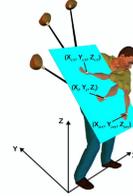Routledge
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Club position relative to the golfer's swing plane meaningfully affects swing dynamics

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Abstract
Previous research indicates that the motion of the golf club is not planar and that the plane traced out by the club is different than that of the golfer's hands. The aim of the present study was to investigate how the position of the club, relative to the golfer's swing plane, influences the motion of the club by using a four-segment (torso, upper arm, forearm, and club), three-dimensional forward dynamics model. A genetic algorithm optimized the coordination of the model's four muscular torque generators to produce the best golf swings possible under six different conditions. The series of simulations were designed to demonstrate the effect of positioning the club above, and below, the golfer's swing plane as well as the effect of changing the steepness of the golfer's swing plane. The simulation results suggest that positioning the club below the golfer's swing plane, early in the downswing, will facilitate the squaring of the clubface for impact, while positioning the club above the plane will have the opposite effect. It was also demonstrated that changing the steepness of the golfer's swing plane by 10° can have little effect on the delivery of the clubhead to the ball.

Keywords: *Computer simulation, forward dynamics, golf, genetic algorithm, coordination, torque generator*

Introduction

In the golf instruction literature, discussion of the swing plane is common and most top instructors stress on the importance of being 'on-plane' and provide their own qualitative descriptions of this concept (Hardy & Andrisani, 2005; Haney, 2009; McLean, 2009). Hardy and Andrisani (2005) loosely define the swing plane as the plane the club generally moves through during the swing. At the top of the swing, they use the orientation of the shoulder line (an imaginary line connecting the shoulders) and lead arm to describe a golfer's swing plane when comparing the so-called 'one-plane' and 'two-plane' swings. Their contention is that for the one-plane swing, the shoulders, lead arm, and shaft should all move in a single plane throughout the swing. Haney (2009) advocates that the golf club should be swung on different planes throughout the swing, but that all of those planes should be at the same angle as the club shaft at impact. He also believes that at the start of the downswing, the lead arm, lead wrist, and clubface should all be on the same plane. In contrast, McLean (2009) states that swinging 'on-plane' does *not* mean that the hands, lead arm, and shaft

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move on the same plane. He believes that the hands should move on a consistent plane during the downswing (or get slightly steeper), while the plane of the shaft should flatten out at the start of the downswing. While potentially helpful for those learning the golf swing, these qualitative descriptions from instructional books cannot be used to quantitatively define the swing plane for the purpose of scientific research. Instructors typically rely on lines drawn between two points to demonstrate the swing plane, while a plane requires three non-collinear points in order to be defined.

The difficulty in quantifying the plane of a golf swing is deciding in which three points to use in the calculation. In previous research, the chosen points have differed somewhat between investigations resulting in the reporting of the plane of the club (Vaughan, 1981; Neal & Wilson, 1985; Nesbit, 2005; Coleman & Anderson, 2007), the plane traced out by the path of the hands (Nesbit, 2005), or a plane representing a combination of the golfer's segments and club (Coleman & Rankin, 2005; MacKenzie & Sprigings, 2009a). Vaughan (1981) found that the plane traced out by the club was nearly constant during the last half of the downswing but variable during the first half. Conversely, Neal and Wilson (1985) suggested the opposite: the club moved in a constant plane only for the first half of the downswing. Nesbit (2005) concluded that the downswing does not take place in a fixed plane and that the plane traced out by the path of the hands was different from that of the club by 9 to 12°. Coleman and Rankin (2005) conducted a study that measured the 'left-arm plane' of the golfer's motions and the position of the club relative to that plane. They concluded that the golfer's motions in the downswing were not planar, and that the motions of the club were not coincident with the plane established by the motion of the golfer's seventh cervical vertebra, left shoulder, and left wrist. MacKenzie and Sprigings (2009a) validated a three-dimensional (3D) forward dynamics model of the downswing, which generated a 'left-arm plane' that agreed well with the experimental findings of Coleman and Rankin (2005). Most recently, Coleman and Anderson (2007) measured changes in the plane of the club during the downswing and reported that the plane was different depending on the type of club (driver, 5-iron, or pitching wedge). They also concluded that while some golfers moved the club in a more consistent plane than others, moving the club in a single plane might be neither possible nor desirable for some golfers.

It could be argued that a golfer should still strive to have the club move with as little variation in plane as possible. Intuitively, this appears to make sense; if the club is optimally positioned in a certain plane at impact, then maintaining the club as close to that plane as possible throughout the swing should reduce the likelihood of error at impact. However, there are other factors that should be considered. The golfer's movements affect the forces and torques being applied to the club, and hence the club's motion. It has been demonstrated that forces acting within the plane of the golfer's motion are large enough to meaningfully deflect the shaft of a driver due to the offset position of the clubhead's center of mass (MacKenzie & Sprigings, 2009b, 2010). Previous research suggests that a similar effect may occur if the center of mass of the entire club is not coincident with the plane of the golfer's motions and that the motion of the club is affected in a predictable way by its position relative to the plane of the golfer's movements (MacKenzie, 2008).

