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The influence of golf shaft stiffness on grip and clubhead kinematics

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ABSTRACT
The purpose of this study was to investigate the influence of shaft stiffness on grip and clubhead kinematics. Two driver shafts with disparate levels of stiffness, but very similar inertial properties, were tested by 33 golfers representing a range of abilities. Shaft deflection data as well as grip and clubhead kinematics were collected from 14 swings, with each shaft, for each golfer using an optical motion capture system. The more flexible shaft (R-Flex) demonstrated a higher contribution to clubhead speed from shaft deflection dynamics ($P < .001$), but was also associated with significantly less grip angular velocity at impact ($P = .001$), resulting in no significant difference in clubhead speed ($P = .14$). However, at the individual level, half of the participants demonstrated a significant difference in clubhead speed between shafts. The more flexible shaft was also associated with significantly different magnitudes of head rotation relative to the grip. More specifically, both bend loft ($P < .001$) and bend lie ($P < .001$) were greater for the R-Flex shaft, while bend close ($P = .017$) was greater for the stiffer (X-Flex) shaft. However, changes in grip orientation resulted in no significant differences in face orientation, between the shafts, at impact.

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Golf; club; kinematics; motion capture; shaft stiffness

1. Introduction

On most golf holes, it is desirable to maximise the displacement of the golf ball down the fairway while using a driver. The influence of the stiffness of a driver shaft on golf ball displacement can be reasoned with a few statements. The displacement of the golf ball is primarily dependent on the ball's initial speed, launch angle and spin. These initial ball parameters are influenced by clubhead speed and clubhead orientation at impact (MacKenzie, 2011). Previous research suggests that clubhead speed and orientation at impact can be influenced by shaft stiffness – likely via shaft deflection. (Betzler, Monk, Wallace, & Otto, 2012; MacKenzie & Sprigings, 2009c; Worobets & Stefanyshyn, 2012).

Several studies have investigated the role of shaft stiffness in generating clubhead speed (Betzler et al., 2012; MacKenzie & Sprigings, 2009c; Worobets & Stefanyshyn, 2012). The amount of speed a shaft adds to the clubhead for a particular swing, relative to a theoretically rigid shaft, is referred to as kick velocity (MacKenzie & Sprigings, 2009c). Specifically, kick velocity is the first time derivative of lead/lag deflection. Shaft deflection during the swing has typically been partitioned into lead/lag and toe-up/down directions based on a reference frame fixed in the grip of the club (MacKenzie & Sprigings, 2009b). Kick velocities reported in the literature, for the driver, have typically been in the range of 4–5% of the total clubhead speed (Butler & Winfield, 1994; Horwood, 1994; MacKenzie & Sprigings, 2009c) with recent findings suggesting values of less than 1% (Betzler et al., 2012). However, the role of shaft stiffness in generating clubhead speed cannot be understood solely through kick velocity. Previous research suggests that shaft deflection influences the kinematics at the grip end of the club as well as the clubhead (MacKenzie & Sprigings, 2009c; Osis & Stefanyshyn, 2012). For example, according to MacKenzie and Sprigings (2009c), a greater kick velocity with a flexible shaft, relative to a stiff shaft, may *not* result in a greater clubhead speed if the flexible shaft is associated with a slower grip speed.

Research into the changes in clubhead speed associated with changes in shaft stiffness is unclear. Worobets and Stefanyshyn (2012) compared five shafts of varying stiffness while using the same clubhead and determined that shaft flex did not have an overall systematic effect on clubhead speed. However, at the individual level, for the majority of the golfers they tested (27/40), shaft stiffness was reported to have a statistically significant influence on clubhead speed. On average, for these 27 golfers, there was a 2.6% increase in clubhead speed between the flexes with the highest and lowest clubhead speed for each golfer individually. Importantly, without information on grip kinematics, it cannot be definitively determined whether the changes in clubhead speed were a result of altered shaft dynamics, modified grip kinematics or both. Betzler et al. (2012) compared two drivers with meaningful differences in shaft stiffness ("ladies" vs. "x-stiff") and determined that the majority of their participants (17/20) generated higher clubhead speed with the more flexible shaft. The result was statistically significant, but the average increase in clubhead speed with the flexible shaft (.4%) was not meaningful.

