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

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Abstract

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

Keywords

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

Introduction

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

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

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

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

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

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

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

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

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

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

Methods

Participants

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

Table 1. Participant information (mean ± standard deviation).

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

Procedures

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

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

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

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

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

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

Data analysis

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

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

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

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

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

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

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

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

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

Results

Clubhead presentation, ball launch and shot outcome variability

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

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

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

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

Principal component analysis

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

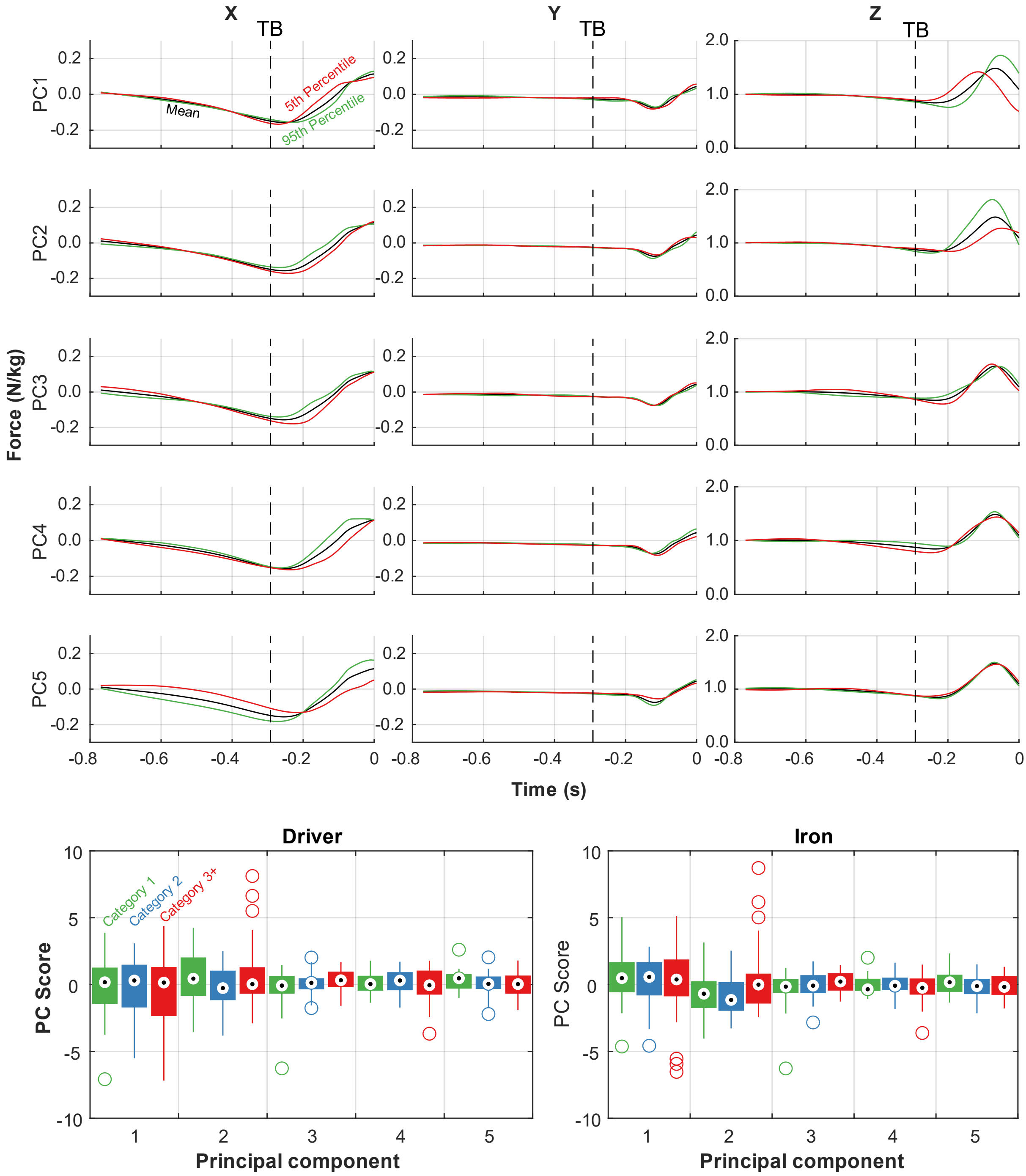

Figure 1. Single component reconstructions for the first five principal components (PC1-5; top) and principal component scores for each handicap group and club (bottom). The average time for the top of backswing event (TB) is indicated by the dashed line on the force-time trajectories. Median values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

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

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

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
	$P_{K\text{-}W}$	0.851	0.210	0.282	0.788	0.296
	z	-	-	-	-	-
	$P_{J\text{-}T}$	-	-	-	-	-
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
	$P_{K\text{-}W}$	0.910	0.033	0.439	0.718	0.387
	z	-	-	-	-	-
	$P_{J\text{-}T}$	-	-	-	-	-

Intra-individual variability

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

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
	$P_{K\text{-}W}$	0.092	0.042	0.013	0.149	**< 0.001**
	z	-	2.24	2.97	-	3.87
	$P_{J\text{-}T}$	-	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
	$P_{K\text{-}W}$	**< 0.001**	0.030	0.013	**0.002**	0.810
	z	4.25	2.63	2.93	3.49	-
	$P_{J\text{-}T}$	**< 0.001**	**0.004**	**0.002**	**< 0.001**	-

Discussion and Implications

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

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

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

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

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

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

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

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

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

Conclusion

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

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