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The relationship between skill and ground reaction force variability in amateur golfers.

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1 Abstract

2 It is accepted that highly skilled golfers are more consistent in their clubhead presentation and shot
3 outcomes than their lesser skilled counterparts. However, the relationships between movement
4 variability, outcome variability and skill in golf are not particularly well understood. This study
5 examined the ground reaction force variability of one-hundred and four amateur golfers for shots
6 with drivers and 5-irons. Principal component analysis was used as a data reduction technique and
7 allowed all three components of ground reaction force to be considered together. There were
8 statistically significant trends for the higher skilled golfers to display lower variability in two of the
9 five principal components (driver) and four of the five principal components (5-iron). A similar trend
10 was also observed in the other principal components, but these trends were not statistically
11 significant. Intra-individual variability was much lower than inter-individual variability across all
12 golfers; the golfers were each relatively consistent in maintaining their own ground reaction force
13 patterns. Lower variability in ground reaction forces may partly explain how highly skilled golfers
14 maintain lower variability in shot outcomes.

15 Keywords

16 Golf, flexibility, variability, ground reaction force, principal component analysis.

17 Introduction

18 There is inter- and intra-individual variability in all repeated movements (Newell and Corcos, 1993),
19 even within the movements of elite athletes with many years of training and very high skill levels
20 (Bartlett et al., 2007). The study of movement variability has provided insight into the control and
21 coordination of sporting movement (for example, Carson et al., 2014; Hiley and Yeadon, 2016;
22 Tucker and Hanley, 2017) and interest in movement variability has grown in the biomechanics
23 community. Movement variability may even have a functional role in performance (for a review of
24 functional movement variability, see Preatoni et al., 2013): for example, by increasing adaptability
25 (e.g., Scott et al., 1997; Wheat et al., 2005) or varying internal loading (e.g. Hamill et al., 1999). Since
26 the movement constraints change from shot-to-shot in golf, functional movement variability allows
27 a golfer to dynamically adapt their swing mechanics to achieve the desired result.

28 Movement variability is often used to make inferences about motor control, in particular the
29 flexibility or stability of a movement. In the golf swing, flexibility relates to the golfers' ability to
30 'achieve the same task outcome using different movement solutions' (Ranganathan et al., 2020),
31 whereas stability relates to the golfers' resistance to change in response to perturbations (van
32 Emmerik et al., 2016). The relationship between movement variability and flexibility or stability is
33 complex and may change depending on the timescale or level of movement.

34 Movement variability can be examined over short timescales, where variability is between
35 repetitions of the same task (e.g., Bernstein, 1967) – repeated shots on a driving range – or longer
36 timescales where the task constraints or movement solutions can change dramatically (Ranganathan
37 et al., 2020) – over a round of golf or several coaching sessions. Similarly, movement variability can
38 occur across different levels of a movement. For instance, a joint or segment level, where
39 independent fluctuations may have negative connotations – variability at the wrist joint resulting in
40 an off-centre impact – or at the whole-body level where coordinated variability in several segments
41 may prove functional – wrist and arm variability compensating for differences in shoulder turn
42 (Woods et al., 2020). This presents a challenge to the researcher or practitioner as increased
43 variability may be functional or dysfunctional.

44 Whereas movement variability has been posited to include functional elements, outcome
45 consistency – or lower 'endpoint variability' – is an agreed feature of skilled performance in a wide
46 range of movement skills (Bootsma and van Wieringen, 1990; Robins et al., 2006; Tucker et al.,
47 2013). The ability to accurately reproduce the intended outcome is a fundamental part of the
48 definition of motor skill (Johnson, 1961). Therefore, outcome consistency in a repeated task is
49 fundamentally related to skill. Indeed, golfers with higher levels of skill display lower variability in
50 clubhead presentation, ball launch and shot outcome variables (Betzler et al., 2012; Kenny et al.,
51 2008; Tucker et al., 2013).

52 Despite the link between endpoint variability and skill, there does not appear to be a general
53 relationship between movement variability and skill. This has been exemplified by Busquets et al.
54 (2016), who reported that some parameters in the gymnastic long swing displayed a U-shaped
55 relationship between movement variability and skill (with moderately skilled gymnasts displaying the
56 least variability), whereas other parameters displayed inverse linear relationships between
57 variability and skill (with higher skilled gymnasts displaying less movement variability). These
58 differences may relate to the timescale or level of movement studied but, despite the lack of a
59 consistent rule, the study of movement variability and skill has provided useful insight into the
60 control and coordination of skilled movement (e.g. Seifert et al., 2013).