As demonstrated by two recent studies, shaft stiffness can also influence clubhead orientation at impact; specifically, loft, face angle and lie (Betzler et al., 2012; Worobets & Stefanyshyn, 2012). Worobets and Stefanyshyn (2012)

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reported no systematic difference in loft across their five test shafts; however, there was a significant influence in 11 out of the 40 participants. The average difference between the flexes with the highest and lowest loft within each of these 11 participants was 2.5°; importantly, the higher loft was not necessarily associated with the more flexible shaft. Lie angle increased systematically with increasing shaft stiffness, with the stiffest shaft being associated with a lie angle that was 1.4° more upright, on average, in comparison to the most flexible shaft. Worobets and Stefanyshyn reported no systematic difference in face angle across their five test shafts. Betzler et al. (2012) did find small, but statistically significant differences, between two disparate levels of shaft stiffness in terms of loft (.44° more loft for the "x-stiff" shaft) and face angle (.65° more open for the "ladies" shaft). The majority of their participants (13/20) achieved higher loft with the stiffer shaft. They did not report lie angle. For either of these studies, it is not known how much of the differences in clubface angles at impact were due to changes in shaft deflection, compared to changes in grip orientation.

Collectively considering these previous findings, the purpose of this study was to determine how shaft stiffness mediates both grip kinematics and shaft deflection to generate a resulting clubhead speed and clubhead orientation at impact. It was hypothesised that a more flexible shaft would increase the speed of the clubhead relative to the grip, but given the findings of MacKenzie and Sprigings (2009c), it was further postulated that, on average, there would also be a reduction in grip speed resulting in no significant difference in clubhead speed relative to the ball. It was also hypothesised that a more flexible shaft would increase the magnitude of head rotation relative to the grip, but that changes in grip orientation relative to the global would moderate the effect relative to the ball.

Previous reports of lead/lag and toe/up down deflection throughout the downswing have been based on strain gauge data (Betzler et al., 2012; Butler & Winfield, 1994; Lee, Erickson, & Cherveny, 2002). Shafts do not deflect uniformly throughout the downswing (Joyce, Burnett, & Matthews, 2013; Mather, Smith, Jowett, Gibson, & Moynihan, 2000), which suggests that the location of strain gauge placement on the shaft will have an influence. As such, a final purpose was to demonstrate lead/lag and toe-up/down deflection curves, throughout the downswing, based on optical motion capture techniques.

2. Methods

2.1 Participants

Thirty-three right-handed male golfers (age: 40.3 ± 12.1, handicap: 12.1 ± 7.4) volunteered to participate. The study was approved by the University's Research Ethics Board, and testing procedures, risks and time required were fully explained to each participant before they read and signed an informed consent document.

2.2 Procedures

Participants performed a standardised golf warm-up consisting of dynamic stretches and swings of increasing intensity, which lasted approximately 5 min. Following this initial warm-up, participants hit six practice drives and were instructed to imagine that they were hitting predominately for distance, with their most typical shot shape (e.g., high draw), on a par-5 that is potentially reachable in two shots. Ball flight simulation software (FlighScope Software V9, FlightScope Ltd, Orlando, FL, USA) was used to display a target, and resulting shot trajectory, onto a projection screen.

Following the practice drives, participants hit 28 drives, in blocks of 7, with 30 s of rest between shots and 120 s of rest between blocks. All tests were conducted with the same Ping i25 10.5 driver head, set in the neutral face angle position. Following the first 14 drives, the shaft of the driver was changed without the participants' knowledge. Two Ping shafts, with disparate levels of stiffness but similar inertial properties, were used in the study: PWR 65 Regular (R-Flex) and PWR 65 Tour X-Stiff (X-Flex). Odd numbered participants (e.g., Participant #1) hit the first 14 drives with the stiff shaft, while even numbered participants hit the first 14 drives with the flexible shaft. The 6 practice drives were performed with the same shaft used for the first 14 drives. The two assembled clubs were matched for mass and moment of inertia (MOI) by placing 6 g of lead tape at a precise point down the shaft. A strip of black tape was placed at the same location on both shafts to make the shafts indistinguishable from the golfer's perspective. MOI was checked using an Auditor MOI Speed Match system (Technorama Co Ltd., Kaohsiung City, Taiwan). Participants were under the impression that they were only participating in a study investigating centre of pressure movements and, following testing, each participant acknowledged that they were unaware of the change in shaft at the midpoint of the session. Twelve Srixon Z-star balls were used for testing and were replaced after every 10 participants.

