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Analysis of the delivery plane in the golf swing using principal components

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Abstract

Although the swing plane has been a popular area of golf biomechanics research, the movement of the club relative to the swing plane has yet to be shown experimentally to have a relationship with performance. This study used principal component and subsequent multiple regression analysis to investigate the relationship between the movement of the club relative to the delivery plane and clubhead characteristics at ball impact. The principal components generally reflected deviations from an individual swing plane, and lower values of these were associated generally with less variability in the club face impact location. Given a situation in which a golf coach wishes to improve the precision of ball striking, the results from this study suggest that both simplicity of the route and alignment of the club to the final trajectory before impact could be a

course of action. However, this does not to suggest technique should be based on a ‘model’ swing plane.

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Introduction

The swing plane in golf has received much attention from both coaching texts and academic study. Jenkins[1] suggested the concept of the swing plane dates back to the turn of the century with Seymour Dunn’s elliptical club path on an inclined plane. Many coaches since have given their own interpretation of the swing plane[2–4]. In each definition, it is the movement of the club or body relative to the plane that is under question.

The question of whether the golf swing occurs in a single plane has been investigated. Coleman and Anderson[5] investigated whether the club shaft could remain parallel to a single plane, by defining multiple planes from the club shaft in consecutive frames. While they suggested that the club movement could be fitted to one plane, the fit varied considerably between players. Kwon, Como, Singhal, Lee and Han[6] and Morrison, McGrath and Wallace[7] suggested an alternative which involved fitting the trajectory of one point to a plane. They found that the clubhead trajectory from mid downswing to impact[7] or from mid downswing to mid follow-through[6] fitted very well to a single plane. More recently, Morrison, McGrath and Wallace[8] quantified a strong relationship between the orientation of this trajectory based swing plane, or delivery plane, and the impact characteristics of the club. However, the method by which golfers manoeuvre the clubhead onto this plane has not been investigated.

Although previous research has shown the full golf swing not to be planar,[5,6] the degree to which the swing approaches planarity may still be relevant in relation to performance. As the intention of the downswing is to generate maximum clubhead speed at impact while maintaining consistency and accuracy, having the clubhead travel on a plane would be the simplest way to achieve this.[6] Although Kwon et al.[6] discussed the maximum deviation of the club head from the swing plane as being important, they did not relate this to skill level. They also attempted to define 'swing styles' from the club head deviation from the plane. However, there was no consideration of how these styles relate to outcome, therefore it is unclear how greater deviation from the swing plane would affect shot outcome. Additionally, as the last link in the kinetic chain, the hands play a major role in directing the clubhead. Therefore, the orientation of the shaft linking the hands and clubhead could also be a valid measure of the simplicity of the swing movement.

The relationship between technique measures and performance is of particular relevance to golf coaches as it is the basis of the analysis of the golf swing.[9,10] Decisions about technique alteration are based on their direct influence on the impact conditions, ball flight or shot outcome. While the relationship between technique and clubhead and ball speed have been established,[11,12] the relationship between technique and the direction and variability of shots has received little attention. This is possibly due to the complexity of the inter-relationships between the golf swing and these specific shot outcome variables.

This study investigated whether the deviation and orientation of the club head from the delivery plane during the swing had a relationship with the variability in the impact conditions between club and ball. As a delivery plane was calculated for every shot, it was the route by which the club arrived at the plane that was under question. It was hypothesised that a more direct route, i.e. having the club closer to the plane and with less of a shaft angle to the delivery plane, would be associated with decreased variability in the impact characteristics of the clubhead.

Methods

Participants

Fifty-two male golfers participated in this study: twenty-seven high skilled golfers with handicaps of 5 and below (mean ± SD: age 25.5 ± 7.5 yrs; mass 79.5 ± 11.5 kg; height

1.82 ± 0.04 m; handicap 0.6 ± 2.8), and twenty-five intermediate skilled golfers with handicaps from 10-18 (age 39.4 ± 11.2 yrs; mass 87.1 ± 11.3 kg; height 1.80 ± 0.07 m; handicap 13.2 ± 2.8). All participants provided written consent, and were free from injury at the time of testing. All procedures used in this study complied with the ethical approval granted by the University's review board.

Procedure

Twelve Oqus 300 cameras sampling at 1,000 Hz through Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden) software were used to collect and calculated the 3-dimesional coordinate data. Calibration residuals of the system were found to be 0.8mm. Three 12.7 mm diameter, spherical, retro-reflective markers were attached to the crown of the driver, along with two pieces of retro-reflective tape 20 cm apart attached near the top of the shaft. Five markers were attached to the club face for static capture (Figure 1). A small circular piece of retro-reflective tape was attached to the summit of the golf ball; during processing this was translated vertically down to represented the ball centre.

