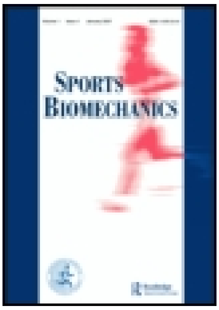

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Nils F. Betzler [a] , Stuart A. Monk [a] , Eric S. Wallace [b] & Steve R. Otto [a]

[a] The R&A, Research and Testing, St Andrews, UK

[b] Sport and Exercise Sciences Research Institute, University of Ulster, Jordanstown, UK

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Effects of golf shaft stiffness on strain, clubhead presentation and wrist kinematics

NILS F. BETZLER[1], STUART A. MONK[1], ERIC S. WALLACE[2], & STEVE R. OTTO[1]

[1]*The R&A, Research and Testing, St Andrews, UK, and* [2]*Sport and Exercise Sciences Research Institute, University of Ulster, Jordanstown, UK*

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Abstract
The aim of this study was to quantify and explain the effect of shaft stiffness on the dynamics of golf drives. Twenty golfers performed swings with two clubs designed to differ only in shaft bending stiffness. Wrist kinematics and clubhead presentation to the ball were determined using optical motion capture systems in conjunction with a radar device for capturing ball speed, launch angle, and spin. Shaft stiffness had a marginally small effect on clubhead and ball speeds, which increased by 0.45% ($p < 0.001$) and 0.7% ($p = 0.008$), respectively, for the less stiff club. Two factors directly contributed to these increases: (i) a faster recovery of the lower flex shaft from lag to lead bending just before impact ($p < 0.001$); and (ii) an increase of 0.4% in angular velocity of the grip of the lower flex club at impact ($p = 0.003$). Unsurprisingly, decreases in shaft stiffness led to more shaft bending at the transition from backswing to downswing ($p < 0.001$). Contrary to previous research, lead bending at impact marginally increased for the stiffer shaft ($p = 0.003$). Overall, and taking effect sizes into account, the changes in shaft stiffness in isolation did not have a meaningful effect on the measured parameters, for the type of shaft investigated.

Keywords: *Shaft bending, shaft flexion, motion analysis, equipment, ball speed*

Introduction

Various researchers have quantified the dynamic behaviour of golf shafts, sometimes using optical methods (Mather et al., 2000), but mostly by attaching strain gauges to the shaft (Milne & Davis, 1992; Butler & Winfield, 1994; Horwood, 1994; Kojima & Horii, 1995; Newman et al., 1997; Lee et al., 2002; Ozawa et al., 2002; Tsujiuchi et al., 2002, 2004; Harper et al., 2005a). In terms of the general pattern of shaft deflection during the swing (Figure 1), these studies showed that there are only small deflections during the backswing. The shaft then deforms significantly in the toe-down direction at the transition from backswing to downswing as a consequence of the inertia of the clubhead and the golfer applying forces and moments at the grip end to accelerate the club. During the downswing, the shaft straightens and then reaches a bent forward shape just before impact (Figure 1; Penner, 2003). Previous research

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Correspondence: N.F. Betzler, The R&A, Research and Testing, 6 Pilmour Links, St Andrews KY16 9JG, UK, E-mail: nilsbetzler@randa.org

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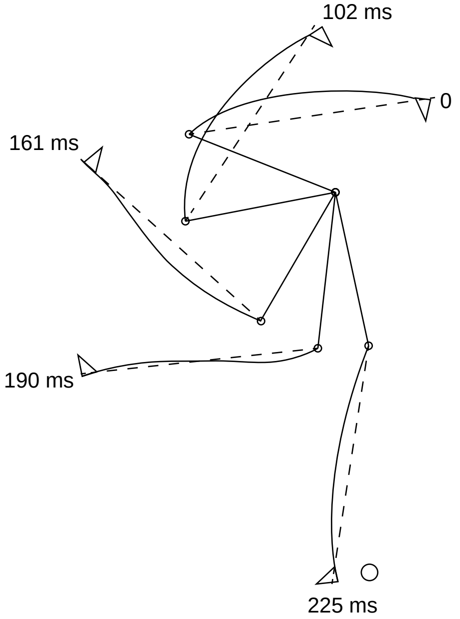

Figure 1. Shaft behaviour during a typical golf swing: simulation of shaft bending according to Milne and Davis' (1992) measurements (bending exaggerated by a factor of 5; reprinted with permission from Penner, 2003, p. 158).

suggested that this forward bending is a consequence of the offset position of the centre of gravity of driver clubheads relative to the centreline of the shaft (Horwood, 1994; Mather & Jowett, 2000; MacKenzie & Sprigings, 2010). As the contact between clubhead and ball lasts approximately 500 μs (Hocknell et al., 1996), the shaft's effect during impact is considered to be negligible (Mather & Jowett, 2000). Of the studies on dynamic shaft behaviour cited above, the majority included a small number of participants ($n \leq 5$).

Shaft deflection patterns have been compared amongst players in experimental studies (Butler & Winfield, 1994; Lee et al., 2002), and marked differences were found. In contrast, the effect of shaft stiffness on loading patterns has primarily been studied with simulation models and not experimentally. As examples, Milne and Davis (1992) and Tsujiuchi et al. (2002) used essentially two-dimensional (2D) reductions of the swing, but it has been suggested that modelling the golf swing in one plane may be too simplistic since the arm and club do not move within a single plane (Coleman & Rankin, 2005).

