HOW TOUGH IS IT TO REPEATEDLY HIT THE BALL IN GOLF?

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Golf is an increasingly popular sport, whose most challenging skill is the driver swing. There have been a large number of studies characterizing golf swings, yielding insightful instructions on how to successfully structure the swing. Achieving a sub 18 handicap is no longer the primary concern for golfers. Instead, players are now most troubled by a lack of consistency during swing execution. The goal of this study is to determine how to consistently execute repeated quality golf swings. By characterizing both successful and failed swings of 22 experienced golfers, we aim to identify swing parameters that are most sensitive and/or prone to motor control variations. We specifically report on five distinct problem areas, as well as provide suggestions for how to address these problems.

KEY WORDS: 3D motion analysis, swing accuracy, transition.

INTRODUCTION: The dominant skill in golf is the swing. Golf swings are complicated movements that require coordination of all major body segments. Consequently, "hitting a long straight tee shot" is ranked as one of the top five most difficult maneuvers in sports by USA Today (USA today, 2010). Based on a survey by Revista Golf International (2010), the four most common sources of frustration for golfers are: 1) 94% suffer from inconsistency 2) 80% cannot achieve a sub 18 handicap 3) 71% slice the ball and 4) 62% cannot achieve distance with their swing. All four frustrations are directly or indirectly related to the swing. Therefore, in this study, our goal is to determine how to consistently execute a good golf swing. By characterizing both successful and failed swings of experienced golfers, we aim to identify parameters (e.g. shoulder and/or trunk orientations) that are most sensitive and/or prone to motor control variations. Through the identification of parameters with low error tolerance, we hope to benefit all levels of golf pedagogy and/or equipment design by pinpointing hidden problem areas that require extra care and attention during practice.

METHODS: This project studied 22 advanced golfers, each with over 10 years of training and/or practice. The subjects (all were right-handed) averaged 35.1$\pm$13.6 years of age, had a 12.3$\pm$10.1 handicap, 16.7$\pm$10.7 years of experience and were1.80$\pm$0.07 m tall, with a mass of 91.4$\pm$14.3 kg. These golfers have developed signature moves to achieve successful swings, producing shot distances of ~230 m (~250 yards), using a driver. Each subject performed 6 swings using a driver, all of which were recorded using 3D motion capture. The accompanying weight transfers of the subjects during each swing were collected using force platforms. Each swing was classified as a success or failure based on ball release direction and speed. Correlation analyses were then used to contrast successful swings with failed swings in order to identify traditional and/or novel parameters most sensitive/prone to motor control variations.

3D Motion Capture and Biomechanical Modeling: A twelve-camera VICON 3D motion capture system (Oxford Metrics Ltd., Oxford, England) was used to quantitatively determine the whole body kinematic characteristics during each swing. VICON software was configured to capture motion at a rate of 250 Hz and reconstruct the captured movements in 3D computer space. Calibration residuals were determined in accordance with VICON's guidelines and yielded positional data accurate to within 1 mm.

Each subject wore a stretchable, black garment with whole-body coverage. Affixed to the garment were 42 reflective markers, each with a diameter of 9 mm. From these 42 markers, a full body biomechanical model with 15 segments was built, using methods previously described (Shan & Westerhoff, 2005), to determine segmental angles, joint angles and their ranges of motion during a swing. The 15 segments in the biomechanical model were head & neck, upper trunk, lower trunk, two upper arms, two forearms, two hands, two thighs, two shanks and two feet. In addition, markers were attached on the shaft (1 marker) and the head (2 markers) of the club to establish club movements. Furthermore, reflective tape was glued to a standard golf ball to determine ball release speed and direction

Ground Reaction Force Measurement: Two KISTLER force platforms (one under each foot) were used to capture the weight transfer during a golf swing. 2D (anterior-posterior and medial-lateral) weight transfer data were collected to characterize the dynamic stability of the swing. All data collection were synchronized to 3D motion capture.