61 Whilst initially counter-intuitive, the consistent outcomes which characterise skilled performance
62 can be achieved in the presence of movement variability (James, 2004). Variability and consistency
63 are opposite terms (Bartlett et al., 2007) but variability in one part of a system (in this case, the
64 golfer) may be counteracted or obscured by variability in another part of the system. For instance,
65 Bootsma and Van Wieringen (1990) found that variability in the initiation timing of a table tennis
66 forehand was compensated for by variability in the mean acceleration during the shot. This example,
67 where one component of the system compensates for differences in another component to
68 maintain consistent task success, is commonly termed 'compensatory variability' (Bootsma and van
69 Wieringen, 1990; Robins et al., 2008). There are compelling arguments for the presence of
70 compensatory variability in the swings of skilled golfers (e.g., Morrison et al., 2016; Sweeny et al.,
71 2014).

72 The growing body of literature on variability in the golf swing has focussed on shot outcomes (e.g.,
73 Betzler et al., 2012; Corke, 2015; Kenny et al., 2008) or clubhead movements during the swing (e.g.,
74 Morrison et al., 2014, 2016; Tucker et al., 2013). Other studies have also investigated kinematic
75 variability in the golf swing (e.g., Bradshaw et al., 2009; Langdown et al., 2013a, 2013b; Parker et al.,
76 2016). Interestingly, several studies have found a pattern of decreasing variability during the
77 downswing for the clubhead, hand or arm (Horan et al., 2011; Morrison et al., 2014; Tucker et al.,
78 2013). However, research in this area is far from comprehensive (Glazier and Lamb, 2018) and, in
79 particular, research on the variability of ground reaction forces in the golf swing is scarce.

80 Ground reaction forces, which occur due to the interaction between the golfers' feet and the
81 ground, are an area of continued interest for biomechanists interested in the golf swing and have
82 been extensively studied (Barrentine et al., 1994; Lynn et al., 2012; Vaughan, 1981; Wallace et al.,
83 1994; Williams and Cavanagh, 1983a). These forces enable the golfer to generate segment rotation
84 velocities and centre of mass translations whilst maintaining balance. Practically, ground reaction
85 force variables can differentiate between golfers of different skill levels (e.g., Barrentine et al., 1994;
86 Lynn et al., 2012; Okuda et al., 2010) or increased clubhead or ball speed (e.g., Chu et al., 2010; Han
87 et al., 2019).

88 Whilst much is known about the kinematic variability, the variability of ground reaction forces has
89 not been extensively examined. Jones et al. (2018), presented an initial examination of ground
90 reaction force variability in a case study of three differently skilled golfers but was primarily focussed
91 on methodological issues. A detailed examination of ground reaction force variability should provide
92 useful insight for scientists or practitioners.

93 The aim of this investigation was to characterise the ground reaction force variability in a group of
94 amateur golfers and to relate this to handicap and outcome variability, both of which can be used as
95 indicators of skill. Inter-individual variability will be examined to provide context; how intra-
96 individual variability relates to the range of ground reaction force trajectories displayed by a large
97 group of golfers. Although the intra-individual variability of ground reaction forces during the golf
98 swing has not been examined in depth, previously described research in other sports suggests that
99 inverse linear relationships (decreasing variability with increasing skill) or U-shaped relationships
100 commonly describe the relationship between variability and skill. As the simpler of the two
101 relationships found in existing literature, we hypothesised that ground reaction force variability
102 would be linearly related to skill level, with higher skilled golfers displaying less ground reaction
103 force variability.

104

105 Methods

106 Participants

107 A sample of one-hundred and four amateur, right-handed golfers were recruited from local clubs to
108 participate in the study (Table 1). Participants covered a range of golfing ability, as defined by the
109 CONGU Unified Handicapping system (CONGU, 2018); Category 1 (handicap of 5 or less), Category 2
110 (handicap of 6 to 12), Category 3 (handicap of 13 to 20) and Category 4 (handicap of 21 and above).
111 Due to smaller numbers of participants in the higher handicap groups, Category 3 and Category 4
112 were grouped in all analysis. Participants provided written informed consent and were free of injury
113 at the time of testing. All procedures complied with the ethical approval granted prior to the
114 investigation by the ethical review board of (institution to be added after review) University.

115 *Table 1. Participant information (mean \pm standard deviation).*

Handicap group	N	Gender (M/F)	Age (Years)	Height (m)	Mass (kg)	Handicap
Category 1 (<5)	31	28/3	44.5 \pm 12.5	1.82 \pm 0.07	92.8 \pm 15.0	2.8 \pm 2.2
Category 2 (6-12)	35	31/4	56.6 \pm 12.9	1.81 \pm 0.07	91.1 \pm 12.0	8.7 \pm 2.1
Category 3+ (>13)	38	19/19	53.9 \pm 14.6	1.72 \pm 0.09	77.0 \pm 18.9	18.9 \pm 4.1

116 Procedures

117 Testing took place in an indoor laboratory with a large (7 m x 3 m) open door allowing shots to be
118 played onto an outdoor driving range. The laboratory was equipped with two motion capture
119 systems (Oqus 300+, Qualisys, Gothenburg, Sweden), one clubhead-focussed and another golfer-
120 focussed, and two force platforms (OR6-6-2000, AMTI, Watertown, MA), one under each foot and
121 securely covered with pieces of thin golf mat. All systems were synchronised using a Qualisys
122 analogue to digital converter, Qualisys Track Manager software and a single acoustic trigger at
123 impact. Data were collected at 1000 Hz (clubhead-focussed motion capture), 240 Hz (golfer-focussed
124 motion capture) and 1200 Hz (force platforms). The front edge of each force platform was
125 perpendicular to the target line and the global coordinate system was such that the origin was
126 oriented with the X-axis pointing away from the target (medio-lateral), the Y-axis perpendicular and
127 pointing forward (posterior-anterior) and the Z-axis vertical.

