HTV is the component of the local angular velocity vector of the handle around its long axis. It is related to the clubhead closing velocity as seen from the deterministic model in Figure 1. The relevant section of the model is shown in Figure 6. From this model we are able to determine how much club handle twist velocity contributes to clubhead closing velocity and ultimately it is clubhead closing velocity that affects the motion of the golf ball.

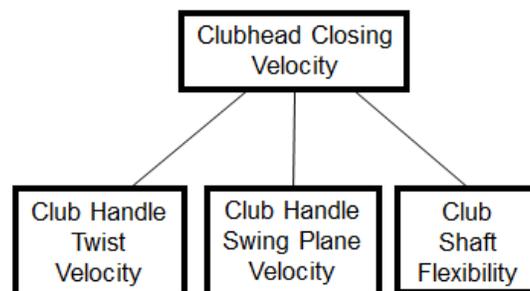


Figure 6. Deterministic Model of Clubhead Closing Velocity and its Sub-Factors

From communication with Ping Corporation engineers (P. Wood, personal communication, May 16, 2014) we found that, in their experiments, the ratio of handle twist velocity to clubhead closing velocity at impact was 0.62 (Figure 7). For their study they captured 150 players with five swings each, swinging a Ping driver. The average handicap was 12 and skill level ranged from four players to 30+ handicappers. The gender ratio was 15% female and

85% male. The age range was from 18 to 70 years old. They used the ENSO 3D motion capture system by Fujikura (Vista, California) to capture their data. It was interesting to see that their club handle twist velocities range from about 500°/s to about 3000°/s, our range was from 652°/s to 2432°/s. Even though their golfers were very diverse, values were in a similar range to our study.

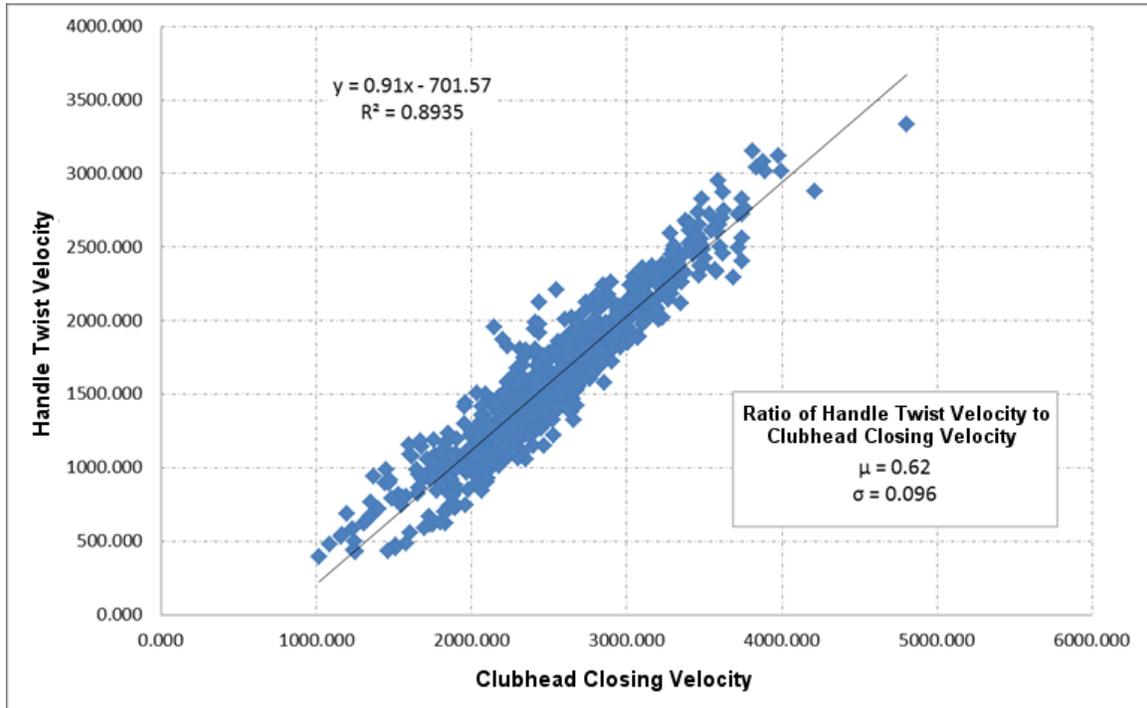


Figure 7. Handle Twist Velocity against Clubhead Closing Velocity

The clubhead closing velocity is higher than handle twist velocity at impact because of the vector relationship shown in Figure 8.

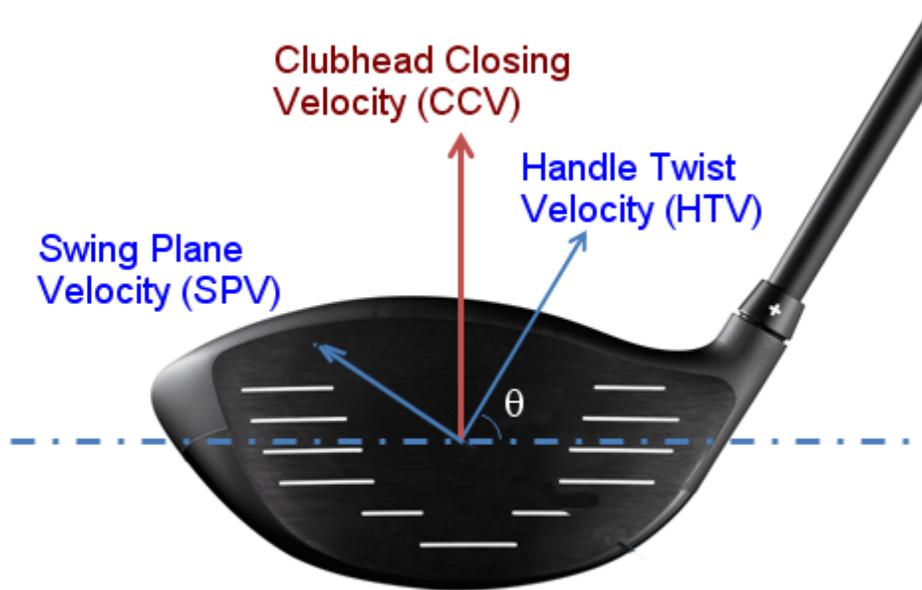


Figure 8. Relationship between Swing Plane, Handle Twist and Clubhead Closing Velocities

In the diagram of the relationship given for a driver with a lie angle of θ we see that:

$$CCV = HTV \sin (\theta) + SPV \cos (\theta)$$

From Figure 8 (E. Henrikson, personal communication, May 22, 2014) we can see that if the shaft was completely upright the clubhead closing velocity would be entirely from handle twist velocity; this would be similar to putting. If the shaft was completely horizontal then the clubhead closing velocity would be completely from the club handle swing plane velocity; this would be similar to baseball batting. There is still one possible factor adding to the clubhead closing velocity and that is the twist from the handle to the clubhead based on the torsional flexibility of the shaft. Perhaps the shaft twists like a torsional spring at the beginning of the downswing and releases right at impact adding to the closing velocity. MacKenzie and Sprigings (2009) have shown this is not the case. The shaft twist they found was only 0.6° and so they didn't even factor it into their dynamic club model, however in a subsequent paper specifically on modeling of club shaft dynamics (MacKenzie & Sprigings, 2009b) clubhead droop and lead were found to be present at impact.

Clubhead lead will increase the loft of the face at impact and clubhead droop will increase the closure of the club face at impact. No data were supplied on how much if anything this would change the clubhead closing velocity.

The methods of computing parameters used in the following studies are defined in the relevant sections. The parameters include; clubhead speed, driving accuracy, wrist/forearm velocities, and body angles. In each study the Person-product method of correlation was used with the appropriate group to determine the strength of correlation between HTV and the parameter in question. Both r and r^2 values are reported, as well as the strength of the correlation based on levels ranging from zero to perfect (Dancey & Reidy, 2004), as shown in

. Subsequently the groups were divided into two sub-groups of 32, one group with the fastest HTV (Hi-HTV) and the other with slowest HTV (Lo-HTV). The slowest HTV from the Hi-HTV group is faster than the fastest HTV from the Lo-HTV group. The Hi-HTV group was compared to the Lo-HTV group using single factor analysis of variance (ANOVA) to determine if there was a significant difference in their means for each parameter compared. The overall significance level used for each study was chosen at $p < .05$. The significance level for each ANOVA comparison was corrected using the Bonferroni method based on the number of comparisons performed in each study in an attempt to avoid Type 1 errors. Effect sizes were computed for each comparison using the "Cohen's d" statistic (Cohen, 1988). These "Cohen's d" effect sizes represent normalized differences between two means in units of their pooled standard deviation. According to Cohen if the means are 0.2 standard deviations apart (i.e., the effect size describing their comparison is 0.2) this is considered small. Further, an effect size of 0.5 is considered medium, and an effect size of 0.8 is considered large (Cohen).

Table 1. Categorization Method for Strength of Correlation Levels

Correlation Coefficient Value	Strength of Correlation
1	Perfect
.7 - .9	Strong
.4 - .6	Moderate
.1 - .3	Weak
0	Zero

A human subjects' exemption was granted by the Institutional Review Board at Arizona State University, Tempe, Arizona, because the data were already in existence and no subject identification was divulged.

CHAPTER 3

STUDY 1 - CLUBHEAD SPEED AND DRIVING ACCURACY

Introduction

During the downswing in a golf drive the release of the golf club is seen as a sudden increase in wrist angular velocity in the swing plane prior to impact, but release also includes an increase in twist velocity around the long axis of the club handle at about the same time. This handle twist velocity (HTV) helps bring the club face into alignment at impact (Nesbit, 2005), but it may also increase clubhead speed due to the offset of the ball contact point from the shaft axis. This means that handle twist velocity may affect both clubhead speed and driving accuracy. This relationship can also be seen from the deterministic model in Figure 1. If one progresses through the deterministic model from handle twist velocity up, one sees that HTV affects ball velocity at launch. Ball velocity at launch is comprised of both speed and direction, and of course the correct direction of flight helps determine the accuracy of the drive.

Many studies have modeled the wrist release in a two-dimensional planar sense (Budney & Bellow, 1979; Campbell & Reid, 1985; Cochran & Stobbs, 1968; Jorgensen, 1999; Lamps, 1975; Milne & Davis, 1992; Pickering & Vickers, 1999; Sprigings & Neal, 2000; Sprigings & MacKenzie, 2002; Williams, 1967). This method of modeling neglects the axial rotation contribution by the arm and handle that occurs later in the downswing. Researchers like Coleman and Rankin (2005) have stated that two-dimensional models of the downswing may be incorrect and more complex simulations should be performed. Newer three-dimensional models (MacKenzie & Sprigings, 2009a; Nesbit, 2007; Nesbit, 2005) have begun to consider that the downswing includes axial rotation of the arms and club and they have looked at this contribution to the swing speed but only hinted at its relationship to accuracy.

One of the earliest studies to consider handle twist velocity as a performance factor was Cochran and Stobbs (1968). Although their mathematical model of the swing was two-

dimensional and planar they anecdotally discussed the concept of rolling the arms and twisting the shaft in the downswing to bring the club face square to the ball and to help increase club head speed. This concept spanned a whole chapter in their seminal work “Search for the Perfect Swing” and was supported later by Suttie, 2011 in his article “The Fine Art of Clubface Control”. Both of these publications based their ideas on supposition from reasonable mechanical principles but did not prove their conclusions with research. Cochran and Stobbs break golfers into three categories; Rollers, Squares, and Pushers, based on how much they twist the club shaft on the backswing and consequently on the downswing. Rollers twist the club more than 90°, Squares 90°, and Pushers less than 90°. They suggest that Pushers will tend to be more accurate because having less than 90° to twist the club back to impact means they can have a slower rate of change of the face angle in the downswing making it easier to get consistently square at impact. They suggest that while this lower twist angle method may have the potential for more accuracy it will lose the mechanical advantage of the “screwdriver action” (p. 96) and will be a less powerful swing. On the other hand Rollers will have more difficulty with the timing, thus affecting their accuracy, but the increased scope of the “screwdriver action” will make their swing more powerful. Suttie (2011) comes to similar conclusions as Cochran and Stobbs but he uses different names to describe the groups. Pushers are called Closed-Face golfers because the face remains more or less closed during the backswing with little or no shaft twist occurring in the backswing and the downswing. Rollers are called Open-Face golfers because they twist the club handle more and open the face of the clubhead during the backswing and therefore they have to close it the same amount on the downswing. It is from this sound reasoning that our hypotheses are formulated. It is hypothesized that world class golfers with high handle twist velocity will have a higher clubhead speed at impact but less driving accuracy than golfers with low handle twist velocity at impact.

Methods

The procedures of subject setup, motion capture, and database make-up that apply across all three studies were described in the general methods section of this dissertation. This

methods section describes the biomechanical and statistical methods specific to this study; Study 1. The AMM3D system calculates the clubhead speed as the magnitude of its resultant linear velocity. A sensor is generally affixed to the club shaft just below the grip and a local coordinate system is created in the clubhead by digitizing three points on the club face; bottom groove at heel, bottom groove at toe and top groove at toe. This coordinate system is computed with respect to the sensor at the base of the handle and resolved back into the global coordinate system. The origin of the coordinate system is the bottom groove at the toe of the club and this is the point from which the clubhead speed is computed for every sample during a swing. It is important to note that the club is modeled as a rigid segment when in reality the shaft can bend. This computed clubhead speed is not exactly the same as the true clubhead speed; however the difference is systematic, so projected clubhead speeds generally ranked in a similar manner to actual clubhead speed. In the book, "The Physics of Golf" (Jorgensen, 1999) it was shown that clubhead speeds for a flexible shaft were approximately 3% faster than with a rigid shaft. MacKenzie and Sprigings (2009b) in their study on shaft stiffness, found an approximate increase of 4% from a rigid to a flexible shaft. Ping engineers (P. Wood, personal communication, May 16, 2014) captured 150 players of different capabilities performing five swings each and swinging a Ping driver. They used the ENSO 3D motion capture system by Fujikura (Vista, California) which allowed them to compute both the actual clubhead speed and calculate the rigid body equivalent clubhead speed. Figure 9 shows a plot of their data and the fitted regression line. They found the mean difference was 2.7 mph (SD = 1.43) or 1.2 m/s (SD = 0.6) with the actual clubhead being faster than the rigid clubhead. Clubhead speeds ranged from approximately 52 mph to 120 mph (23.2 m/s to 53.6 m/s).