MacKenzie and Sprigings (2009a) demonstrated that their model could mimic the main characteristics of the 3D kinematics of a human golf swing, including club rotation around the shaft's longitudinal axis. However, a validation of the model's forward-dynamics optimisation based on 3D data from a more diverse group of golfers was not performed. In short, MacKenzie and Sprigings (2009b) found in subsequent applications of their model that shaft stiffness would likely affect clubhead orientation at impact, but that (i) the magnitude of clubhead speed generated from the dynamic recoil of the shaft would only differ marginally between shafts and that (ii) optimisation of the swing to match the shaft stiffness would not result in meaningful changes in overall clubhead speed for specific shaft/player combinations. MacKenzie & Sprigings (2010) found that the magnitude of forward bending (and hence dynamic loft) and the shaft's contribution to clubhead speed at impact increased in faster swings but decreased in stiffer shafts.

Wallace and Hubbell (2001) analysed the launch data of 84 golfers swinging five irons with three different shaft stiffness ratings and found a small (0.9%), but statistically significant increase in clubhead speed generated with a flexible shaft compared to a stiff shaft. Stanbridge et al. (2004) measured impact location, distance, and dispersion for 30 junior golfers performing swings with seven irons with three different shaft stiffness ratings. For the group of golfers as a whole, there were no significant differences between distances achieved with any of the clubs. In these studies there was some evidence of a matching between player and particular shaft flexibilities, which was also found by Worobets and Stefanyshyn (2008).

The primary objective of this research was to establish whether driver shaft stiffness affects performance variables such as clubhead speed, clubhead presentation including impact location and ball speed. Secondary objective was to determine the effect of changes in shaft stiffness on shaft loading patterns and wrist kinematics, thereby aiding the interpretation of any shaft effects on performance variables.

Methods

Twenty right-handed, male golfers participated in this study (handicap ≤ 5): 0.25 ± 1.68 for handicap (professional golfers are assumed to have a scratch (zero) handicap) 31.8 ± 10.5 years for age, 1.78 ± 0.06 m for height, and 79.5 ± 8.65 kg for body mass. The study was approved by the Ethics Committee of Edinburgh Napier University, and informed consent was obtained from each player prior to testing.

Test clubs

Each participant used two clubs with shafts that were marked as ‘ladies’ (l-flex) and ‘x-stiff’ (x-flex) by the shaft manufacturer and that were closely matched in all properties apart from shaft stiffness as indicated by the shaft’s first bending frequency and average rigidity from static bending tests (Table I), as described by Betzler et al. (2011). The location of each clubhead’s centre of gravity was determined as part of a moment of inertia test procedure and found to be consistent within 2 mm (R&A Rules Limited, 2005). The shafts were painted black to obscure any markings which would allow players to identify them. Clubheads and grips were also closely matched. This resulted in test clubs with differences in effective swingweight that have been found to be undetectable by golfers (Harper et al., 2005b). Each

Table I. Properties of matched shafts, clubheads, and assembled clubs.

Property	Unit	l-Flex	x-Flex	Tolerance
Shaft mass	G	56.8	57.7	± 0.2
Frequency	Hz	3.62	4.52	± 0.02
Rigidity	Nm^2	38.3	57.6	± 0.5
Bend point	mm	514	521	
Clubhead mass	g	197	198.4	± 0.2
Clubhead COG_x[a]	mm	64	19	
Clubhead COG_y[a]	mm	66	17	
Loft angle	°	10.8	11.5	± 0.2
Length[b]	mm	1143	1143	± 0.5
Swingweight[b]		C9.7	D0.0	± 0.1
Total mass[b]	g	306.8	307.7	± 0.2

[a] COG (center of gravity) relative to hosel, x from heel to toe direction, y towards back (R&A Rules Limited, 2005); [b] Measurements for the assembled club. Swingweight presented in lorythmic scale (Maltby, 1995).

club was equipped with four foil strain gauges (2 mm, 120 Ω resistance, Kyowa, Japan) (Figure 2a). This position was chosen to be in the proximity of the location of maximum bending, determined via a static shaft deflection test, because first mode (bending) oscillations dominate during the downswing (Butler & Winfield, 1994), although it is noted that shaft shape in the swing may differ from static tests (Mather & Jowett, 1998). The strain gauges were aligned with the longitudinal axis of the shafts and placed so that one pair of strain gauges registered lead/lag bending of the shaft and the other pair toe-up/down bending, thereby forming two half-bridges (Figure 2a). Strain data were transmitted via a shielded cable attached to the butt end of the grip. Players reported that this did not interfere with execution of their swings.

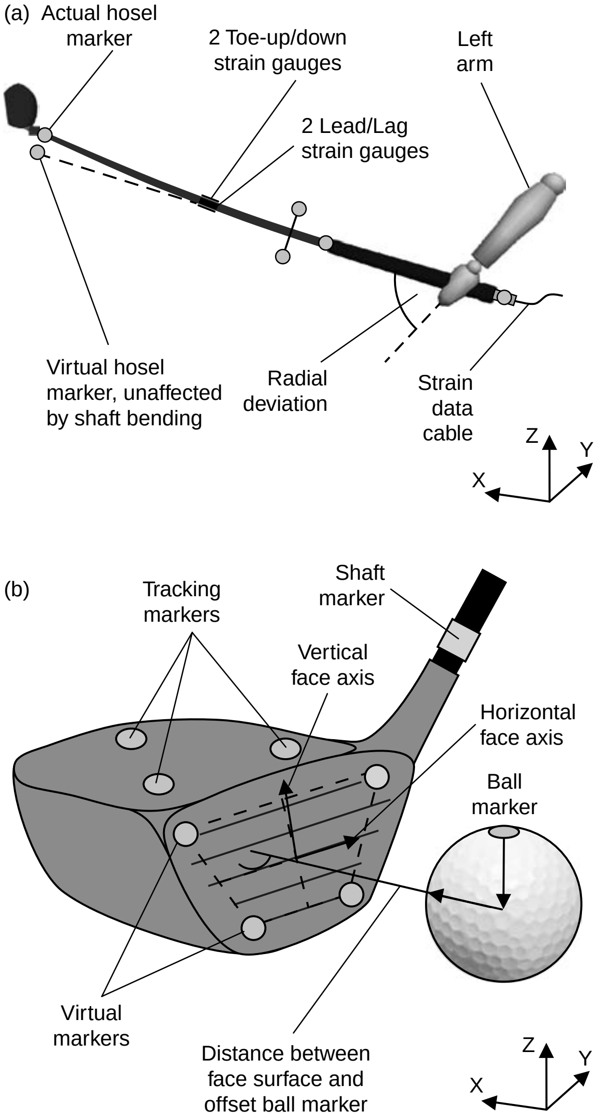

Figure 2. (a) Club instrumentation, wrist ulnar/radial deviation angle, and position of a virtual offset marker placed at tip end of shaft; (b) definition of club face and distance to offset ball marker.