Previous investigations have only described the plane of the club, the golfer, or a combination of the two. Therefore, the primary aim of this study was to investigate how the position of the club, relative to the golfer's swing plane, influences the motion of the club. On the basis of the initial work of MacKenzie (2008), the first hypothesis was that positioning the club below the swing plane at the start of the downswing will facilitate squaring the clubface for impact, while positioning the club above the swing plane at the start of the downswing will have the opposite effect. Regardless of how it is calculated, or defined, it is generally believed by

instructors that the swing plane affects a golfer's ability to execute a golf shot. Yet, it has never been explicitly demonstrated how the swing plane can influence outcome variables at impact such as clubhead speed, clubhead path, or face angle. Therefore, a second objective was to determine how the steepness of the golfer's swing plane affects the delivery of the clubhead to the ball. Given the differences in swing plane demonstrated among successful professional golfers during the downswing, a second hypothesis was that the steepness of the golfer's swing plane would have little influence on the delivery of the clubhead to the ball.

Methods

Defining the swing plane

The golfer's swing plane was defined by the path of the lead hand, which was represented by a single point at the center of the wrist joint. A plane is any flat 2-D surface, requires three non-collinear points to be calculated, and can be represented by the equation $aX + bY + cZ + d = 0$ (Weisstein, 2011). To calculate a plane using a single point on the golfer, three consecutive frames of data were required. Similar to numerical differentiation, the instantaneous plane at frame i was calculated using the wrist coordinates (X, Y, Z) from frames i-1, i, and $i + 1$ (Figure 1). The instantaneous plane for the initial frame was calculated using the first three frames, while the plane for the final frame was calculated using
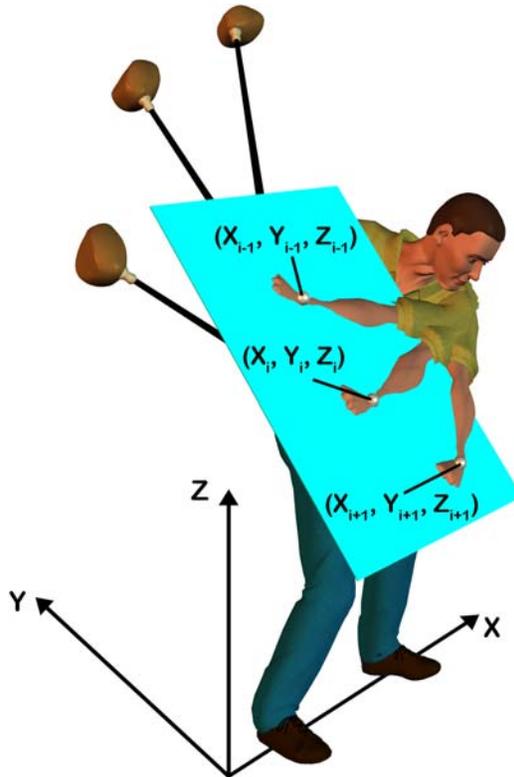

Figure 1. Graphic depiction of how the instantaneous plane being traced out by the lead hand at frame i can be determined using the wrist coordinates (X, Y, Z) from frames i-1, i, and $i + 1$. To improve the clarity of the image, the displacement of the wrist marker between consecutive frames has been greatly exaggerated.

the last three frames. The angle of the plane relative to the negative *Y*-axis (Figure 1) was then calculated for each frame of data using the procedures of Coleman and Rankin (2005).

The methods described by Coleman and Anderson (2007) were used to calculate the plane traced out by the golf club to enable a better comparison with the data presented in their study. For the club, two points were used: one at the grip end of the shaft and a second located at the center of the clubface. The instantaneous plane was calculated using three frames of data, which provided six sets of *X*, *Y*, and *Z* coordinates. A plane of best fit was then calculated for each frame using the six points. The angle of the plane relative to the negative *Y*-axis (Figure 1) was then calculated for each frame of data using the procedures of Coleman and Rankin (2005).

Model description

A representative mathematical model of a golfer was constructed using a four-segment (torso, left upper arm, left forearm, and club), 3D, linked system (Figure 2a). The model had four degrees of freedom: torso rotation, horizontal abduction–adduction at the shoulder, pronation–supination at the elbow, and ulnar-radial deviation at the wrist. The torso rotated about its longitudinal axis, which was fixed. Four torque generators that adhered to the activation rates and force–velocity properties of human muscle were inserted at the proximal end of each segment, and provided the model with the capability of controlling energy to the system. A similar version of this model has previously been validated and explained in greater detail (MacKenzie & Sprigings, 2009a). However, in this study the lead arm was modeled as two segments coplanar with the torso and did not include a flexible shaft.

To most clearly demonstrate the influence of club position relative to the path of the lead hand (the golfer's swing plane), the path of the lead hand was constrained to move in a set plane. Although golfers may not move their lead hand in a set plane throughout the downswing, this allowed a fixed plane to be shown for all positions of the downswing, which makes it much easier for the reader to visualize the mechanisms investigated in this study. Depending on the simulation (see *Experiments* below), the lead hand was constrained to move in a plane fixed at either 125° or 135°, relative to the negative *Y*-axis (Figure 1).

