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

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8 **Abstract**

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

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

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23

24 **Introduction**

25 The swing plane in golf has received much attention from both coaching texts and
26 academic study. Jenkins¹ suggested the concept of the swing plane dates back to the
27 turn of the century with Seymour Dunn’s elliptical club path on an inclined plane. Many
28 coaches since have given their own interpretation of the swing plane²⁻⁴. In each
29 definition, it is the movement of the club or body relative to the plane that is under
30 question.

31 The question of whether the golf swing occurs in a single plane has been investigated.
32 Coleman and Anderson⁵ investigated whether the club shaft could remain parallel to a
33 single plane, by defining multiple planes from the club shaft in consecutive frames.
34 While they suggested that the club movement could be fitted to one plane, the fit varied
35 considerably between players. Kwon, Como, Singhal, Lee and Han⁶ and Morrison,
36 McGrath and Wallace⁷ suggested an alternative which involved fitting the trajectory of

37 one point to a plane. They found that the clubhead trajectory from mid downswing to
38 impact⁷ or from mid downswing to mid follow-through⁶ fitted very well to a single
39 plane. More recently, Morrison, McGrath and Wallace⁸ quantified a strong relationship
40 between the orientation of this trajectory based swing plane, or delivery plane, and the
41 impact characteristics of the club. However, the method by which golfers manoeuvre
42 the clubhead onto this plane has not been investigated.

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

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

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

71 **Methods**

72 *Participants*

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

75 1.82 ± 0.04 m; handicap 0.6 ± 2.8), and twenty-five intermediate skilled golfers with
76 handicaps from 10-18 (age 39.4 ± 11.2 yrs; mass 87.1 ± 11.3 kg; height 1.80 ± 0.07 m;
77 handicap 13.2 ± 2.8). All participants provided written consent, and were free from
78 injury at the time of testing. All procedures used in this study complied with the ethical
79 approval granted by the University's review board.

80 *Procedure*

81 Twelve Oqus 300 cameras sampling at 1,000 Hz through Qualisys Track Manager
82 (Qualisys AB, Gothenburg, Sweden) software were used to collect and calculated the 3-
83 dimensional coordinate data. Calibration residuals of the system were found to be
84 0.8mm. Three 12.7 mm diameter, spherical, retro-reflective markers were attached to
85 the crown of the driver, along with two pieces of retro-reflective tape 20 cm apart
86 attached near the top of the shaft. Five markers were attached to the club face for static
87 capture (Figure 1). A small circular piece of retro-reflective tape was attached to the
88 summit of the golf ball; during processing this was translated vertically down to
89 represented the ball centre.

90



91

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

95

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

100 Testing took place in an indoor biomechanics suite. Participants hit from a golf mat into
101 a net situated 10m away with a fairway and target projected onto it. The global x-axis
102 was defined as being parallel to the ball-to-target line pointing towards the target, the z-

103 axis was vertically up, and the y-axis was the cross product of the x- and z-axes.
104 Participants performed a self-directed warm up, then hit 40 shots that were all captured
105 for analysis regardless of the quality of the shot outcome. Players were encouraged to
106 use the same shot strategy for each shot. A minimum 45 s break between shots and a 5
107 minute break after every 8 shots were enforced. Pilot work showed that with these
108 precautions the players were able to avoid fatigue, evidenced by their clubhead speed
109 not decreasing over the 40 shots.

110 ***Data analysis***

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

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

134 Impact characteristics were calculated using the same clubhead model and unfiltered
135 data.^{15,16} As the last frame before impact was unlikely to be the first contact between
136 club and ball, even at 1000 Hz, cubic extrapolation was used to determine the time at
137 which this occurred.^{15,16} Impact characteristics were based on this between-frame time.

138 Golf swing events used in the analysis were those used by Kwon et al.,⁶ i.e. takeaway,
139 mid-backswing (MBS), late backswing (LBS), top of the backswing, early downswing
140 (EDS), mid-downswing (MDS), and impact. These were determined from the
141 orientation of the shaft to the lab⁶, except for takeaway, which was the time at which the

142 club head velocity exceeded 0.5m/s away from the target, and impact which was
143 described previously. Of the fifty-two players analysed for this study, two participants
144 from the intermediate skilled group had swings that did not reach the late backswing
145 event. While this study did not deem this to be ‘incorrect’ technique, these players were
146 removed from all analyses. Removing the late backswing variables would have
147 weakened the analysis; therefore, only 50 players were included.

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

158 The variables used in the PCA (Table 1) were based on the orthogonal deviation of the
159 clubface centre from the plane, and the angle of the shaft to the plane, defined by the
160 two shaft markers. The club face centre was chosen as it is also used to define the
161 delivery plane here and in previous research.⁷ Positive values for deviation were above

162 the plane. A positive shaft angle means the club face centre was deviated more
163 positively (above the plane) or less negatively (below the plane) from the plane than the
164 hand.