Data collection procedure

All shots were performed in an open hitting bay with each player instructed to aim at the same flag on the driving range as if performing a drive in a normal round of golf. After performing their own warm-up routine, players performed eight swings with each of the two test clubs. For each series of swings with a given club, data recording commenced after two familiarisation swings. This was immediately followed by a repetition of this test protocol, resulting in the execution of four groups of eight swings with data collected for six trials for each group. Half the players tested in the order x–l–x–l with the remainder testing l–x–l–x. During the test, players were not made aware of the variable being considered in the study nor were they made aware that they would test the same clubs twice. Players selected their own pace and were able to take breaks between shots as required. The total duration of a typical test session was approximately 45 min. For each shot, a Trackman Doppler radar device (Trackman A/S, Vedbæk, Denmark) recorded the ball speed, launch angle, and spin rate immediately after impact.

A seven-camera, Oqus 300 motion capture system (Qualisys AB, Gothenburg, Sweden) operating at 500 Hz recorded the trajectories of reflective markers attached to the body (Figure 3). These markers were placed at the posterior side of the left hand (three markers), the distal end of the left forearm (three markers, in close proximity to the radial and ulnar styloids), the left medial and lateral epicondyles, the posterior surface of the left upper arm, the incisura jugularis, C7, and below the angulus inferior of each scapula. A second motion capture system, consisting of three Oqus 300 cameras operating at 1000 Hz, was used to track the movement of the clubhead in the proximity of the ball for approximately 0.5 m before and after impact. Both systems were calibrated according to the manufacturer's instructions using the same reference frame. The residuals reported by both motion capture systems were < 1 mm. The accuracy (root mean square error when measuring a known distance) and the precision (*SD* of length of a rod) were approximately 0.3 mm for both systems. Detailed information on the clubhead tracking system's accuracy and precision has been presented previously (Betzler et al., in press).

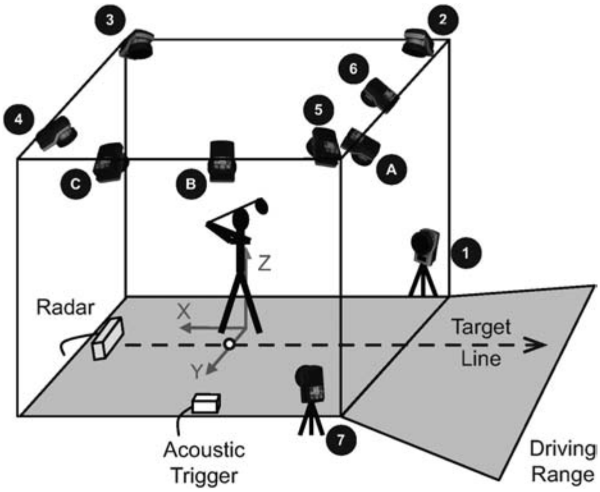

Figure 3. Test set-up. Numbers in black circles denote positions of the body motion capture cameras, and letters in circles denote cameras pertaining to the impact location motion capture system.

In a separate experiment, the reliability of the wrist joint angle measurement was assessed using a golf robot. For 10 repeated shots at three speeds (35.8, 44.7, and 53.6 m/s), the wrist joint angle data were cropped to 300 pre-impact data points. The average *SD* of the wrist joint angle per data point for the repeated measurements was 0.13°.

The analogue strain signals were amplified with a FE-366-TA amplifier (Fylde, Preston, UK) and recorded simultaneously with the body movement via a Qualisys USB-2533 A/D board at a sampling rate of 2000 Hz. After identifying the time of impact in the strain data, a low-pass filter with a 50 Hz cut-off frequency was used to remove high-frequency noise from the pre-impact strain data. Following this, the strain data were post-processed with Matlab (Mathworks, Inc., Natick, MA, USA) to extract the peak toe-up strain at the transition from backswing to downswing, the lag area (area between abscissa and lag strain), the lead/lag recovery rate, and the amount of lead strain at impact.

Clubhead presentation and impact location

Impact locations were measured for each swing using the movement of three reflective makers attached to the crown of the clubhead and a single, flat, self-adhesive marker attached to the ball (diameter of all markers: 5 mm). Players were instructed to tee the ball at their preferred height and position and to place the ball with the reflective marker facing upwards, aligned with the vertical axis of the global reference system. For each clubhead, a calibration routine was performed to determine the position of 'virtual markers' located on the club face. During this calibration, a local coordinate system was constructed for the clubhead with a horizontal axis running from toe to heel (parallel to the scorelines), a vertical axis pointing upwards, and a third axis pointing in a direction normal to the club face (Figure 2b). Following data collection, a Matlab routine reconstructed the position of this coordinate system based on the three tracking markers attached to the crown of the clubhead. The club face was assumed to be part of a sphere with a diameter of 254 mm (the approximate radius of curvature of the face of a modern driver). The centre of the sphere was determined using the virtual markers on the club face and a simple optimisation method. To characterise the clubhead presentation to the ball, the last frame before the distance between the centre of the sphere and the ball position was less than the total of the sphere and ball radius was considered to be the final pre-impact sample.