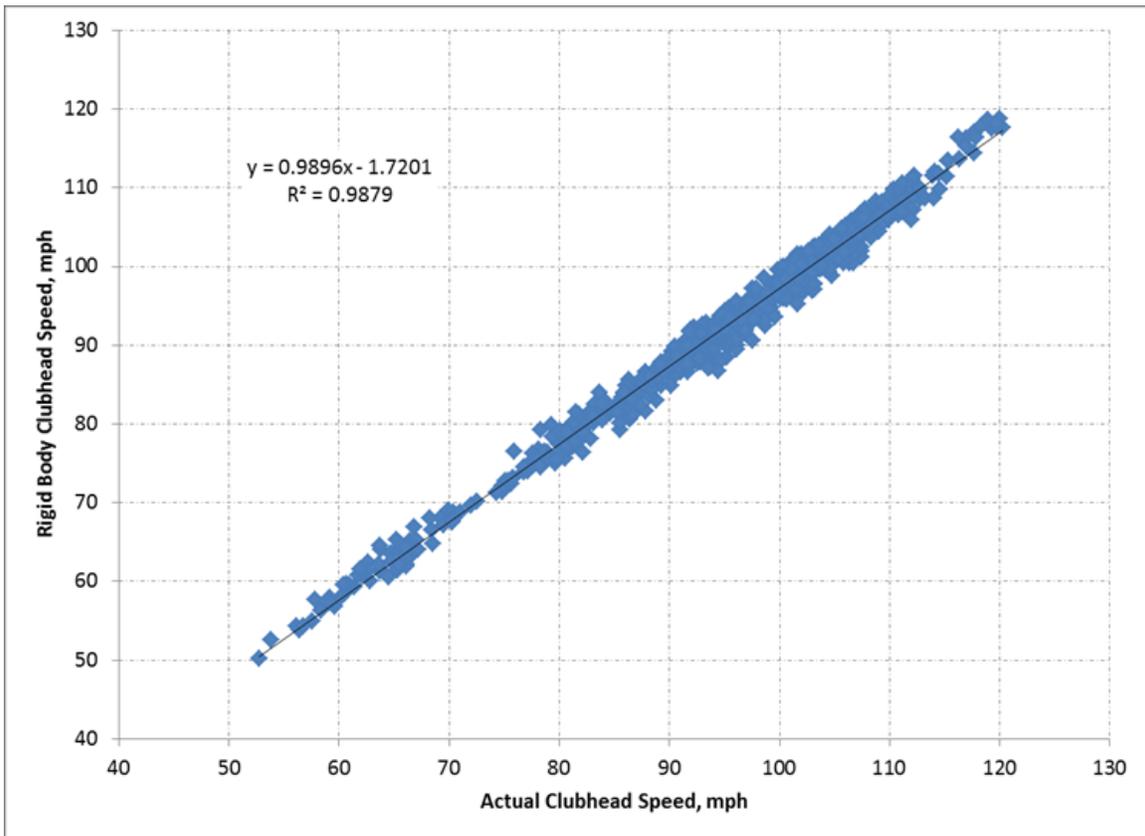


Figure 9. Rigid Body Clubhead Speed against Actual Clubhead Speed

For the analysis of the relationship of clubhead speed and HTV the database containing a single normal driver swing of each of 94 PGA and European tour players was used. Driving accuracy for each golfer was collected from the PGA Tour website (www.pgatour.com). It is defined as the percentage of time a tee shot comes to rest in the fairway. For the analysis of the relationship of percent driving accuracy and HTV a database of 70 PGA tour professionals was used. This was a sub-group of the 94 golfers used in the clubhead speed analysis. Only the professionals that have played in a USA PGA Tour event were included in this group because their driving accuracy statistics were available on the PGA Tour website. No accuracy measurements were captured directly with each swing, however the data from the website was from the same year as the captured swing. In this study, two correlations were performed; HTV

20, with clubhead speed, using the database of all 94 touring professionals, and HTV with driving accuracy using the database of 70 touring professionals. Further to this and using methods described in the general methods section, two single factor ANOVAs were performed. They were between HTV and both clubhead speed and driving accuracy. In order to preserve an overall significance level of $p < .05$ in this study a Bonferroni corrected value of $p < .025$ was used for each of the two ANOVA comparisons made. Effect sizes were also computed using the “Cohen’s d ” statistic (Cohen, 1988). This gives the difference between the compared means in multiples of the pooled standard deviations.

Results

Descriptive statistics of HTVs for the total groups and sub-groups are shown in Table 2.

Table 2. Descriptive Statistics for Handle Twist Velocities

Handle Twist Velocity (°/s)	Mean	SD	Highest	Lowest
Clubhead Speed Analysis Group				
HTV Total Group (n=94)	1307	304	2432	652
Hi-HTV (n=32)	1631	205	2432	1408
Lo-HTV (n=32)	996	150	1173	652
Driving Accuracy Analysis Group				
HTV Total Group (n=70)	1296	301	2432	652
Hi-HTV (n=32)	1544	225	2432	1315
Lo-HTV (n=32)	1049	158	1266	652

The means and standard deviations for both clubhead speed and driving accuracy for each total group are summarized in

Table 3. It should be noted that there were 94 golfers in the clubhead speed analysis and 70 golfers in the driving accuracy analysis. The mean clubhead speed of 48.4 m/s equals 108.3 mph.

Table 3. Means and Standard Deviations for Clubhead Speed and Driving Accuracy

	Mean	SD
Clubhead Speed m/s (n=94)	48.4	2.5
Driving Accuracy % (n=70)	62.8	6.4

Pearson product-moment correlation compared HTV with clubhead speed and found only a weak positive correlation ($r = .14$) and when comparing HTV with driving accuracy a weak negative correlation ($r = -.14$) was found. Table 4 shows these relationships.

Table 4. Correlation Statistics for HTV with Clubhead Speed and Driving Accuracy

Parameter	r	r^2	Strength
Clubhead Speed m/s (n=94)	.14	.02	Weak
Driving Accuracy % (n=70)	-.14	.02	Weak

Figure 10 and Figure 11 show the scatter plots of both clubhead speed and driving accuracy plotted against handle twist velocity with the best fit regression line and its equation shown in each case.

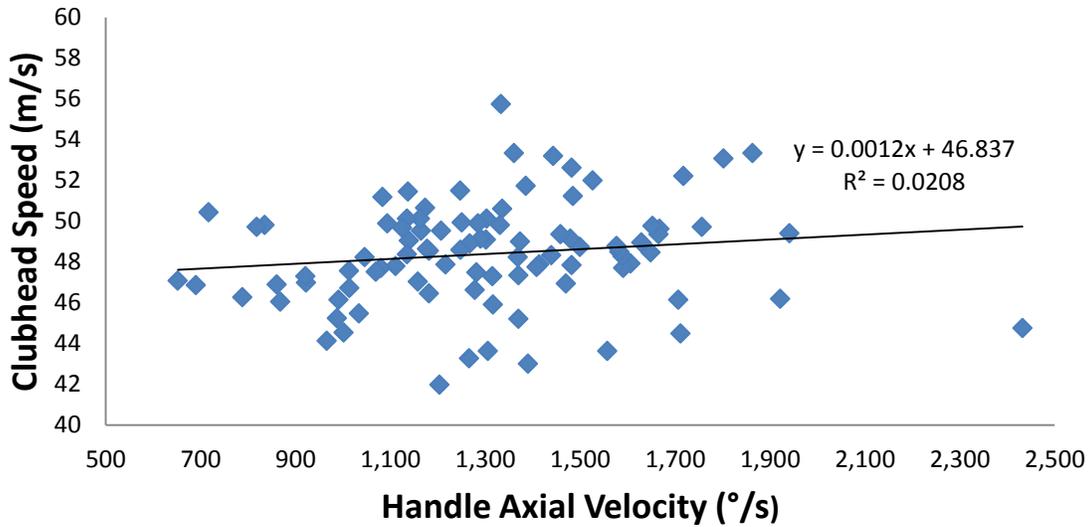


Figure 10. Scatter Plot of Clubhead Speed and HTV (n=94)

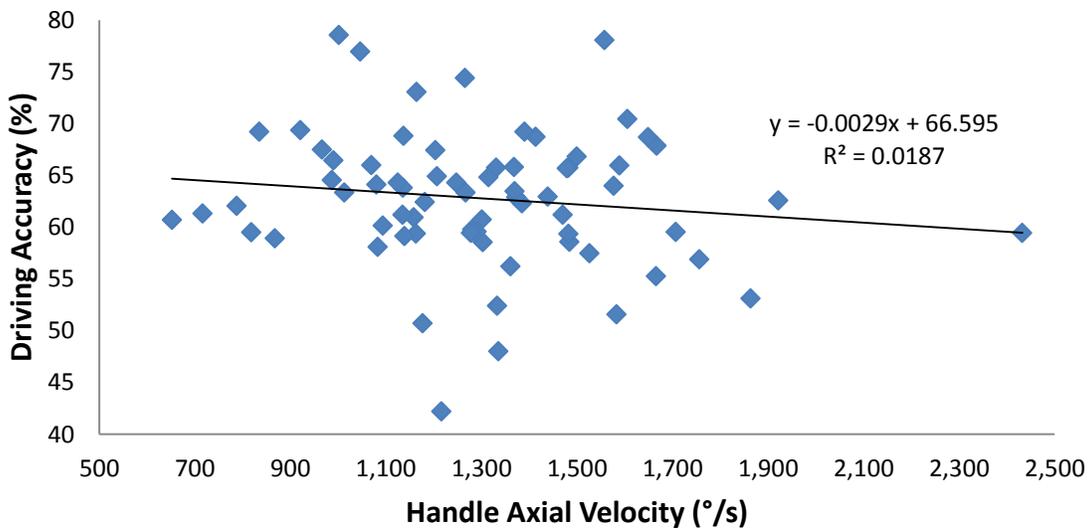


Figure 11. Scatter Plot of Driving Accuracy and HTV (n=70)

Single factor ANOVA tests between HTV and clubhead speed, and HTV and driving accuracy revealed no significant differences between the means of the groups for either variable. Results are shown in Table 5 with p -values given to three decimal places. Effect sizes using the “Cohen’s d ” method are also included.

Table 5. Single Factor ANOVA Results for Clubhead Speed and Driving Accuracy

Speed and Accuracy	Hi-HTV		Lo-HTV		Sig at			Cohen's d
	Mean	SD	Mean	SD	F[1,62]	p	p < .025	
Clubhead Speed m/s (n=94)	48.9	2.5	48.0	2.0	2.79	.100	No	0.42
Driving Accuracy % (n=70)	62.2	6.3	63.9	7.0	0.98	.320	No	0.26

Discussion

Of the 32 golfers in each of the accuracy analysis groups, 23 in each group had been PGA Tour event winners, that is, there were the same amount of winners in the Lo-HTV group as the Hi-HTV group. This supports the statement that golfers with either low or high HTV swing technique can be successful in competition at a world class level. Our interest for this study was to find out if either method produced a higher clubhead speed or better driving accuracy. To study these questions we hypothesized that world class golfers with high HTV at impact will have a higher clubhead speed, but less driving accuracy than golfers with low HTV at impact. The results of this research showed that these hypotheses were not supported in either case.

In regard to clubhead speed, the Hi-HTV group did have a higher mean clubhead speed at impact than the Lo-HTV group, 48.9 m/s versus 48.0 m/s (109 mph versus 107 mph) but it was not enough difference to reach significance. In addition, the effect size between the HTV groups for clubhead speed was 0.42 which is classified as small to medium. This also shows that the difference between means was not large and supports the ANOVA result that there is no significant difference between the means. These results were counter to our hypothesis that the hi-HTV group golfers would have a significantly higher clubhead speed at impact than the lo-HTV group. Nesbit (2005) called handle twist velocity, gamma velocity, and he found from his analysis that for a scratch golfer the gamma velocity generates approximately 1.5 m/s extra velocity of the clubhead mass center. We found an increase in the mean value of 0.9 m/s from the Lo-HTV group to the Hi-HTV group, but this was not a large enough difference to be significant.

In regard to driving accuracy, even though the Lo-HTV group did have a higher mean driving accuracy percentage than the Hi-HTV group, 63.9% versus 62.9%, it was not enough to reach statistical significance. The effect size was 0.26 which is classified as small. This adds to

support to the ANOVA results of no significant difference between the means. Both techniques achieved a similar driving accuracy. Our hypothesis that the hi-HTV golfers would have a less driving accuracy than the lo-HTV group proved to be unsupported by our data.

Our results are contrary to advice from Cochran and Stobbs (1968). They did create a two-dimensional model of the golf swing that modeled the release characteristics of the wrist, but it did not include either forearm rotation or club handle twist, so their advice on Pushers versus Rollers was based on logic and not mathematical or statistical proof. Suttie (2011) who based his ideas on those of Cochran and Stobbs came to the same conclusions as they did; Closed-Face golfers would be more accurate than Open-Face golfers, again though our data does not support this conclusion. Despite their ideas on which method would be more accurate and which would drive the ball further, both sets of instructors suggested that either method could be used successfully depending on the golfer's physical abilities.

Now we will review the outcome statistic that we used for driving accuracy. Driving accuracy is defined as the percentage of times a tee shot comes to rest in the fairway for each golfer during a PGA tournament and it is also known as fairways hit. Broadie (2014) statistician and columnist for Golf Magazine pointed out that this may be a flawed statistic. He says that it fails to distinguish drives that land in the first cut of rough from those that land in the water, both of these simply count as a missed fairway. A ball that is in the first cut of the rough is still almost as playable as a ball at the edge of the fairway, but the former would not be counted in the statistic, also either is certainly better than landing it in the water. He has proposed a new combined approach to take into account both driving distance and driving accuracy. His new approach will be adopted by the PGA Tour in the near future. It is called strokes gained driving. It will supersede the combination of driving distance and fairways hit as a measure of driving performance. He explains it as follows:

Suppose the average score for Tour pros on a given par 4 is 4.0. One player hits a long drive down the middle of the fairway to a position where the average to hole out is 2.8

strokes. The drive moved the pro 1.2 strokes closer to the hole. Since an average drive moves the player 1.0 stroke closer to the hole, this drive "gained" 0.2 strokes against his competition. Do this for all tee shots on par 4s and par 5s—not just on two holes—and calculate the results. The result is Strokes Gained Driving, which has properties that just make sense: Longer in the fairway is better than shorter in the fairway. Fairway is better than rough. Rough is better than hitting into the drink (p. 40).

He also points out that using this new method Bubba Watson, the current Master's Champion, has been either first or second for the last four years, whereas using total driving in those years he was never ranked better than 22nd. The point of this discussion is that perhaps if this new statistic were used to compare the golfers in our study maybe we would show a difference between the Lo-HTV and Hi-HTV groups. This is an idea for future research.

In addition to this discussion on our outcome measure of driving accuracy we could also look critically at clubhead speed as our outcome measure. From our deterministic model (Figure 1) we can see that clubhead velocity at impact affects ball velocity at launch which then directly affects ball displacement at landing. Is this relationship enough to make a difference if we were to correlate our high and low handle twist velocity groups to driving distance instead of clubhead speed? Even though we have found that there are no significant differences between the clubhead speeds of the Hi-HTV and Lo-HTV groups perhaps these other factors may make the ball go significantly further for one group or the other. We do not have statistics on ball launch characteristics as would be supplied from a ball launch monitor such as Trackman (Vedbaek, Denmark). Perhaps the low handle twist velocity golfers have better smash factors, which is a measure of quality of contact (Lynn, Frazier, Wu, Cheetham, & Noffal, 2013; Tuxen, 2008), or perhaps better ball spin rates and maybe this may allow their shots to be more accurate and travel farther. This is also an idea for future research.

