A biomechanical approach to investigate swing characteristics in elite golfers

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Abstract
Background: The current study aims to compare the variability of positional control of the club in the starting period of downswing and the orientation of the clubface during impact in elite and intermediate golfers.

Methods: Seven elite and 13 intermediate golfers were recorded by an eight-camera VICON motion capture system while putting with a pitch club. Six retro-reflective markers were attached to the club to build a biomechanical model for analyzing swinging movements. Group comparisons of outcome variables regarding the turning point, sweet spot, elevation angle (EA), and azimuth angle (AA) of the club head were made between the elite and intermediate players.

Results: There were significant differences between groups in SDs of the location of the club tail along the x, y, and z axes at the turning point ( \( p = 0.004; y, p = 0.015; \) and z, \( p = 0.035 \)); the minimum distance between the center of the sweet spot and the ball at impact ( \( p = 0.007; \) the EA ( \( p = 0.001; \) and the AA ( \( p = 0.001 \) of the club head. Results showed that the elite players displayed more converged locations of turning points, shorter distances between the center of the sweet spot and the ball at impact, greater EAs, and smaller AAs compared with those of the intermediate players.

Conclusion: These findings proposed a biomechanical approach of a practical way to observe swing behaviors. These findings suggest that the stability of locations of turning points is a golden reference for differentiating levels of golfers’ performance.

Keywords: Downswing; Golf; Sweet spot; Top of the backswing; Turning point

1. INTRODUCTION
In 1969, Cochran and Stobbs utilized high-speed filming techniques to study the movement of golf swing, ball aerodynamics, and equipment dynamics. Since then, a vast range of biomechanical studies have focused on golf swing. Based on the movement characteristics, golf swing can be decomposed into five phases: take-away, backswing, downswing, acceleration, and follow-through. Most studies on golf swing have focused on the downswing movement, which is incorporated with four crucial periods (starting, acceleration, impact, and follow-through), and is completed within 300 ms. Accordingly, downswing is believed to be a rapid chain-reaction movement, which begins with starting the downswing and results in the flying trajectory of the ball.

It has been shown that small movement variability in torso and pelvic rotation during downswing is the key capability in skilled golfers. Tuck et al, however, found a group of highly skilled golfers who maintained consistency of ball speed despite variability of movements. They stressed that rather than variabilities of body movements, the variability from club trajectory to club head-to-ball contact was the most influential factor.

Choi et al investigated downswing movement by comparing skilled and unskilled golfers. They found that unskilled golfers displayed large positional variability of club head in the top of the downswing position, whereas skilled golfers demonstrated smaller variability in the position of the club head right before downswing. Zero handicap is a great challenge for positive-5-handicap golfers. Lowering the variability of the top of the downswing position of a club could be one of the crucial barriers that stop intermediate golfers from advancing their ability to the zero handicap level.

Studies have shown that skilled golfers tend to perform ideal downswing motions, which results in impacting the golf ball with the sweet spot of the clubface. The sweet spot is a tiny point about two grooves above the leading edge of the clubface. Mechanically, the sweet-spot impact is a collision force that is collinear between the center of mass of the club head and golf ball. During such impact, less unnecessary twisting motion would be generated. It has been observed that any slight body sway during downswing performance would miss the sweet-spot hit. For that reason, the orientation of the clubface at impact of the downswing phase could be another critical barrier stopping intermediate golfers from achieving zero handicap.

The purpose of the current study is, therefore, to compare the variability of positional control of the club in the starting period of downswing and the orientation of the clubface during impact in golfers with different skill levels. We hypothesized that the elite players would demonstrate the following: (1) more stable positional control of the club at the turning point, and (2) better orientation control of the club-face that results in shorter distance between the sweet spot and the ball during impact compared to the intermediate players. Results from this study are expected to help coaches and golfers to achieve the goal of under zero handicap.
2. METHODS

2.1. Participants
Twenty right-handed golf players (seven elite and 13 intermediate) without a history of musculoskeletal disease participated in this study. Participants were categorized into two groups according to performance level: elite and intermediate level. Players in the elite level were equal or below handicap plus 4 and players in the intermediate level were handicap plus 5 to 18. All participants were asked to sign an informed consent form, which was reviewed and approved by the National Yang-Ming University Institutional Review Board.