Data Analysis: In order to identify parameters that influenced swing consistency, we contrasted successful swings with failed swings. Successful swings were defined by good swing power and swing accuracy. Swing power was quantified via ball release speed (v). Normal biological variation of the tested subjects was approximately 8%, thus successful swings were required to have v ≥ 92% of individual maximum. Swing accuracy is quantified by ball release direction and ball launch angle. Ball release direction (A_D) refers to the angle between the intended trajectory (defined by toe markers during Address & Stance [golfer readies his stance]) and actual trajectory of the golf ball. Using the local fairway width of 22 m (24 yards) and the subjects' average shot distance of 210 m (230 yards), we calculated the maximum deviation to be 3.0° ($A_D \leq |\tan^{-1}(11/210)|$). Launch angle (A_L) refers to the angle between the golf ball trajectory and the ground. The optimal launch angle is reported to be 11° (Tutelman, 2009); normal biological variation of the tested subjects is 2.7°, thus successful swings were required to have A_L between 8.3° and 13.7°. Correlation analysis was used to identify parameters that influenced swing consistency (i.e. most sensitive/prone to variation).

RESULTS: The success rate of the subjects tested is shown in Table 1. We contrasted successful and failed swings of 22 experienced golfers to identify parameters that are most sensitive/prone to motor control variations and thus require extra care and attention during a swing. Our data showed five problem areas, some of which are well-known in the field, others are novel.

Table 1
Swing success rate of all subjects (22 subjects x 6 swings)

	Release Speed	A_D	A_L
Average	65.6 m/s	3.1°	11.8°
Standard deviation	5.1	2.1	2.7
Success rate	68.3%	43.4%	40.6%
Overall success rate	30.1%		

Note: Overall success rate is determined by successful swings (v ≥ 92% of individual maximum, $A_D \leq |3.0°|$ and A_L within 8.3° - 13.7°) divided by 132

Accurate ball launch requires precise ball position: The relative ball positioning to the leading foot (left) is on average 34% of stance length. Variations in this position directly influence the ball launch angle (A_L). The launch angle negatively correlates with the left foot-ball distance (r = -0.67); i.e. the smaller the left foot-ball distance, the higher the launch angle.

Club horizontal angle at the end of backswing: Correlation analyses showed that both the ball release speed (v) and ball release direction ($|A_D|$) are positively correlated to club horizontal angle at the end of backswing (r=0.59 and 0.57 respectively). When the angle is larger than 180° (club below horizontal line), $|A_D|$ for some subjects increased to outside the tolerated range (0.0°±3.0°) needed for a straight shot. Additionally, ground reaction forces showed increased weight transfer in both medial-lateral and anterior-posterior directions (r=0.84 and 0.76 respectively), showing dynamic balancing is challenged, further compromising swing accuracy for the subjects.

Transition phase is essential for a powerful swing: Not all swings exhibited a short pause (i.e. Transition) between backswing and downswing. For swings without Transition (or a short pause), X-factor (Angle between shoulders' line and hips' line) maximized at the end of Backswing. Our data showed that pausing for Transition allowed for pelvic rotation prior to shoulder rotation, which further increased the X-factor. Correlation analyses showed positive correlations between X-factor and v (r=0.80) as well as Transition time and v (r=0.86). These findings suggest that Transition increases ball release speed.

Precise wrist control is needed for both swing power and swing accuracy: The wrist movement onset during downswing influences both swing accuracy and swing power. Our data showed that later onset increased ball release speed v (r=0.76), but decreased left forearm-club angle to more than 180° at impact, consequently reducing the ball launch angle A_L (r=0.84). The opposite occurs when the initiation of the wrist movement is too early.

Rigorous compensation of persistent differences in Takeaway and Impact is required for swing accuracy: Our data showed persistent differences between Takeaway and Impact positioning for advanced golfers. These differences are most noticeable in *Swing Plane Discrepancy*. Of the 132 swings tested, 0 swings followed the same plane during Backswing and Downswing. The angle ranged from 1.9° to 6.1° and correlated positively with club head migration distance between Takeaway and Impact and ball release direction A_D (r=0.79 and 0.77, respectively). Larger discrepancy angles led to greater migration distance and A_D, consequently compromising swing accuracy (Fig.1)

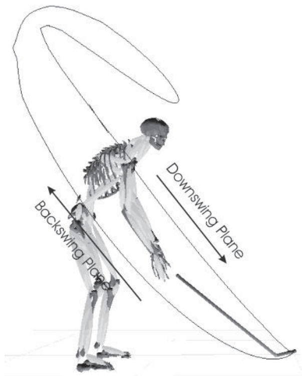

Figure 1: Persistent differences between Takeaway (backswing plane characterized by club angle at Takeaway) and Impact positioning (downswing plane characterized by club angle at Impact) for tested golfers, as well as the club head migration revealed by the club head marker.