165 A particular mishit in golf involves the club striking the ground before the ball. As the
166 current study looked to investigate the relationship between technique and impact
167 characteristics, a collision that occurs after the predictor variables and before the
168 response variables could have had an undue influence on the any relationship. With over
169 2000 shots collected for the current study, ground strike detection needed to be
170 automated in post-processing. A method was devised using pilot data of intentional
171 ground strikes and clean strikes. A straight line was fitted to the clubhead speed in the
172 last 10 frames for each shot. The median slope of the lines was then calculated for the
173 40 shots. An impact value was predicted from the median slope and the data point 10
174 frames pre-impact. If the actual clubhead speed was more than 0.75 m/s below the
175 predicted clubhead speed, then the shot was deemed to be a ground strike and removed
176 from the analysis. During the pilot this proved 100% accurate when compared with self-
177 reported ground strikes. From the fifty players 2,000 golf shots were recorded, of which
178 65 were deemed to have been ground strikes and eliminated from the analysis. The most
179 shots removed from one player was 18 shots. Nineteen players had shots removed.

180 *Statistical analysis*

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

190

191 **Table 1.** Definitions of variables used in the principal component and regression analysis
 192 (MBS=Mid backswing, LBS=Late backswing, EDS=Early downswing, MDS=Mid
 193 downswing, MAD=median absolute deviation) (impact location refers to the predicted point
 194 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

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197 For the PCA, many diagnostic factors were taken into account to ensure a robust

198 analysis. As per Field,¹⁴ any variables in the diagonal of the anti-image correlation

199 matrix of less than 0.5 were excluded. As the output scores from the PCA were going to
200 be used for multiple linear regressions, Varimax, an orthogonal rotation method, was
201 used. Once the component scores were calculated, these were used as the predictor
202 variables in the multiple regression analysis models. A stepwise method was used for
203 entry of the variables, with entry criteria of $p < 0.05$ and removal at 0.10. Outliers were
204 removed that did not meet the criteria set out by Field¹⁴ for Standardised Residuals,
205 Cooks Distance, Leverage and DFBetas. This was to ensure that outliers did not have an
206 undue influence on the regression model. During the multiple linear regression analysis,
207 one outlying player was removed for each of the following models due to not meeting
208 these criteria: Distance from the centre of the player's impact cluster, clubhead speed
209 MAD, horizontal impact position MAD, vertical impact position MAD, and distance
210 from the centre of the player's impact cluster MAD. In four of the cases this was the
211 same player.

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

217 The outcome variables for the regression analysis were the variability in the impact
218 characteristics. The reason the variability in the impact characteristics were chosen as

219 opposed to the impact characteristics themselves was due to the nature of the delivery
220 plane. The delivery plane defined here changes with every shot and every player. Had
221 the plane we used been fixed to the address position and target line, then deviations
222 above the plane may have been associated with an impact path directed left, a steeper
223 angle of attack⁸ and possibly an open clubface to the path to create a fade, or vice versa
224 for below the plane. However, as the plane defined here is fitted to the trajectory of the
225 club head near impact, then swings where the path is left or right of the target would be
226 treated the same. For instance, take a theoretical player with a “neutral” swing (plane
227 not left or right) who sets up aiming left of the target and swings the club as normal
228 (now left of the target) but with the clubface open to the path and hit a fade. The same
229 player could setup aiming right of the target with the club face closed to the path and hit
230 a draw. In both cases the deviation from the plane and the angle of the shaft to the plane
231 would be the same (accepting natural variation), as the swing plane would be pointing in a
232 different direction. Therefore, it would be difficult to suggest that players with open
233 club faces or steep angles of attack would swing differently relative to this type of
234 swing plane. Therefore, regression models were created for the variability in those club
235 head impact characteristics.

236 Regression models were created for the accuracy of strike (based on intention to strike
237 the centre of the club face), precision of strike (repeatability of the impact location on
238 the face regardless of location), and the median absolute deviation (MAD) of the 8

239 clubhead impact characteristics (Table 1). The variability of these impact characteristics
240 were selected as they have been found to have a direct relationship with the variability
241 of the launch conditions of the shot.¹⁶ More specifically, face and path angle at impact
242 have been shown to have a relationship to launch angle and ball spin.²⁰ Off centre
243 impacts have been shown to have an effect on ball speed.²¹ Angle of attack has been
244 shown to affect shot distance through the launch angle²². With the lack of shot outcome
245 data due to indoor testing, handicap was used as a representation of skill level in the
246 regression analysis. It is accepted that this is not an accurate measure of skill level, and
247 this remains a limitation of the study.