128 Retro-reflective markers were placed on the club and golfer as follows: 3 shaft markers (2 and 20 cm
129 below the grip and 2 cm above the hosel), 3 or 4 clubhead markers (as in Betzler et al., 2014; Corke
130 et al., 2019) and 4 foot markers (on the centreline of the shoe at the front and rear, and above the
131 first and fifth metatarsophalangeal joints).

132 A Doppler radar-based launch monitor (Trackman 3e, Trackman, Vedbæk) was used to measure ball
133 launch and shot outcomes, and previously described algorithms (Betzler et al., 2014; Corke et al.,
134 2019) were used to measure calculate clubhead presentation from the data captured by the
135 clubhead-focussed motion capture system. These variables were defined according to the
136 conventions reported by Betzler et al. (2014).

137 A set of five drivers and four 5-irons were built for the study. Clubs in each club type were matched
138 for key characteristics, including clubhead model and grip, except for shaft stiffness and with one
139 short club in each set to accommodate personal preferences (Table 2). Participants were informed of
140 the characteristics of the clubs and could try each in a self-directed warm-up and familiarisation
141 period, after which they chose one driver and one iron which they used during the main testing
142 session. Participants could select to hit shots from a range of tees or hit from the golf specific
143 artificial turf (for the 5-iron).

144 *Table 2. Characteristics of standardised drivers and 5-irons.*

		Club loft (°)	Club length (m)	Club mass (g)	Swingweight (Lorythmic)	Shaft stiffness
Driver	A	10.5	1.143	323.0	D1	X
	B	10.5	1.143	319.8	D1	S
	C	10.5	1.143	321.0	D1	R
	D	10.5	1.143	327.6	D1	L
	E	10.5	1.105	329.0	C9	L
Iron	A	24.5	0.953	427.8	D1	X
	B	24.5	0.953	430.2	D1	S
	C	24.5	0.953	424.0	D1	R
	D	24.5	0.927	433.2	C9	R

145 Participants were asked to hit two sets of at least five valid shots with each club (starting with the
 146 driver), aimed toward a target positioned approximately 230 m downrange. Valid shots were those
 147 in which valid data were recorded by all measurement systems. On some occasions, issues with a
 148 shot’s data were not discovered until after testing or data could be recovered from a previously
 149 discarded shot, so the number of valid shots per golfer ranged between 8 and 14 with the driver
 150 (mean = 11.54, standard deviation = 0.94) and between 6 and 18 with the 5-iron (mean = 11.50,
 151 standard deviation = 1.41). Rather than discard a proportion of the overall data, all valid shots were
 152 analysed (1201 driver shots and 1196 iron shots in total).

153 **Data analysis**

154 Data were exported from Qualisys Track Manager and exported into MATLAB 2019b (Mathworks,
 155 Natick, MA). The timing of key swing events (namely takeaway, top of backswing and impact) were
 156 calculated from the club movements (as in Ball and Best, 2007). Data analysis procedures were the
 157 same for the total and the front-/rear-foot ground reaction forces (included in supplement).

158 As the focus of the investigation was primarily intra-individual variability, the ground reaction forces
 159 were normalised by dividing them by the participant’s bodyweight (measured during a static trial).
 160 This was primarily driven by an a priori hypothesis that intra-individual variability would not be
 161 related to bodyweight and that normalisation would simplify interpretation of the results.
 162 Preliminary post-hoc analysis was conducted to confirm that this assumption was justified. Whilst
 163 inter-individual variation was strongly related to differences in bodyweight, intra-individual
 164 variability was weakly related to bodyweight.

165 Principal component analysis, previously used to identify patterns in golfers’ ground reaction force
 166 data (e.g., Lynn et al., 2012; Smith et al., 2017), was used as a method of data reduction, enabling
 167 variability in the three components of ground reaction force across the swing to be reduced to a
 168 small number of principal component scores.

169 All potential methods for creating equal length signals have some compromise, as comparing like for
 170 like in both time and space is not possible for a movement with varying length. To create signals of
 171 equal length in the present study, ground reaction forces were aligned at impact and trimmed to the
 172 length of the shortest swing (from takeaway to impact). The shortest time from takeaway to impact
 173 was 0.77 s (925 frames) and the average amount trimmed from each trajectory was 0.33 s (394
 174 frames). Alternative methods of alignment, including linear length normalisation and dynamic time
 175 warping (e.g. Helwig et al., 2011), were considered, but this basic method was preferred because (i)
 176 the other methods distort the differentials of the signals and (ii) because the period of interest was
 177 primarily the downswing (not the initial movements after takeaway).