DISCUSSION: Three of the five problem areas identified are well-known: ball position, club horizontal angle at the end of backswing and wrist control. Our data showed that a variation in ball positioning as small as 1% of stance length can fail an otherwise well-executed driver swing. This failure is most directly reflected in the ball launch angle, a minute variation of which can drastically change the drive length. Thus players need to stay within ±0.6 cm of their optimal ball positioning to execute a successful driver swing. The club horizontal angle at the end of backswing is a double-edged sword. It increases swing power at the expense of swing accuracy. At angles higher than 180°, the stability of the handgrip may further be compromised. It, thus, might be interesting for future studies to examine handgrip pressure distribution at various transverse club angles. Wrist control affects both the power and the accuracy of the swing. Optimal onset of wrist movement is often discussed in literature and in training (Chen et al., 2007; Pickering & Vickers, 1999). The consensus is that the best onset of wrist movement is when the leading forearm is below parallel line to the ground. However, most of the experienced golfers tested were not able to conform to this established guideline. It is possible that they fear later onset of wrist movement may compromise club position and velocity at impact, due to lack of wrist unlock/extension time.

One novel finding in this study is the characterization of the Transition phase. To date, Transition is more commonly recognized by practitioners than by biomechanists and is only loosely understood to be the short time period between backswing and downswing. Part of its obscurity may be due to the fact that not every player exhibits a Transition phase. However, our data suggest that there are quantifiable benefits to having a Transition. Allocating time to Transition most directly improves the X-factor. X-factor is known as a relevant contributor to swing power (Burden, et al., 1998). In all individuals, X-factor reaches maximum immediately before downswing. Spending time in Transition can increase the maximum X-factor to allow for a more powerful swing.

One surprising finding of this study is the persistent discrepancy between Takeaway and Impact positions. All golfers are trained to follow the same swing plane during backswing and downswing. Assuming proper positioning during the Stance and Address, following the same swing plane ensures a square hit at Impact. Of the 132 swings analyzed in this study, none was found to actually follow the same swing plane with backswing and downswing planes differing by as much as 6.1 degrees. Consequently, there was persistent discrepancy in positioning between Takeaway and Impact, which greatly compromised swing consistency. The most likely cause of this discrepancy is trunk instability. We suspect this instability is introduced by rapid trunk rotation. Thus it should benefit swing accuracy to particularly regulate trunk positions during swing. Alternatively, experienced golfers may want to consider compensation strategies. Our data showed a common control problem for our cohort of experienced golfers: club migration between Takeaway and Impact. Habit like these, once formed, is often difficult to correct. Thus our suggestion is to adjust Address and Stance by positioning the club head off-centre (depending on an individual habit, usually in anterior direction) during Takeaway, so that the club head will be centred by migrations, at Impact, Future studies will examine how best to design compensation strategies for experienced golfers. It would also be interesting to examine professional golfers to determine if these habitual control problems can eventually be corrected with intensive training.

CONCLUSION: In this study, we aimed to determine how to consistently repeat an effective golf swing. We characterized both successful and failed swings of 22 experienced golfers and identified swing parameters that are highly sensitive and/or prone to motor control variations. These parameters sensitized five distinct areas of the swing to variation: 1) ball positioning, 2) club horizontal angle at the end of backswing, 3) Transition, 4) wrist control, and 5) posture migration between Takeaway and Impact. We provided specific suggestions on how to address these problem areas. Correcting the identified parameters should improve consistency of swing execution, so that golfers can achieve higher success rates.

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