Parameter values for segment length, moment of inertia, and mass for a representative golfer with a body mass of 80 kg, and a standing height of 1.83 m, were calculated using the regression equations provided by Zatsiorsky (2002, Appendix A.2) (Table I). Parameter values for the club segments were based on taking direct measurements of a standard driver
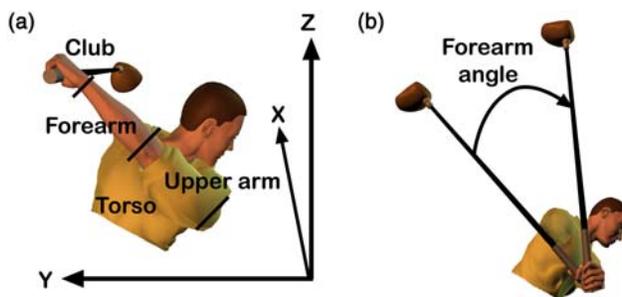

Figure 2. (a) The initial configuration at the start of the downswing for the 3D, four-segment model. The positive *X*-axis was directed toward the target; and (b) convention used to express the forearm's longitudinal rotation. The forearm angle was initially set to 0°at the top of the backswing. If the model was placed in the typical address position assumed by a professional golfer, then the forearm angle would be approximately 90°.

Table I. Golfer model segment parameters.

Segment	Mass (kg)	Length (cm)	CM_{A-P} (cm)	CM_{M-L} (cm)	CM_L (cm)	I_{A-P} (kg·cm^2)	I_{M-L} (kg·cm^2)	I_L (kg·cm^2)
Torso	34.8	40.0	–	20.0	–	–	–	3655
Upper arm	2.17	28.0	–	–	26.1	114.4	127.3	38.95
Forearm	1.30	34.0	–	–	5.6	60.2	64.7	12.60
Club-hand	0.79	112	1.5	-1.4	37.1	1774	1778	13.12

Note: CM_{A-P}, CM_{M-L}, CM_L: position of center of mass along the anteroposterior, mediolateral, and longitudinal axis of each segment. I_{A-P}, I_{M-L}, I_L: moments of inertia of each segment about the anteroposterior, mediolateral, and longitudinal axes.

designed in 2009 (Table I). The equations governing the motion of the mathematical model were based on Newton's laws of motion and were formulated according to Kane's method (Yamaguchi, 2001). The software Autolev$^{©}$ (OnLine Dynamics, Sunnyvale, California, United States) was used to facilitate the generation of the 3D dynamical equations into FORTRAN$^{©}$ (Compaq Computer Corporation, Fremont, California, United States) programming code. To solve the set of first order differential equations determining the motion of the system, numerical integration was performed using a modified Kutta–Merson algorithm provided by Autolev$^{©}$ (OnLine Dynamics, Sunnyvale, California, United States). A variable time-step was used, but the model's output was reported every 0.001 s.

Experiment A: Simulations 1 and 2

The location of the club relative to the swing plane was manipulated by changing the amount of forearm rotation (supination/pronation) at the start of the downswing (Figure 2b). Simulation 1 (Sim1) started with the forearm angle set to -10°, which placed the club below the swing plane (Figure 3). Simulation 2 (Sim2) started with the forearm angle set to 10°, which placed the club above the swing plane (Figure 3). A forearm angle of zero would position the shaft of the club exactly within the swing plane, which was set to 135° for both Sim1 and Sim2. For both Sim1 and Sim2, the forearm torque generator was set to zero for the entire downswing. In other words, the golfer model was not capable of actively supinating the forearm to square the clubface for impact. Removing forearm torque permitted a clearer portrayal of how the location of the club relative to the swing plane could affect the motion of the club. Any rotation of the forearm would be a result of the passive forces (McGeer, 1990) generated during the downswing and not muscular forces.

Experiment B: Simulations 3 and 4

A common technique flaw exhibited by many amateurs is 'coming over the top' (Anderson, 2002; Flick, 2009). Essentially, this refers to the golfer moving the club above the swing plane during the early stages of the downswing. Experiment B was designed to understand the implications if the golfer moved the club above the swing plane early into the downswing. Simulation 3 (Sim3) was considered the reference condition, as the downswing swing was initiated with the shaft perfectly within the golfer's swing plane and the optimization was conducted with all the torque generators available to supply energy to the system. For Simulation 4 (Sim4), the downswing was initiated with the club within the golfer's swing plane, and all the torque generators were optimally timed with the exception of the forearm supination torque that was started at the initiation of the downswing. For both Sim3 and Sim4, the golfer's swing plane was 135°.

Experiment C: Simulations 5 and 6

The purpose of Experiment C was to determine the effect of the golfer's swing plane on the delivery of the clubhead to the ball. Experiment B was repeated but with the model constrained to move the lead arm in a plane that was set to 125°. In Experiments A and B the swing plane was constrained to 135°. These swing plane values were selected as they fell within the range shown in Coleman and Anderson (2007, Figure 6a). With the exception of the 10° change in the golfer's swing plane, Simulation 5 (Sim5) was the same as Sim3, while Simulation 6 (Sim6) was the same as Sim4. Comparing Sim5 with Sim3, and Sim6 with Sim4 addresses the second objective of this study.

Model optimization

The objective in each of the simulations described above was to maximize horizontal clubhead speed at impact with the golf ball. The objective function was equal to the clubhead velocity in the X direction (Figure 2a) at impact minus any penalty variables accumulated during the simulated golf swing. Penalties were incurred if the model performed movements that were not executable by a human golfer, such as having the arm segment pass through the torso segment. Penalties were also incurred if the model was not in a proper position at impact, such as having the clubface misaligned with the target. For example, the penalty for a misaligned clubface was calculated using an expression (penalty $= [2 \times \text{misalignment}]^2$) that reduced the objective function by 4 m/s if the clubface was misaligned by 1°. The optimization scheme used a single activation muscle control strategy in which the onset of voluntary torque at each joint was controlled separately. The control variables were the onset and duration times for the four torque generators. This resulted in a total of eight control variables that were optimized to determine maximum horizontal clubhead speed at impact.