Using only data collected up to and including the pre-impact sample, an iterative scheme (Secant method) was used in conjunction with an extrapolation scheme (cubic best fit) to determine the time between camera frames at which the distance between club face and ball was closest to zero. This time was deemed to be the impact time, and the coordinates of the virtual markers at this time were determined using a similar extrapolation. The impact position between club face and ball was then converted from the global coordinate system to the local club face coordinate system. The speed of the three tracking markers immediately before impact was determined using third-order backward finite differences with non-uniform step size. The orientation of the horizontal club face axis relative to the global y-axis (Figure 2b) defined the face angle at impact. Effective loft was expressed as the angle between the vertical club face axis and the global z-axis, thereby representing the total loft at impact, which is expected to be a combination of the static loft of the clubhead and any additional loft generated by shaft behaviour or swing characteristics (Maltby, 1995).

Other kinematic variables

Movement of the forearm of the player was tracked using three reflective markers (diameter 12 mm), forming a triangle at the distal end of the forearm (posterior side). The position of the elbow joint was defined relative to these markers using a dynamic calibration procedure (Schwartz & Rozumalski, 2005), implemented in Visual3D (C-Motion, Inc., Germantown, MD, USA). The position of the wrist joint centre was assumed to coincide with the midpoint between a medial and a lateral landmark at the wrist, which were located using a digitising pointer (Cappozzo et al., 1995).

The grip of the club was tracked using four markers (Figure 2a). Each marker was placed close to the grip end of the club to avoid shaft deflection influencing the calculated grip position. Visual3D was used to place a virtual offset marker at the tip end of the shaft with its position defined relative to the grip markers. This enabled the theoretical speed of the tip end of the shaft ('hosel') to be calculated in the absence of shaft deflection. This was then compared to the actual speed of a marker placed at this position (Figure 2a), recorded using the impact location motion capture system. The backward finite differences algorithm used to calculate the speed of the club head was also used to calculate these marker speeds.

Together the forearm and the grip segments allowed calculation of ulnar and radial deviation at the wrist. To do so, the longitudinal axis of the grip was projected onto the frontal plane of the forearm (as defined using the anatomical landmarks). Then, the angle between this line and the longitudinal axis of the forearm was calculated. This angle was zero when the projection of the shaft axis and the longitudinal axis of the forearm were parallel to each other, with positive values indicating radial deviation (Figure 2a).

In order to characterise the global movement of the grip section of the club, a plane was fitted to the path of the grip based on the position of the grip at the grip-horizontal and impact events (see below for event definitions). The position of the grip segment at the time of impact was determined using a third-order polynomial to extrapolate its trajectory from the pre-impact frame to the time of impact. Then, the trajectories of two markers defining the longitudinal axis of the grip were projected onto the plane by evaluating the same polynomial at 100 equally spaced points in time. This enabled calculation of the angular velocity of the grip just before impact, using conventions similar to those used in previous studies (MacKenzie & Sprigings, 2009b). Furthermore, an angle between the grip and the vertical was defined so that it was positive as the club aproached the ball during the downswing and zero when the grip was vertical.

Event detection

As discussed above, a number of events were identified to facilitate interpretation of the results. These occur in sequence as follows:

- Transition from backswing to downswing: defined as the time at which the x-component of shaft velocity changes from negative (towards target) to positive.
- Grip-vertical: defined as the time at which the longitudinal axis of the grip, projected onto a plane defined by the global x- and z-axis, is parallel to the vertical z-axis and pointing upwards.
- Grip-horizontal: defined as the time at which the longitudinal axis of the grip, projected onto a plane defined by the global x- and z-axis, is parallel to the horizontal x-axis.
- Impact: for the body motion capture system (seven cameras), this was based on the signal recorded from an acoustic trigger. For the impact motion capture system (three cameras), this was determined by the impact position algorithm (see above).

The grip-vertical and grip-horizontal events have been adapted from a previous study (Ball & Best, 2007).

Statistical analysis

Prior to conducting the main statistical analysis, the repeated use of each shaft by each player allowed the data to be inspected for any systematic trends caused by factors other than shaft stiffness, such as warm-up, familiarisation, or fatigue effects. To do so, an additional independent variable 'set' was introduced. Its value was 1 for the trial numbers 1–12, and 2 for the repetition of the protocol (trial numbers 13–24). Following this, a univariate analyses of variance (ANOVA) was performed on the clubhead speed results, using player, shaft stiffness, and set as factors, with the model including main effects only.

In the analysis for shaft effects, shaft stiffness, player, and trial number were all included as factors (independent variables) to account for the fact that repeated trials recorded from the same player under the same test conditions cannot be regarded as independent observations. Following this, a series of three multivariate analyses of variance (MANOVA) was performed for each group of outcome variables separately (clubhead presentation, strain, and wrist kinematics). The Pillai's trace statistic was used to aid interpretation of the MANOVA results. Additionally, the difference in speed between the actual and virtual hosel marker was examined using a mixed-design ANOVA, using the speed of the two reference markers as repeated measures for each shot, and player, shaft stiffness, and trial number as between-sample factors. The α-level for the complete statistical analysis was set to 0.05, and the analysis was performed using Minitab 16 (Minitab, Inc., State College, PA, USA) and R v2.11.1 (R Foundation for Statistical Computing, Vienna, Austria).

A range of statistics was included in the MANOVA and ANOVA evaluations, and the statistical significance of these variances with fixed factors was included. The analysis also included an assessment of the effect size. This was presented using partial η^2 values for the multivariate analyses of variances, which is defined as $SS_{factor}/(SS_{factor} + SS_{error})$. It is noted that this is the same as η^2 for the ANOVA calculation involving one factor, since $SS_{factor} + SS_{error} = SS_{total}$. The value of partial η^2 indicated the proportion of total variation attributable to the factor, whilst excluding other factors, whereas η^2 described the proportion of variation associated with the factor (Pierce et al., 2004).