2.3 Data collection and processing

Golf club kinematics were collected using an 8-camera optical system (Raptor-E, Motion Analysis Corporation, Santa Rosa, CA, USA). Four tracking markers were placed near the grip end of the club to create a grip reference frame and four tracking markers were placed on the club head to create a clubface reference frame (Figure 1). If ball contact was made with the lie, loft and face angle equal to 0°, then the clubface reference frame would be perfectly aligned with the global reference frame. During a calibration trial, markers were temporarily placed on wands extending from the shaft in order to calculate virtual markers located within the length of the shaft. During this calibration trial, markers were also precisely placed on the face of the driver to create the clubface reference frame (Figure 1). Two virtual face reference frames were created. One virtual face reference frame was calculated throughout the swing based on the tracking markers on the clubhead. This indicated the actual position and orientation of the face. A second virtual face reference frame was calculated throughout the swing based on the tracking markers at the grip. This second face reference frame indicated how the face would be positioned and oriented if the shaft were perfectly rigid. Camera shutter speeds were set to 3000 Hz, and data were sampled at 500 Hz. The software application Cortex (version

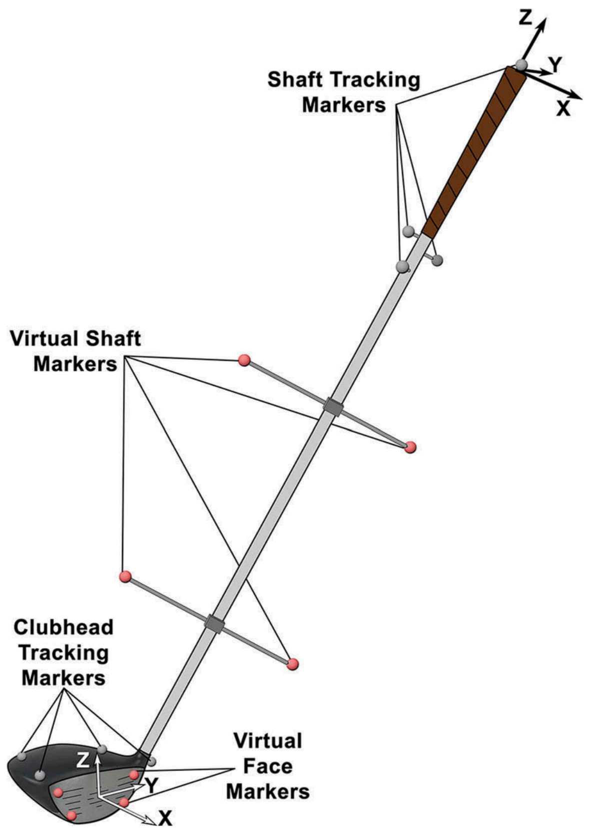

Figure 1. Grip reference frame, clubface reference frame and marker set. If ball contact was made with the lie, loft and face angle equal to 0°, then the clubface reference frame would be perfectly aligned with the global reference frame.

5.3, Motion Analysis Corporation, Santa Rosa, CA, USA) was used to generate and export the 3D coordinate data for each marker. The residuals reported by the system were <1 mm and the accuracy (root mean square error when measuring a known distance) and precision (SD of the length of a rod) were approximately .3 mm. A bespoke software program was written in MatLab (version R2010a, MathWorks, Natick, MA, USA) to process the 3D coordinate data and generate dependent variables of interest. All variables reported at impact were calculated using the marker data up to and including the last frame prior to impact. A forward prediction procedure was then employed to determine the value of each variable at the anticipated moment of contact with the ball. The forward prediction procedure involved fitting a second-order polynomial to the 13 data points prior to impact as a function of time. The polynomial was then evaluated at the predicted time of impact.