The optimization search engine developed by the author of this study (SJM) used an evolutionary algorithm approach as generally expressed by Michalewicz (1996). The method was based on Darwin's theories of evolution and natural selection in which the fit individuals survive and pass on their genetic code to the next generation. In the case of the golfer model, fitness was measured using the objective function (clubhead speed minus penalties) and an individual was represented by a set of specific values for the eight control variables. At the start of the optimization procedure, a population of individuals was randomly generated and their fitness was evaluated. Starting values for each control variable were selected randomly between 0 and 0.3 s. This range approximately represents downswing time. The optimization process maintained a population of 200 individuals that continually evolved over 2000 generations. The higher an individual's fitness relative to the population, the greater the chance that individual had in passing their genetic code (control variables) on to the next generation. All offspring underwent a mutation in which one or more of their control variables were modified by a random amount between 0 and 0.3 s. The range of values decreased as the generation number increased so as to facilitate narrowing in on a maximum. In addition to passing on their genetic code for mutation, the individual with the greatest relative fitness persisted unaltered into the next generation. The programming language MATLAB© (Mathworks, Natick, Massachusetts, United States) was used to create the optimization algorithm, which communicated with the golfer model, developed in FORTRAN© (Compaq Computer Corporation, Fremont, California, United States). To evaluate each individual, values for the eight control variables were sent to the golfer model. The objective function was evaluated in

FORTRAN© (Compaq Computer Corporation, Fremont, California, United States) (a simulated swing was executed) and the value (clubhead speed minus penalties) was returned to the optimization algorithm where it represented an individual's fitness in the population. The fittest individual after the 2000th generation represented the optimal set of control variables (torque start and duration times) for the particular simulation condition that was being optimized. The optimization algorithm took approximately 50 min to execute using a Lenovo PC with a 2 GHz processor and 3 GB RAM. The entire optimization process was repeated for each simulation experiment until the same results were found three times in succession. This ensured that the optimal muscular torque coordination pattern was found. Each simulation started at the initiation of the downswing with the model's segments oriented as shown in Figure 1a.

Results

Experiment A: Simulations 1 and 2

Sim1 started with the forearm angle set to -10° (Figure 3a), which placed the center of mass of the club 7.3 cm below the golfer's swing plane (Figure 3b). Sim2 started with the forearm angle set to -10° (Figure 3a), which placed the center of the mass of the club 4.6 cm above the golfer's swing plane (Figure 3b). The differences in the distance of the center of mass from the plane are due to the offset position of the clubhead from the shaft. In Sim1, the forearm angle showed a small decrease during the first 0.1 s and then slowly supinated to approximately 30° at 0.25 s. The forearm then rapidly supinated to approximately 90°, which resulted in the clubface being square at impact. In Sim2, the forearm angle showed a gradual decrease throughout the first half of the downswing, crossing 0° at 0.17 s, and remaining negative until 0.28 s. The forearm then rapidly supinated to 36°, which resulted in the clubface being open by more than 50° to the target line at impact.

The combined angular momentum of the forearm, hand, and club, relative to longitudinal axis of the forearm, was positive for the majority of the downswing during Sim1 (Figure 3c). The opposite was true for Sim2 as it showed only a small amount of positive angular momentum very late into the downswing (after 0.25 s). Positive angular momentum indicates that the forearm was supinating (Figure 3c).

The combined moment of inertia of the left forearm, hand, and club, relative to longitudinal axis of the forearm, was nearly identical for both simulations over the first 0.1 s of the downswing (Figure 3d). This was a result of both simulations maintaining the same relative wrist ulnar deviation angle of 70° during this time period. The respective increases in the moment of inertia were a result of the wrist ulnar deviation angle increasing to 90°, which placed the center of mass of the club at the maximum distance from the longitudinal axis of the forearm. The moment of inertia then dropped quickly due to the ulnar deviation at the wrist bringing the center of mass of the club nearly in-line with the forearm.

While the peak clubhead speeds were similar for Sim1 (37.1 m/s) and Sim2 (38.2 m/s), Sim2 dropped to 31.8 m/s at impact, while Sim1 only dropped to 36.2 m/s at impact (Figure 2e; Table II).