Results

Within-player consistency

For clubhead presentation, there were main effects due to the set ($F(1,1) = 6.39, p \leq 0.001$), player ($F(1,19) = 30.9$, $p < 0.001$), and shaft stiffness ($F(1,1) = 15.6$, $p < 0.001$) factors. Set, being a main effect, suggested that players did not perform consistently throughout the course of their test sessions independent of shaft stiffness. Examination of the means of clubhead speeds for the two levels of the set variable indicated that clubhead speeds for the second set of swings (trial numbers 13–24) were marginally but significantly higher than for the first set of swings (45.8 vs. 46.0 m/s).

To confirm this finding, the clubhead speeds were normalised using the mean clubhead speed for each player over all 24 trials. It was found that, despite a low Pearson correlation coefficient ($r = 0.326$), there was a significant correlation ($p = 0.001$) between trial number and normalised clubhead speed. Further inspection of the data revealed that this correlation was not present ($p = 0.051$, $r = 0.127$) if only trials performed during the second half of the test session were included (trial numbers 13–24). Thus, the second set of trials for each player were analysed in order to isolate shaft stiffness. All subsequent results in this section will be based solely on the second set of trials to isolate shaft stiffness as the primary factor.

Shaft effects

The descriptive statistics for the clubhead, ball, strain, and wrist variables are summarised in Table II.

The factors player ($F(1,19) = 16.4$, $p < 0.001$, partial $\eta^2 = 0.618$) and shaft stiffness ($F(1,1) = 13.7$, $p < 0.001$, partial $\eta^2 = 0.267$) were all main effects. The factor trial number ($F(1,5) = 1.26$, $p = 0.18$) was not a main effect and was not analysed further. The interaction player × shaft was significant ($F(1,19) = 2.12$, $p < 0.001$, partial $\eta^2 = 0.173$).

The player and shaft effects were further examined using univariate ANOVAs for each variable. Player was a main effect for all clubhead presentation variables: clubhead speed ($F(1,19) = 928$, $p < 0.001$, $\eta^2 = 0.985$), horizontal impact position ($F(1,19) = 6.1$, $p < 0.001$, $\eta^2 = 0.341$), vertical impact position ($F(1,19) = 4.9$, $p < 0.001$, $\eta^2 = 0.292$), face angle ($F(1,19) = 17$, $p < 0.001$, $\eta^2 = 0.595$), and effective loft ($F(1,19) = 28.4$, $p < 0.001$, $\eta^2 = 0.655$). There was a main effect of shaft stiffness on clubhead speed ($F(1,1) = 33$, $p < 0.001$, $\eta^2 = 0.002$), face angle ($F(1,1) = 5.1$, $p = 0.025$, $\eta^2 = 0.009$), and effective loft ($F(1,1) = 4.1$, $p = 0.045$, $\eta^2 = 0.005$). Horizontal and vertical impact locations were unaffected by shaft stiffness ($F(1,1) = 1.1$, $p = 0.29$ and $F(1,1) = 0.5$, $p = 0.48$, respectively). Additionally, there was a significant interaction of the factors, player and shaft, for the variables clubhead speed ($F(1,19) = 2.4$, $p < 0.001$, $\eta^2 = 0.011$) and effective loft ($F(1,19) = 4.4$, $p < 0.001$, $\eta^2 = 0.239$). These interactions were examined using interaction plots (Field, 2005; not presented). It was found that the majority of players followed the trend of achieving higher clubhead speeds with the l-flex shaft, with the exception of 3 out of the 20 players. Effective loft was higher for the x-flex shaft for 13 out of the 20 players.

Table II. Descriptive statistics (*M* ± *SD*) for clubhead presentation, ball launch conditions, strain, and wrist ulnar/radial deviation.

Variable	Units	l-Flex		x-Flex	
		M	*SD*	*M*	*SD*
Clubhead presentation					
Clubhead speed	m/s	46.1	± 2.6	45.9	± 2.4
Horizontal impact location	mm	-0.375	± 8.2	0.426	± 7.8
Vertical impact location	mm	2.78	± 5.6	2.22	± 6.5
Face angle	°	2.84	± 3.0	2.19	± 3.0
Effective loft	°	11.23	± 2.8	11.67	± 3.5
Ball launch					
Ball speed	m/s	67.5	± 3.6	67.2	± 3.4
Launch angle	°	10.96	± 2.49	11.01	± 2.72
Spin	rpm	2824	± 790	2874	± 843
Strain					
Peak toe strain	µm/m	3683	± 869	2212	± 491
Recovery rate	1/s	0.053	± 0.022	0.044	± 0.016
Lag area	µm/m s	439	± 230	275	± 136
Lead strain at impact	µm/m	692	± 481	736	± 365
Wrist angle at event					
Top of backswing	°	97.3	± 17.0	96.6	± 17.4
Grip vertical	°	86.9	± 9.5	86	± 9.4
Grip horizontal	°	56.0	± 5.7	55.3	± 5.4
Impact	°	16.9	± 9.5	17	± 9.2
Club grip kinematics					
Orientation at impact	°	4.79	± 2.94	4.82	± 2.71
Angular velocity	rad/s	39.85	± 2.88	39.67	± 2.50

In addition to the increase in clubhead speed (Table II), the mean ball speed for the l-flex club was 0.4 m/s (0.4%) higher than for the x-flex club. Using an ANOVA with player and shaft stiffness as factors, it was found that this difference was statistically significant albeit with a small effect size ($F(1,1) = 7.19$, $p = 0.008$, $\eta^2 = 0.003$).