2.4 Statistical analysis

Paired *t*-tests were used to compare the effects of the two levels of shaft stiffness on specific dependent variables at impact. Effect sizes, specific to repeated measures tests, were also calculated (Dunlap, Cortina, Vaslow, & Burke, 1996). The strength of the relationship between select variables was determined using Pearson product–moment correlations. For example, what is the relationship between clubhead speed and kick velocity at impact? The reliability of these relationships was assessed by converting the correlations to *t*-scores and determining the associated *P*-value. There were 14 data points per condition for each participant; therefore, it was possible to make reasonable inferences at the individual participant level using *t*-tests as well. Statistical significance was set at $\alpha \leq .05$ for all tests. Statistical analyses were performed using SPSS V22.0 for Windows (IBM Co., New York, NY, USA).

3. Results

Average kick velocity, at impact, for the R-Flex shaft (1.7 $m \cdot s^{-1}$) was significantly higher than that for the X-Flex shaft (1.2 $m \cdot s^{-1}$), and the effect size was also large ($t(32) = 6.96$, $P < .001$, $d = .80$) (Figure 2a). Individually, all participants demonstrated a higher average kick velocity at impact with the R-Flex shaft. The magnitude of angular velocity of the grip, about the *Y*-axis of the grip, was significantly higher for the X-Flex shaft ($t(32) = 3.5$, $P = .001$, $d = .20$) (Figure 2b). It should also be noted that this component of grip angular velocity had a strong and significant correlation of with clubhead speed ($r = .95$, $P < .001$), while kick velocity had virtually no association with clubhead speed ($r = -.04$, $P = .40$). On average, there was no significant difference between shafts with respect to clubhead speed ($t(32) = 1.52$, $P = .14$, $d = .03$) (Figure 2c).

Despite no overall differences in clubhead speed between shafts, approximately half of the participants (17/33) demonstrated a statistically significant difference between shafts in terms of clubhead speed (Figure 3). Of those for which there was a significant difference, the majority (12/17) generated higher clubhead speeds with the R-Flex shaft. Considering clubhead speed, faster swingers seem to have responded better to the X-Flex shaft, while slower swingers seemed to have responded better to the R-Flex, but there were certainly exceptions. Interestingly, neither the fastest nor slowest swinger demonstrated a significantly higher clubhead speed with either shaft. Of note, no participants showed an average difference in clubhead speed greater than 1 $m \cdot s^{-1}$ (Figure 3). In order to get an indication of the source of any change in clubhead speed between shaft conditions, Pearson product–moment correlations were computed between differences in kick velocity and differences in clubhead speed ($r = .07$, $P = .36$) as well as differences in grip angular velocity and differences in clubhead speed ($r = .32$, $P = .04$).

Bend loft represents the change in the static loft of the club due to the bending of the shaft (Figure 4a). This has previously been referred to as “dynamic loft” in the literature (Horwood, 1994; MacKenzie & Sprigings, 2009c); however, the term dynamic loft is now associated with the loft reported by launch monitors. Average bend loft, at impact, for the R-Flex shaft (5.82°) was significantly higher than that for the X-Flex shaft (3.84°), and the effect size was also large ($t(32) = 12.9$, $P < .001$, $d = 1.1$) (Figure 4b). Average shaft lean (rotation of the shaft about its own *Y*-axis; see Figure 1), at impact, was significantly higher for the R-Flex shaft in comparison to the X-Flex shaft ($t(32) = 4.01$, $P < .001$, $d = .17$) (Figure 4c). Positive shaft lean delofts the clubhead. On average, delivered loft was .39° higher for the R-Flex shaft in comparison to the X-Flex