Despite suggested improvements to our research, the result that there is no significant difference between either of the two methods of club handle manipulation is important information

to golf instructors. It means that they can teach either of the two methods with confidence in their results regarding clubhead speed and percent driving accuracy, and according to Cochran and Stobbs (1968) and Suttie (2011) there is nothing wrong with teaching either method. Cochran and Stobbs suggest that the golfer must discover by trial and error which method is best for them. Suttie states that the Closed-Face method is just as effective as the Open-Face method; it all depends who's using it. He also suggests that there should be a balance between accuracy and distance and that they are mutually exclusive. If you promote one excessively then you sacrifice the other to some degree. He does suggest however that you must be consistent in the motions that you combine for each method. This has important coaching implications also. One needs to understand the characteristics of each method and be consistent with these characteristics when teaching a particular method.

Cochran and Stobbs (1968) suggest that you must be stronger to use the Pusher method as it needs more body action to achieve the same clubhead speed as the Roller method that uses the arms more to create the speed. The Pusher method is the low HTV method and the Roller method is the high HTV method. Suttie (2011) suggests if you wish to use the Closed-Face method, the one with the low handle twist velocity, then you must limit the amount of forearm roll on the backswing and keep the club face from opening at the top. He suggests that the Closed-Face method is easier to time because of the low amount of handle twist, but suggests that you must be in top physical shape to swing this way because it demands more body action than hand and arm action. In fact with this action if you ever use the hands too much, that is, use too much arm roll on the downswing; you may hit a severe hook. With this method he recommends that you should have fast hips in the downswing; that you are flexible and capable of making a large shoulder turn in the backswing, and your swing feels more dynamic and powerful when you use your lower body. If you wish to use the Open-Face method, the one with the high handle twist velocity, then you must use your arms more and roll them in the backswing so the toe of the club points down to the ground at the top. He states you do not need to turn your body as much and so it requires less flexibility. He also notes that at impact you will be "on top of the ball with your upper body" (p. 100), meaning that your body will be less open to the target. In response to the

recommendations of these top instructors of the past and the present, we chose to further study the rolling action of the arms, that is, forearm supination-pronation velocities in the downswing. This was the focus of Study 2. We also researched the action of the pelvis and thorax, and specifically how open to the target and bent toward the ball each was at impact. This was the focus of Study 3.

CHAPTER 4

STUDY 2 - WRIST AND FOREARM ANGULAR VELOCITIES

Introduction

Study 1, showed that there was only a weak correlation between HTV and clubhead speed, as well as HTV and driving accuracy for the group of world class golfers analyzed. It also showed that there was no significant difference between the Hi-HTV and Lo-HTV groups for both of these variables. It concluded that both swing techniques using either high or low handle twist velocity produced similar results for both clubhead speed and driving accuracy. The question is now: What is the difference in forearm and wrist velocities between these two groups in order to attain one style or the other, and which is more important to the twist action of the handle? Because the forearm and wrist angles are changing rapidly during the downswing in relation to the position of the arm and the club shaft it is important to review which ones cause rotation and investigate each. These actions are the final link between the golfer and the club. It is thought that these actions will be different between the low and high HTV groups.

In the past, many three-dimensional motion analysis studies of golf have defined the wrist as having only a single degree of freedom (Chu, Sell, & Lephart, 2010; Fedorcik, Queen, Abbey, Moorman, & Ruch, 2012; McLaughlin & Best, 1994; Robinson, 1994; Zheng, Barrentine, Fleisig, & Andrews, 2008a, 2008b). They have assumed that wrist cocking-uncocking is the only motion occurring. This maybe historically based because most of the models of the golf swing in the past, dating back to Cochran and Stobbs (1968) have been two-dimensional. The wrist angle was defined by the angle between the junction of two vectors representing the lead arm and the club shaft. This definition of the wrist angle may also be due to convenience because all of the cited three-dimensional studies used optical motion analysis systems to capture their data, and measuring more than a single-degree-of-freedom of the lead wrist is difficult due to occlusion of markers on the hands and wrists. Typically even three-dimensional analysis systems have looked at the wrist angle in a similar way, that is, by calculating the angle between the lead

forearm and club shaft. The AMM3D system also has this calculation and calls it the lead wrist set angle. Figure 12 shows an illustration of how this angle is defined. It is the true angle between the lead forearm and the club shaft when viewed from a perpendicular perspective.

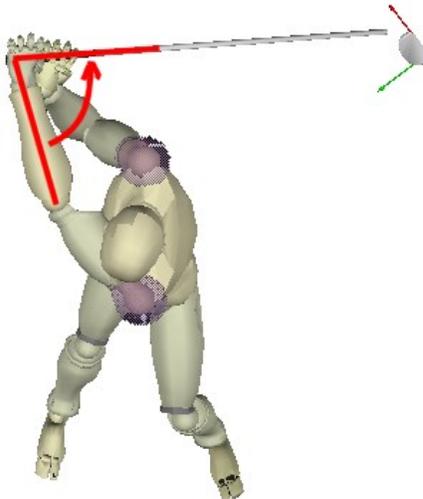


Figure 12. Definition of Lead Wrist Set Angle

In the following section Figure 13 through Figure 17 are graphs from the AMM3D system (“AMM 3D-Golf,” 2008). They show different forearm and wrist kinematics for the same professional golfer and swing from the database. They are used as examples to explain each topic under discussion.

Figure 13 shows a typical example of the lead wrist set angle throughout the swing of one of the best players in the world today. It can be seen that from the top of backswing to a substantial way down the wrist angle doesn't change, it remains fixed in the set position. Then just after the lead arm passes horizontal it releases very rapidly to impact. This is indicated in the graph by the curve rising very rapidly after the release point. The golfer's position in the diagram to the side corresponds to the release point. Although Penner (2003) suggests that this is the typical release profile of a professional golfer, from our experience measuring swings with the AMM3D system over the last several years, there are actually a few variations on this basic wrist release method; some golfers continue to decrease the wrist angle at the beginning of the

downswing, others maintain the angle and then decrease it rapidly just before release, and yet others release it in two stages slightly at first and then rapidly into impact.

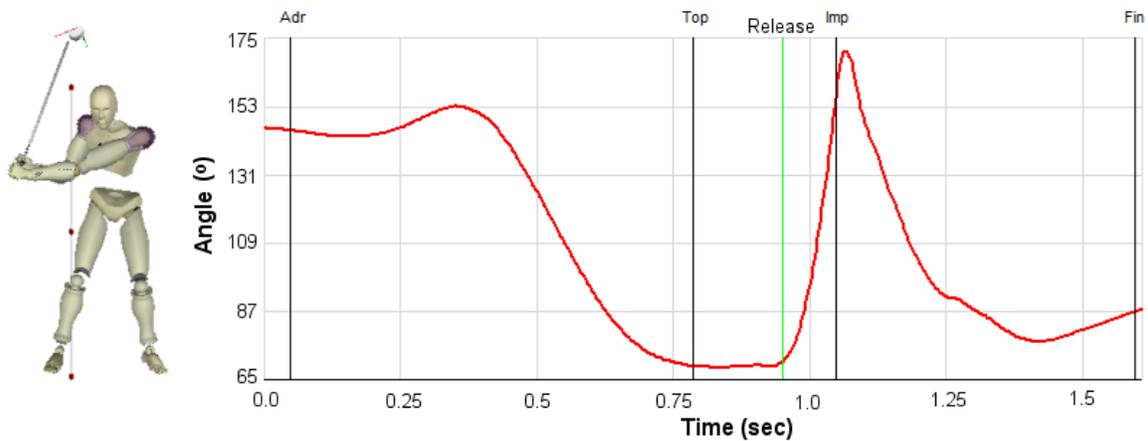


Figure 13: Lead Wrist Set Angle and the Golfer's Position at Release

Even though Figure 13 is very instructive in looking at the basics of the wrist release it is an oversimplification of what actually happens with the wrists during the downswing. Both left and right wrists go through a series of complex motions that are similar in general between all world class players but different in their subtleties. The wrist and forearm are able to rotate around three axes and so have three-degrees-of-freedom of angular motion, these are, wrist ulnar-radial deviation, wrist flexion-extension, and forearm supination-pronation. Each of these motions is crucial to the correct coordination of the release of the club during the downswing and in bringing the clubhead into correct alignment at impact. The AMM3D system measures all of these motions. Figure 14 shows the graph of lead wrist ulnar-radial deviation, flexion-extension, and forearm supination-pronation from the same swing as shown in Figure 13. Referring to Figure 14 we see at the top of backswing the lead wrist/forearm is radially deviated, extended, and pronated. This can be seen from the graph because all three curves are negative at the top and the first direction referred to in the legend is positive. During the downswing, flexion begins first, then a little extra pronation, followed by ulnar deviation, then supination, and finally just before impact the wrist begins to extend. At impact the lead wrist/forearm is ulnar deviated, flexed, and supinated. We see this from the graph in Figure 14 because all three curves are

positive at this point. Note that in Figure 13 up until release the wrist angle looks fixed, but reviewing the same section of the graph in Figure 14 we see that the wrist is moving from extension towards flexion (the green curve with triangles is going up) and the forearm is increasing the amount of pronation (the blue curve with squares is dropping down). Even though the wrist and forearm are moving around these two axes at this time, the combination of these actions still maintains a fixed angular relationship between the lead forearm and the club shaft.

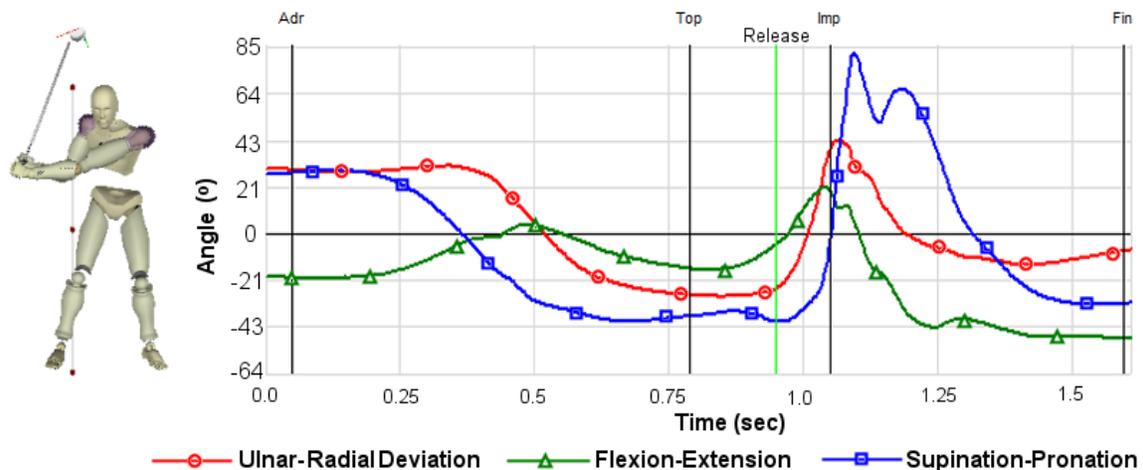


Figure 14. Lead Forearm and Wrist Angle Components and the Golfer's Position at Release

The wrist and forearm angular velocities are the rates of change of each of the different wrist and forearm angles. The angular velocities describe how fast each of the angles is changing and in what direction. The wrist set velocity, the angular rate of change of the club shaft with respect to the forearm, is displayed in Figure 15 with only the phase from top to impact shown for clarity. It is actually termed release velocity in the graph because the set angle has two directions, setting and releasing. Setting is when the angle decreases, as in the backswing, and releasing is when the angle increases, as in the downswing. The wrist velocity is near zero early in the downswing, and then increases rapidly as the wrist is released into impact. The release point shown in the graph corresponds to the golfer's position in the image on the left.

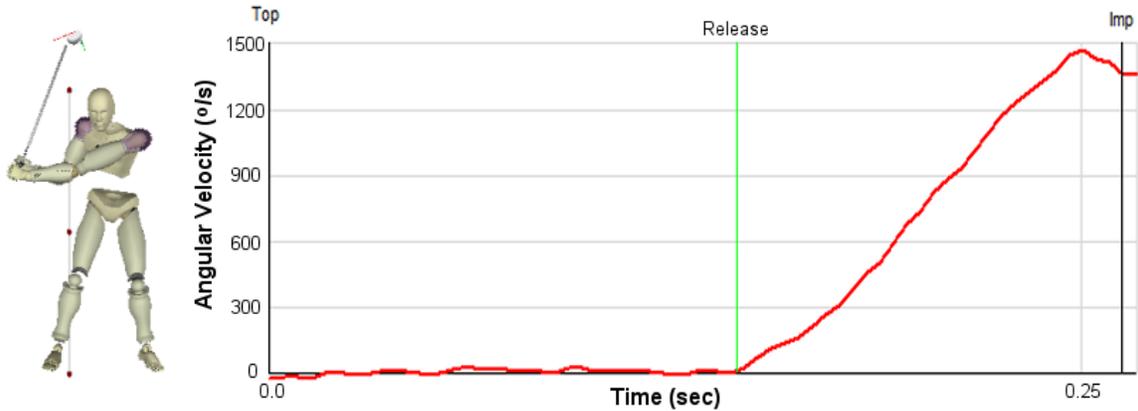


Figure 15. Lead Wrist Release Velocity in the Downswing

In Figure 16, we see the velocities of each of the lead wrist and forearm angles. Again the release point shown in the graph corresponds to the golfer's position in the image on the left. The legend has the positive direction as the first parameter. Note that the positive direction for flexion-extension is opposite in this graph to Figure 14. Key features of this graph are that ulnar deviation velocity peaks then decelerates just before impact, flexion-extension velocity is extending at impact (positive), and supination velocity is by far the fastest one of the three at impact. This is a typical example of the three lead wrist/forearm angular velocity components during the downswing for a professional golfer.