On average and across both shaft conditions, the speed of the actual hosel marker was marginally higher than the speed of the virtual marker (0.24 m/s, 0.56%). The mixed-model ANOVA confirmed that this difference was significant ($F(1,1) = 29.2$, $p < 0.001$). The magnitude of this effect was more pronounced for the l-flex shaft (0.34 m/s, 0.80%) than for the x-flex shaft (0.09 m/s, 0.21%), as confirmed by the significant interaction between the magnitude of the speed difference and shaft stiffness ($F(1,1) = 10.24$, $p = 0.002$). Furthermore, the speed of the x-flex virtual marker (42.29 m/s) was approximately 0.1 m/s lower than the l-flex virtual marker (42.38 m/s).

For the strain variables, the player ($F(1,19) = 71.8$, $p < 0.001$, partial $\eta^2 = 0.868$) and shaft stiffness factors ($F(1,1) = 1485$, $p < 0.001$, partial $\eta^2 = 0.967$) were main effects. The trial number factor was not a main effect ($F(1,5) = 0.42$, $p = 0.989$), indicating that there were no systematic trends present within the repeated trials. The ANOVA results for the individual variables confirmed these main effects for all four strain variables and both the player and strain factors: peak toe strain (player: $F(1,19) = 90$, $p \leq 0.001$, $\eta^2 = 0.435$; shaft: $F(1,1) = 2015$, $p < 0.001$, $\eta^2 = 0.511$), recovery rate (player: $F(1,19) = 37$, $p < 0.001$, $\eta^2 = 0.738$; shaft: $F(1,1) = 39$, $p < 0.001$, $\eta^2 = 0.040$), lag area (player: $F(1,19) = 130$, $p < 0.001$, $\eta^2 = 0.774$; shaft: $F(1,1) = 507$, $p < 0.001$, $\eta^2 = 0.159$), and lead strain at impact (player: $F(1,19) = 212$, $p < 0.001$, $\eta^2 = 0.948$; shaft: $F(1,1) = 9$, $p = 0.003$, $\eta^2 = 0.002$). The peak toe strain, recovery rate, and lag area were significantly higher for the l-flex than for the x-flex shaft (Table II). In contrast, the lead strain at impact was greater for the x-flex shaft.

The descriptive statistics (Table II) indicate that there were only small, typically less than 1°, differences between wrist angles measured for the two shaft conditions. For the body movement group of variables as a whole (including grip angle and angular velocity, see below), there were main effects both due to the player (Pillai's trace: $F(1,19) = 105$, $p < 0.001$, partial $\eta^2 = 0.905$) and shaft stiffness factors ($F(1,1) = 9.05$, $p < 0.001$, partial $\eta^2 = 0.220$). There was no main effect associated with the trial number ($F(1,5) = 0.826$, $p = 0.734$). When using ANOVA to determine where these differences lay, it was found that the shaft stiffness factor was only associated with changes in the wrist angle at the grip-vertical ($F(1,1) = 36.0$, $p < 0.001$, $\eta^2 = 0.003$) and grip-horizontal events ($F(1,1) = 42.9$, $p < 0.001$, $\eta^2 = 0.007$). The wrist angle at the top of the backswing was unaffected ($F(1,1) = 2.3$, $p = 0.131$), as was the wrist angle at impact ($F(1,1) = 0.028$, $p = 0.8664$). The descriptive statistics in Table II indicate that the wrist angle at the grip-vertical and grip-horizontal events was smaller for the l-flex than for the x-flex shaft.

Individual ANOVAs also revealed that shaft stiffness effects were not present for the grip angle ($F(1,1) = 0.04$, $p = 0.844$) but for grip angular velocity ($F(1,1) = 8.98$, $p = 0.003$, $\eta^2 = 0.001$). Players achieved higher angular velocities with the l-flex shaft than with the x-flex shaft (relative difference: 0.4%).

Discussion and implications

Clubhead presentation

Clubhead speeds were found to be marginally, yet significantly, higher for the l-flex shaft than for the x-flex shaft small (absolute difference: 0.18 m/s, relative: 0.4%). The ball speed results—measured independently from the clubhead data—confirmed this. Marginal changes associated with changes in shaft flex were also detected for face angle and effective loft. However, the size of the effect of stiffness quantified using η^2 for clubhead speed, face angle, and effective loft (0.002, 0.009, and 0.005, respectively) indicates that these changes were very small compared to the role of changing player (0.985, 0.595, and 0.655, respectively). The magnitude of the change in clubhead speed associated with the recovery process of the shaft (virtual vs. actual shaft marker, 0.24 m/s) was similar to the average within-participant *SD* in clubhead speed for a given condition (0.28 m/s). This result and also the low effect sizes for the shaft factor show that, despite being statistically significant, the difference in clubhead speed is most likely of little practical relevance for a golfer.

The finding related to clubhead speed is in agreement with data presented by Wallace and Hubbell (2001), their data showing only an increase in clubhead speed of 0.3 m/s (0.8%) between the stiffest and most flexible shafts in their five-iron study. Other authors (Stanbridge et al., 2004) found no general effect of shaft stiffness on distances achieved by their test group as a whole. Marginal differences in clubhead speed were also found for the range of shaft stiffnesses simulated by MacKenzie and Sprigings (2009b), but, again, they were not large enough to provide a meaningful advantage to the player.

On average, effective loft was higher for the x-flex shaft (absolute: 0.44°, relative: 3.9%, $p < 0.001$); however, the magnitude of this difference did not exceed the difference in static loft between the two clubheads (Table I, 0.7°). As it is uncertain how the difference in static loft translates to changes in effective loft, it is unclear whether this result contradicts previous findings that show an increased association between increased dynamic loft and with less flexible shafts (Maltby, 1995; MacKenzie & Sprigings, 2009b).