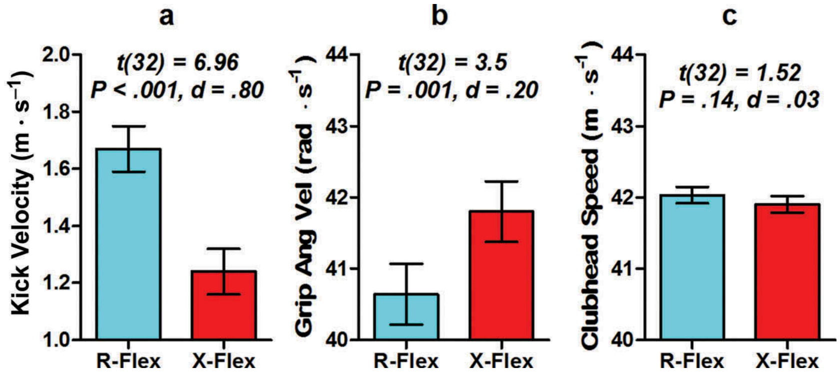

Figure 2. This figure compares, for each shaft flex, three club kinematic variables at impact. (a) Kick velocity, (b) magnitude of the angular velocity of the grip about the *Y*-axis of the shaft (see Figure 1) and (c) speed of the centre of the clubface. These are average values across all participants. Error bars represent 99% within-participant confidence intervals. Results of two-tailed paired *t*-tests and effect sizes are also included.

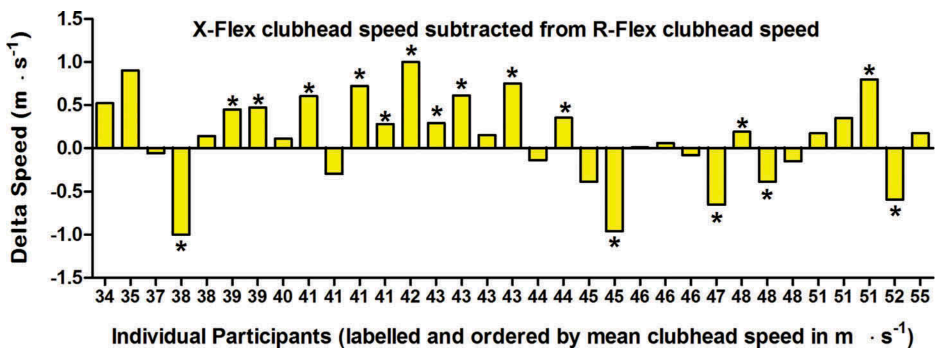

Figure 3. Each bar represents the average difference in clubhead speed between shafts for each participant. Positive values indicate a higher average clubhead speed with the R-Flex. As determined by a two-tailed paired *t*-test ($\alpha = .05$), the * indicates a significant difference between shafts for that participant.

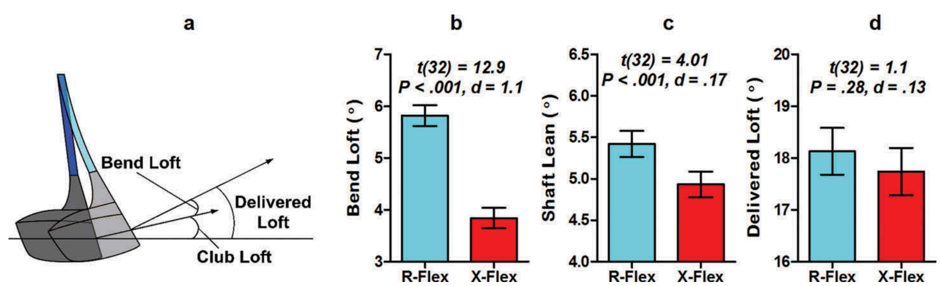

Figure 4. (a) Graphical definition of club loft, bend loft and delivered loft. The solid head represents position if shaft did not bend. The transparent head shows the position of the actual clubhead at impact. (b) Bend loft at impact. (c) Shaft lean at impact. Positive shaft lean delofts the clubhead. (d) Delivered loft. These are average values across all participants. Error bars represent 99% within-participant confidence intervals. Results of two-tailed paired *t*-tests and effect sizes are also included.

shaft, but the difference was not statistically significant ($t(32) = 1.1$, $P = .28$, $d = .13$) (Figure 4d).

Average lead deflection, at impact, for the R-Flex shaft (42.8 mm) was significantly higher than that for the X-Flex shaft (32.6 mm), and the effect size was medium ($t(32) = 8.05$, $P < .001$, $d = .45$) (Figure 5a). Average toe-down deflection, at impact, for the R-Flex shaft (78.3 mm) was significantly higher than that for the X-Flex shaft (59.7 mm), and the effect size was large ($t(32) = 14.0$, $P < .001$, $d = .88$) (Figure 5b). Bend lie represents the change in the static lie of the club due to the bending of the shaft. Average bend lie, at impact, for the R-Flex shaft (10.1°) was significantly higher (more toe-down) than that for the X-Flex shaft (8.0°), and the effect size was also large ($t(32) = 14.9$, $P < .001$, $d = .94$) (Figure 5c). Bend face angle represents the change in the static face angle of the club due to the bending of the shaft. Average bend face angle, at impact, for the X-Flex shaft (3.9°) was significantly more closed (relatively to the target line) than that for the R-Flex shaft (3.5°) ($t(32) = 2.52$, $P < .017$, $d = .19$) (Figure 5d).