Figure 1. Clubhead marker setup. The five face markers were 6 mm diameter and located in the geometric centre of the club face and at the ends of the top and bottom groove of the clubface.

Golfers were asked to use their own drivers to maintain their natural technique. The clubhead markers weighed an additional 10 g, but no negative consequences of marker attachment were reported by the participants. This amount of weight adjustment has been shown not to be reliably detected by golfers, with little effect on performance.[13]

Testing took place in an indoor biomechanics suite. Participants hit from a golf mat into a net situated 10m away with a fairway and target projected onto it. The global x-axis was defined as being parallel to the ball-to-target line pointing towards the target, the zaxis was vertically up, and the y-axis was the cross product of the x- and z-axes. Participants performed a self-directed warm up, then hit 40 shots that were all captured for analysis regardless of the quality of the shot outcome. Players were encouraged to use the same shot strategy for each shot. A minimum 45 s break between shots and a 5 minute break after every 8 shots were enforced. Pilot work showed that with these precautions the players were able to avoid fatigue, evidenced by their clubhead speed not decreasing over the 40 shots.

Data analysis

To investigate the relationship between club movement relative to the plane and impact characteristics, a combination of principal component analysis (PCA) and multiple regression analysis was used. PCA can been used to reduce a data set while retaining much of the original information. This is achieved by taking a set of partially correlated variables and transforming them into a smaller set of orthogonal variables for more manageable analysis.[14] Due to the output variables, or principal components, being orthogonal they are ideal for multiple regression analysis. Therefore, the variables included in the PCA were those relating to the movement of the club during the swing. The subsequent principal components extracted would then but used as the predictor variable in the multiple regression analysis. The outcome variables for the multiple regression analysis were the variabilities in the impact characteristics of the club head.

The clubhead model used has previously been validated and was identical to that of Betzler, Monk, Wallace and Otto.[15,16] This model involved the five clubface markers being fitted to a sphere of radius 253 mm, and this sphere being tracked dynamically using the three crown markers. Before filtering, the last frame before impact was identified and the data after this were removed. This pre-impact frame was identified as the last frame in which the club head sphere centre and ball centre were less than their combined radii apart. Data were filtered using a zero-lag 4th order Butterworth filter. To minimise the distortion of the data near impact (the final frame), 20 data points were added for padding using linear extrapolation before filtering, and later removed.[17,18] Residual analysis was used to identify a cut-off frequency of 40 Hz.[19] The start of the trial was also trimmed up to the takeaway event. All data analysis was carried out in Matlab (R2014a, The Mathworks, Inc., Natick, MA, USA).

Impact characteristics were calculated using the same clubhead model and unfiltered data.[15,16] As the last frame before impact was unlikely to be the first contact between club and ball, even at 1000 Hz, cubic extrapolation was used to determine the time at which this occurred.[15,16] Impact characteristics were based on this between-frame time. Golf swing events used in the analysis were those used by Kwon et al.,[6] i.e. takeaway, mid-backswing (MBS), late backswing (LBS), top of the backswing, early downswing (EDS), mid-downswing (MDS), and impact. These were determined from the orientation of the shaft to the lab[6], except for takeaway, which was the time at which the club head velocity exceeded 0.5m/s away from the target, and impact which was described previously. Of the fifty-two players analysed for this study, two participants from the intermediate skilled group had swings that did not reach the late backswing event. While this study did not deem this to be 'incorrect' technique, these players were removed from all analyses. Removing the late backswing variables would have weakened the analysis; therefore, only 50 players were included.

A least squares orthogonal distance fitting method was used to fit the trajectory of the club face centre from mid downswing to impact to a plane for each shot, and defined as the delivery plane.[7] The club face centre was used as this is the intended strike point with the ball. The projection of this plane onto the xy reference plane was used to define its horizontal orientation. The angle of the projection to the x-axis represented the horizontal plane angle, for which a positive angle pointed right of the target. The angle of greatest slope between the delivery plane and x-y plane represented the vertical plane angle, for which an increasing angle approached vertical. The fit of the delivery plane to the trajectory of the club from mid downswing to impact had a mean RMSE of 1.1 mm per shot. This is comparable to Morrison et al.[7] and Kwon et al.[6].

The variables used in the PCA (Table 1) were based on the orthogonal deviation of the clubface centre from the plane, and the angle of the shaft to the plane, defined by the two shaft markers. The club face centre was chosen as it is also used to define the delivery plane here and in previous research.[7] Positive values for deviation were above the plane. A positive shaft angle means the club face centre was deviated more positively (above the plane) or less negatively (below the plane) from the plane than the hand.