248 **Results**

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

251 *Principal components analysis*

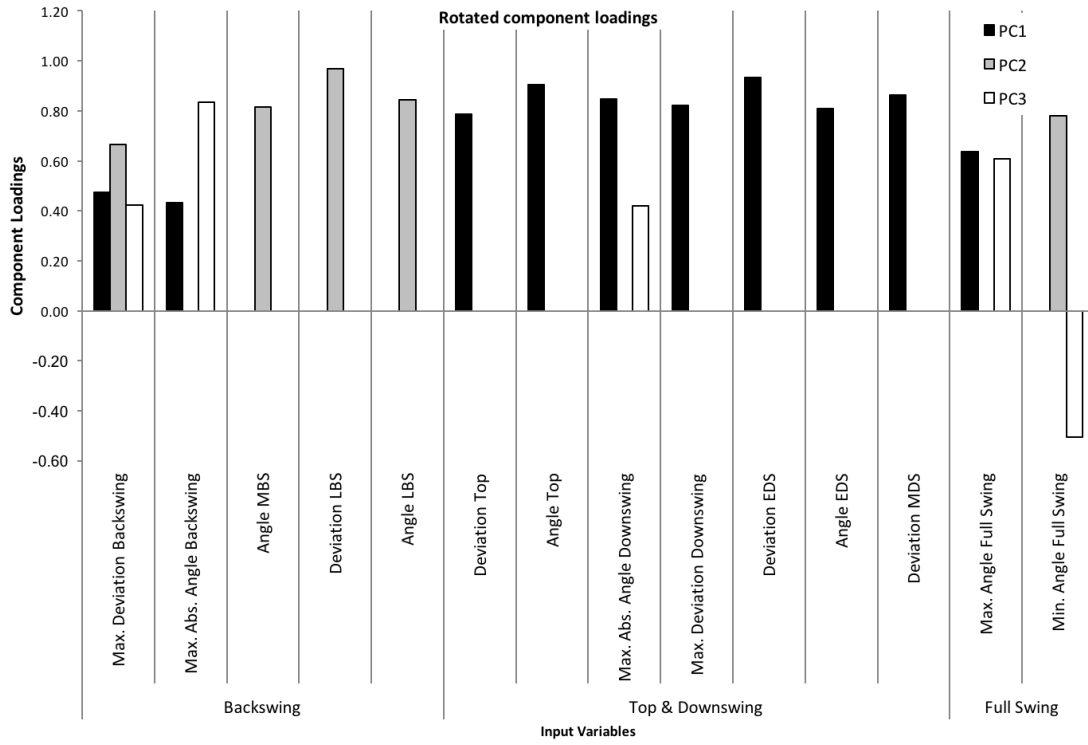
252 During the diagnostics for the PCA, four of the original 18 variables were removed due
253 to having anti-image correlation values less than 0.5 or a correlation with another
254 variable of 1 (Address angle and deviation, MBS deviation and MDS angle from the
255 plane). With these 14 variables (Table 1) the Kaiser-Meyer-Olkin measure of sampling
256 adequacy was 0.79, which was suggested to be 'good'.¹⁴ Bartlett's test of sphericity was
257 also found to be significant ($p < 0.001$). As all communalities were greater than 0.7, the

258 number of principal components was determined using Kaiser's criterion of retaining
259 eigenvalues greater than 1.¹⁴ Therefore, three principal components were extracted. The
260 three principal components account for 84.7% of the variance in the original swing
261 variables, with the individual components accounting for 42.8%, 26.8% and 15.1%
262 respectively.

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

268

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



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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%

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283

284 ***Multiple regression analysis***

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

290 **Table 3.** Means and standard errors of the predictor variables used to generate the principal
 291 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

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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%	

295

296 **Table 5.** Median and median absolute values (MAD) for plane orientation of both skill levels and all
 297 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

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

303

304 **Discussion and Implications**

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

311 ***Delivery plane***

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

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

320 *PCA interpretation*

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

332 The 2nd principal component appeared to correlate positively with mainly backswing
333 variables. This suggests that during the backswing greater deviation from the plane and
334 greater shaft angle above the plane was associated with an increasing 2nd principal
335 component. The 3rd principal component only correlated with maxima and minima variables.
336 Minimum full swing angle had a negative correlation with the component. As the actual
337 values for maximum and minimum angle in the full swing were either side of zero (Table 3),
338 it appeared here that as the shaft angle to the plane moves away from zero in either direction,

339 the 3rd principal component increases. The only deviation variable that correlated with this
340 variable was maximum deviation in the backswing, but this was only 0.42. This is
341 noteworthy, as while the angles to the plane appear to centre around zero, particularly in the
342 high skilled group (Table 3), the variables regarding deviation from the plane do not.