Experiment B: Simulations 3 and 4

Both Sim3 and Sim4 started with the forearm supination angle set to 0° (Figure 4a), which placed the shaft within the golfer's swing plane, and the center of mass of the club 1.4 cm below (Figure 4b). In Sim3, the forearm angle showed a small decrease during the first half of
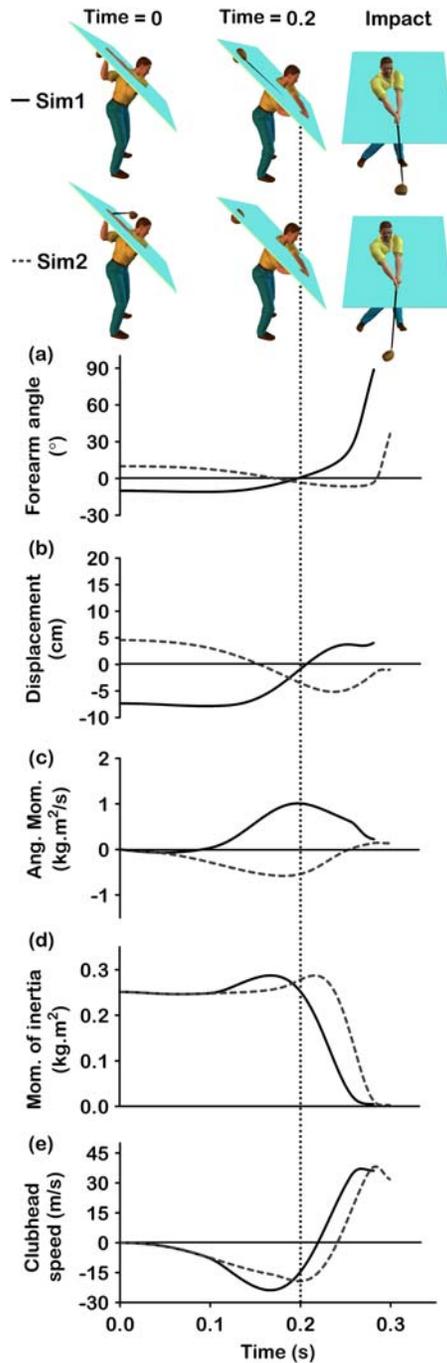
Figure 3. Results from Experiment A. The golfer graphics at the top of the figure show the orientation of the club relative to the golfer's swing plane at three points in the downswing (a) forearm angle: a value of 90° at impact indicates a square clubface; (b) position of the center of mass of the club relative to the golfer's swing plane; (c) combined angular momentum of the forearm, club, and hand relative to the longitudinal axis of the lead forearm; (d) combined moment of inertia of the forearm, club, and hand relative to the longitudinal axis of the lead forearm; and (e) clubhead velocity along the X-axis.

Table II. Velocity components and path of the clubhead at impact.

	X (m/s)	Y (m/s)	Z (m/s)	Vertical Path (°)	Horizontal Path (°)
Sim1	36.2	1.5	-0.2	0.3 down	2.4 left
Sim2	31.8	2.7	-1.5	2.7 down	4.9 left
Sim3	44.1	-3.3	-3.2	4.2 down	4.3 right
Sim5	44.1	-2.8	-3.8	4.9 down	3.6 right
Sim4	35.5	9.9	5.6	9.0 up	15.6 left
Sim6	35.8	8.6	7.3	11.5 up	13.5 left

Note: The positive X-axis is directed down the center of the fairway, the positive Y-axis is directed to the left of the fairway, and the positive Z-axis is directed vertically up. Refer to Figures 1 and 2a for depictions of the X, Y, and Z directions.

the downswing due to gravity pulling the club below the swing plane. The forearm supination torque generator was then activated at approximately 0.16 s which resulted in the forearm rapidly supinating and the clubface becoming square at impact. In Sim4, the forearm torque generator was activated at the initiation of the downswing. This was clear due to the immediate supination of the forearm that showed a local peak of 32° at 0.17 s. Despite continued activation of the forearm supination torque generator, the forearm then pronated to an angle of 20° at 0.23 s before rapidly supinating, which resulted in the clubface being square at impact.

For Sim3, the combined angular momentum of the forearm, hand, and club, relative to longitudinal axis of the forearm, was just below zero for the first half of the downswing due to gravity pulling the club below the swing plane (Figure 4c). The angular momentum then became positive for the second half of the downswing due to the forearm torque actively producing supination. For Sim4, the angular momentum profile showed the opposite pattern. The early supination torque resulted in positive angular momentum during the first half of the downswing. However, despite continued activation of the forearm supination torque generator, the angular momentum was negative between 0.17 and 0.23 s, and became only slightly positive during the final 0.05 s. Interestingly, the forearm torque was peaking (30 Nm, not shown) when the angular momentum was peaking in the opposite direction (-0.56 kg·m^2/s) at 0.19 s (Figure 4c).

The combined moment of inertia of the left forearm, hand, and club, relative to longitudinal axis of the forearm, was nearly identical for both simulations over the first 0.1 s of the downswing (Figure 4d). The moment of inertia then dropped quickly due to the ulnar deviation at the wrist bringing the center of mass of the club nearly in-line with the forearm. Ulnar deviation was delayed considerably for Sim3 in comparison to Sim4; hence, the associated delay in the timing of the decrease in moment of inertia for Sim3.

The clubhead speed at impact for Sim3 (44.1 m/s) was 24% higher than that generated during Sim4 (35.5 m/s; Table II). The optimization algorithm found the muscle coordination pattern that resulted in the highest clubhead speed at impact while also ensuring the clubface was square to the target line. The clubhead speed for Sim3 (44.1 m/s) was 22% higher than that generated during Sim1 (36.2 m/s), which indicates as to how much active rotation of the forearm from a muscular torque can contribute to clubhead speed.