2.2. Instrumentation
The experiments were conducted in a gait laboratory (8 x 8 x 2.6 m³) using the VICON computer-assisted video motion analysis system (Oxford Metrics Ltd, Oxford, UK) with a sampling rate of 125 Hz. Six reflective markers (14-mm diameter) were used to characterize the trajectory of the pitching clubs they carried (Fig. 1). Three reflective markers were attached on the club surface and three reflective markers were attached on club's body (Fig. 1).

2.3. Experimental procedures
A pitching club (Titleist pitch wedge) was used for testing. All participants were asked to warm up by practicing several swing movements until they expressed their readiness for the six swing movements in the formal experimental trials.

2.4. Data analysis
The three-dimensional kinematic data coordinates were exported using Nexus software and processed in Matlab (Mathworks, Natick, MA, USA). To eliminate noise due to artifacts, all coordinates were processed by using 4th order Butterworth low-pass filter and 6 Hz cutoff frequency before data management. The following outcome variables were calculated and analyzed.

2.4.1. Coordinate SD of the club tail at the turning point.
The turning point is defined as the three-dimensional position of the club tail at the time of transition from backswing to downswing (Fig. 2). Coordinate SD of the club tail at turning-point position was calculated and used to examine differences between elite and intermediate level golf players.

2.4.2. Minimum distance between sweet spot and ball.
When the center of gravity (CoG) of the club head is moving directly toward the CoG of the golf ball at impact, this provides the optimal energy transfer from the club head to the ball. This collision point is defined as sweet spot. Sweet spot is on the club surface from the center to nearer the top of the clubface. The minimum distance between the sweet spot on the club face and the golf ball was used to characterize the coherence of each impact between the club head and the golf ball as performed by each player. The sweet spot is believed to be on the lower one-third of the club face, near the bottom edge. Using three reflective markers placed on the club tail, the sweet spot can be easily identified by calculating its relative position. The golf ball was placed at a known position in the laboratory coordinate system. Shorter distances between these two points among trials of a player's swing movements indicate impact coherence.

2.4.3. Elevation angle.
The elevation angle (EA) is defined as the angle formed by the horizontal line and the face of the club's head (Fig. 3). The EA was used to characterize a player's capability of orienting the face of the club's head at impact phase to achieve an ideal travel distance of a ball.

2.4.4. Azimuth angle.
The azimuth angle (AA) is defined as the angle formed by the normal vector of the face of the club's head and the target line (Fig. 3). The target line is a horizontal line parallel to the player's feet and oriented toward the ball-flying direction. The AA was used to characterize a player's capability of orienting the face of the club's head at impact phase to achieve an ideal travel direction of a ball.

2.5. Statistical analysis
With unequal variances and sample sizes between the two groups, Welch's t-test was used to compare the differences between the elite and intermediate players. The level of significance was set at $\alpha < 0.05$. Statistical analyses were performed using SPSS 20.0.

Fig 1. Experiment setup.
Fig 2. Golf's swing movement. In this figure, T1 indicates taking-away phase, T2 indicated backswing phase, T3 indicates turning point, T4 indicates downswing phase, T5 indicates impact phase and rest is following phase.

Fig 3. Elevation and azimuth angle at impact of the swing movement.
3. RESULTS

The statistical results of variables in the elite and intermediate groups are summarized in Table.

3.1. SDs of the location of the club tail along the x, y, and z axes at the turning point

Results showed that there were significant differences in SDs of the location of the club tail in three-dimensional space at the top swing position between the elite and intermediate groups (Fig. 4). The elite group demonstrated significantly smaller SDs of the club tail along the x (p = 0.004, elite: 17.70 ± 5.11 mm; intermediate: 33.52 ± 15.18 mm), y (p = 0.015, elite: 14.52 ± 4.32 mm; intermediate: 23.17 ± 10.01 mm), and z (p = 0.035, elite: 18.97 ± 7.745 mm; intermediate: 27.77 ± 8.38 mm) axes compared with the intermediate group.

3.2. The minimum distance between the center of the sweet spot and the ball

Results showed that there was a significant difference in the minimum distance between the center of the sweet spot and the ball between the elite and intermediate groups (Fig. 5). The elite group demonstrated substantially shorter distances between the center of the sweet spot and the center of the ball at impact (p = 0.007, elite: 35.45 ± 17.75 mm; intermediate: 45.58 ± 19.94 mm).