A particular mishit in golf involves the club striking the ground before the ball. As the current study looked to investigate the relationship between technique and impact characteristics, a collision that occurs after the predictor variables and before the response variables could have had an undue influence on the any relationship. With over 2000 shots collected for the current study, ground strike detection needed to be automated in post-processing. A method was devised using pilot data of intentional ground strikes and clean strikes. A straight line was fitted to the clubhead speed in the last 10 frames for each shot. The median slope of the lines was then calculated for the 40 shots. An impact value was predicted from the median slope and the data point 10 frames pre-impact. If the actual clubhead speed was more than 0.75 m/s below the predicted clubhead speed, then the shot was deemed to be a ground strike and removed from the analysis. During the pilot this proved 100% accurate when compared with self-reported ground strikes. From the fifty players 2,000 golf shots were recorded, of which 65 were deemed to have been ground strikes and eliminated from the analysis. The most shots removed from one player was 18 shots. Nineteen players had shots removed.

Statistical analysis

The variables that were used in the PCA were taken at the first six events, not including impact (Table 1). Using the impact event as a predictor seemed redundant considering the purpose of the investigation was to establish any relationship between technique within the swing and impact characteristics. Backswing variables were included as the initial movement of the club directly impacts the position and orientation of the club at the top of the backswing, thus influencing the orientation and position of the club in the downswing. Maximum and minimum values were also included to capture any important data between events (Table 1). The swing variables were the mean values from the 40 shots, discounting the shots deemed to be ground strikes.

Table 1. Definitions of variables used in the principal component and regression analysis (MBS=Mid backswing, LBS=Late backswing, EDS=Early downswing, MDS=Mid downswing, MAD=median absolute deviation) (impact location refers to the predicted point on the club face sphere that the ball first makes contact before any compression occurs)

VARIABLES	DEFINITIONS
Input Variables for PCA (mean of repeated trials)	
Max. Deviation Backswing (cm)	Maximum orthogonal deviation of the club face centre from the delivery plane during the backswing (+ve and –ve values)
Max. Absolute Angle Backswing (deg)	Maximum value of the magnitude of the angle between the shaft and the delivery plane in the backswing (+ve values only)
Angle MBS (deg)	Angle between the shaft and the delivery plane at mid backswing (+ve and –ve values)
Deviation LBS (cm)	Orthogonal distance of the club face centre from the delivery plane at late backswing (+ve and –ve values)
Angle LBS (deg)	Angle between the shaft and the delivery plane at late backswing (+ve and –ve values)
Deviation Top (cm)	Orthogonal distance of the club face centre from the delivery plane at top of the backswing (+ve and –ve values)
Angle Top (deg)	Angle between the shaft and the delivery plane at the top of the backswing (+ve and –ve values)
Max. Absolute Angle Downswing (deg)	Maximum value of the magnitude of the angle between the shaft and the delivery plane in the downswing

Max. Deviation Downswing (cm)	Maximum orthogonal distance of the club face centre from the delivery plane during the downswing (+ve and –ve values)
Deviation EDS (cm)	Orthogonal distance of the club face centre from the delivery plane at early downswing (+ve and –ve values)
Angle EDS (deg)	Angle between the shaft and the delivery plane at early downswing (+ve and –ve values)
Deviation MDS (cm)	Orthogonal distance of the club face centre from the delivery plane at mid downswing (+ve and –ve values)
Max. Angle Full Swing (deg)	Maximum angle of the shaft above the delivery plane (+ve values only)
Min. Angle Full Swing (deg)	Minimum angle of the shaft below the delivery plane (-ve values only)
Multiple Regression Outcome Variables	
Clubhead speed MAD	Mean speed of the three crown markers, median absolute deviation of that value for each player
Club face angle MAD	Angle of the club face vector relative to the target line (XZ plane) evaluated at the impact location using a combination of the horizontal impact location, the radius of curvature of the bulge and the clubhead orientation. Median absolute deviation of that value for each player
Club path MAD	Angle of the clubhead trajectory at impact to the xz plane (right +ve). Median absolute deviation of that value for each player
Angle of attack MAD	Angle of the clubhead trajectory at impact to the xy plane (up +ve). Median absolute deviation of that value for each player
Horizontal and vertical impact locations MAD	The x and y coordinates of the ball impact location with the origin at the centre of the club face. Median absolute deviation of that value for each player
Mean distance from the centre of the face	Mean distance from the ball impact location to the centre of the club face across trials (i.e. accuracy of ball striking).
Distance from the centre of the face MAD	Median absolute deviation of the variable above for each player
Mean distance from the centre of the player's impact cluster	Centre of impact location cluster is taken as the mean ball impact location of the player's shots on the club face. This variable is the mean distance of each shot from this location across trials (i.e. precision of ball striking).
Distance from the centre of the player's impact cluster MAD	Median absolute deviation of the variable above for each player
Handicap	The official playing handicap of the player