Experiment C: Simulations 5 and 6

Adjusting the angle of the golfer's swing plane relative to the horizontal did not noticeably affect any of the dependent variables graphed in Figure 4. For all variables, Sim5 was nearly
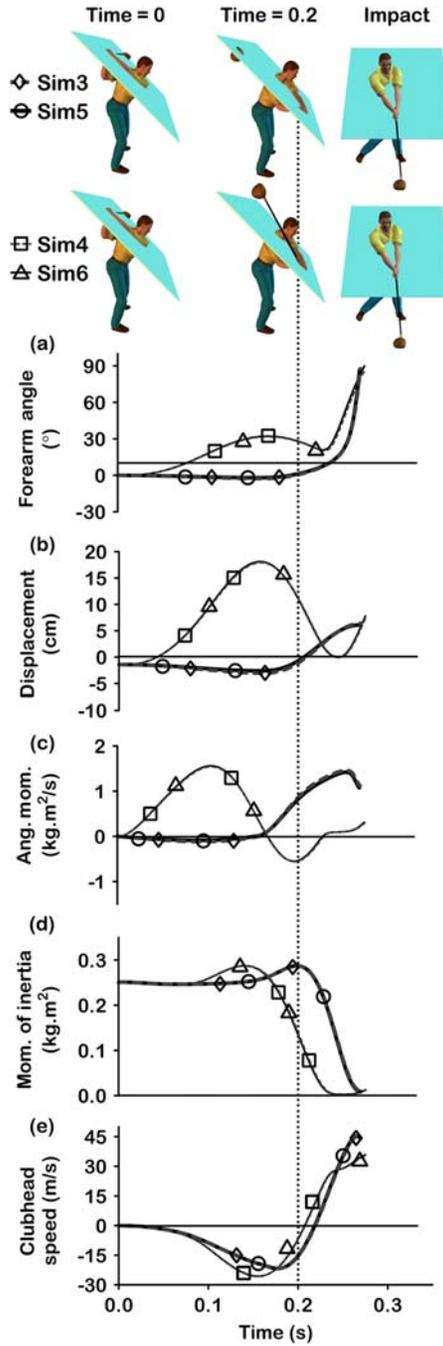
Figure 4. Results from Experiments B and C. The golfer graphics at the top of the figure show the orientation of the club relative to the golfer's swing plane at three points in the downswing. The same graphics are used for Sim3 and Sim5 as well as for Sim4 and Sim6 due to their nearly identical results. (a) Forearm angle: a value of 90° at impact indicates a square clubface; (b) position of the center of mass of the club relative to the golfer's swing plane; (c) combined angular momentum of the forearm, club, and hand relative to the longitudinal axis of the lead forearm; (d) combined moment of inertia of the forearm, club, and hand relative to the longitudinal axis of the lead forearm; and (e) clubhead velocity along the X-axis.
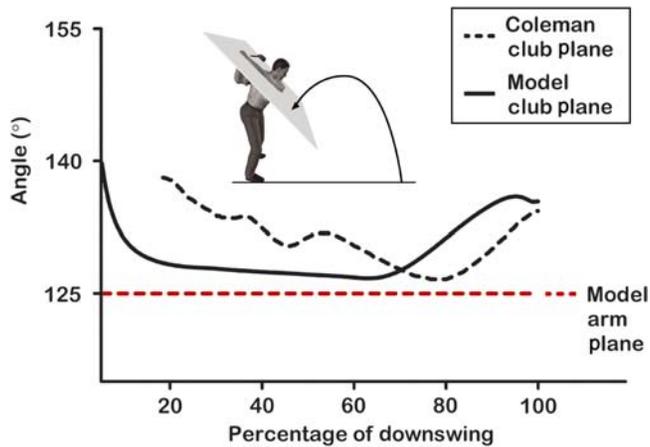
Figure 5. The instantaneous plane of the club, as well as the lead arm, during Sim5. The inset graphic shows the convention for measuring the angle of a plane relative to the *Y*-axis. Also shown is the club plane for a driver swing presented by Coleman and Anderson (2007) in their Figure 6(a). The data were obtained by using ImageJ to digitize 135 points in their Figure 6(a) and using the *X*- and *Y*-axis information to create a scale.

identical to Sim3, while Sim6 was nearly identical to Sim4. The *X*, *Y*, and *Z* components of clubhead velocity as well as the path of the clubhead at impact are shown in Table II. For the normal swing, the steeper swing plane (Sim5) resulted in a 0.7° reduction in the inside-to-outside path of the clubhead compared to Sim3, as well as a 0.7° increase in the downward path of the clubhead at impact. However, Sim6 resulted in a slightly less (2.1°) outside-to-inside path relative to Sim4, as well as a 2.5° increase in the upward path of the clubhead at impact. Also, all simulations with the exception of Sim2 generated square clubfaces, relative to the target line, at impact.

Sim5, the normal swing, generated a golf club plane that was on an average 4.5° flatter than the plane traced out by the path of the hands (125°), over the entire downswing (Figure 5). At impact, the instantaneous plane of the club (136°) was 11° flatter than the golfer's swing plane. The motion of the club during Sim5 was not planar.

The clubhead speed at impact for Sim5 (44.1 m/s) was 23% higher than that generated during Sim6 (35.8 m/s; Table II). The optimization algorithm found the muscle coordination pattern that resulted in the highest clubhead speed at impact while also ensuring the clubface was square to the target line. The clubhead speed for Sim5 (44.1 m/s) was 22% higher than that generated during Sim1 (36.2 m/s), which indicates as to how much active rotation of the forearm from a muscular torque can contribute to clubhead speed.

The output from each of the muscular torque generators during Sim5 was consistent with the force–velocity properties of muscle in that the torque output diminished as the relative joint angle speed increased. The optimal activation of the torque generators was in a proximal to distal pattern with the torso rotation torque generator being activated at $t = 0$ s and remaining active for the entire downswing (Figure 6). The shoulder abduction torque generator was activated second at $t = 0.06$ s, while the wrist ulnar deviation and forearm supination torque generators were activated last, both at $t = 0.16$ s.