178 The data collected formed an $n \times m \times p$ array; where n was the number of shots measured (2397), m
179 was the number of components of ground reaction force (3) and p was the length of the time series
180 (925 frames). To understand the overall variability, a principal component analysis was performed
181 which considered the three components collectively. The data were reshaped to form a single $n \times (m$
182 $\times p)$ matrix (2397 x 2775) where each shot was in a single column containing the three components
183 of ground reaction force. After the principal component analysis was performed, using MATLAB's
184 inbuilt *pca* function, the mean trajectory and the principal component coefficients were reshaped to
185 the original dimensions.

186 The variance explained by each principal component was examined and the first five components
187 selected for analysis. This selection considered both the overall variance explained by the principal
188 components and the reconstruction error. For the combined ground reaction force, these principal
189 components explained 77.7% of the variance in the data; individually explaining 34.9, 25.0, 7.7, 5.3
190 and 4.8% respectively. Data reconstructed from only these five components had a mean root mean
191 square difference of 0.05 bodyweights when compared to the original data. Single component
192 reconstruction (Brandon et al., 2013) was used to visualise the effect of each principal component.

193 Each principal component score indicated the amount which features, described by the principal
194 components, were present in that individual swing. Inter-individual variability was examined using
195 each golfer's median principal component scores (five for each club, representing their median
196 ground reaction force trajectory with that club). Intra-individual variability was examined using each
197 golfer's median absolute deviation of principal component scores (five for each club, representing
198 the variability of their ground reaction force trajectories with that club). For each club, the
199 relationship between handicap category and inter-individual variability and intra-individual
200 variability were assessed using Kruskal-Wallis tests.

201 A non-parametric test was used because Levene's test indicated differences in variance between the
202 groups, violating the assumption of homogeneity of variance required for an ANOVA test. The
203 median absolute deviation (mad) was calculated as the median of absolute differences from the
204 median. Median-based measures of central tendency and variability were used as these are less
205 sensitive to outliers (Pham-Gia and Hung, 2001).

206 In the case of statistically significant results, a Jonckheere-Terpstra test was used to assess whether
207 these differences were ordered, since meaningful differences were assumed to be ordered across
208 handicap category groups. Separate statistical tests were performed for each club using a Bonferroni
209 corrected significance level of $\alpha = 0.005$ (0.05/10; where 10 was determined based on the 5 principal
210 components multiplied by 2, the number of clubs, in each instance). Descriptive statistics were also
211 calculated for the swing timing, clubhead presentation, ball launch and shot outcome data, but no
212 statistical analysis was performed on this data.

213 Results

214 Clubhead presentation, ball launch and shot outcome variability

215 As expected, the lower handicap categories displayed higher clubhead speed, ball speed and total
 216 distance (Table 3). The average deviation from the target line (total side) was also smaller for lower
 217 handicap golfers; indicating that they not only hit the ball further, but with greater accuracy. The
 218 intra-individual variability of clubhead presentation variables was lower for golfers in the lower
 219 handicap categories with both the driver and iron clubs (Table 4). Golfers in lower handicap
 220 categories tended to take less time to complete the downswing (Table 5).

221 Table 3. Average clubhead speed, ball launch and shot outcome (median ± mad).

	Handicap group	Clubhead speed (m/s)	Ball speed (m/s)	Launch angle (°)	Spin (rad/s)	Total distance (m)	Total side (m)
Driver	Category 1 (<5)	44.3 ± 2.4	63.6 ± 3.5	11.5 ± 1.8	348.7 ± 49.4	219.8 ± 13.4	0.6 ± 11.0
	Category 2 (6-12)	40.2 ± 3.0	57.3 ± 4.1	11.2 ± 2.7	320.2 ± 71.2	192.4 ± 15.8	5.2 ± 9.8
	Category 3+ (>13)	33.2 ± 4.5	47.2 ± 6.5	11.4 ± 2.7	323.8 ± 89.0	149.1 ± 31.8	6.2 ± 9.8
Iron	Category 1 (<5)	37.0 ± 1.8	52.9 ± 3.2	13.7 ± 1.8	485.1 ± 59.3	167.8 ± 10.1	0.9 ± 6.6
	Category 2 (6-12)	33.2 ± 2.4	47.3 ± 3.8	13.3 ± 2.6	416.5 ± 61.6	148.1 ± 15.8	0.0 ± 6.9
	Category 3+ (>13)	27.9 ± 3.9	38.8 ± 5.8	14.3 ± 2.6	372.1 ± 88.9	115.1 ± 26.3	0.2 ± 7.5