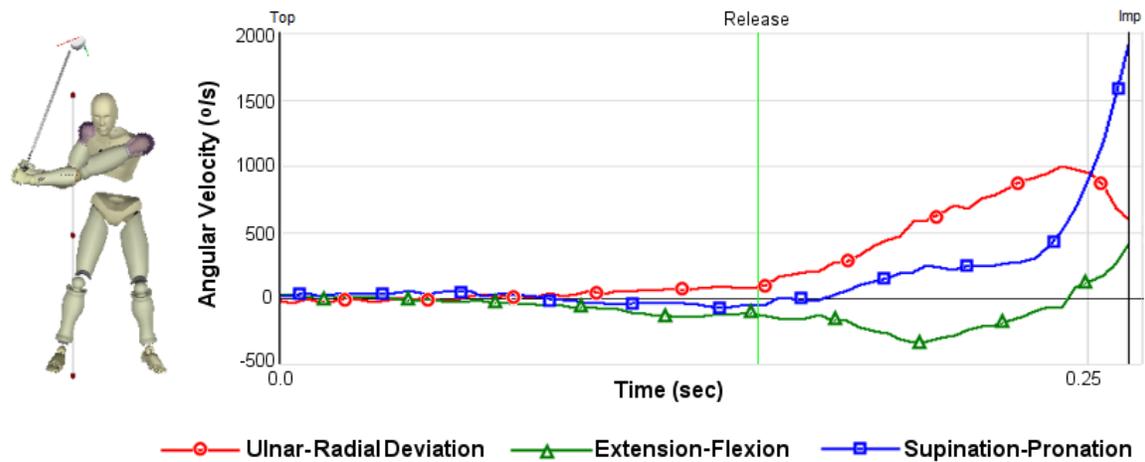


Figure 16. Lead Forearm and Wrist Release Angular Velocity Components in the Downswing

If we graph the handle twist velocity (Figure 17) for the same swing we can see how it relates to the lead wrist/forearm component velocities. In the figure, "O" represents opening and "C" represents closing. The golfer's position corresponds to the swing plane release point. At the swing plane release point we see that the handle twist velocity is actually opening, this is due to the slight pronation velocity that is occurring at this point as seen in Figure 16. Slightly later the handle twist velocity goes positive, this means that the club handle is now twisting rapidly in the closing direction, a point we term the twist release point. This is due to the occurrence of flexion and supination of the lead wrist/forearm that can be seen in Figure 16 at the same point in time.



Figure 17. Club Handle Twist Velocity during the Downswing and the Twist Release Point

From these graphs we have seen that the release of the club in the downswing is a complex combination of the three angular degrees-of-freedom of the lead wrist/forearm (and of course the trail wrist/forearm, although that was not examined here). These angles combine to produce the standard swing plane release that is commonly known as uncocking the wrists, as shown in Figure 13; the lead wrist set angle, and Figure 15; the lead wrist release velocity. We have also shown that there is another type of lesser known release and that is what we term twist release; it is shown in Figure 17. It is at this point that the club handle begins to twist rapidly in the closing direction, increasing the handle twist velocity, and aiding in aligning the club face to be square at impact.

In typical graphs of lead wrist/forearm velocities from the AMM3D system we have seen that generally the supination velocity is higher at impact than either ulnar deviation velocity or extension velocity and that at impact the lead arm is typically extended and close to in-line with the club shaft, from this evidence it is expected that supination velocity of the lead forearm will be a major contributor to club handle twist velocity at impact. It is therefore hypothesized that lead forearm supination velocity at impact will show a positive correlation with club handle twist velocity, and that the Hi-HTV group will have a significantly higher mean lead forearm supination velocity at impact than the Lo-HTV group.

Regarding wrist extension; from reviewing the wrist velocity graphs of many of the professional golfers in the TPI 3D professional database, we generally see that by impact, the lead wrist has finished flexing and has begun to extend into impact, but is not yet extended. It is extending but is still flexed at impact. Because the lead forearm is not completely in line with the shaft of the club at impact, lead wrist extension may also affect the rotation of the shaft. With this logic it is hypothesized that the Hi-HTV group will have a significantly higher lead wrist extension velocity at impact than the Lo-HTV group.

On reviewing lead wrist ulnar deviation velocity on the AMM3D system and from the TPI 3D professional database, at the moment of release the lead wrist set angle in elite golfers is generally less than 90° and the lead arm is approximately parallel to the ground. At this point ulnar deviation is the primary wrist motion that will cause the angle to open in the swing plane. As the wrist release continues and the lead arm begins to supinate (externally rotate), the contribution of ulnar deviation will convert into keeping the club on plane (MacKenzie & Sprigings, 2009a). That is to say, at impact radial deviation would just lift the club in front of the golfer but not swing or move it toward the target. From this logic, ulnar deviation velocity is not expected to substantially contribute to HTV during late downswing and at maximum. It is therefore hypothesized that there will be no significant difference of the mean maximum lead wrist ulnar deviation velocities in the downswing between the Hi-HTV and Lo-HTV groups.

The definition of the lead wrist set angle is the angle between the long axes of the lead forearm and the club handle. This is the angle that is typically analyzed in the two-dimensional pendulum models of the swing (see Study 1) and as such it is expected to have a large influence on the handle angular velocity in the swing plane, but it is not expected to affect the handle twist velocity during late downswing and at its maximum velocity. It is therefore hypothesized that there will be no significant difference of the mean maximum lead wrist release velocities between the Hi-HTV and Lo-HTV groups.

The trail elbow extension velocity may have an influence on the angular velocity of the club shaft in the swing plane but it is not expected to have an effect on handle twist velocity. It is therefore hypothesized that there will be no significant difference of the mean maximum trail elbow extension velocities between the Hi-HTV and Lo-HTV groups.

Methods

The methods of setup, capture, and calculation of the database were described in the general methods section. This section will now describe the biomechanical and statistical methods unique to this study; Study 2. Particular to this study, are the wrist/forearm angular velocities. During the digitizing process, using the AMM3D system, points are digitized on the forearms and hands to define local anatomically relevant coordinate systems in a method similar to Cappozzo, Catani, Della Croce, and Leardini (1995). This process creates a transformation matrix that converts sensor data from the global reference frame to each respective local anatomical reference frame. The assumption is made that the sensors do not move with respect to the body segments during the swing. Electromagnetic sensors have been successfully used in other studies to measure the wrist angle (Johnston, Bobich, & Santello, 2010). Once aligned, the system returns six-degrees-of-freedom data in real-time from each limb segment.

The AMM3D system calculates wrist/forearm angles using the Joint Coordinate System (JCS) method (Grood & Suntay, 1983). The wrist angles include flexion-extension, radial-ulnar deviation, and forearm supination-pronation (Figure 14). Wrist/forearm angular velocities are

found by calculating the angular velocity of the hand with respect to the forearm using standard biomechanical methods (Zatsiorsky, 1998). The lead wrist set angle (Figure 13) is the angle between the long axis of the lead forearm and the club handle, and its velocity is simply its derivative with respect to time. This is typically the angle looked at by instructors when discussing basic wrist set in the backswing and the wrist release in the downswing. It automatically combines all three anatomical wrist angles in to one easily viewable angle. It is a true angle and not a projected angle, which means it accurately represents the wrist release action during the downswing. In older terminology it is typically referred to as cocking and uncocking, the more modern term is setting and releasing the wrist hinge. It should be noted that capturing both lead and trail wrist/forearm anatomical angles and velocities during the golf swing is especially difficult for optical marker based motion capture systems because three markers are needed on each hand in order to compute all three rotation angles. Typically in the swing and due to the rapid rotation of the hands through the impact area the markers get hidden from the cameras or merge with one another and data is lost. This is not a problem with the Polhemus system as the human body is transparent to its electromagnetic field position and orientation data is never lost. It is believed that our database of world class touring professionals is unique at this time, especially by having all three wrist/forearm angle components for both arms.

The database of 94 world class PGA and European tour player swings was used for the research in this study, with the same statistical methods as outlined in the general methods section. One correlation was performed between HTV and lead forearm supination velocity at impact. Five single factor ANOVAs were performed between HTV and lead forearm supination velocity at impact, lead wrist extension velocity at impact, lead wrist ulnar deviation velocity at maximum, lead wrist release velocity at maximum and trail elbow extension velocity at maximum. In order to preserve an overall significance level of $p < .05$ in this study a Bonferroni corrected value of $p < .01$ was used for each of the five ANOVA comparisons made. Effect sizes were also computed using the “Cohen’s d” statistic (Cohen, 1988). This gives the difference between the compared means in multiples of the pooled standard deviations.

Results

Table 6 shows the correlation values and qualitative strength of correlation between HTV and lead forearm supination, plus the mean and standard deviation.

Table 6. Correlation Statistics for HTV with Lead Forearm Supination Velocity at Impact

Angular Velocity	Mean (°/s)	SD (°/s)	<i>r</i>	<i>r</i> ²	Strength
Lead Forearm Supination (Imp)	1569	338	.68	.46	Moderate

A scatter plot of the lead forearm supination velocity graphed against handle twist velocity is shown in Figure 18, we see a moderate positive correlation ($r = .68$), so as handle twist velocity increases so does lead forearm supination velocity.

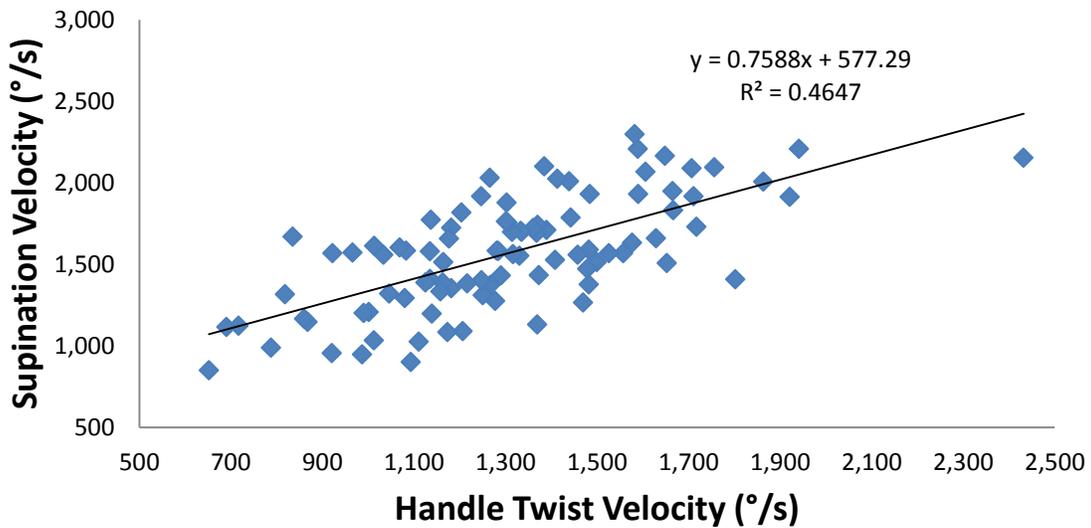


Figure 18. Scatter Plot of Lead Forearm Supination Velocity against Handle Twist Velocity

Single factor ANOVA tests between HTV and each angular velocity variable revealed that there was a significant difference between HTV and lead forearm supination velocity at impact, but not for the other four velocities tested. Results are shown in Table 7 with *p*-values given to three decimal places. Effect sizes using the “Cohen’s *d*” method are also included.

Table 7. Single Factor ANOVA Results for Forearm, Wrist and Elbow Angular Velocities

Angular Velocities	Hi-HTV (°/s)		Lo-HTV (°/s)		F[1,62]	p	Sig at p < .01	Cohen's d
	Mean	SD	Mean	SD				
Lead Forearm Sup. (Imp)	1811	286	1295	256	58.1	.000	Yes	1.90
Lead Wrist Extn. (Imp)	433	195	446	228	0.1	.813	No	0.06
Lead Wrist Ulnar Dev. (Max)	922	126	859	180	2.6	.109	No	0.40
Lead Wrist Release (Max)	1249	138	1186	180	2.5	.119	No	0.39
Trail Elbow Extn. (Max)	931	190	851	156	3.4	.070	No	0.46

Discussion

Table 6 supports our hypothesis that that lead forearm supination velocity at impact would show a positive correlation with club handle twist velocity, ($r = .68$). Our hypothesis that the Hi-HTV group will have a significantly higher mean lead forearm supination velocity than the Lo-HTV group is supported by the data in Table 7. The mean velocity for the Hi-HTV group was 1811°/s and 1295°/s for the Lo-HTV group. The mean for the Hi-HTV group is 40% faster than that of the Lo-HTV group. The effect size was 1.90 which is very large, further supporting the significant difference found between the high and low HTV groups with the ANOVA test. This is the first study to investigate this relationship in world class touring professionals.

The Golfing Machine by Kelley (1982) recognizes this lead arm roll action as the third power accumulator, and MacKenzie and Sprigings (2009a) have modeled lead arm axial rotation in their three-dimensional dynamic model of the golf swing. They cite this axial rotation of both the lead arm and forearm as the primary mechanism for bringing the club face square to the target line at impact. The lead arm supination concept is also in agreement with both Cochran and Stobbs (1968) and Suttie (2011). They both state there are different types of arm roll actions and subsequent club handle twist actions in the downswing; Rollers and Pushers as named by Cochran and Stobbs and Open-Face and Closed-Face golfers as described by Suttie. Our results clearly support the notion that lead forearm supination velocity is strongly related to handle twist velocity.

Our hypothesis that the Hi-HTV group will have a significantly higher lead wrist extension velocity than the Lo-HTV group was not supported by our data (Table 7). A small effect size of 0.06 further supports the lack of difference between the means of the high and low HTV groups. The Hi-HTV group had a mean lead wrist extension velocity of 433 °/s and the Lo-HTV groups value was 446 °/s. The interesting results here are that these velocities were very similar to each other for each group and were substantially lower than the supination velocities. Also they were positive, meaning that the lead wrist was extending at impact. This action was very consistent within our database of golfers, as 92 of the 94 had positive lead wrist extension velocities at impact. This is the case because lead wrist flexion-extension velocity changed from flexing to extending just milliseconds before impact in these golfers, but it is important to note however, that at impact the lead wrist had a mean value of 2° of flexion for the entire group.

Our hypothesis for lead wrist ulnar deviation velocity at maximum stated that there would be no significant difference between the low and high handle twist velocity groups. Although it is seen from Table 7 that the mean of the maximum ulnar deviation velocity for the Hi-HTV group (922°/s) was higher than that of the Lo-HTV group (859°/s), it was not enough to be significantly different. A small to medium effect size of 0.40 further supports the lack of a large difference between the means of the high and low HTV groups. Our hypothesis was supported.

Our hypothesis for lead wrist release velocity at maximum stated also that there would be no significant difference between the low and high handle twist velocity groups, and again, although it is seen from Table 7 that the mean of the maximum release velocities for the Hi-HTV group (1249°/s) was higher than that of the Lo-HTV group (1186°/s), this was not enough to be significantly different. A small to medium effect size of 0.39 further supports the lack of a large difference between the means of the high and low HTV groups. Our hypothesis was supported.

Trail elbow extension is the pushing or extending action of the trail elbow against the back of the club handle and its action will help in the release action of the club. It was expected that this action would primarily affect the motion of the club in the swing plane and not in the

handle twist direction. An increase in velocity here could be either due to the golfer actively extending the trail elbow, or as a result of the centrifugal force of the club shaft pulling on the golfer's arm and extending it. Without an investigation of the pressure between the palm of the hand and the grip of the club this cannot be determined. However, this kinematic parameter was still of interest as it does demonstrate the action of the trail elbow, whether active or passive. Our hypothesis was that there would be no significant difference in the mean trail elbow extension velocities between the Hi-HTV and Lo-HTV groups at maximum. A non-significant ANOVA result of $p = .07$ and a small to medium effect size of 0.46 further supported the lack of a large difference between the means of the high and low HTV groups. Our data supported our hypothesis suggesting that trail elbow extension velocity is not a differentiating factor in producing handle twist velocity during the downswing.