3.3. The AA and EA angles of the club head right at impact

Results showed that there were significant differences in the AA and EAs of the club head at impact between the elite and intermediate groups (Fig. 6). The elite group had smaller AAs (p = 0.001, elite: 4.98º ± 3.99º; intermediate: 8.61º ± 5.92º) and greater EAs (p = 0.001, elite: 44.83º ± 6.70º; intermediate: 39.38º ± 8.62º) when compared with the intermediate group.

4. DISCUSSION AND IMPLICATIONS

Results from the current study provide empirical evidence of differences in biomechanical characteristics between the elite and intermediate groups during a golf swing. The following

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Table

Statistics summary of variables in the elite and intermediate groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Elite level</th>
<th>Intermediate level</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>xSD, mm</td>
<td>17.70</td>
<td>5.11</td>
<td>33.52</td>
</tr>
<tr>
<td>ySD, mm</td>
<td>14.52</td>
<td>4.32</td>
<td>23.17</td>
</tr>
<tr>
<td>zSD, mm</td>
<td>18.97</td>
<td>7.75</td>
<td>27.77</td>
</tr>
<tr>
<td>To SP mini, mm</td>
<td>35.45</td>
<td>17.75</td>
<td>45.58</td>
</tr>
<tr>
<td>EA, deg</td>
<td>44.83</td>
<td>6.70</td>
<td>39.38</td>
</tr>
<tr>
<td>AA, deg</td>
<td>4.98</td>
<td>3.99</td>
<td>8.61</td>
</tr>
</tbody>
</table>

Note: xSD, ySD, and zSD represent the SD of the location of the club tail along the x, y, and z axes at the turning point. To SP mini represents the minimum distance between the center of the sweet spot and the ball.

AA = azimuth angle; EA = elevation angle.

*p value <0.05.
subsections discuss the practical applications of each characteristic from our findings for developing coaching and practicing strategies.

4.1. SDs of the location of the club tail along the x, y, and z axes at the turning point

Our results showed that the location of the club tail at the turning point was more convergent in the elite group than it was in the intermediate group. More specifically, the difference was around 10 mm on average along each axis between groups. This finding supports the notion that the turning point is a decisive factor for successful play, which has long been recognized by professional golf players, even though it had not been investigated quantitatively. The location of the turning point by the end of the backswing provides an important division between the backswing and downswing. Keeping the locations of the turning point less varied across shots sets up a foundation for a stable and accurate trajectory of the downswing.

4.2. The minimum distance between the center of the sweet spot and the ball

Parallel to the findings regarding the turning point, our results showed that the distance between the center of the sweet spot and the ball at impact was about 10 mm shorter in the elite group. Interestingly, the quantity of group difference was similar to the results regarding the turning point. Although a direct comparison was not conducted, this finding highlights the close relationship between the variability of the location of the turning point and the distance to the center of the sweet spot when a ball is struck. That is, the more convergent the locations of the turning points are, the more convergent impact between sweet spot of the club’s surface and ball.

From world golf champions’ personal experiences, it has been mentioned that a good turning point makes for a wonderful downswing. However, many players have wondered whether this observation is only perceived by elite players, and would therefore not generalize to other players. Our findings provide quantitative evidence to support the claim that a stable turning point would result in an ideal impact at the sweet spot. The sweet spot is an area on the head of the club, and when a ball is struck by the sweet spot, the energy of the swing movement is most effectively transferred from the club to the ball.3 Based on the view of energy conversion, by the end of the downswing, the restored potential energy at the turning point would convert into kinetic energy, which would be released most efficiently if the ball were hit at the sweet spot.

Building from our findings, we further proposed that the turning point serves as a blind aiming point. It has been declared that once the location of the turning point is established at the end of the backswing, the trajectory of the downswing would be irreversible and the spot on the club where the ball is hit would be definite. Therefore, if we draw an analogy between golfing and shooting, then, like shooting, there is a procedure of “aiming” in golf. The turning point is considered as the “blind aiming point” as the eyes are fixed on the ball rather than on the turning point. With the continuity and chain reaction of the swinging movement in golf, stable manipulation of dynamic features of this blind aiming at the turning point plays a critical role in performing a perfect shot.