222 Table 4. Intra-individual variability of clubhead presentation variables (median intra-individual mad ± mad).

	Handicap group	Clubhead speed (m/s)	Face angle (°)	Effective loft (°)	Attack angle (°)	Club path (°)	Horizontal impact location (mm)	Vertical impact location (mm)
Driver	Category 1 (<5)	0.2 ± 0.1	1.1 ± 0.2	0.7 ± 0.2	0.5 ± 0.1	0.5 ± 0.2	5.0 ± 1.2	3.9 ± 1.0
	Category 2 (6-12)	0.3 ± 0.1	1.7 ± 0.5	1.0 ± 0.3	0.5 ± 0.1	0.7 ± 0.2	6.0 ± 1.6	4.9 ± 1.4
	Category 3+ (>13)	0.3 ± 0.1	2.0 ± 0.7	1.5 ± 0.5	0.8 ± 0.2	0.7 ± 0.2	8.3 ± 2.1	6.1 ± 1.7
Iron	Category 1 (<5)	0.2 ± 0.1	1.0 ± 0.3	0.8 ± 0.3	0.4 ± 0.1	0.6 ± 0.1	3.6 ± 0.9	3.2 ± 1.0
	Category 2 (6-12)	0.2 ± 0.1	1.4 ± 0.4	1.2 ± 0.3	0.6 ± 0.1	0.8 ± 0.2	5.2 ± 1.4	4.2 ± 0.5
	Category 3+ (>13)	0.3 ± 0.1	2.4 ± 0.5	1.7 ± 0.5	0.9 ± 0.3	0.8 ± 0.3	7.5 ± 2.0	5.5 ± 1.5

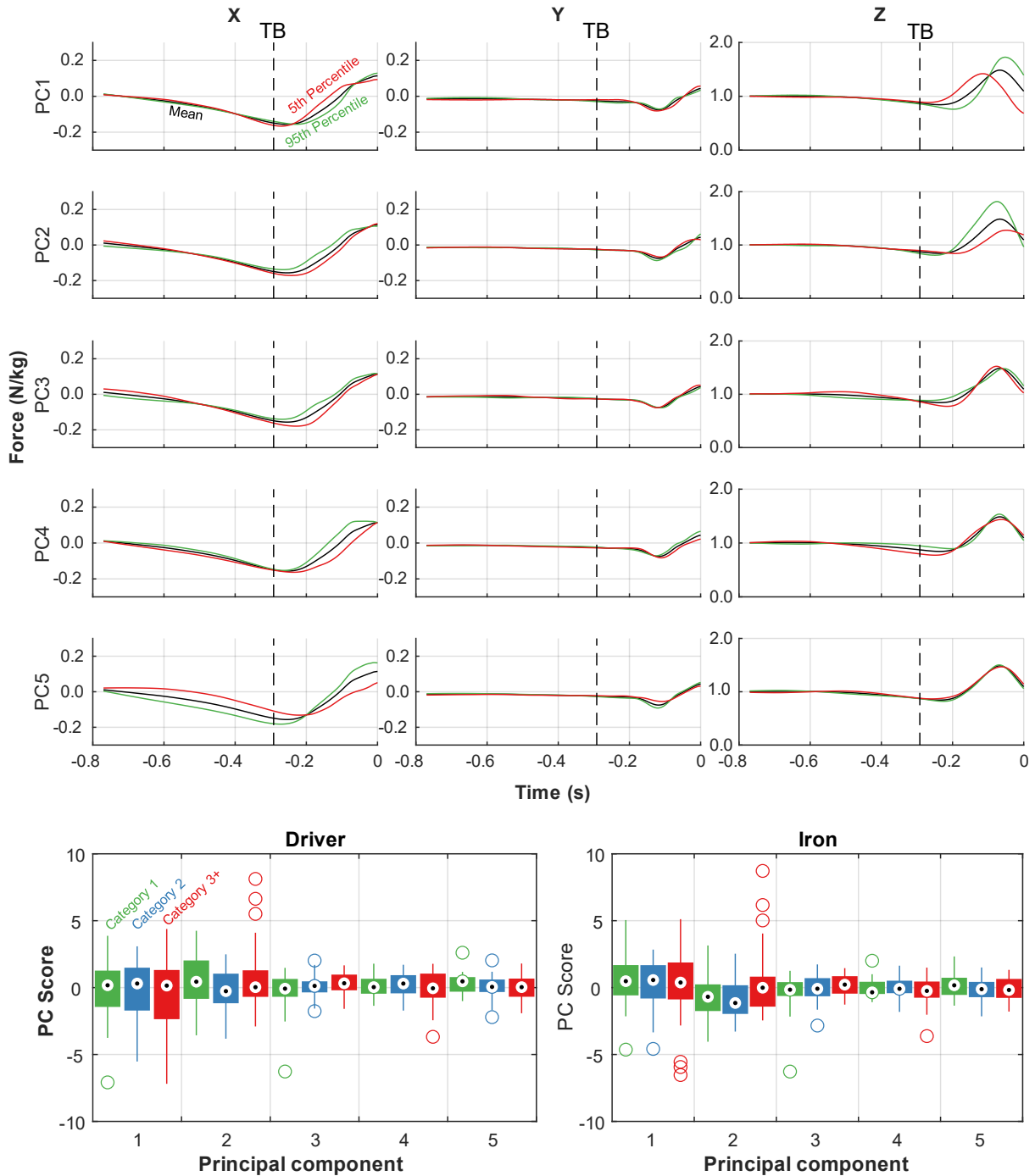
223 Table 5. Average backswing and downswing time (median ± mad) and intra-individual variability of swing time (median
 224 intra-individual mad ± mad).