In summary, of the forearm, wrist and elbow velocities that were investigated, only lead forearm supination velocity showed a significant difference between the high and low HTV groups. This is considered important because several researchers have suggested that rolling the lead arm will help square the club face at impact (MacKenzie & Sprigings, 2009a; Nesbit, 2005) and we have shown that how fast one rolls the lead arm directly affects how fast the handle of the club will twist the club face into impact. This makes intuitive sense because if the lead arm is in line with the club shaft and it twists, then so will the club shaft. Supporting this concept further we see that the angle between the lead forearm and the club shaft at impact has a mean value of 161° for the golfers in this study. This is only 19° away from a straight line. Even though the other angular velocities investigated did not show significant differences between groups, it was still of interest to see that the lead wrist was extending at impact in the majority of the golfers in the database, but was still flexed by a mean value of 2° . Many instructors believe that the lead wrist should be in flexion and flexing at impact, we found that the lead wrist is typically in flexion but extending at impact. Our result will be surprising to many. The results of this study have implications to teaching professionals because they clarify which wrist/forearm actions affect club handle twist velocity and subsequently affect club face closing speed at impact.

CHAPTER 5

STUDY 3 - PELVIS AND THORAX ANGLES

Introduction

We have established that two techniques of swinging the club into impact involve how fast the club handle is twisting during the downswing, either it is twisting slowly (Lo-HTV) or it is twisting quickly (Hi-HTV). Certainly there is a continuum of handle twist velocities but we are reviewing the differences between those at the high and low ends of the continuum. We have shown that there is no significant difference in clubhead speed and driving accuracy between the low and high handle twist velocity groups, so either of these two techniques can be used successfully at the world class level. We have also shown the Hi-HTV group has significantly higher mean forearm supination velocity at impact than the Lo-HTV group. Now in this study we will explore the body posture at impact for these two styles of downswing; specifically the pelvis and thorax side bend and rotation angles. Our basic question is: Are these angles different at impact for each of these two techniques and if so how?

Cochran and Stobbs (1968) dedicate a chapter of their book, "Search for the Perfect Swing" to different types of club axial twist action in the backswing and downswing. They call the golfers that use the different handle twisting actions; Squares, Rollers, and Pushers. The Rollers twist the handle of the club more, so that at the top of backswing the clubface is open to the swing plane. Pushers only twist the club handle a small amount and so the clubface is closed to the swing plane at the top of backswing. They state that the Rollers will use their arms more in the downswing than the Pushers, whereas the Pushers will use their body more in the downswing than the Rollers. Suttie (2011) also discusses differences between methods of clubface control during the swing. He groups the methods into three categories, Square-Face, Open-Face or Closed-Face, which he adapted from Cochran and Stobbs. His Open-Face technique corresponds to the Rollers, and the Closed-Face technique corresponds to the Pushers. Open-Face technique golfers have the club face open at the top of backswing and so have to close it

rapidly in the downswing because they have a large twist angle to rotate the handle through to get the face square at impact. This corresponds to the high HTV technique in our study. The Closed-Face method golfers have the clubface closed at the top of backswing and so do not have to close the face rapidly in the downswing because they have a small twist angle to rotate the handle through to get the face square at impact. This corresponds to the low HTV technique in our study. The Square-Face method has a club face angle at top which is intermediate between the Open-Face or Closed-Face methods. Suttie also outlines the swing characteristics that these different golfers will need to perform in order to complete the different techniques successfully. He states that the Open-Face golfers must have slow to medium hips, suggesting that their hips won't be very open to the target at impact. In contrast the Closed-Face golfers must use their bodies more because their hands are not as dominant when compared with the Open-Face golfers. This, he states, means that their body will be more open to the target at impact. Now if the golfer's body is more open at impact it also may follow that the body will be more side bent towards the ball. This will aid the golfer in reaching the ball and making solid contact. On the other hand the golfer whose body is not as open at impact will not need to side bend as much to make good contact. Adapting the concepts of these authors to our research, it follows that the Lo-HTV group will be more open to the target and more side bent to the trail side at impact than the Hi-HTV group. Consequently it is hypothesized that there will be a negative correlation between HTV and pelvis rotation, thorax rotation, pelvis side bend and thorax side bend. The negative direction means that as the handle twist velocity decreases the pelvis and thorax rotation at impact will increase, so too will the amount of side bend to the trail side. To further strengthen the evidence that this relationship exists we will use single factor ANOVAs to determine if the means of these two groups are different and we hypothesize that the Lo-HTV group will be significantly more rotated toward the target and more side bent to the trail side at impact with both the thorax and pelvis.

Methods

The methods of setup, capture, and calculation for the database of 94 tour professionals were described in the general methods section. This section will now describe the biomechanical and statistical methods unique to this study; Study 3. The AMM3D system creates local coordinate systems in both the pelvis and thorax as explained in the general methods section. The thorax is the upper torso as measured by a single six-degree-of-freedom sensor attached dorsal to T4 using a harness. The pelvis is the lower torso as measured by a single six-degree-of-freedom sensor attached dorsal to the sacrum with a belt. Both the thorax and pelvis are digitized in the setup procedure before the swing capture session. The assumption is made that the sensors do not move with respect to the body segments during the swing. For the thorax, the left and right acromioclavicular (AC) joints are digitized and the line between them defines the direction of one local axis. A ruler is then placed on the mid-axillary line of the thorax, and two points are digitized on the edge of the ruler to define this line. The direction of this line is used in a cross-product calculation with the first line to create a normal vector to this plane. A second cross-product is then calculated between the normal vector and the vector from AC joint to AC joint. This creates the direction vectors for a local coordinate system based in the thorax with origin midway between the AC joints. For the pelvis, a superior point on the left and right greater trochanter is digitized. A ruler is placed on the left lateral side of the pelvis to estimate anterior tilt. It is placed next to the digitized point on the trochanter and aligned to be parallel with a visualized line from the left PSIS to the pubic symphysis (Burch, 2002). A point several inches above the trochanter point on this ruler is then digitized. In a similar manner to the thorax, these three points are used to create an anatomical coordinate system in the pelvis centered midway between the left and right greater trochanters. One axis is between the trochanters and the other is parallel to the anterior tilt angle of the pelvis, the third is perpendicular to both of these. Thorax and pelvis rotation is calculated using the Joint Coordinate System method (Grood & Suntay, 1983). The global coordinate system is used as the proximal segment and the body segment as the distal segment. This is a novel approach and has the unique property for the distal segment's rotation calculation of it not being affected by the bend action of the segment. This is in contrast

to projecting the angle onto the floor plane, which is compromised by any bending action. Rotation is measured in degrees with respect to the target, with open being turned toward the target as in the follow through, and closed being turned away from the target as in the backswing. Side bend is measured in degrees with respect to the horizontal with trail being to the right side for a right hander and lead being to the left side for a right hander. The terms trail and lead are considered to be more appropriate than left and right because they remain consistent with both left and right handed golfers.

The database of 94 world class PGA and European tour player swings was used for the research in this study, with the same statistical methods as outlined in the general methods section. Four correlations and four single factor ANOVAs were performed between HTV and thorax rotation, thorax side bend, pelvis rotation and pelvis side bend. In order to preserve an overall significance level of $p < .05$ in this study a Bonferroni corrected value of $p < .0125$ was used for each of the four ANOVA comparisons made. Effect sizes were also computed using the “Cohen’s d” statistic (Cohen, 1988). This gives the difference between the compared means in multiples of the pooled standard deviations.

Results

Table 8 shows the results of the correlations between HTV and each variable, plus each mean and standard deviation. There was a moderate negative correlation between both thorax rotation and side bend with HTV, and a weak negative correlation between pelvis rotation and side bend with HTV, supporting our hypothesis.

Table 8. Correlation Statistics for Pelvis and Thorax Angles

	Mean (°)	SD (°)	<i>r</i>	<i>r</i>²	Strength
Thorax Rotation (Open)	27	9	-.40	.16	Moderate
Thorax Side Bend (Trail)	31	5	-.50	.25	Moderate
Pelvis Rotation (Open)	41	9	-.36	.13	Weak
Pelvis Side Bend (Trail)	9	4	-.28	.08	Weak

Figure 19 through Figure 22 show the scatter plots for all four relationships.

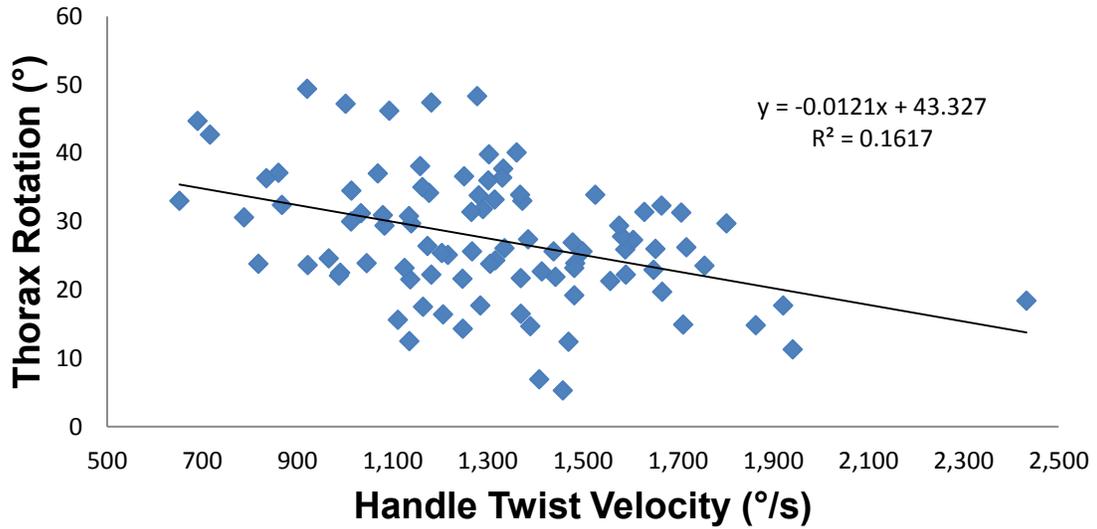


Figure 19. Scatter Plot of Thorax Rotation against Handle Twist Velocity at Impact

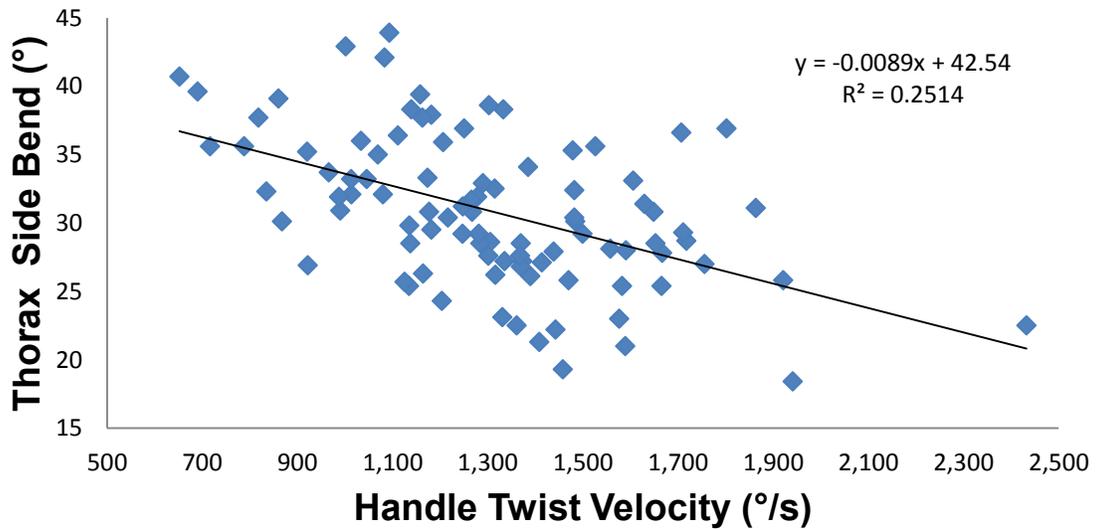


Figure 20. Scatter Plot of Thorax Side Bend against Handle Twist Velocity at Impact

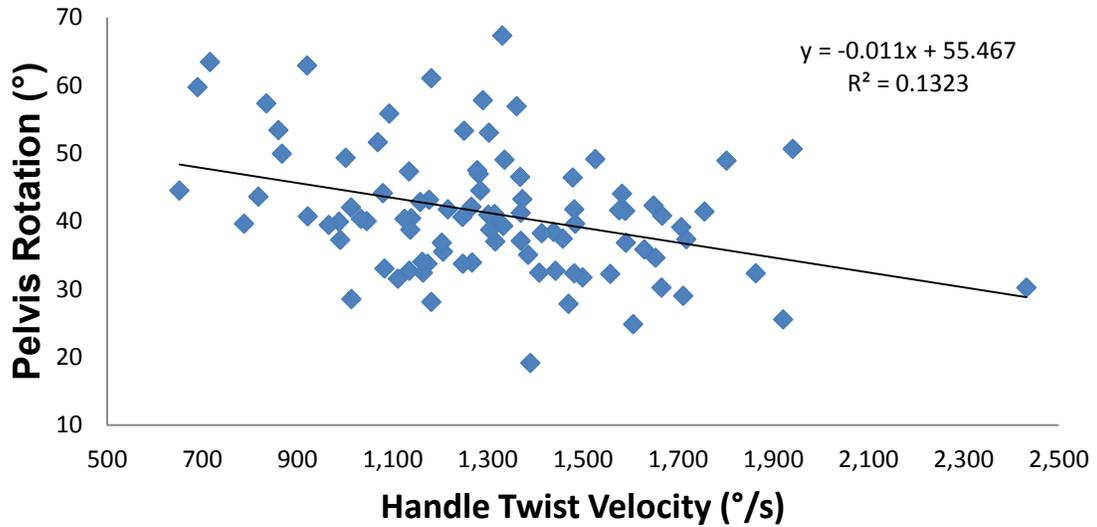


Figure 21. Scatter Plot of Pelvis Rotation against Handle Twist Velocity at Impact

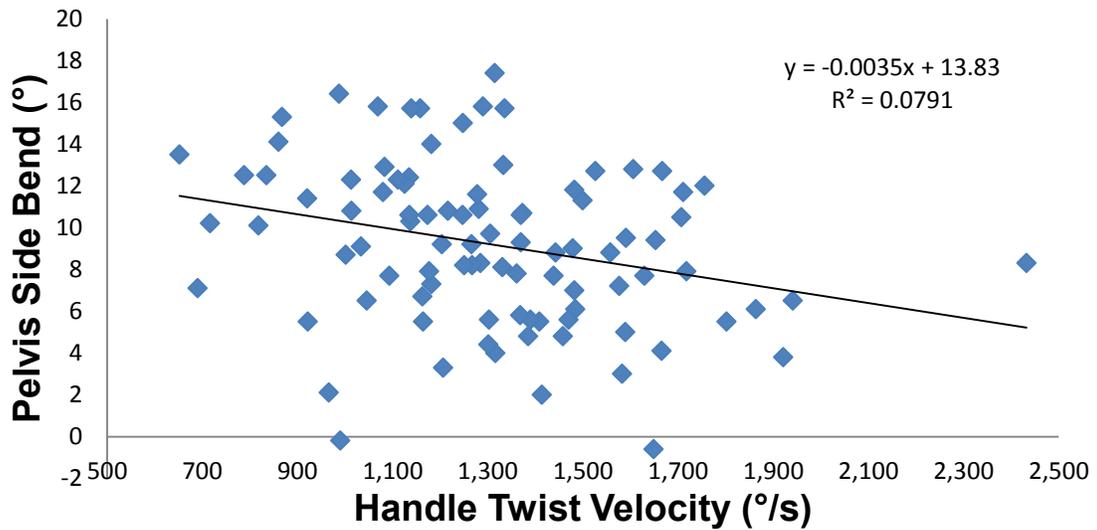


Figure 22. Scatter Plot of Pelvis Rotation against Handle Twist Velocity at Impact

Single factor ANOVA test results are shown in Table 9. They show that there was a significant difference between the means of the high and low HTV groups for all the variables tested. Effect sizes using the “Cohen’s d” method are also included in the results.