4.3. The EA and AA

The EA right after impact greatly determines the trajectory of a ball. Similarly, the loft angle, which varies from club to club, determines the distance a ball travels. In the current study, a P club was used and its standard loft angle was 52°. Our results showed that the elite group had greater EAs when compared with the intermediate group. Specifically, the difference between the average EA of the elite group (44°) and the standard loft angle of the P club (52°) was 5° less than that of the intermediate group (39°). This finding strongly suggests that the elite group was able to properly adapt the feature of the P club to produce a better EA at impact that would eventually lead to a better trajectory of the ball. On the contrary, the intermediate group demonstrated an EA far from the standard loft angle of the P club, which might have flattened the trajectory of the ball and resulted in an ineffective or inefficient shot. Taken together, the more convergent the locations of the turning points, the more similar the EA to the loft angle.

The AA right after impact significantly controls the direction of the ball. A perfect situation would be one in which the AA is equal to 0°, in which case the ball travels right along the target line. Findings from the current study showed that the elite group had smaller AAs compared with the intermediate group. Specifically, the average AA in the elite group (4°) was half of that in the intermediate group (8°). There is no doubt that the result of a tiny deviation from the target line at the very beginning would be amplified to an greater amount depending on the distance the ball travels. Therefore, even a slight difference in the AA between groups reflects a huge impact on the desired goal. Once again, our results implied that the more convergent the locations of the turning points are, the smaller the AA is.

Findings from the current study may provide a way to reevaluate the myth that the time right before impact is the most important moment for a successful shot. The rationale for this myth in traditional training is that the ideal EA mainly results from the adjustment of the face of a golf club nearing impact. However, such a strategy not only disrupts the fluency of a swing movement but also causes injury. As mentioned earlier, during the downswing, there is an irreversible feature of movements. Any sudden adjustment through additional movements in joints of the upper extremity during the process would interfere with energy flow. Therefore, we speculated that training should not focus on the phase of the downswing or the period close to impact, but on the turning point.

4.4. Applications

In this subsection, we provide two further applications of the results from the current study. First, our findings suggest that data regarding turning points, the minimum distance between the sweet spot and the ball, and the EA and AAs of the club head can be used as critical indicators for selecting new potential players in golf. Based on the results from the current study, the variability of locations of turning points profoundly influences the outcome at impact, as shown by the consequences regarding the sweet spot, the relationship between the EA and the loft angle, and the relationship between the AA and the target line.20 Accordingly, the stability of locations of turning points can be viewed as a powerful reference for identifying a gifted player. That is, the steadier the locations of turning points of multiple swings, the better the ability and potential of a player. There is no doubt that golf is a sport that demands the skill of precision. Stable performance at turning points may reflect a player’s talent for preparing the body for proper actions. Building on this ability, the skill of precision is expected to be further developed through appropriate coaching and practice focusing on the turning point.

Second, the methodology built in the current study displays a practical scientific approach to monitor the progression of a player and to record a player’s performance across a life-long career in golf. Traditional coaching relies heavily on a coach’s personal experiences and subjective visual investigation,21 which limit the capacity to detect a player’s performance characteristics during a swing. The methodology established in the current study provides a way to track a player’s learning process objectively.
and quantitatively. Moreover, compared with athletes in other sports, a golf player has a relatively long sports career. But, even the world’s top players encounter ups and downs in their professional performance. Until now, however, there has been no systematic and longitudinal method for recording and tracking these changes. Hence, the current situation is one in which players may randomly capture an ideal turning point with a sense of fluency during a swing, which results in a great performance, but they may not realize the underlying causes of improvement. Moreover, when players lose the ability, they may not be able to identify the most important barrier and search for solutions to regain their abilities and enhance their performance. The current study provides a feasible approach to solve this problem and suggests a shift in attention from the moment during impact to the period of time before the downswing.

In conclusion, the current study combines biomechanical principles and motion analysis techniques to investigate the swing characteristics of golf players. Findings from the current study show that the variability of locations of turning points, together with the distance between impact sites and the center of the sweet spot, and the EA and AAs of a club head during impact are essential indicators for identifying skill levels among players. It also supports the claim that this quantitative approach is valid and feasible for diagnosing swing behaviors of golf players. Our results further highlight the importance of the stability of locations of turning points. The training focus of swing movements, therefore, should pay extra attention to achieve ideal and stable turning points. In previous studies, a sequential association between attaining an optimal turning point and shifting the CoG to the leading leg has been noticed. This finding suggests that the dynamics among the turning point, the location of the ball, and the target line is essential for successful performance, which requires further examination in future studies.

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REFERENCES