As demonstrated by the 99% within-participant confidence intervals (shaded bands), lead/lag and toe-up/down deflections were significantly greater throughout the vast majority downswing for the R-Flex shaft in comparison to the X-Flex (Figure 6). There were no significant differences, between shafts, for the following variables at impact: horizontal clubhead path, vertical clubhead path, delivered loft, delivered lie

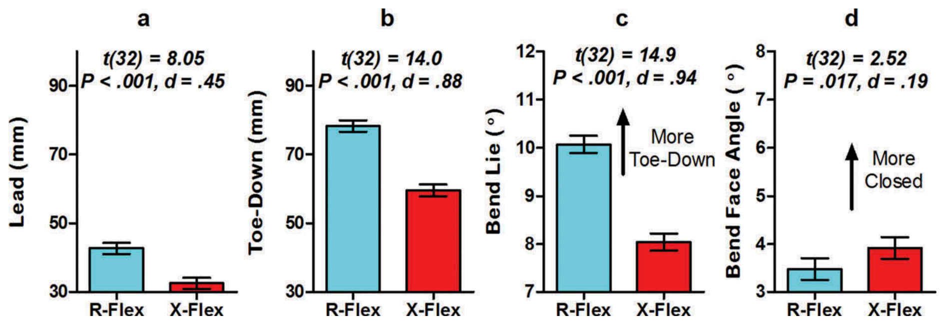

Figure 5. This figure compares, for each shaft flex, four shaft deflection dependent variables at impact. (a) Lead deflection, (b) toe-down deflection (note that these are presented as positive values for easier comparison to lead deflection), (c) bend lie and (d) bend face angle. These are average values across all participants. Error bars represent 99% within-participant confidence intervals. Results of two-tailed paired *t*-tests and effect sizes are also included.

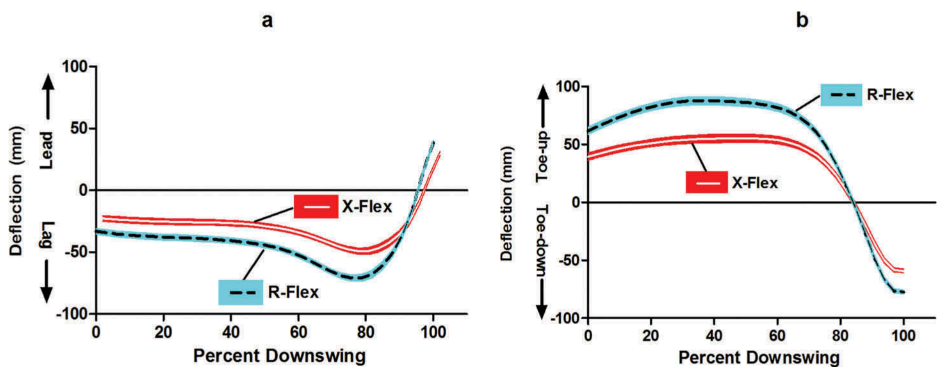

Figure 6. Ensemble average graphs of shaft deflection, for all swings, of all 33 participants as a percentage of downswing duration. (a) Lead/lag deflection (note that the X-Flex curve has been "nudged" 2% along the horizontal axis for clarity). (b) Toe-up/down deflection. Shaded bands represent 99% within-participant confidence intervals. At 0% clubhead speed has reached a local minimum at the top of the swing, while 100% represents impact with the ball.

or delivered face angle. Importantly, the delivered face angle approached significance (P = .06) with the X-Flex shaft being associated with a less closed face angle at impact (–.23°) relative to the R-Flex shaft (–.71°).