For the PCA, many diagnostic factors were taken into account to ensure a robust analysis. As per Field,[14] any variables in the diagonal of the anti-image correlation matrix of less than 0.5 were excluded. As the output scores from the PCA were going to be used for multiple linear regressions, Varimax, an orthogonal rotation method, was used. Once the component scores were calculated, these were used as the predictor variables in the multiple regression analysis models. A stepwise method was used for entry of the variables, with entry criteria of $p < 0.05$ and removal at 0.10. Outliers were removed that did not meet the criteria set out by Field[14] for Standardised Residuals, Cooks Distance, Leverage and DFBetas. This was to ensure that outliers did not have an undue influence on the regression model. During the multiple linear regression analysis, one outlying player was removed for each of the following models due to not meeting these criteria: Distance from the centre of the player's impact cluster, clubhead speed MAD, horizontal impact position MAD, vertical impact position MAD, and distance from the centre of the player's impact cluster MAD. In four of the cases this was the same player.

Additionally, it was a concern that any regression results could be driven by inter-group difference between skill levels. Therefore, to verify that a similar pattern was observed in the individual skill level groups, the data was split by skill level and additional regression models were created. By observing the trends in these models, it could be verified if the overall regression was a universal trend.

The outcome variables for the regression analysis were the variability in the impact characteristics. The reason the variability in the impact characteristics were chosen as opposed to the impact characteristics themselves was due to the nature of the delivery plane. The delivery plane defined here changes with every shot and every player. Had the plane we used been fixed to the address position and target line, then deviations above the plane may have be associated with an impact path directed left, a steeper angle of attack[8] and possibly an open clubface to the path to create a fade, or vice versa for below the plane. However, as the plane defined here is fitted to the trajectory of the club head near impact, then swings where the path is left or right of the target would be treated the same. For instance, take a theoretical player with a "neutral" swing (plane not left or right) who sets up aiming left of the target and swings the club as normal (now left of the target) but with the clubface open to the path and hit a fade. The same player could setup aiming right of the target with the club face closed to the path and hit a draw. In both cases the deviation from the plane and the angle of the shaft to the plane would the same (accepting natural variation), as the swing plane would be pointing in a different direction. Therefore, it would be difficult to suggest that players with open club faces or steep angles of attack would swing differently relative to this type of swing plane. Therefore, regression models were created for the variability in those club head impact characteristics.

Regression models were created for the accuracy of strike (based on intention to strike the centre of the club face), precision of strike (repeatability of the impact location on the face regardless of location), and the median absolute deviation (MAD) of the 8 clubhead impact characteristics (Table 1). The variability of these impact characteristics were selected as they have been found to have a direct relationship with the variability of the launch conditions of the shot.[16] More specifically, face and path angle at impact have been shown to have a relationship to launch angle and ball spin.[20] Off centre impacts have been shown to have an effect on ball speed.[21] Angle of attack has been shown to affect shot distance through the launch angle[22]. With the lack of shot outcome data due to indoor testing, handicap was used as a representation of skill level in the regression analysis. It is accepted that this is not an accurate measure of skill level, and this remains a limitation of the study.

Results

The age of the intermediate skilled group was significantly higher than that of the high skilled group ($p<0.05$).

Principal components analysis

During the diagnostics for the PCA, four of the original 18 variables were removed due to having anti-image correlation values less than 0.5 or a correlation with another variable of 1 (Address angle and deviation, MBS deviation and MDS angle from the plane). With these 14 variables (Table 1) the Kaiser-Meyer-Olkin measure of sampling adequacy was 0.79, which was suggested to be ‘good’.[14] Bartlett’s test of sphericity was also found to be significant ($p<0.001$). As all communalities were greater than 0.7, the number of principal components was determined using Kaiser's criterion of retaining eigenvalues greater than 1.[14] Therefore, three principal components were extracted. The three principal components account for 84.7% of the variance in the original swing variables, with the individual components accounting for 42.8%, 26.8% and 15.1% respectively.

The highest correlations to PC1 were deviation from the plane at EDS ($r = 0.93$) and angle of the shaft to plane at the top of the backswing ($r = 0.9$). The highest correlation to PC2 was deviation from the plane at HBS ($r = 0.97$). The highest correlation to PC3 was the maximum absolute angle of the shaft to plane in the backswing ($r = 0.84$) (Figure 2).