Table 9. Single Factor ANOVA Results for Pelvis and Thorax Angles at Impact

Pelvis and Thorax Angles at Impact	Hi-HTV (°)		Lo-HTV (°)		Sig at			Cohen's d
	Mean	SD	Mean	SD	F[1,62]	p	p < .0125	
Thorax Rotation (Open)	23	7	31	9	15.9	.000	Yes	0.99
Pelvis Rotation (Open)	37	6	43	7	9.7	.003	Yes	0.92
Thorax Side Bend (Trail)	28	5	34	5	27.1	.000	Yes	1.20
Pelvis Side Bend (Trail)	8	3	11	4	10.2	.002	Yes	0.85

Discussion

The mean values at impact for rotation were found to be positive, which means that the segments were rotated open to the target (Table 9). Reviewing the pelvis and thorax rotations we see that the Hi-HTV group had a mean thorax rotation value at impact of 23° while the Lo-HTV group was 31°; for pelvis rotation the values were 37° and 43°, respectively. The Lo-HTV group was significantly more open at impact than the Hi-HTV group, supporting our hypothesis. Notice also that the pelvis was more open than the thorax. Figure 23 shows a golfer from each group at the impact position from three different views, the Lo-HTV golfer being on top and the Hi-HTV golfer on the bottom. The effect size for the thorax was 0.99 and for the pelvis it was 0.92; large in each case. With a difference in the means of approximately one standard deviation, one should be able to see the differences visually. Focusing on just the rotational aspects of the body in Figure 23, one can in fact see the differences from these pictures; the Lo-HTV golfer is facing the target more (i.e. more open) than the Hi-HTV golfer.

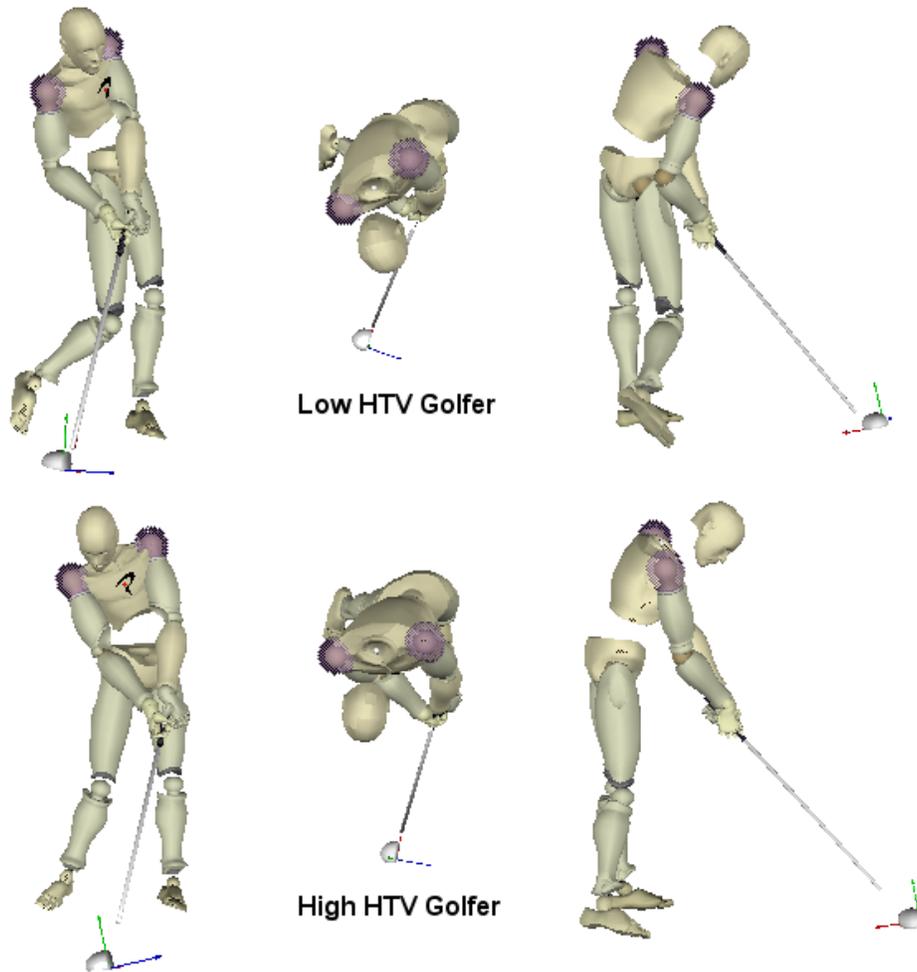


Figure 23. Low and High Handle Twist Velocity Golfers shown at Impact

These results corroborate the conclusions of Cochran and Stobbs (1968), that the Roller (high HTV golfer) uses the arms more during the downswing. A consequence of this, they suggest, is that the body is less open at impact. This was supported by our data. The low HTV golfer, in contrast, is equivalent to the Pusher, who they say uses the body more during the downswing. A consequence of this, they say, is that they are more open at impact; again our data support this conclusion. With regard to the work of Suttie (2011), his Open-Face method corresponds to the Hi-HTV group and he suggests that they will use an arm-driven swing because they need to twist the club more during the downswing and there will be an active closing of the club face through impact. This results in a slow to medium hip speed, meaning that

the body won't be as open at impact when compared to the Closed-Face group (Lo-HTV group). In contrast, the Closed-Face group does not need to twist the club handle as much to square the club face at impact and he says they will have fast hips and as a result will arrive at impact more open to the target. This conclusion was also supported by our data.

Reviewing the research literature we find that no one has done comparisons between different techniques within world class PGA tour players other than our study. McTeigue, Lamb, Mottram, & Pirozzolo (1994) did compare PGA, Senior PGA, and amateurs directly. They used an instrumented spatial link system attached via a belt on the hips and a harness on the chest. This method allowed them to measure the pelvis and thorax separately and not treat the torso as one rigid segment as is often done by instructors using qualitative video analysis. Typically when teaching professionals measure the spine angle they simply draw a line from the shoulders to the hips and then down the thigh to the knee. They treat the abdomen area and the thorax as one solid segment; however the pelvis and the thorax can bend, tilt, and twist independently because they are connected by a flexible spine. The AMM3D technology allows one to measure these as three separate angles for both the pelvis and thorax; rotation, bend and side bend, thus giving more detailed and realistic information during the swing.

Myers et al. (2008) used 3D analysis to analyze 100 amateur golfers of varying skill levels. They divided the golfers into three categories based on their ball speed; low, medium, and high, and then reviewed pelvis and thorax angles and motion to find relationships to driving performance. Ball speed was the performance measure. They concluded that X-Factor, both at top and at maximum contribute to increased thorax rotation velocity during the downswing, which ultimately contributes to increased ball velocity. In their descriptive statistics are some relevant results and comparison values for our study. Table 10 summarizes these values. Horan, Evans, Morris, and Kavanagh (2010) profiled the 3D kinematics of the thorax and pelvis during the downswing to determine if differences exist between male and female skilled golfers. They found that females were more open with the both pelvis and thorax, but less side bent while having the same forward bend at impact. Table 10 summarizes their results for rotation. So while being

more open than the men, the women were more upright at impact. From Table 10 it can be seen in all the represented studies that the pelvis is more rotated toward the target at impact than the thorax, and certainly more open than at the address position, which would be close to 0°. This dispels an instructional myth that the pelvis and thorax at impact should have similar rotation values as at address.

Table 10. Pelvis and Thorax Rotation Values at Impact from Several Studies

Rotation Angle	Type	Pelvis (°)	Thorax (°)	Skill Level
Cheetham	Hi-HTV	37	23	Tour Pro
	Lo-HTV	43	31	Tour Pro
McTeigue et al.	PGA Male	32	26	Tour Pro
	PGA Senior	34	28	Senior Pro
	Amateur	35	27	Amateur
Myers et al.	Hi Vel	38	25	Amateur
	Med Vel	35	23	Amateur
	Lo Vel	29	20	Amateur
Horan et al.	Male	44	26	Skilled
	Female	50	29	Skilled

In examining the pelvis and thorax side bend we find that the Hi-HTV group had a mean thorax side bend toward the trail side at impact of 28° while the Lo-HTV group was 34° and for pelvis side bend, the values were 8° and 11°, respectively. The Lo-HTV group was significantly more side bent to the trail side at impact than the Hi-HTV group, supporting our hypothesis. Regarding these differences in pelvis and thorax side bend angles, it follows from the corresponding rotation values, that if the chest is very open at impact then the lead arm will be more across the chest and the trail arm will be more behind the club, with the trail elbow more flexed, positioning the shoulders at a steeper side bend angle toward the ball. In contrast golfers with high HTV would be less open on average, that is, more square to the ball with the arms more extended away from the body at impact and so would not have the same need to side bend as much to contact the ball. The effect size for the thorax was 1.20 and for the pelvis it was 0.85; large in each case. With a difference in the means of approximately one standard deviation, one

should be able to see the differences in side bend visually, and this is the case as seen in Figure 23. The low HTV golfer has observably more right side bend of both the pelvis and thorax than the high HTV. Of the research already cited, only Horan et al. (2010) had comparative values for pelvis and thorax side bend at impact. The females had a mean pelvis side bend toward the trail side at impact of 6° while the males was 11°, and for the thorax side bend, the values were 33° and 38°, respectively. These results show that the females were more upright than the males, whereas in our study the Hi-HTV group was more upright, with respect to side bend, than the Lo-HTV group.

Of interest is the point that just measuring the body angles at impact of a group of similarly skilled golfers and creating a database from these data does not mean you have a homogeneous group, at least not for rotations and side bends. These values may be significantly different at impact for different swing techniques, in this case, the twist velocity of the handle at impact. The practical application of discovering differences in the torso angles at impact between the Hi-HTV group and the Lo-HTV group is in the area of coaching. Our results give the golf instructor information with which to be more specific when coaching golfers with differing handle twist techniques. The golf instructor can now be aware that a swing with a low HTV will tend to be more open to the target and more side bent toward the ball at impact. The instructor should not attempt to bring this golfer into a more square position at impact, and vice-versa for the golfer with a high HTV swing. This would evidently counter the natural tendencies of each technique. Our data support the recommendations of both Cochran and Stobbs (1968) and Suttie (2011) in this matter.

The AMM3D system used to capture the swings in this research can also supply the user with a report and data tables that include these critical variables that allow the instructor to monitor the golfers progress. Handle twist velocity, pelvis, thorax, and spine angles, plus forearm, elbow and wrist angles, are all available immediately after the swing for the instructor to review. This allows the instructor to track the golfer's progress and synchronize the wrist/forearm and club twist velocity with the appropriate body angles at impact. Audio tones and audible

biofeedback can also be used to demonstrate to the golfer where the correct positions are in a simulated impact position. The results of this study will provide a template for instructors to follow in order to emulate the techniques of the best golfers in the world and teach those techniques to their own golfers.

CHAPTER 6

GENERAL CONCLUSION

This dissertation focused on discovering the similarities and differences between world class golfers with very different club handle twist velocities at impact. The general feeling from the coaching literature is that excessive rolling of the forearms during the downswing, high handle twist velocity and consequently high clubhead rate of closure at impact will increase clubhead speed and hence distance, but in contrast, will also reduce accuracy. Despite these feelings, it is also thought that in the correct hands and for the appropriate golfer either technique is effective and neither could be considered wrong. With these opinions in mind we designed three studies to investigate handle twist velocity, one reviewed its influence on clubhead speed and driving accuracy, the next discovered its relationship to wrist and forearm angular velocities and the final one ascertained its relationship to body angles at impact.

In Study 1 we looked at the relationship of handle twist velocity to clubhead speed and driving accuracy. For driving accuracy we used the percent driving accuracy statistics from www.pgatour.com for each of the golfers in our study (n=70). All of them were USA PGA tour players at some time in their careers, with 51 of them having won at least one tour event. We performed two different statistical measures, correlation and analysis of variance (ANOVA). Pearson product-moment correlation was used to see if there was a correlation between handle twist velocity and both clubhead speed and driving accuracy. A very weak negative correlation was found. To investigate if this very weak result was meaningful we used ANOVA to see if there were differences between golfers with either high or low handle twist velocities. We divided our databases of golfers into two groups of 32. One group with high handle twist velocities, the Hi-HTV group, and the other with low handle twist velocities, the Lo-HTV group. For both accuracy and clubhead speed at impact we found that there was no significant difference between the group means between the Hi-HTV and Lo-HTV groups. These results are contrary to popular belief among many instructors. The coaching implication of this study is that either high or low

handle twist velocity can produce an effective swing, provided that wrist/forearm actions and body movements are consistent with the chosen technique.

Study 2 investigated the correlation between lead forearm supination velocity and handle twist velocity. A moderate correlation of $r = .68$ was found. This suggests that both supination velocity and handle twist velocity increase in a corresponding manner. A subsequent single factor ANOVA found the Hi-HTV group to have a significantly higher lead forearm supination velocity at impact than the Lo-HTV group, supporting the concept that this forearm roll and forearm supination action is a major contributor to the handle twist velocity. Lead forearm supination velocities ranged from 851 $^{\circ}/s$ to 2299 $^{\circ}/s$, with the Lo-HTV group having a mean of 1295 $^{\circ}/s$ and the Hi-HTV group having a mean of 1811 $^{\circ}/s$. From these data we saw that the Hi-HTV group had a 40% higher forearm supination velocity than the Lo-HTV group. Also studied were lead wrist extension velocity at impact, maximum downswing lead wrist ulnar deviation velocity, maximum downswing lead wrist release velocity and maximum downswing trail elbow extension velocity. It was found that lead wrist extension velocity at impact was not significantly different between groups and so did not have a major effect on handle twist velocity. It may perhaps affect the shafts angular velocity in the swing plane, but this is left for a future study. The means of the groups were very close; 433 $^{\circ}/s$ for the Hi-HTV group and 446 $^{\circ}/s$ for the Lo-HTV group. Of extra interest was that of the 94 golfers in the database, 92 had a positive lead wrist extension velocity at impact. This means that the overwhelming majority of golfers from both groups were in the process of extending their lead wrist, even though it may have been still slightly flexed at impact. Lead wrist ulnar deviation velocity, lead wrist release velocity, and trail elbow extension velocity all analyzed at their maximum value in the downswing showed no significant difference between both high and low handle twist velocity groups, suggesting that they did not play a part in increasing or decreasing the handle twist rate.