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

347 *Multiple Regression Interpretation*

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

352 The highest values of R^2 observed in the analysis were related to the impact location of the
353 ball on the club face, and this was corroborated by the separate skill group regressions. More
354 specifically, the highest values related to ball striking precision (repeatability) as opposed to
355 accuracy (proximity to the club face centre). The models relating to horizontal impact
356 location MAD and distance from impact cluster centre showed R^2 values of 57.4% and 55.9%
357 respectively. These variables represent the variability in the impact location without regard
358 for the distance from the centre of the face. From the regression coefficients of both of these
359 models it can be seen that outcome variables correlate positively with the 1st principal
360 component and negatively with the 2nd principal component. From the interpretation of the
361 PCA, this suggests that a more positive angle of the shaft and the deviation of the clubhead
362 from the plane in the downswing are associated with increased variability in horizontal

363 impact position. As previously stated, care should be taken with interpretation, and the
364 original variables should be taken into account. In this case, the deviation of the club from the
365 plane at the top of the backswing is highly positive (Table 3). Interpretations should not
366 assume that the clubhead being on the plane will yield optimum results, as the means of both
367 groups are very much above the plane.

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

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

385 It has been shown previously that impact characteristic variability decreases with handicap¹⁵.
386 Some of these correlations may simply be an artefact of the correlation with handicap. This

387 suggests that the better players may be more highly coached, and have adopted this planar
388 swing through coaching preference. However, it is of note that horizontal impact location
389 MAD had a higher R^2 value than handicap, suggesting that this correlation goes beyond
390 handicap alone and into an aspect of the outcome of the skill.

391 Other correlations were found with the principal components but most were well below 50%
392 R^2 values. Distance of the impact location from the centre of the club face showed moderate
393 positive and negative correlations with the 1st and 2nd principal components respectively (R^2
394 = 32.7%), similarly to the other impact location based variables. Although these correlations
395 were significant, the findings should not be overstated, as there were inherent limitations in
396 the analyses used. Although combining PCA and multiple regression analysis has been
397 suggested as a viable statistical method, there are still potential errors involved. The three
398 components extracted from the PCA accounted for 84.7% of the variance in the original
399 swing variables, indicating some error in the prediction of the original variables. Carrying
400 this error forward to the multiple regression analysis, the highest R^2 value had these principal
401 components accounting for 57.4% of the outcome variable. The consecutive use of the two
402 methods may therefore propagate this error. Rigorous diagnostics and high R^2 values of all
403 impact location variables helps to verify the findings for the relationship between club
404 movement and ball striking precision. However, other significant relationships with greater
405 error in the fit should be interpreted with caution.

406 ***Implications***

407 Overall the highest R^2 values were in the precision of ball striking (i.e. the repeatability of the
408 strike), as opposed to the accuracy of striking the club face centre (i.e. proximity to the club
409 face centre). From a motor control perspective, variability in club head location has been
410 shown to decrease from the top of the backswing to impact,^{7,25,26} which fits with the

411 dynamical system approach which suggests that the body has to adapt to external variability
412 in the environment and the task to produce the desired outcome.²⁷ Other authors have also
413 suggested that there is no single technique model that will best achieve this.²⁸⁻³⁰ The results
414 presented here do not suggest an optimum golf swing technique, what they do suggest is that
415 simplicity in the movement of the golf club during the swing is related to decreased
416 variability in the impact, and potentially the performance. To arrive at the final trajectory of
417 the golf club, characterised by the delivery plane, fewer manipulations of the club appeared to
418 be favourable. Fewer manipulations in the swing may make it easier for the player to make to
419 required adaptations to the environment suggested in dynamical systems theory. Further
420 research is required to understand how the body segments are coordinated to arrive at this
421 final trajectory. Although the way in which the body coordinates segments to reduce
422 variability in club head orientation and impact location have been investigated,²⁶ research
423 into the coordination towards the delivery plane is also recommended.

424 The findings here confirm the importance of minimising the deviations from this final
425 trajectory, and this may be practically applicable for golf coaches. In their analysis of the golf
426 swing, coaches are taught to identify the aspect of the flight of the ball that they wish to
427 change, determine the impact characteristic that is causing the ball flight, and then make
428 alterations to the aspect of technique that will change the impact characteristic in question
429 ^{10,31}. Given a situation in which a golf coach wished to improve the precision of ball striking,
430 simplifying the route of the golf club during the swing could be a suggested course of action.
431 This type of intervention would ideally lead to a more consistent energy transfer between
432 club and ball, and thus more consistent shot distance¹⁶. Additionally, more consistent impact
433 location should result in more consistent launch conditions such as vertical and horizontal
434 launch angle and ball spin rate resulting in more consistent shot direction.¹⁶

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

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

452 **Conclusion**

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

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