4. Discussion

As expected, the R-Flex shaft demonstrated a greater kick velocity (~1 mph on average) relative to the X-Flex. However, at impact, the grip of the R-Flex shaft was associated with significantly less angular velocity. If the grip angular velocities were the same for each shaft, then the kick velocity results would translate into a comparable difference of about 1 mph in clubhead speed in favour of the flexible shaft. However, on average, the actual difference in clubhead speed was only about .2 mph (Figure 2c). This suggests that the same mechanism that increases the speed of the clubhead relative to the grip may also reduce the grip angular velocity about the *Y*-axis of the shaft.

This association between grip angular velocity and kick velocity has previously been identified with the use of a forward dynamics model (MacKenzie & Sprigings, 2009c). While this earlier computer simulation research demonstrated that the relationship existed, there were two notable external validity limitations: (1) The model essentially represented a single "type" of golf swing and (2) human golfers may alter how they swing (perhaps subconsciously) based on a change in "feel" associated with altering shaft stiffness. The participant-specific responses to shaft stiffness, with respect to clubhead speed (Figure 3), suggests that individual golfers may have differing abilities to lessen the reduction in grip angular velocity associated with higher kick velocities. For example, an R-Flex "responder" would be able to maintain the same grip velocity they had with the X-Flex shaft, and but the higher kick velocity associated with the more flexible shaft would result in higher clubhead speed. However, this does not appear to have been the case, as there was no correlation (r = .07, P = .36) between changes in kick velocities and changes in clubhead speed between shafts. However, there was a significant correlation between changes in grip velocity and changes in clubhead speed between shafts. This suggests that participants simply swung a club with a particular shaft stiffness with more angular velocity at impact. It seems probable that golfers adjust how they swing the club (e.g., altered force profile applied to the grip) based on the feel associated with a change in shaft stiffness (MacKenzie, 2011; Osis & Stefanyshyn, 2012). The results from this study are in agreement with the findings of Betzler et al. (2012) as well as Worobets and Stefanyshyn (2012) in that shaft flex did *not* have an overall meaningful systematic effect on clubhead speed. Also similar to Worobets and Stefanyshyn, a large number of participants did generate significantly higher clubhead with a particular shaft flex.

As expected, the R-Flex shaft was associated with an average increase to the static loft of the clubhead, which was approximately 2° more than the amount of loft added due to the bending of the X-Flex shaft. A 2° increase in the loft of a driver would be very impactful to the resulting ball trajectory. However, the actual delivered loft of the club (at the moment of first contact with the ball) was, on average, only .4° higher for the more flexible shaft. This can be partially explained by the average difference in shaft lean between the two conditions, which indicates that the participants tended to deloft the clubface more with the flexible shaft, thus reducing the influence of bend loft on delivered loft. It should be noted that unlike bend loft, in which all participants showed more of an increase with the R-Flex shaft, there were six participants that demonstrated increased shaft lean with the X-Flex shaft. This finding demonstrates the potential challenge for a club fitter; while changing to a more flexible shaft will almost certainly tend to increase delivered loft (via bend loft), some golfers will augment this effect, while others will diminish it via club orientation at impact. Again, this suggests that it is likely that golfer's may adjust how they swing the club (e.g., altered force profile applied to the grip) based on the feel associated with a change in shaft stiffness.

The amount of lead deflection at impact was the primary factor affecting bend loft. Every participant demonstrated increased lead clubhead deflection at impact with the R-Flex shaft in comparison to the X-Flex. The same was true for toe-down deflection at impact; however, the magnitude of difference between shafts was greater in the toe-down direction (Figure 5). The magnitude difference between the deflection directions can partially be explained by the location of the clubhead's centre of gravity (CoG) relative to the shaft. The CoG of the clubhead used in this study was further from the shaft along the *Y*-axis of the grip (−4.1 cm), then it was along the *X*-axis of the grip (−2.5 cm). The offset of the clubhead's CoG plays an important role in the magnitude of shaft deflection at impact (MacKenzie & Sprigings, 2009b). Bend lie represents the change in the static lie of the club due to the bending of the shaft and is primarily influenced by the amount of toe-down deflection at impact. As expected, the R-Flex shaft was associated with an average change in lie (in the "toe-down" direction), which was approximately 2° more than the amount of lie change due to the bending of the X-Flex shaft (Figure 5c). Every participant demonstrated more bend lie with the R-Flex shaft relative to the X-Flex. Interestingly, there was no significant difference between the shaft conditions, in the lie of the clubhead, at the moment of impact. This suggests that, on average, the changes in clubhead orientation due to shaft deflection were moderated by alterations in grip orientation at impact.