Figure 2. Graph of the data from the rotated component matrix with variables ordered chronologically through the swing (correlations with a magnitude below 0.4 have been removed) (MBS = mid backswing, LBS = late backswing, Top = top of the backswing, EDS = early downswing, MDS = mid downswing, PC=principal component, Abs.=Absolute, Max.=Maximum)

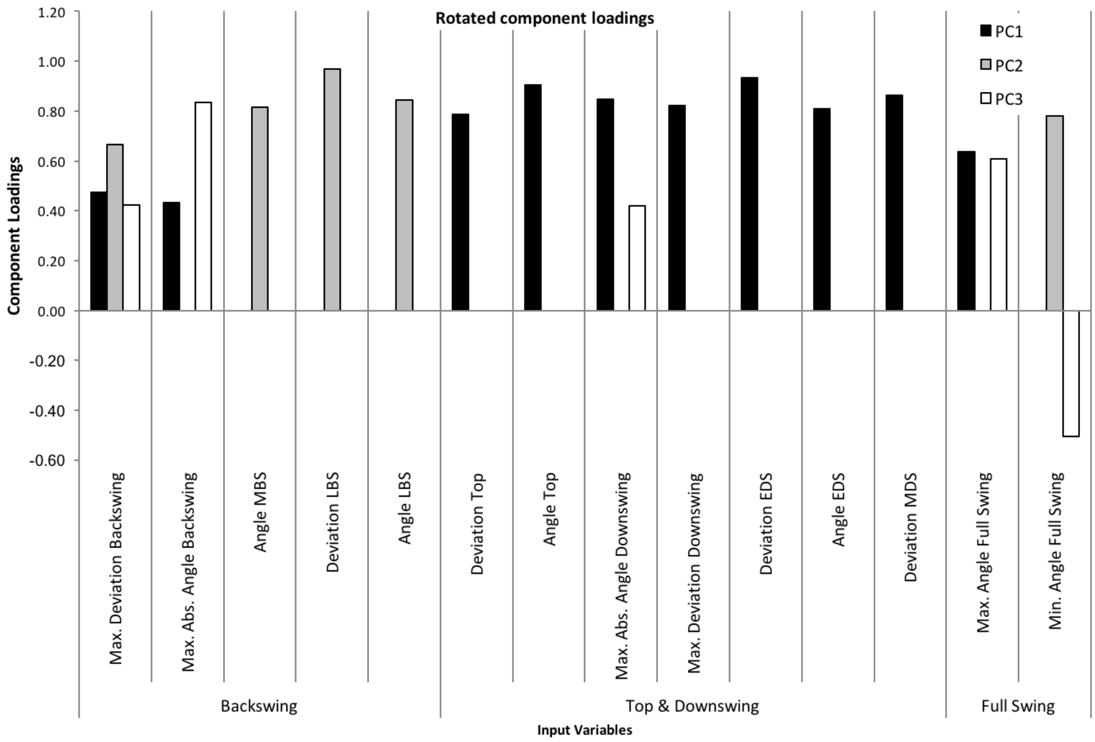
Rotated component loadings
PC1
PC2
PC3
Component Loadings
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
Max. Deviation Backswing
Max. Abs. Angle Backswing
Angle MBS
Deviation LBS
Angle LBS
Deviation Top
Angle Top
Max. Abs. Angle Downswing
Max. Deviation Downswing
Deviation EDS
Angle EDS
Deviation MDS
Max. Angle Full Swing
Min. Angle Full Swing
Backswing
Top & Downswing
Full Swing
Input Variables

Table 2. Regression models for impact characteristic variability and handicap. Coefficients (B) and standard error coefficients (σ_e) for multiple linear regression fits between principal components and outcome variables and R^2 values for the models. Variable with no R^2 values had no significant correlations and therefore no regression models were created. (MAD = Median absolute deviation)

	Constant		PC1		PC2		PC3		R^2
	B	σ_e	B	σ_e	B	σ_e	B	σ_e	
Handicap	6.440	0.694	2.630	0.701	-3.617	0.701	2.376	0.701	53.2%
Club head speed MAD (m/s)									
Face angle MAD (deg)	1.694	0.073			-0.227	0.074			16.5%
Club path MAD (deg)	0.710	0.032	0.085	0.032	-0.093	0.032			24.2%
Angle of attack MAD (deg)	0.642	0.027	0.070	0.028	-0.061	0.028			19.2%
Horizontal impact location MAD (mm)	6.720	0.196	1.007	0.205	-1.404	0.211			57.4%
Vertical impact location MAD (mm)	5.113	0.160	0.709	0.198	-0.680	0.159	0.503	0.209	43.5%
Distance from face centre (mm)	12.666	0.569	1.605	0.575	-2.232	0.575			32.7%
Distance from face centre MAD (mm)	4.910	0.198	0.492	0.200	-0.869	0.200			34.6%
Distance from impact cluster centre (mm)	9.315	0.252	1.299	0.311	-1.433	0.250	1.024	0.328	55.9%
Distance from impact cluster centre MAD (mm)	4.304	0.140	0.533	0.172	-0.667	0.138	0.466	0.182	45.5%