For the most part, results in the current study were interpreted for the sample group as a whole. Other researchers (Stanbridge et al., 2004; Worobets & Stefanyshyn, 2008) have taken a different approach, interpreting results on an individual basis, and suggesting that a particular shaft flex may fit a particular swing in terms of increased clubhead speed or distance. In the present study, 3 out of 20 players did not follow the trend for increased clubhead speed with the l-flex shaft, but as this represents only a minority of the players, the treatment of the results on a pooled basis is justified when considered alongside the aims of this study.

Clubhead speed generated from shaft recovery

From the work of previous authors (Butler & Winfield, 1994; MacKenzie & Sprigings, 2009b), the recovery of the shaft from lag to lead bending may have been expected to generate up to 4–5% of the total clubhead speed. In the current study, this was investigated by the comparison of the speeds of a virtual (unaffected by shaft bending) and actual hosel marker, and the magnitude of this contribution was considerably smaller (0.6%). This may be explained by differences between shaft properties, although the shafts in the current study were selected to cover the stiffness range commonly used in driver shafts. Despite the difference in magnitudes, all three studies found an association between an increase in clubhead speed and the recovery of the shaft. The mixed-model ANOVA indicated that the magnitude of speed gain from shaft recoil differed between shafts. This appears to agree with the numerical results presented by MacKenzie and Sprigings (2009b), showing that the clubhead speed contribution from the shaft increased with decreasing shaft stiffness.

It is noted that the clubhead mass is 1.4 g heavier for the head used with the x-flex shaft than the one used with the l-flex (Table I). If the player supplies the same amount of energy to the clubhead, then we would expect the player to swing the l-flex club faster by 0.35%.

It is worth noting that shaft flexibility has been found to contribute to the end point speeds of implements in other sport skills such as ice hockey wrist shots (Worobets et al., 2006) and lacrosse shots (Crisco et al., 2009).

Strain

The present study found shaft effects for all four strain variables (peak toe strain, lag area, recovery rate, and lead strain at impact). Assuming that the shaft arcs identically in the dynamic swing as in a static strain gauge calibration—which may not be the case (Mather & Jowett, 1998)—peak toe strains would on average correspond to toe-up deflections of 124 and 88 mm and the lead strains at impact to 23 and 28 mm for the l-flex and x-flex shafts, respectively. It should be noted, however, that the effect sizes associated with the shaft factor for recovery rate and lead strain at impact were small (0.04 and 0.002, respectively). No previous study could be identified that compared strain patterns for shafts of different stiffness levels. In line with previous research (Betzler et al., 2011), strain rates did not exceed 0.1 1/s (Table II), assuming that peak strain rates will occur just prior to impact. This suggests that strain-rate dependency of the shaft's material will only play a minor role throughout the backswing and downswing. The finding of an increase in lead strain at impact for the x-flex shaft compared to the l-flex shaft did not agree with findings from previous authors (Maltby, 1995; MacKenzie & Sprigings, 2009b), who predicted that forward bending of the shaft at impact (and hence dynamic loft) would increase as shaft stiffness decreases, potentially leading to higher launch angles for more flexible shafts.

An aggregate plot of the strain results (Figure 4) helps to visualise the typical bending patterns throughout the swing. The strain curves for the two different shaft stiffness levels are offset, most strongly for the toe-up/down component at the transition from backswing to downswing (peak toe strain variable). The amount of lag bending during the first half of the downswing is also markedly greater for the l-flex shaft (lag area variable). During the last 0.1 s before impact, however, traces for the two different shafts begin to overlap and are indistinguishable at impact for the lead/lag component (lead strain at impact variable).

One possible explanation for the finding of increased lead bending for the x-flex shaft at impact may be that the l-flex shaft did not have enough time to develop as much lead bending as the x-flex shaft, given that the l-flex starts the recovery process at a similar time but with more lag bending than the x-flex shaft (Figure 4). Given the use of a single strain gauge location and the shaft deflection shapes observed by previous authors (Mather & Jowett, 1998), the increased lead strain at the strain gauge location is not necessarily equivalent to a proportional increase in forward deflection of the clubhead at impact.

No data are available on the static and dynamic torsional behaviour of the shafts, which is a limitation of this study.

Wrist kinematics

The present study found that, depending on shaft stiffness, the wrist angle of the players changed significantly at two out of four swing events. Figure 5 shows that players appeared to 'release' the x-flex club slightly earlier than the l-flex club, as evident from the slight downwards shift of the curve for the x-flex shaft relative to the l-flex shaft. It is worth noting that *SD*s shown in Figure 5 were calculated across the shots performed by all participants and were not the average within-participant *SD*, which were substantially smaller. As evident from the small effect sizes for the changes at the grip-vertical and grip-horizontal events and Figure 5, the magnitude of this effect is small. It is unknown whether this is a result of active