	Handicap Group	Backswing time (s)	Downswing time (s)	Backswing time variability (s)	Downswing time variability (s)
Driver	Category 1 (<5)	0.804 ± 0.250	0.250 ± 0.096	0.013 ± 0.004	0.005 ± 0.001
	Category 2 (6-12)	0.775 ± 0.251	0.251 ± 0.088	0.015 ± 0.004	0.005 ± 0.002
	Category 3+ (>13)	0.840 ± 0.313	0.313 ± 0.106	0.018 ± 0.006	0.006 ± 0.002
Iron	Category 1 (<5)	0.750 ± 0.079	0.246 ± 0.020	0.013 ± 0.009	0.004 ± 0.005
	Category 2 (6-12)	0.731 ± 0.075	0.245 ± 0.066	0.013 ± 0.008	0.004 ± 0.004
	Category 3+ (>13)	0.796 ± 0.100	0.309 ± 0.038	0.017 ± 0.012	0.005 ± 0.007

225

226 Principal component analysis

227 The analysis yielded similar conclusions for the combined, front- and rear-foot ground reaction
228 force. For brevity, only the full analysis of the combined ground reaction force is presented here and
229 front- and rear-foot analyses are presented in the supplement.



230

231 *Figure 1. Single component reconstructions for the first five principal components (PC1-5; top) and principal component*
232 *scores for each handicap group and club (bottom). The average time for the top of backswing event (TB) is indicated by the*
233 *dashed line on the force-time trajectories. Median values are displayed as dots on the box plots.*

234

235 The single component reconstruction plots for the first five principal components show the features
 236 described by each principal component (Figure 1). The first principal component (PC1) primarily
 237 described an increase in peak vertical ground reaction force and a shift toward this occurring later in
 238 the swing. The second principal component (PC2) described an increase in peak vertical ground
 239 reaction force and (smaller) shift toward this occurring earlier. This component also described a
 240 more positive medio-lateral ground reaction force in the downswing. The third principal component
 241 (PC3) described a shift in peak vertical ground reaction force, toward this occurring later, lower
 242 vertical ground reaction force in the backswing and more positive medio-lateral ground reaction
 243 force in the downswing. The fourth principal component (PC4) described more positive medio-
 244 lateral ground reaction forces, a small increase in peak vertical ground reaction force and a
 245 sharpening of the peak in vertical ground reaction force. The fifth principal component (PC5)
 246 described an increase in the magnitude of medio-lateral ground reaction force and a shift toward
 247 peak negative medio-lateral ground reaction force occurring earlier in the swing. This component
 248 also described an increase in peak anterior-posterior ground reaction force.

249 Statistical tests did not indicate any differences between the group medians in the principal
 250 component scores (Table 6). This suggested that there was not a relationship between a golfers'
 251 ground reaction force trajectory and their handicap because differences did not tend to reflect the
 252 ordered nature of the groups.

253 *Table 6. Average principal component scores for each handicap group and club (median ± mad).*

	Handicap group	PC1	PC2	PC3	PC4	PC5
Driver	Category 1 (<5)	0.17 ± 1.27	0.44 ± 1.30	-0.08 ± 0.65	0.04 ± 0.53	0.47 ± 0.54
	Category 2 (6-12)	0.30 ± 1.60	-0.27 ± 1.20	0.13 ± 0.46	0.30 ± 0.67	0.05 ± 0.54
	Category 3+ (>13)	0.15 ± 2.00	0.03 ± 0.98	0.32 ± 0.63	-0.05 ± 0.80	0.03 ± 0.70
	$\chi^2(2, N = 101)$	0.32	3.12	2.53	0.48	2.44
	P_{K-W}	0.851	0.210	0.282	0.788	0.296
	z	-	-	-	-	-
	P_{J-T}	-	-	-	-	-
Iron	Category 1 (<5)	0.48 ± 1.08	-0.69 ± 0.97	-0.16 ± 0.54	-0.35 ± 0.47	0.17 ± 0.69
	Category 2 (6-12)	0.57 ± 1.19	-1.15 ± 1.19	-0.08 ± 0.59	-0.09 ± 0.48	-0.12 ± 0.57
	Category 3+ (>13)	0.38 ± 1.41	-0.01 ± 0.93	0.22 ± 0.67	-0.25 ± 0.69	-0.18 ± 0.69
	$\chi^2(2, N = 101)$	0.19	6.84	1.65	0.66	1.90
	P_{K-W}	0.910	0.033	0.439	0.718	0.387
	z	-	-	-	-	-
	P_{J-T}	-	-	-	-	-

254

255 **Intra-individual variability**

256 The median absolute deviation of a golfer’s principal component scores indicated the intra-
 257 variability of the features highlighted by each of the principal components. There was a general
 258 pattern of decreasing variability from handicap Category 3+ through to handicap Category 1 for all
 259 principal components with both the driver and the 5-iron and these differences were statistically
 260 significant in six of the ten principal components (Table 7). This general pattern was also observed in
 261 the separate force platforms but was only statistically significant for four of the principal
 262 components of the rear-foot ground reaction force (analysis included in the supplement) and none
 263 of the principal components of the front-foot ground reaction force.