Study 3 researched the relationship between the handle twist velocity and body posture, specifically pelvis and thorax angles at impact. The angles reviewed were rotation; how turned toward the target these body segments were, and side bend; how tilted to the trail side these

segments were. Correlations were performed for these four parameters; thorax rotation, thorax side bend, pelvis rotation, and pelvis side bend. Thorax rotation had a moderate negative correlation of $r = -.40$, meaning that for higher handle twist velocities thorax rotation was less open to the target at impact. Thorax side bend was found to have a moderate negative correlation of $r = -.50$, meaning that as handle twist velocity increased thorax side bend decreased. Both pelvis rotation and side bend had a weak negative correlation of $r = -.36$ and $r = -.28$, respectively, suggesting the same relationship as for the thorax, but to a lesser extent. Next, the same parameters were investigated using ANOVA to verify that the high and low handle twist velocity groups had differing means for each of these variables. That proved to be the case for each variable. In summary, the data suggested that golfers with lower handle twist velocities would tend to be more open and more side bent toward the ball with both the thorax and pelvis at impact. This has definite coaching implications, suggesting that handle twist rates and body angles at impact should remain consistent. Mixing handle twist methods and with non-appropriate postures may be counter indicated.

Areas of importance for future studies that were not investigated include the type of grip used, the differences between a strong and a weak grip and which would best correspond to differing handle twist velocities. An in depth look at all wrist/forearm angles and their relationships at top of backswing and at impact would also be important, plus their relationship to the kinematic sequence of the pelvis, thorax, arm, and shaft (Cheetham et al., 2008). Of particular interest to health care providers may be the relationship of these two techniques to the propensity for back injury. Does the fact that the Lo-HTV group golfers have larger pelvis and thorax side bend angles at impact put them at higher risk for injury, and does this increase the crunch factor in the spine during the downswing? Crunch factor is the product of maximum spine rotation velocity and maximum spine side bend during the swing and is thought to be a risk factor for injury (Cole & Grimshaw, 2009; Gluck, Bendo, & Spivak, 2008; McHardy & Pollard, 2005; Morgan, Cook, Banks, Sugaya, & Moriya, 1999; Sugaya, Tsuchiya, Moriya, Morgan, & Banks, 1999). With respect to clubhead and ball contact parameters at impact, we did not look at them in depth, but perhaps there is a significant difference between high and low handle twist velocity

in relation to smash factor. Smash factor is the ratio of ball speed at launch to club head speed at impact and is a measure of the quality of contact (Tuxen, 2008). Maybe those with slower handle twist velocity have a better smash factor and so in fact may have higher ball launch velocity. This is unknown from our data and should be investigated separately.

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APPENDIX A

A DETERMINISTIC MODEL OF THE FULL SWING IN GOLF

To get a complete picture of the theoretical relationships between the various mechanical factors in the golf swing that contribute directly to driving performance we have developed a deterministic model of the golf swing as shown in Figure 24.

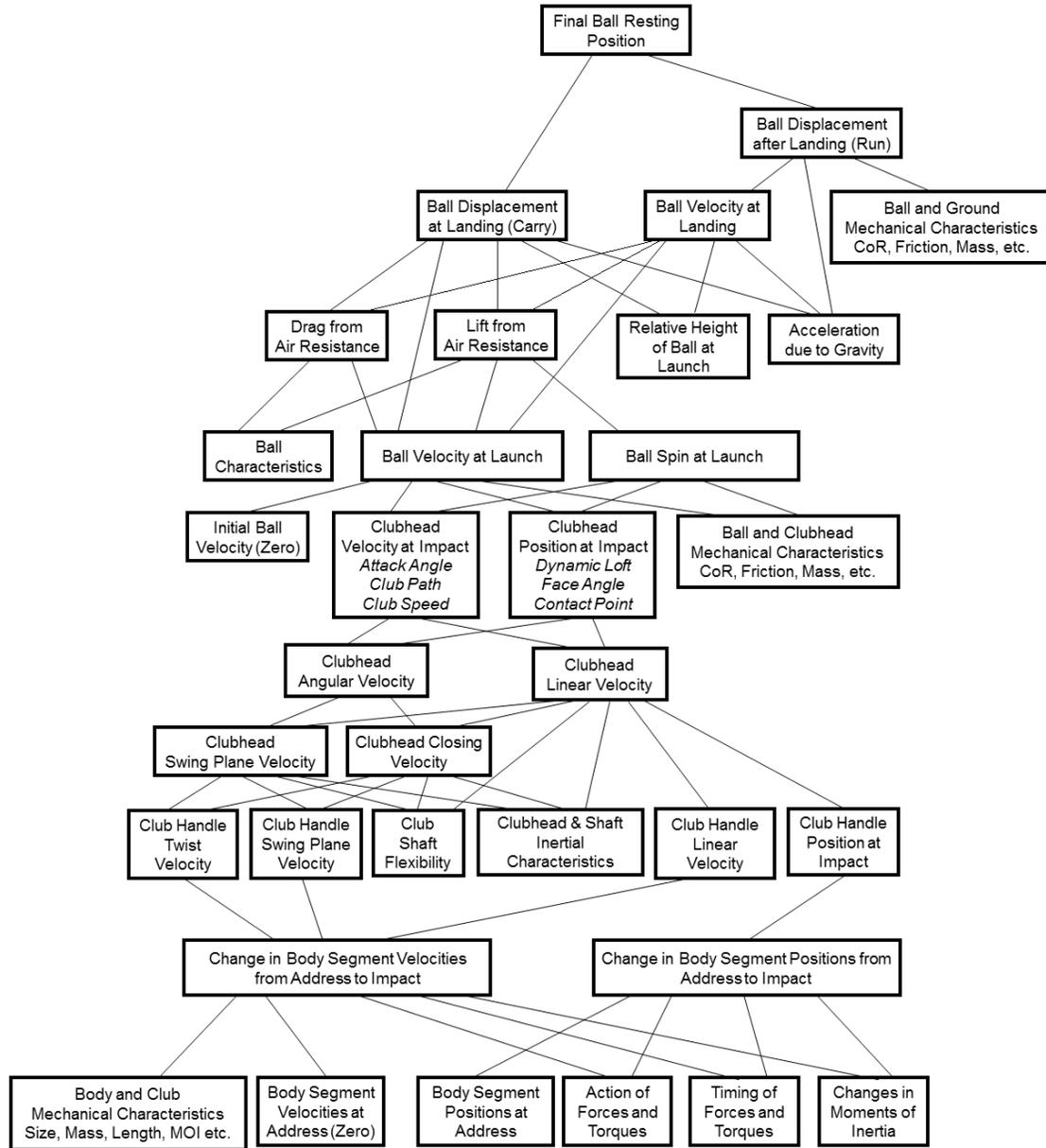


Figure 24. Deterministic Model of the Golf Swing with a Driver

This process was developed by Dr. James Hay (Hay & Reid, 1988). The deterministic model method uses a top-down, block-style, flow chart to completely map out the mechanical parameters that determine the result of the performance of a motor skill. The mechanical parameters are shown as factors and sub-factors in the diagram (Figure 24).

The goal of the full swing is to propel the ball as far as possible in the required direction. The required outcome is the most advantageous final ball resting position. This becomes the top block of the model. Having defined the key factor we now break it into its two constituent factors, ball carry and run. Carry is the displacement of the ball from the tee off position to its initial landing point. Run is the displacement of the ball from its initial landing position to its final resting position, which probably includes several bounces and some rolling. Run's determining factors include; the velocity of the ball at landing, the coefficient of restitution of the ball and the ground at landing and each bounce, the mass of the ball, friction between the ball and the ground, and acceleration due to gravity because the ball may bounce. Carry is determined by several factors including; the acceleration of gravity on the ball during flight, the relative height of ball launch from tee off position to landing position, air resistance on the ball during flight, and the velocity of the ball at launch. Velocity includes both the ball's speed and direction. Launch is the moment the ball leaves the clubface. Air resistance against the ball can be divided into both drag and lift components. These two components are both affected by ball characteristics such as size and shape, but also it can be shown that drag on the ball is governed by the equation:

$$D = \frac{1}{2}C_dA\rho v^2$$

The major factor is v^2 which is the square of the velocity of the ball at launch. The other factors are C_d the coefficient of drag, ρ the density of the air, and A the cross-sectional area. All of which are not in control of the golfer. Lift is governed mainly by spin and the Magnus effect. On one side of the spinning ball air is moving faster than the other. The difference in air speed from one side to the other causes a pressure differential and hence lift is created and the ball deviates from its normal trajectory. Because the ball is a sphere it has no other inherent lift capability other

than that created by spin. Spin is the result of the tangential component of the velocity vector of the club head during impact, the position or angle of the club head at impact and friction between the ball and the clubface. The velocity of the ball at launch is dependent on the impact dynamics of the club with the ball. It has been found that in the golf drive, at the moment of impact, the club head acts as if it were not attached to the shaft, which means that the conservation of momentum equations apply between the ball and the club head (Cochran & Stobbs, 1968). These factors include; effective mass of the club, mass of the ball, friction between the club face and the ball, coefficient of restitution between the club head and the ball, and the initial velocity of the ball, which is zero. In addition, probably the two most important factors influencing the velocity of the ball at launch are clubhead velocity at impact, that is, how fast and in what direction the clubhead is moving as it hits the ball, and clubhead position at impact with the ball, that is, how close the ball is to the sweet spot (center of percussion) of the club face at contact. Club head velocity at impact is made of two components, angular velocity and linear velocity. The angular velocity of the clubhead has in turn two major components; its angular velocity in the swing plane and its closing velocity, that is, the angular velocity about a local vertical axis through the center of gravity of the head. One may argue that there is another angular velocity component called pitch, that is the angular velocity perpendicular to the swing plane, but especially in the impact zone, the motion of the clubhead is mostly planar so this component is minimal and not in the direction of the required ball flight anyway. The linear velocity of the clubhead is directly affected by the club handle position at impact, club handle linear velocity, club handle angular velocities, and clubhead-shaft inertial characteristics.

Clubhead closing velocity is dependent on two main components; club handle twist velocity and club handle swing plane velocity. Figure 25 shows the relationship.

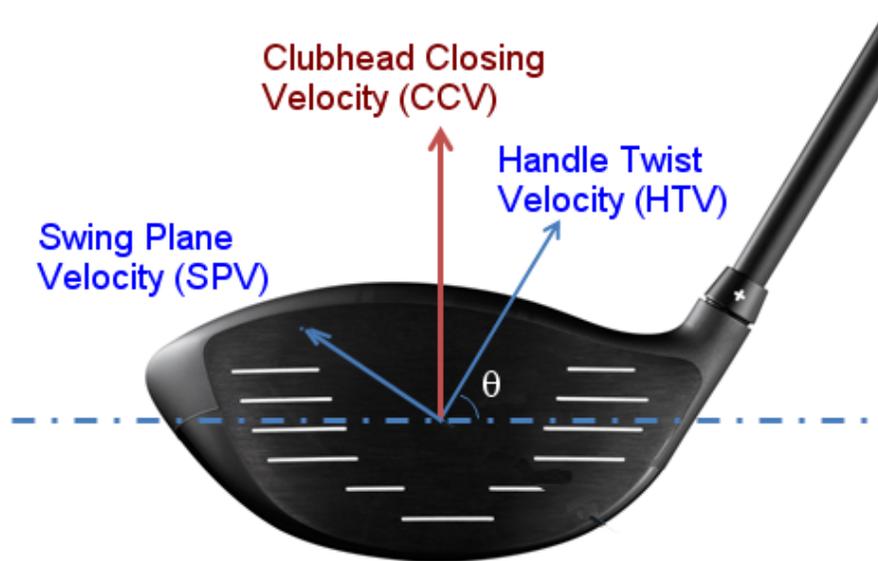


Figure 25. Relationship between Swing Plane, Handle Twist and Clubhead Closing Velocities

For a club with a lie angle of θ , this is a vector relationship governed by the equation:

$$CCV = HTV \sin (\theta) + SPV \cos (\theta)$$

From Figure 25 (E. Henrikson, personal communication, May 22, 2014) we can see that if the shaft was completely upright the clubhead closing velocity would be entirely from handle twist velocity; this would be similar to putting. If the shaft was completely horizontal then the clubhead closing velocity would be completely from the club handle swing plane velocity; this would be similar to baseball batting. Because the golf swing is on an oblique plane, handle twist velocity and swing plane velocity combine to create the resulting clubhead closing velocity. Two more factors that may contribute to the clubhead closing velocity are club shaft flexibility and the inertial characteristics of both the shaft and clubhead.

From this level down the motion of the golfer's body comes into the model. Here we see change in body segment velocities and positions from address to impact. These two are very important components of the swing. They take into account all the changes in velocity and

position of the golfer's body segments during the entire swing, starting from zero velocity at address to maximum clubhead velocity at impact. Changes in velocity are governed by the impulse momentum equation. Because the golf swing has both rotational and linear motions we must consider both the linear and rotational versions of this equation. The linear version of the principle is: $\Delta v = (F t) / m$ where Δv is the change in velocity from address to impact, F is created by the forces acting at the floor, at the joints, and finally on the club head, t is the time these forces act and m is the mass of each body segment taken in sequence, and finally the mass of the clubhead. The rotational version is: $\Delta H = Mt$ where ΔH is change in angular momentum, which equals moment of inertia multiplied by angular velocity: $H = I\omega$. Both I and ω change during the swing. Which moment of inertia and angular velocity apply at any specific instant depends on which segment is acting and which we are analyzing. Because the golf swing is a complicated action of the interrelated motions of a series of linked segments with many degrees-of-freedom, the actual equations of motion become very complicated very quickly (Putnam, 1993). The impulse momentum equations explained apply in turn to each of the body segments as the motion is generated and transferred from the legs, to the pelvis, the thorax, the arms, and finally the club. For the purpose of our model we will apply these equations in general overall terms. Taking both these equations into consideration we find that change in club handle velocity during the swing is caused by forces and torques exerted at the joints and at the floor, by the timing of the action of the forces and torques, and by the changes in the moments of inertia of the body resulting from the rearrangement of the segment and club positions during the swing. Additionally the mechanical characteristics of the club and the mechanical characteristics of the body segments come into account in affecting the change in club head velocity during the swing. Such characteristics as the club head mass and its distribution in the head, shaft mass, length, and center of gravity location are important, as is the shaft flexibility. These are characteristics that every golfer is familiar with and has control over when being fitted for new clubs. There is however not much one can do about the mechanical characteristics of one's body in the short term. One could exercise and change them over time, but not instantly during the swing.