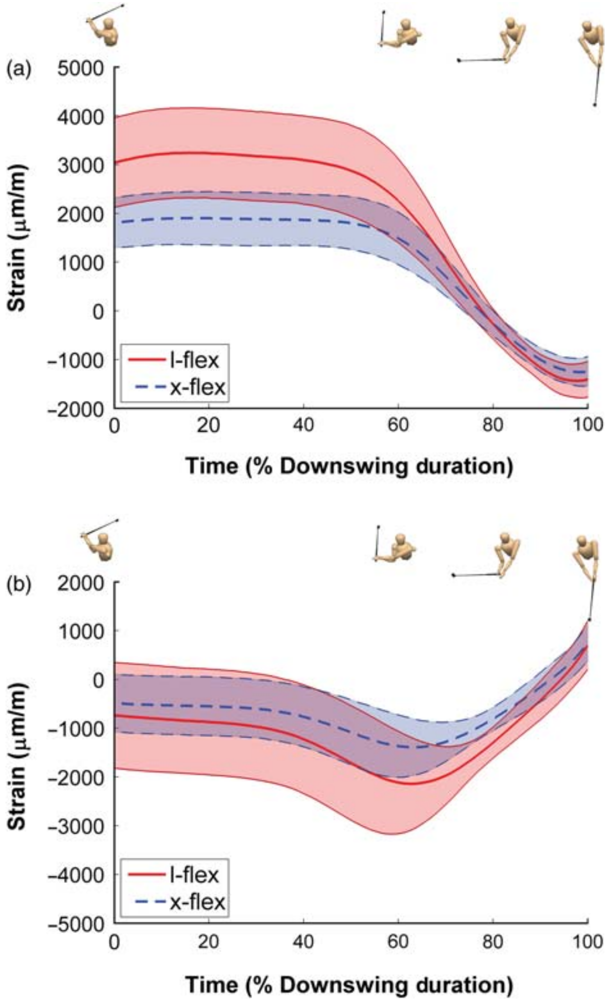

Figure 4. Aggregate strain results for all participants: (a) toe-up/down, where toe-up is positive; (b) lead/lag strain, where lead is positive. Lines indicate mean, and shaded areas indicate ± 1 *SD*. Each time series has been normalised to downswing duration before calculation of mean and *SD*.

player adaptation, differences in the club's inertia, or because the players applied the same muscular coordination strategy for both shafts. It is noted that delayed wrist action has been found to be a characteristic element of the swings of more skilful golfers who also achieve higher clubhead speeds (Zheng et al., 2008).

Two additional kinematic variables were studied: the orientation of the grip relative to the vertical at impact, and the angular velocity of the grip segment at impact. No differences were found for grip orientation, indicating that players did not adjust the global orientation of the grip at impact to compensate for potential changes in effective loft caused by shaft bending. However, there was a main effect due to the shaft stiffness factor for the angular velocity at impact. The mean difference in angular velocity between the two stiffness levels was 10 °/s (0.18 rad/s). In order to estimate the effect of this change on the linear velocity of the clubhead at impact, the instantaneous centre of rotation of the club segment just before impact was calculated for each trial (McCane et al., 2005). The distance of the tip end of the

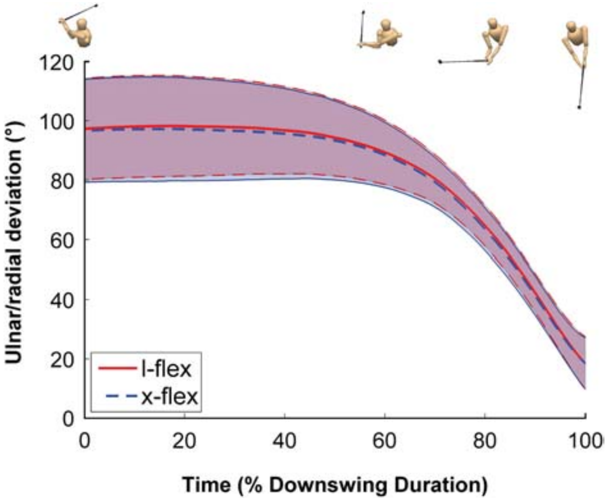

Figure 5. Aggregate wrist angle results for all participants. Lines indicate mean, and shaded areas indicate ± 1 *SD*.

club to the centre of rotation was estimated to be approximately 1 m. Hence, the increase in grip angular velocity for the l-flex shaft (0.18 rad/s) would be expected to result in an increase in linear clubhead speed of approximately 0.18 m/s. This tends to support the finding that the speed of the virtual tip marker (which was unaffected by shaft bending) was approximately 0.1 m/s faster for the l-flex shaft than for the x-flex shaft.

Summary

Clubhead speed was found to be underestimated by 0.8% (l-flex) or 0.2% (x-flex) when shaft bending was not taken into account. This is due to the recovery of the shaft from a lagging to a leading position just before impact resulting in increased clubhead speed. This finding was confirmed using the strain data, which showed that in all cases shafts were in the process of changing from lag to lead bending just before impact (as indicated by a positive value for the recovery rate variable). Typically, at impact the clubhead was leading relative to the centreline of the unbent shaft.

When comparing the two shafts, a marginal but statistically significant increase by 0.4% in clubhead speed at impact was associated with decreasing shaft stiffness from x-flex to l-flex. A number of factors contributed to the increase in clubhead speeds for the more flexible shaft. Firstly, wrist release appeared to be slightly delayed for the more flexible shaft. This may have resulted in the increase in grip segment angular velocity at impact that was observed for the l-flex compared to the x-flex shaft. Secondly, the recovery process of the shaft just before impact generated more additional speed for the l-flex than for the x-flex shaft. This was evident from the comparison of a virtual and the actual shaft tip marker and the strain data (recovery rate).

Unexpectedly, lead strain at impact was marginally higher for the x-flex club, and effective loft and launch angle did not appear to increase in the more flexible shaft. This is contrary to mechanisms presented previously (Maltby, 1995) and does not agree with the observation that shaft lead deflection at impact increases as shaft stiffness decreases (MacKenzie & Sprigings, 2009b). As the centre of gravity position of the two clubheads used in this study was matched, this finding tends to support the hypothesis that this characteristic is a factor which influences shaft behaviour (MacKenzie & Sprigings, 2010).

Increased bending in the toe-up/down plane was registered for the l-flex shaft at the top of the backswing compared to the x-flex shaft, but it is not known to what extent this affects the behaviour of the shaft just before impact. Future studies will need to determine the amount of coupling between the two bending planes.

Conclusion

Overall, the observed shaft effects were very small and it is unlikely that the golfers tested were able to detect any effect. The small effect sizes for the shaft effects further support this conclusion, especially when compared to the effect of changing player. Future studies need to determine whether other modifications of shafts (e.g. decreased stiffness) or changes to stiffness distribution might allow golfers to see greater effects, especially when these occur in tandem with changes in other parameters.

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