It seems clear that a more flexible shaft will increase bend loft as well as bend lie; however, the influence of shaft deflection on face angle is more complex. On average, shaft deflection resulted in the stiffer shaft being more closed (relative to a rigid shaft) by approximately .5° in comparison to the more flexible shaft. However, 11/33 participants demonstrated the opposite relationship with the R-Flex shaft having a more closed bend face angle. This ambiguity can be explained by the fact that both lead deflection and toe-down deflection have meaningful – but opposite – effects on face angle. Relative to a clubhead attached to a theoretically rigid shaft, lead deflection will tend to close the face, while toe-down deflection will tend to open the face. For a right-handed golfer, "more open" simply means that a vector normal to the centre of clubface will be pointing more to the right. The effect is similar to playing from an uneven lie; for example, with the ball below the level of the golfer's feet, clubhead loft will tend to launch the ball right as well as up. Of note, for all but one participant, the net influence of shaft deflection was to close the face relative to a theoretically rigid club. For this single participant, the net influence of shaft deflection resulted in a slightly open face relative to a virtual clubhead head attached to a theoretical rigid shaft. On average, at impact with the R-Flex shaft, this participant had approximately 120 mm of toe-down deflection coupled with only 12 mm of lead deflection.

Previously, shaft deflections throughout the swing have been represented by bending moment curves (Lee et al., 2002; Milne & Davis, 1992), strain profiles (Betzler et al., 2012) or predicted clubhead displacements (Butler & Winfield, 1994) each based on strain data collected at discrete locations along the shaft. As demonstrated by Mather et al. (2000) and Joyce et al. (2013), shaft deflection is not uniform along the length the shaft, which highlights a potential advantage of using optimal motion capture techniques; the net effect of shaft deflection on clubhead displacement can be determined throughout the swing. In this study, the R-Flex shaft was deflected to a greater degree throughout the entire downswing relative to the X-Flex, with the only exception being the moment in time when the shafts changed deflection polarities (Figure 6). These deflection curves agree well with the experimental stain gauge data previously mentioned as well as shaft deflection curves generated using 3D forward dynamics (MacKenzie & Sprigings, 2009a).

5. Conclusions

This study has provided novel insights into the understanding of how shaft stiffness influences clubhead kinematics at impact with a driver. Shaft stiffness's effects on grip kinematics seem to be almost as important as the changes in clubhead kinematics due to shaft deflection. Certain golfers were found to generate upwards of an additional 1 $m \cdot s^{-1}$ of clubhead speed with a particular shaft stiffness. The increased clubhead speed was partly explained by the players simply swinging the club with more angular velocity, perhaps due to how the club felt during the swing. It was also found that the more flexible shaft was deflected to a greater extent at impact, which tended to increase the loft and the lie angle (in the toe-down direction); however, the more flexible shaft was also associated with a grip orientation that tended to neutralise the influence of shaft deflection. There are two probable explanations regarding how shaft stiffness influenced grip kinematics. It is possible that participants used the same motor pattern with each shaft, but due to the varied bending profiles, each shaft applied unique reaction force patterns to the golfer, which in turn resulted in altered grip kinematics. It is also possible that some participants felt a difference between the shafts, which resulted in a shaft-stiffness-specific motor pattern being implemented during the swing. The findings of this study can be applied when customising the parameters of a driver. For example, assume a club fitter wants to reduce delivered loft in order to improve ball launch conditions (i.e., reduce ball spin) for a particular golfer. If changing to a stiffer shaft actually increases delivered loft, then the fitter can be confident that while the stiffer shaft is still deflecting less in the lead direction at impact (less bend loft) the golfer has altered (perhaps unknowingly) the grip orientation at impact. In this scenario, it may be advisable for the fitter to achieve less delivered loft by using a lower lofted clubhead.

Disclosure statement

No potential conflict of interest was reported by the authors.

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