APPENDIX B

LITERATURE REVIEW

In golf, the swing off the tee with the driver holds a special place of importance. It is the club that hits the ball the furthest. There have been many studies that have looked at how to improve driving performance, and specifically, increasing distance. Several studies have shown that the biggest factor to increasing driving distance is clubhead speed (Fletcher & Hartwell, 2004; Sprigings & Neal, 2000). Appendix A describes a deterministic model (Hay & Reid, 1988) of the golf swing. This shows the relationship between the factors that determine driving performance. There is a strong correlation between clubhead speed and driving distance. Fletcher and Hartwell showed a correlation of 0.86 between these two parameters. Sprigings and Neal stated that the speed of the clubhead at impact is the biggest single factor in determining the distance that the ball will travel. This implies that it is important to understand how to make the clubhead achieve maximum velocity at impact. What are the key factors to increasing clubhead speed? There have been two main approaches to answering this question in the research literature, the mathematical model using forward dynamics principles (Budney & Bellow, 1979; Campbell & Reid, 1985; Cochran & Stobbs, 1968; Jorgensen, 1999; Lamps, 1975; MacKenzie & Sprigings, 2009a; Milne & Davis, 1992; Nesbit, 2007; Pickering & Vickers, 1999; Sprigings & Neal, 2000; Sprigings & MacKenzie, 2002; Williams, 1967) and the experimental approach using three-dimensional motion analysis principals and statistical analysis of actual swings (Cheetham et al., 2008; Chu et al., 2010; McLaughlin & Best, 1994; Myers et al., 2008; Nesbit & McGinnis, 2009; Robinson, 1994; Zheng et al., 2008a, 2008b).

Dillman and Lange (1994) in their review article suggested that cocking and uncocking the wrists in the downswing correctly had been found to largely determine the clubhead speed and that uncocking too early decreases clubhead speed. Robinson (1994) used a linear regression model on data from a three-dimensional analysis study of professional golfer swings and found that keeping the angle between the arm and the club until well into the downswing was the most significant swing characteristic in increasing clubhead speed. Zheng et al. (2008a) looked at 3D kinematics of male professional and amateur golfers and found that wrist release speeds were significantly higher in the professionals than the mid and high handicap amateurs and that the time of maximum wrist release velocity for the professionals was later in the downswing. Zheng et al. (2008) in a similar study looked at the 3D kinematics of male

and female professional golfers and found that male golfers had significantly higher wrist release velocities at impact than the females.

Two-dimensional forward dynamic models came to similar conclusions that delayed wrist release is important to clubhead speed. Cochran and Stobbs (1968) made one of the first two-dimensional double pendulum models of the swing. They described the differences between a free hinge and a power hinge model, and suggested that using a late power hinge would create a greater maximum speed at impact than the free hinge release technique. Pickering and Vickers (1999) used their two dimensional double pendulum model to investigate the effect of positioning the ball to allow for maximum contact speed with the club. In addition they also found from their model that the late hit or delayed release of the club resulted in a higher resultant clubhead speed. Sprigings and Neal (2000) created a two-dimensional model with three segments. Their interesting finding was that an active wrist torque to forcefully uncock the wrists in the later stage of the downswing just prior to impact could increase the clubhead speed up to 9%. Penner (2003) in his review of two-dimensional swing models found that an expert golfer normally maintains a fixed wrist cock beyond the natural release point and that this delay will allow the club to swing out much more rapidly than a natural release, due to larger centrifugal forces. Sprigings modified the model that he had done earlier with Neal, in order to add more realistic muscle torque generators (Sprigings & MacKenzie, 2002). They considered this model more realistic and again found that assistive delayed active wrist torque was advantageous to increasing clubhead speed at impact. White (2006) used a two segment two-dimensional model with both free and driven pendulum calculations and concluded that the wrist cock angle in the downswing is the most significant efficiency determining parameter under the golfer's control. There are many more pendulum models and for a complete list and more in depth review one should read Betzler, Monk, Wallace, Otto, and Shan (2008).

It is interesting to see that overwhelming evidence, from the above mentioned research, shows that it is a delayed wrist release that increases clubhead speed the most. However, the assumption that the golf swing is planar and even that it can be accurately modeled in two-dimensions has been challenged (Coleman & Rankin, 2005; Kwon et al., 2012; Neal & Wilson, 1982; Nesbit, 2005; Vaughan, 1981). Coleman and Rankin showed that the left arm and shoulder do not move in a consistent plane

during the downswing and that the clubhead also does not move in a planar fashion. They concluded that planar models are not adequate and that three-dimensional models should be used. Kwon et al. captured the motion of 14 skilled golfers and performed three-dimensional kinematic analysis to assess the planarity of the swing and in particular to determine the functional swing plane of the clubhead and the motion planes of the shoulder-arm points. They defined the functional swing plane as the plane formed by the clubhead near impact. They concluded that skilled golfers exhibit well-defined functional swing planes and shoulder-arm motion planes but the shoulder and arm points move on different planes which are different from the functional swing plane of the clubhead.

Recently the models have become more complex and three-dimensional. Nesbit (2007) published a comprehensive three-dimensional full body mathematical model of the human for use in analyzing the biomechanics of the golf swing, which they had been working on for many years previous. This model was commissioned by the United States Golf Association and has been used successfully in kinematic and kinetic studies (Nesbit, 2005), plus work and power analysis (Nesbit & Serrano, 2005), as well as other tasks. The kinematic-kinetic study highlighted the importance of the wrists in generating clubhead velocity and orienting the club face at impact. In his studies he modeled the club three-dimensionally and called its angular three-degrees-of-freedom, alpha, beta, and gamma. The alpha component is the swing angular motion, the beta motion is the pitch angle of the club in and out of the swing plane, and the gamma motion is the twist motion of the shaft around its long axis. He used motion captured data of 84 males and one female of various skill levels to validate the model and help calculate the mechanical parameters. He found that the alpha torque should be positive up to impact to achieve maximum clubhead velocity and that delaying initiation of this motion aids in generation of club speed, validating the active delayed wrist action concept. Important to our study though, he shows the first evidence of the handle twist action into impact. He states that the most important function of the gamma motion (handle twist) is to square up the club face for impact. He also notes, however, that this handle twist action contributes to clubhead velocity, quoting in one example that it added 1.5 m/s to clubhead linear velocity. Suzuki et al. (2009) also added the ability of their model to twist around the long axis of the shaft to accommodate lead forearm supination. They analyzed the relationship of shaft elasticity to the release characteristics of the golfer. They found that the natural release of the club at the zero-

crossing point of the bending vibration of the shaft, the point when the shaft returns to the straight position in the downswing, could help increase speed at impact. They also found that late hitting could be achieved by increasing the shoulder acceleration torque in the downswing and that this would further improve the efficiency of the swing motion. MacKenzie and Sprigings (2009) developed a three-dimensional forward dynamics model that was capable of representing the four primary motions of the upper body in the downswing; torso rotation, shoulder horizontal abduction, wrist ulnar deviation, and lead forearm longitudinal rotation. They found from their model that the external rotator torque of the lead arm was the final muscle torque generator to be active and it remained active at least until impact. The importance of these three-dimensional models to our research is that they include the influence of lead arm long axis rotation and hence include the effects of handle twist velocity on clubhead speed and its influence on squaring the clubface at impact. It is these works that have solidified the notion of investigating the handle twist velocities of world class players for our study.

It has been mentioned that there have been many three-dimensional motion analysis studies that have treated the lead wrist as a simple single angle. This technique calculates the wrist angle as the angle between the long axis of the forearm and club shaft (Chu et al., 2010; McLaughlin & Best, 1994; Zheng et al., 2008a, 2008b), others have calculated both flexion-extension and radial-ulnar deviation but neglected pronation-supination (Fedorcik et al., 2012). The reason that all three wrist/forearm angle components have not been studied in depth to date, is because it is very difficult for an optical motion analysis system to capture all angular degrees-of-freedom of the wrist and forearm. The three components include flexion-extension, radial-ulnar deviation, and pronation-supination. Optical motion analysis systems track attached reflective markers and the markers on the hands and wrists generally become hidden around the impact position. Other technologies have been recently employed to solve this problem, Teu et al. (2006) used goniometers as well as optical markers to get all three angles of the wrist and forearm. The wrist release action in the downswing is much more complex than just a simple angle from shaft to forearm. It includes a sophisticated combination of the motions of all three angular degrees-of-freedom. The TPI Golf Biomechanics Level 2 Manual (Rose & Cheetham, 2006) briefly discusses this complex motion. In our study we used the Polhemus Liberty electromagnetic system to capture data and this allows us to capture all degrees-of-freedom of the wrist/forearm because the body

is transparent to this particular technology and sensor data is never lost. As a result, our study is the first to report on the angles and angular velocities of all three-degrees-of-freedom of the wrist/forearm and their relationship to club handle twist velocity.

Although only a few studies have looked at the lead forearm rotation and club shaft long axis rotation during the downswing, it is an extremely important action and is necessary to square the club face at impact. If there is too much handle twist at impact the face will be closed and the ball may go left. If there is too little handle twist at impact, the face will be open and the ball may go right. This long axis shaft rotation or handle twist action has been referred to in coaching circles by instructors for many years even though they have had no specific research to support their ideas. Cochran and Stobbs (1968) dedicated an entire chapter to it in their landmark publication "Search for the Perfect Swing", called "Wrist Actions: Squares and Rollers". They noted that the amount of shaft long axis rotation can vary significantly from player to player. They categorized golfers into three categories based on this amount of handle twist; large twist is called a Roller, medium amount of twist is a Square and small amount of twist is called a Pusher. They stated that Rollers twist the club through a large angle and so would have a fast handle twist velocity, whereas Pushers only need to close the face through a small angle and so would have a low handle twist velocity. Rollers correspond to the Hi-HTV group in our research and Pushers to the Lo-HTV group. They also surmise that Rollers may have trouble with accuracy and consistency whereas Pushers may have a better chance at squaring the club at impact. They comment that Rollers use their arms more and Pushers have more of a body driven swing. They believe that Rollers may have a more powerful swing based on the mechanical advantage of a screwdriver type action on twisting the club, in conclusion though they believe that there is nothing wrong with either one of these methods and that both techniques can be used successfully. Suttie (2011) expanded on the Cochran and Stobbs concepts in his article "The Fine Art of Clubface Control". He categorizes golfers as Open-Face, Square-Face or Closed-Face golfers. These categories correspond to Rollers, Squares or Pushers in Cochran and Stobbs terminology. According to Suttie, golfers who use the Open-Face method will have the club face open at the top of backswing, which means the toe of the club will be pointing down at the ground. During the downswing they will have to twist the handle rapidly to square the club face at impact because there is a large twist angle to rotate the handle through; these golfers form the Hi-HTV group in our

terminology. Suttie also says they will need to have a hand driven swing and a slow to medium hips; meaning that he thinks their hips will not be very open at impact. On the other hand, a Closed-Face technique golfer, will have the club face pointing to the sky at the top of backswing and so will not have as large an angle to twist the handle through during the downswing, therefore they will not need as high of a handle twist velocity to square the club at impact. This group will match our Lo-HTV group. He says they will need to use their bodies more to generate speed and so will be more open with their hips at impact.

Table 11 summarizes the relationship between the terminologies from the methods discussed.

Table 11. Arm Rolling and Shaft Twisting Terminologies of Different Investigators

Cochran & Stobbs	Suttie	Cheetham
Rollers	Open	High Handle Twist Velocity (hi-HTV)
Squares	Square	
Pushers	Closed	Low Handle Twist Velocity (lo-HTV)

Kelley (1982) in his popular book, “The Golfing Machine”, defines four Power Accumulators (PA) as methods of accumulating and producing power during the swing. PA1 is the bending and straightening of the trail arm. PA2 is the cocking and uncocking of the left wrist. PA3 is the roll of the lead forearm and club shaft into impact. PA4 is the swing of the lead arm across the chest. All of the pendulum models that have been discussed apply to PA2 and PA4. Lead forearm roll and handle twist velocity, the main focus of our research, correspond to PA3.

In the research in Study 3 we investigated the body posture at impact, specifically the pelvis and thorax rotations and side bends. Unfortunately there is no agreed standard for measuring body angles. Many researchers use projected angles onto the floor for rotational measurements (Burden, Grimshaw, & Wallace, 1998; Meister et al., 2011; Myers et al., 2008; Zheng et al., 2008a, 2008b) and others use variations of Euler angle calculations (Horan et al., 2010; McTeigue et al., 1994; Nesbit, 2005; Teu et al., 2006) to measure segment and joint angles. Another popular method of measuring joint angles in human motion analysis is the Joint Coordinate System method (Cole, Nigg, Ronsky, & Yeadon, 1993; Grood & Suntay, 1983). There is a definite problem with using projected angles as is pointed out by Anderson (2007). He notes that generally in the golf swing segment motions do not coincide with the plane of the

floor and so changes in the computed rotation angles will occur due to changes in side bend and forward bend, and hence there will be errors in the results. Euler angles and Joint Coordinate System angles produce more accurate results as they are true three-dimensional orientation angles and do not suffer from planar projection errors. The key is to choose the most accurate angle calculation while remaining clinically relevant and intuitive to the reader. An angle is only truly accurate if it is measured around its axis of rotation, and viewed from a perpendicular perspective, if this axis moves then so must the point of view for the measurement. For a more complete discussion of the angles used in this dissertation refer to the appropriate methods sections.

Regarding studies that have reviewed body posture during the swing we find that no one has done comparisons between different techniques within world class PGA tour players other than our current study. McTeigue, Lamb, Mottram, and Pirozzolo (1994) did compare PGA, Senior PGA, and amateurs directly. They used an instrumented spatial link system attached via a belt on the hips and a harness on the chest. This method allowed them to measure the pelvis and thorax separately and not treat the torso as one rigid segment. Myers et al. (2008) used 3D analysis to analyze 100 amateur golfers of varying skill levels. They divided the golfers into three categories based on their ball speed; low, medium, and high, and then reviewed pelvis and thorax angles and motion to find relationships to driving performance. Ball speed was the performance measure. They concluded that X-Factor, both at top and at maximum contribute to increased thorax rotation velocity during the downswing, which ultimately contributes to increased ball velocity. Horan, Evans, Morris, and Kavanagh (2010) profiled the 3D kinematics of the thorax and pelvis during the downswing to determine if differences exist between male and female skilled golfers. They found that females were more open with the both pelvis and thorax, but less side bent while having the same forward bend at impact. So while being more open than the men, the women were more upright at impact. From Table 10 it can be seen in all the referenced studies that the pelvis is more rotated toward the target at impact than the thorax, and certainly more open than at the address position, which would be close to 0°. This dispels an instructional myth that the pelvis and thorax at impact should have similar rotation values as at address.