Multiple regression analysis

The highest values of R^2 were for horizontal impact location MAD, distance from the impact cluster centre and handicap, for each of which the principal components accounted for over 50% of the variability in the outcome variable (Table 2). No significant correlation was found for clubhead speed MAD, therefore, no regression model was created for that variable (Table 2).

Table 3. Means and standard errors of the predictor variables used to generate the principal components

Variables	All players		
	Mean		SE
Max. Deviation Backswing (cm)	31.5	±	2.3
Max. Absolute Angle Backswing (deg)	14.1	±	0.9
Angle MBS (deg)	-2.2	±	1.2
Deviation LBS (cm)	6.6	±	3.2
Angle LBS (deg)	-0.1	±	1.3
Deviation Top (cm)	26.8	±	2.2
Angle Top (deg)	5.5	±	1.3
Max. Absolute Angle Downswing (deg)	9.3	±	1.1
Max. Deviation Downswing (cm)	27.9	±	2.2
Deviation EDS (cm)	9.3	±	1.2
Angle EDS (deg)	1.8	±	5.8
Deviation MDS (cm)	0.2	±	0.1
Max. Angle Full Swing (deg)	12.4	±	6.8
Min. Angle Full Swing (deg)	-8.3	±	6.1

Table 4. Regression models for impact characteristic variability for each skill level group. Coefficients (B) and standard error coefficients (σ_e) for multiple linear regression fits between principal components and outcome variables and R^2 values for the models. Variable with no R^2 values had no significant correlations and therefore no regression models were created. (MAD = Median absolute deviation)

		Constant		PC1		PC2		PC3		R^2
		B	σ_e	B	σ_e	B	σ_e	B	σ_e	
High Skilled	Club head speed MAD (m/s)	0.397	0.022			-0.061	0.025			19.7%
	Face angle MAD (deg)									
	Club path MAD (deg)									
	Angle of attack MAD (deg)									
	Horizontal impact location MAD (mm)	6.206	0.285	0.627	0.29	-0.772	0.281	-0.85	0.306	38.3%
	Vertical impact location MAD (mm)	4.303	0.184			-0.534	0.211			20.4%
	Distance from face centre (mm)	12.301	0.821	2.534	0.837	-1.913	0.81	-2.636	0.881	42.9%
	Distance from face centre MAD (mm)	4.811	0.218	0.592	0.222	-0.895	0.215	-1.126	0.234	59.3%
	Distance from impact cluster centre (mm)	8.283	0.342	0.621	0.348	-1.055	0.337	-0.981	0.367	38.9%
	Distance from impact cluster centre MAD (mm)	3.93	0.175			-0.633	0.184	-0.452	0.195	35.5%
Intermediate Skilled	Club head speed MAD (m/s)									
	Face angle MAD (deg)									
	Club path MAD (deg)									
	Angle of attack MAD (deg)									
	Horizontal impact location MAD (mm)	7.507	0.337	1.089	0.296	-1.242	0.335			44.9%
	Vertical impact location MAD (mm)									
	Distance from face centre (mm)									
	Distance from face centre MAD (mm)									
	Distance from impact cluster centre (mm)	10.465	0.379	1.273	0.333	-1.267	0.377			44.1%
	Distance from impact cluster centre MAD (mm)	4.627	0.296	0.547	0.26	-0.671	0.295			22.4%

Table 5. Median and median absolute values (MAD) for plane orientation of both skill levels and all participants

	Horizontal plane angle			Vertical plane angle		
	Median		MAD	Median		MAD
All	0.4	±	4.4	49.7	±	2.3
High skill	1.6	±	3.5	49.5	±	1.2
Intermediate skill	-2.1	±	3.6	51.2	±	3.5

To corroborate the findings of the overall regression models, skill level regression models were also created (Table 4). These regression models appeared to follow similar trends to that found in the overall analysis. The highest R^2 values for the high and intermediate skilled group were also seen in the impact location related variables.