Discussion and implications

The primary aim of this study was to investigate how the position of the club, relative to the golfer's swing plane, influences the motion of the club. It was hypothesized that positioning
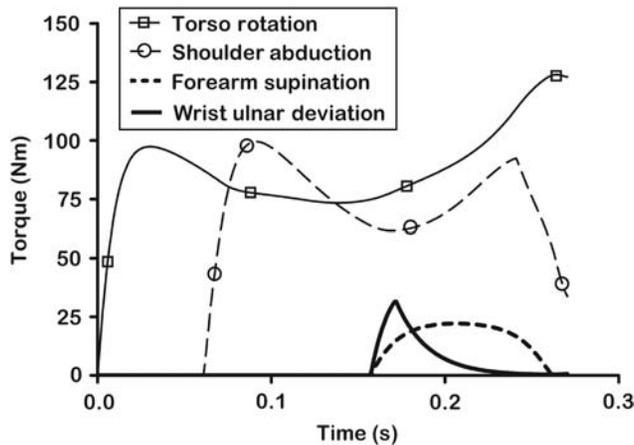
Figure 6. Optimal torque output from the four muscular torque generators for Sim5.

the club below the swing plane at the start of the downswing would facilitate squaring the clubface for impact, while positioning the club above the swing plane at the start of the downswing would have the opposite effect. A second objective was to determine how the steepness of the golfer's swing plane affects the delivery of the clubhead to the ball. It was hypothesized that the steepness of the golfer's swing plane would have little influence on the delivery of the clubhead to the ball.

The results from Experiment A confirmed the first hypothesis by demonstrating how the position of the club can affect the club's rotation about the longitudinal axis of the lead arm, and hence, the golfer's ability to square the clubface for impact. In the absence of a forearm supination torque, the clubface can still be squared for impact if the club is below the golfer's swing plane at the start of the downswing. Conversely, if the club is above the swing plane at the start of downswing, then the action of squaring the clubface for impact will be inhibited. The mechanism for this phenomenon is analogous to the effect observed in previous two-dimensional models, in which the wrist ulnar deviation angle opens without the application of a muscular torque at the wrist joint (Sprigings & MacKenzie, 2002). Newton's laws dictate the relationship between cause and effect in the physical world, and the cause is always a force or torque. The relationship that any variable (e.g. weight shift, delayed release, or swing plane) has on the outcome of a golf swing (e.g. clubhead speed, path, or face angle) can be understood by determining how that variable affected the force and/or torque being applied to the club by the golfer.

If the club is below the golfer's swing plane, then a force acting at the grip end of the club, and within the arm abduction plane, produces a torque on the club about the longitudinal axis of the lead arm (Figure 7). This torque will act until the center of mass of the club moves within the arm abduction plane. The angular impulse generated by the torque creates angular momentum about the longitudinal axis of the lead arm. It is this angular momentum about the longitudinal axis of the lead arm that caused the clubhead to square for impact, during Sim1, in the absence of a muscle torque acting about the longitudinal axis of the forearm (Figures 3a and 3c). The moment arm drawn in Figure 7 is essentially shown as a function of downswing time in Figures 3b and 4b. It should be noted that the increase in angular momentum was not clearly evidenced in the longitudinal rotation of the forearm until the moment of inertia began to decrease rapidly near the end of the downswing (Figure 3d). As demonstrated in Figure 3, if the moment of inertia is small, then a small
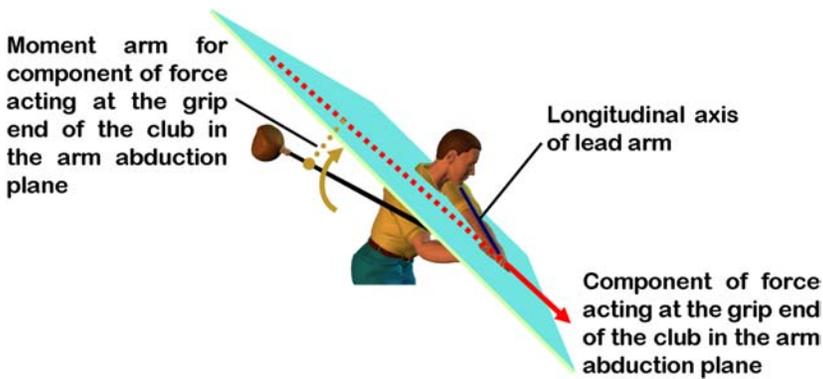
Figure 7. A component of force acting within the arm abduction plane produces an angular impulse on the club about the longitudinal axis of the lead arm.

amount of angular momentum can be associated with a high rate of change in angular displacement.

The same mechanism, but with the opposite effect, was responsible for the clubface remaining open at impact in Sim2. Starting the downswing with the club above the plane (Figure 3b) resulted in the generation of negative angular momentum (Figure 3c), and therefore negative rotation (pronation) of the forearm (Figure 3a). At the midpoint of the downswing in Sim2, the club was positioned below the swing plane (Figure 3b), which eventually resulted in the forearm supinating, but not sufficiently to square the clubface.