264 *Table 7. Intra-individual variability of principal component scores for each handicap group and club (median ± mad).*

	Handicap group	PC1	PC2	PC3	PC4	PC5
Driver	Category 1 (<5)	0.32 ± 0.10	0.24 ± 0.08	0.14 ± 0.05	0.12 ± 0.04	0.10 ± 0.04
	Category 2 (6-12)	0.32 ± 0.05	0.23 ± 0.05	0.15 ± 0.04	0.13 ± 0.04	0.11 ± 0.03
	Category 3+ (>13)	0.43 ± 0.15	0.28 ± 0.08	0.18 ± 0.05	0.15 ± 0.06	0.16 ± 0.04
	$\chi^2(2, N = 101)$	4.76	6.34	8.63	3.81	16.49
	P_{K-W}	0.092	0.042	0.013	0.149	< 0.001
	z	-	2.24	2.97	-	3.87
	P_{J-T}	-	0.013	0.001	-	< 0.001
Iron	Category 1 (<5)	0.24 ± 0.07	0.18 ± 0.04	0.11 ± 0.04	0.08 ± 0.03	0.11 ± 0.02
	Category 2 (6-12)	0.29 ± 0.07	0.25 ± 0.07	0.15 ± 0.03	0.10 ± 0.03	0.11 ± 0.03
	Category 3+ (>13)	0.42 ± 0.08	0.27 ± 0.13	0.19 ± 0.08	0.14 ± 0.04	0.11 ± 0.03
	$\chi^2(2, N = 101)$	20.71	6.98	8.72	12.41	0.42
	P_{K-W}	< 0.001	0.030	0.013	0.002	0.810
	z	4.25	2.63	2.93	3.49	-
	P_{J-T}	< 0.001	0.004	0.002	< 0.001	-

265

266 Discussion and Implications

267 The aim of this investigation was to characterise the ground reaction force variability of amateur
268 golfers and to relate this to handicap and outcome variability. Inter-individual variability was also
269 examined, as this provides a useful context for the main results.

270 The ground reaction force patterns of the golfers in this investigation can be characterised as
271 relatively consistent because the average intra-individual variability in principal component scores
272 were much lower than the inter-individual variability. For example, with a driver, Category 1 golfers
273 displayed an average intra-individual variability in the first principal component (PC1) of 0.32 (Table
274 7) whilst the corresponding inter-individual variability was 1.27 (Table 6). For comparison, the
275 average intra-individual variability of Category 3+ golfers in this component was 0.43 (Table 7). This
276 suggests that amateur golfers of all skill levels have a relatively consistent individual pattern, when
277 compared to the range of different patterns displayed by the population; as also found in previous
278 research (Barrentine et al., 1994; Williams and Cavanagh, 1983b).

279 There was also an indication that intra-individual variability in ground reaction force was lower for
280 higher skilled golfers, which is a novel finding. For the combined front- and rear-foot ground reaction
281 forces the intra-individual variability in principal component scores suggested that, with the driver,
282 higher skilled golfers were less variable in the features described by the third and fifth principal
283 components (PC3 and PC5). These components were associated with the timing of peak vertical
284 ground reaction force (PC3), the magnitude of vertical ground reaction force in the backswing (PC3)
285 and the magnitude of medio-lateral ground reaction force in the downswing (PC3) as well as the
286 magnitude of medio-lateral ground reaction force (PC5) and the timing of peak negative medio-
287 lateral ground reaction force (PC5). With the 5-iron, higher skilled golfers were less variable in the
288 features described by the first four principal components. These components were associated with
289 the magnitude (PC1 and PC2) and timing (PC1, PC2 and PC3) of peak vertical ground reaction force,
290 the magnitude of vertical ground reaction force in the backswing (PC3), the magnitude of medio-
291 lateral ground reaction force in the downswing (PC2 and PC3) and the magnitude of vertical and
292 medio-lateral ground reaction forces (PC4). Differences in intra-individual variability were small but
293 consistent across most principal components (also for the front- and rear-foot analyses – included in
294 the supplement).

295 The ground reaction forces are the main external forces in the golf swing and, as external forces are
296 required to change the motion of an object, the results might suggest increased movement stability
297 or a higher level of control in higher skilled golfers. The variability in ground reaction force
298 (movement variability) and shot outcomes (task outcome variability) were both lower in higher
299 skilled golfers, which supports the suggestion of stability because stability is related to consistency of
300 both movement and outcome (Ranganathan et al., 2020). However, it remains unclear whether this
301 stability is the result of consistent movements or compensatory variability, since the same force may
302 be created by different movement patterns.