Discussion and Implications

This study has provided new insights into how the swing plane is related to the impact characteristics of the golf club. The hypothesis that the route and orientation of the club to the delivery plane was related to the impact characteristics has been corroborated in some cases. This was particularly evident in the impact location on the club face. The following discussion will examine the implications of these findings within golf coaching and biomechanics.

Delivery plane

As with previous studies,[6–8] the trajectory of the club head leading up to impact was found to fit well to a plane, reconfirming the validity of the chosen plane for analysis. The orientation of the plane was also similar to previous studies. The vertical angle of the plane of 49.7°

(Table 5) was similar to Morrison et al.[7] (44.6°-54.6°) and Kwon et al.[6] (47.2°±2.3°). Kwon et al. [6] also fitted a plane to the full downswing, which they found to be more upright than the plane near impact. Although in this study a plane was not fitted to the full downswing, the positive nature of the deviation of the club head from the plane at the top of the swing suggest that this would also have been the case in the current sample.

PCA interpretation

Although often found to be challenging,[23] the interpretation of the principal components here appear to show some useful structure. Before relating the principal components to impact variables, they will first be interpreted in their own right. The 1st principal component was positively correlated with variables mainly from the top of the backswing and the downswing (Figure 2). This suggests that, during the downswing, greater deviation from the plane and greater angle above the plane was associated with increasing values of the 1st principal component. This principal component also weakly correlated with maximum backswing values. These were above the cut-off of 0.4, but only marginally. Values considerably lower than the majority of the other component correlations can be discounted for interpretation.[24] In many cases the maximum backswing angle or deviation occurred at the top of the backswing, this small correlation may reflect this.

The 2nd principal component appeared to correlate positively with mainly backswing variables. This suggests that during the backswing greater deviation from the plane and greater shaft angle above the plane was associated with an increasing 2nd principal component. The 3rd principal component only correlated with maxima and minima variables. Minimum full swing angle had a negative correlation with the component. As the actual values for maximum and minimum angle in the full swing were either side of zero (Table 3), it appeared here that as the shaft angle to the plane moves away from zero in either direction, the 3rd principal component increases. The only deviation variable that correlated with this variable was maximum deviation in the backswing, but this was only 0.42. This is noteworthy, as while the angles to the plane appear to centre around zero, particularly in the high skilled group (Table 3), the variables regarding deviation from the plane do not.

Overall, it is interesting to note that the analysis separated the backswing and downswing variables. This would suggest that across the players the backswing and downswing varied separately, i.e. one type of backswing movement does not necessarily result in a specific downswing movement.

Multiple Regression Interpretation

Several strong relationships were found between technique and impact characteristics, but again interpretation should be undertaken carefully. It should be reiterated that the principal components are normalised for mean and standard deviation. Therefore, the linear equation derived from the model clearly cannot be used with angular or deviation values.

The highest values of R^2 observed in the analysis were related to the impact location of the ball on the club face, and this was corroborated by the separate skill group regressions. More specifically, the highest values related to ball striking precision (repeatability) as opposed to accuracy (proximity to the club face centre). The models relating to horizontal impact location MAD and distance from impact cluster centre showed R^2 values of 57.4% and 55.9% respectively. These variables represent the variability in the impact location without regard for the distance from the centre of the face. From the regression coefficients of both of these models it can be seen that outcome variables correlate positively with the 1st principal component and negatively with the 2nd principal component. From the interpretation of the PCA, this suggests that a more positive angle of the shaft and the deviation of the clubhead from the plane in the downswing are associated with increased variability in horizontal impact position. As previously stated, care should be taken with interpretation, and the original variables should be taken into account. In this case, the deviation of the club from the plane at the top of the backswing is highly positive (Table 3). Interpretations should not assume that the clubhead being on the plane will yield optimum results, as the means of both groups are very much above the plane.

The negative correlation with the 2nd principal component suggests that a more positive deviation and angle to the plane in the backswing is associated with less variability in horizontal impact location. With mean mid and late backswing shaft angle being negative here (i.e. the clubhead was further below the plane than the hands) (Table 3), it appears that the increased precision of ball striking is associated with a shaft angle close to parallel to the plane or a positive angle in the backswing. Conversely, a positive mean early downswing shaft angle and a positive correlation with the 1st principal component would suggest that increased precision of ball striking is associated with a shaft angle close to parallel or a negative angle to the plane in the downswing. In coaching terms, this would suggest taking the club back "outside" of the plane on the backswing, and on or "inside" the plane on the downswing would be advantageous. However, it should be reiterated that the plane is not fixed before the swing, and is only generated during delivery.