Experiment B was conducted to address the primary aim of the study in a more realistic scenario. In Experiment B, the model was capable of exerting a muscle torque about the longitudinal axis of the lead forearm. If that torque is exerted too early in the downswing (the golfer attempts to square the club for impact prematurely), the club moves into a position above the arm abduction plane (Figure 4b). From this position, the force acting on the grip end of the club will produce a torque about the longitudinal axis of the lead forearm that will tend to bring the club back down toward the arm abduction plane. The angular impulse generated by the torque creates angular momentum about the longitudinal axis of the lead arm. Unfortunately for the golfer, the angular momentum generated in this scenario tends to inhibit the squaring of the clubface for impact. This results in an open clubface at impact, and the inevitable slicing action of the golf ball trajectory. As was programmed into the optimization scheme of this study, to mediate slicing, the golfer must sacrifice clubhead speed to obtain the correct sequencing, which will square the face at impact. It is important to note that the magnitude of the torque generated by the club being above the golfer's swing plane in Sim4 and Sim6 exceeded the maximum supination torque capable of the forearm torque generator. While it is possible that the addition of a right (trailing) arm in the model may have prevented this, the maximum torque capability of the forearm torque generator was increased to compensate for a lack of a trailing arm. In fact, the maximum torque produced by the forearm torque generator (30 Nm) was three to eight times greater than the maximum supination values reported in the literature (Salter & Darcus, 1952; Gallagher et al., 1997; O'Sullivan & Gallwey, 2002; Gordon et al., 2004), which should account for any additional torque applied to the club by a trailing arm during a real golf swing. While an attempt was made to account for the muscular contribution from a trailing arm, the mass and moment of inertia of the trailing arm were not accounted for and should be noted as a limitation of the model.

The second objective of this study was to determine how the steepness of the golfer's swing plane affects the delivery of the clubhead to the ball. In the popular golfing literature, it is common to read about a golfer's swing plane being incorrect (Haney, 2001; Hardy & Rudy, 2008), which implies that the swing plane can affect the delivery of the clubhead to the ball. A golfer can steepen the path traced out by the hands by abducting the lead arm about the shoulder on a steeper plane. Alternatively, a golfer could maintain the same motion of the lead arm relative to the torso and flex (bend) more at the hips, which was the approach used in this study to increase the steepness of the golfer's swing plane. Assuming that the golfer is able to execute the movement pattern effectively, as was the case with the model used in this study, the steepness of the golfer's swing plane does not appear to have much influence on the delivery of the clubhead to the ball (Table II), which supports the second hypothesis. This can best be confirmed by comparing the results of Sim3 (135° swing plane) with Sim5 (125° swing plane). These two simulations will most closely represent the coordinated downswings of actual golfers. Both of these simulations started the downswing with the shaft perfectly within the golfer's swing plane and the optimizations were conducted with all torque generators available to supply energy to the system. In comparing Sim3 with Sim5, both generated square clubfaces and identical clubhead speeds at impact. The horizontal and vertical clubhead paths each differed by 0.7° between simulations, which would yield very little practical difference in ball flight.

It would appear that comparing the plane traced out by the club with the plane of the golfer (Figure 5) does not hold as much predictive value as comparing the position of the club relative to the golfer's swing plane. The plane of the club was flatter than that of the golfer for the entire downswing. Although the instantaneous plane of the club shown in Figure 5 was generated by a simplistic four-segment 3D model, it agrees very well in both magnitude and pattern over the downswing with the elite golfer results presented in Coleman and Anderson (2007). Although the results are not identical, it is important to note that no attempt was made to manipulate the model to match the club plane for the 'typical' golfer presented by Coleman and Anderson. The authors started their plot at 20% due to very inconsistent club plane calculations early in the downswing. The typical errors inherent in any experimental kinematic data collection procedure were the cause of the inconsistent plane calculations. The fact that the golfer's swing plane does not appear to have much influence on the delivery of the clubhead to the ball suggests why professional golfers with both flat and steep swing planes have been successful: the paths they move their golf clubs on are appropriately matched to the paths traced out by their hands. However, this is purely speculative and must be confirmed by measuring the hand and club planes of successful golfers who use different swing planes. Although this simulation study lacks a subject-specific model validation, the club plane results do compare well with the experimental results of Coleman and Anderson (2007).

While not directly supported by the results, the mechanism revealed in this study does provide an explanation for a prevalent scenario faced by many amateur golfers. Often those golfers that typically hit a slice, also frequently hit pulls. As demonstrated in Sim5 and Sim6, coming over the top places the club above the golfer's swing plane and impedes the squaring of the clubface. To square the clubface to the path of the clubhead at impact, without sacrificing a significant amount of clubhead speed, the golfer would have to change the path of their hands. Their hands would have to move in the positive Y direction, i.e. pulled across their bodies. By changing the path of the hands, the plane containing the hands changes relative to the position of the club. The club will now lie within the golfer's swing plane and they will now be able to square the clubface to the path. Unfortunately, this will result in a pulled golf shot that will end up left of the target.

Conclusion

In conclusion, it was found that the positioning of the club relative to the plane traced out by the lead hand of the golfer can have a meaningful effect on the golfer's ability to square the clubface for impact. Positioning the club below the golfer's swing plane, early in the downswing, will facilitate the squaring of the clubface for impact, while positioning the club above the plane will have the opposite effect. It was also demonstrated that changing the steepness of the golfer's swing plane does not appear to have any meaningful effect on the delivery of the clubhead to the ball. In future, rather than generally referring to the 'swing plane', golf instructors should refer specifically to either the golfer's swing plane (the plane traced out by the hands), or the plane traced out by the club.

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