303 In terms of flexibility, the lower variability in ground reaction forces displayed by higher skilled
304 golfers suggests that they were not engaged in exploratory behaviour. Exploratory behaviour is often
305 associated with functional movement variability but the consistent task goal in this investigation
306 may not have encouraged the skilled golfer to display their entire range of flexible movement
307 patterns. The increased ground reaction force variability of the lower skilled golfers may be due to
308 exploratory behaviour, but we would expect this to be accompanied by gradual decrease in task
309 outcome variability were this the case (Ranganathan et al., 2020), and the timescale examined was

310 not sufficient to examine this. Therefore, this investigation does not find evidence for functional
311 movement variability in the ground reaction forces of amateur golfers.

312 Practitioners have been encouraged to accept that variability in movement may be functional
313 (Bartlett et al., 2007), and the results of this investigation, whilst providing no evidence for
314 functional movement variability, do not refute this suggestion. Practitioners should be open to
315 manipulating task constraints in practise to encourage variation in swing mechanics, as this may
316 facilitate greater exploration of potential movement solutions (Button et al., 2003). The variability of
317 ground reaction force could potentially be used to monitor skill progression because higher skilled
318 golfers tended to display lower variability than lower skilled golfers, but care should be taken to
319 account for exploratory behaviour which may be beneficial. Furthermore, care should be taken to
320 not extrapolate these results to professional golfers, who are more skilled than the amateur golfers
321 in this investigation.

322 This investigation considered the magnitude of the ground reaction force variability but did not
323 consider the structure of this variability. Research suggests that the structure of variability is
324 important (Harbourne and Stergiou, 2009; Newell and Slifkin, 1998; Jones et al., 2018) and it has
325 been suggested that optimum movement has a structure somewhere between complete
326 randomness and complete regularity (Harbourne and Stergiou, 2009). The measures used to
327 understand the structure of variability and the treatment of data require careful consideration, since
328 these can significantly influence results (James, 2004), but the structure of ground reaction force
329 variability and, more generally, the structure of movement variability in the golf swing remains an
330 interesting avenue for future research.

331 Previous research has reported increased peak force and changes in the timing of peak as key
332 differentiators between golfers of different skill levels (Barrentine et al., 1994; Chu et al., 2010; Lynn
333 et al., 2012). However, in this investigation the inter-individual ground reaction forces did not
334 suggest that any specific features of ground reaction force patterns differentiated between the
335 handicap groups. Only one of the principal components studied showed statistically significant
336 differences which were ordered between the handicap categories. This was the fifth principal
337 component (PC5) in the front-foot ground reaction force (see supplement), which explained 4.1% of
338 the variance in ground reaction force and mainly described a decrease and flattening of the medio-
339 lateral and vertical ground reaction force peaks.

340 Lynn et al. (2012) performed a similar principal components analysis of ground reaction forces in
341 golfers and is the most comparable study examining ground reaction force and skill. Unlike this
342 investigation, Lynn et al. (2012) observed differences in ground reaction force between groups of
343 beginner and established collegiate golfers, which is likely to be due to the greater disparity in the
344 cohorts. Another potential difference between Lynn et al. (2012) and the current investigation was
345 the use of time-normalisation or trimming. This investigation did not time-normalise the data,
346 instead preferring to trim the data to a specified period of interest (0.77 s before impact, equal to
347 the length of the shortest swing). As noted earlier this was utilised to maintain the integrity of the
348 derivatives of the signals, for instance for the velocities and associated forces. Time-normalisation
349 may be more appropriate for movements where there is less temporal variation, such as gait, or for
350 intra-individual analyses. For example, Hausdorff et al. (1998) reported the coefficient of variation of
351 stance timing in a healthy control participant to be 2.0%. In contrast, the inter-individual coefficient
352 of variation of swing timing in this investigation was 19.4%. This difference in procedure could
353 account for some of the difference in findings between the studies.

354 Conclusion

355 Principal component analysis was used to examine the variability of ground reaction forces in the
356 golf swings of amateur golfers with a driver and a 5-iron. Ground reaction force variability tended to
357 be lower in lower handicap golfers – an interesting and novel finding. This suggests that maintaining
358 a consistent ground reaction force may help golfers maintain outcome consistency, regardless of the
359 presence of compensatory coordination elsewhere in the system. Practitioners may find that the
360 variability of ground reaction forces could provide a useful measure of skill progression, recognising
361 the need to be aware of exploratory behaviour. As expected, the intra-individual variability in ground
362 reaction force was much lower than the inter-individual variability. Further research should consider
363 the structure of ground reaction force variability and the relationship between ground reaction force
364 variability and kinematic variability to contribute further to our understanding of how skilled golfers
365 achieve consistent outcomes.

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