In the case of the distance from the impact cluster centre, there is also a positive correlation with the 3rd principal component. With this principal component also suggesting maxima and minima values approaching zero were associated with a reduction in the outcome variables, the overall interpretation changes very little: extreme distances and shaft orientations to the delivery plane are associated with increased impact location variability.

It has been shown previously that impact characteristic variability decreases with handicap[15]. Some of these correlations may simply be an artefact of the correlation with handicap. This suggests that the better players may be more highly coached, and have adopted this planar swing through coaching preference. However, it is of note that horizontal impact location MAD had a higher R^2 value than handicap, suggesting that this correlation goes beyond handicap alone and into an aspect of the outcome of the skill.

Other correlations were found with the principal components but most were well below 50% R^2 values. Distance of the impact location from the centre of the club face showed moderate positive and negative correlations with the 1st and 2nd principal components respectively (R^2 = 32.7%), similarly to the other impact location based variables. Although these correlations were significant, the findings should not be overstated, as there were inherent limitations in the analyses used. Although combining PCA and multiple regression analysis has been suggested as a viable statistical method, there are still potential errors involved. The three components extracted from the PCA accounted for 84.7% of the variance in the original swing variables, indicating some error in the prediction of the original variables. Carrying this error forward to the multiple regression analysis, the highest R^2 value had these principal components accounting for 57.4% of the outcome variable. The consecutive use of the two methods may therefore propagate this error. Rigorous diagnostics and high R^2 values of all impact location variables helps to verify the findings for the relationship between club movement and ball striking precision. However, other significant relationships with greater error in the fit should be interpreted with caution.

Implications

Overall the highest R^2 values were in the precision of ball striking (i.e. the repeatability of the strike), as opposed to the accuracy of striking the club face centre (i.e. proximity to the club face centre). From a motor control perspective, variability in club head location has been shown to decrease from the top of the backswing to impact,[7,25,26] which fits with the dynamical system approach which suggests that the body has to adapt to external variability in the environment and the task to produce the desired outcome.[27] Other authors have also suggested that there is no single technique model that will best achieve this.[28–30] The results presented here do not suggest an optimum golf swing technique, what they do suggest is that simplicity in the movement of the golf club during the swing is related to decreased variability in the impact, and potentially the performance. To arrive at the final trajectory of the golf club, characterised by the delivery plane, fewer manipulations of the club appeared to be favourable. Fewer manipulations in the swing may make it easier for the player to make to required adaptations to the environment suggested in dynamical systems theory. Further research is required to understand how the body segments are coordinated to arrive at this final trajectory. Although the way in which the body coordinates segments to reduce variability in club head orientation and impact location have been investigated,[26] research into the coordination towards the delivery plane is also recommended.

The findings here confirm the importance of minimising the deviations from this final trajectory, and this may be practically applicable for golf coaches. In their analysis of the golf swing, coaches are taught to identify the aspect of the flight of the ball that they wish to change, determine the impact characteristic that is causing the ball flight, and then make alterations to the aspect of technique that will change the impact characteristic in question [10,31]. Given a situation in which a golf coach wished to improve the precision of ball striking, simplifying the route of the golf club during the swing could be a suggested course of action. This type of intervention would ideally lead to a more consistent energy transfer between club and ball, and thus more consistent shot distance[16]. Additionally, more consistent impact location should result in more consistent launch conditions such as vertical and horizontal launch angle and ball spin rate resulting in more consistent shot direction.[16]

There are alternative explanations for the results presented here. It may be that the high skilled players have been coached towards a perceived swing template. However, no data was taken on the time playing the game or how much coaching they had received. There was also a significant difference in age between the two groups. While it is unlikely that the age difference itself would necessarily cause a difference in kinematics, a different generation of players may have been coached differently. For instance, McHardy et al.[32] suggested the existence of traditional and modern swings which involved differing mechanics. To examine this question fully would require an experimental protocol with an appropriate coaching intervention.

Importantly, the findings here do not suggest that the golf club should be swung relative to a plane that is set prior to the initiation of the movement as used in many coaching texts.[2,3,33] The delivery plane for each shot does not come into existence until the club reaches that portion of the swing. Two players with very different plane orientations may both keep the shaft parallel to the plane through the swing but have completely different looking swings. These findings suggest that simplicity of the route and alignment of the club to that are important in maximising striking precision, not that the technique should be based on a ‘model’ swing plane.

Conclusion

The movement of the golf club relative to the delivery plane during the golf swing was investigated in relation to the impact characteristics. The results suggest that less deviation of the club from the delivery plane was associated generally with less variability in the club face impact location. This is the first study to present findings of a possible relationship between the golf swing movement and the impact location variability. These findings may be applicable to coaches in their current methods of analysis of the golf swing.

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