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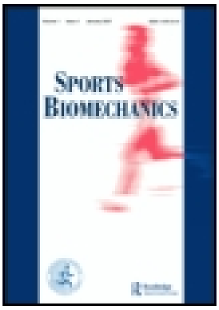

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Abstract
The role of shaft stiffness on the golf swing is not well understood. Studies in which golfers hit balls with clubs of varying shaft flex have reported changes in ball distance. The results of mathematical models suggest that shaft stiffness affects only the orientation of the clubhead at impact, not the speed of the clubhead, but there are no experimental results validating these findings. The purpose of this study was therefore to experimentally examine the influence of shaft stiffness on clubhead kinematics at ball impact. Forty golfers hit 10 balls with each of five drivers varying in shaft stiffness from 'Ladies' to 'Extra-Stiff,' in a double-blind study design. The motions of three reflective markers attached to the clubhead were captured with a high-speed motion analysis system. At ball impact, shaft stiffness had a statistically significant influence on clubhead speed for 27 subjects, on loft angle for 11 subjects, and on lie angle for all 40 subjects. No effect was observed on face angle, in to out path angle, or attack angle. These results show that shaft stiffness can affect ball launch conditions by altering clubhead speed and/or loft angle.

Keywords: *Biomechanics, sport equipment, performance, loft angle, clubhead speed*

Introduction

Shaft bending stiffness is an aspect of the golf receiving the most attention among the scientific community (Penner, 2003). However, the role of shaft stiffness, more commonly referred to shaft flex, on golfing performance is not yet completely understood. Studies in which golfers hit balls with clubs of varying flex have reported changes in ball distance achieved (Pelz, 1990; Stanbridge et al., 2004); however, the exact mechanism affecting these changes has not been adequately described. Very few studies have focused explicitly on the influence of shaft flex on clubhead parameters at ball impact (Milne & Davis, 1992; Wallace & Hubbell, 2001; MacKenzie & Sprigings, 2009) and the results are conflicting.

There is no question that the golf club shaft bends during the backswing and downswing, and recoils as the clubhead approaches impact with the ball. This has been shown experimentally with the use of high-speed photogrammetry (Mather & Jowett, 2000; Mather et al., 2000) as well as with strain gauge instrumented shafts (Milne & Davis, 1992; Butler & Winfield, 1994; Horwood, 1994; Masuda & Kojima, 1994; Lee et al., 2002; Ozawa et al., 2002; Tsujiuchi et al., 2002).

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In the studies that collected data on shafts of varying flex (Masuda & Kojima, 1994; Mather & Jowett, 2000; Mather et al., 2000; Tsujiuchi et al., 2002), it was found that the different shaft flexes had distinctly different bending profiles throughout the swing.

Milne and Davis (1992) and MacKenzie and Sprigings (2009) used mathematical models to determine the role of shaft stiffness on the golf swing. Both studies concluded that shaft deformations do not influence clubhead speed; it is only the orientation of the clubhead which is affected: a more flexible shaft will be bent forward more at impact, resulting in a higher loft angle. This conclusion is supported by the golf community and by professional clubfitters in particular (Wishon, 2005) assumingly based on years of anecdotal evidence.

However, the results of these theoretical models were not validated in published comprehensive experimental studies on shaft flex. Wallace and Hubbell (2001) collected clubhead data from 83 golfers hitting balls with clubs of varying shaft flex, and found that flex did in fact influence clubhead speed to a statistically significant degree. Although the magnitude of this influence (0.9%) was deemed too small to be relevant, the test clubs used in the study were mid-range irons, not a club designed to maximize ball distance. It may be that these small differences become amplified in the driver, a club with a longer and more flexible shaft. Unfortunately, loft angle at impact was not measured in their study. The purpose of this study was, therefore, to add to the limited understanding of the effect of shaft flex on clubhead kinematics at impact by experimentally collecting clubhead data from a variety of different golfers hitting balls with drivers of varying shaft stiffness.

Methods

Forty recreational golfers were recruited for the study (age, 35.1 $\pm$ 14.9 years; height, 1.79 $\pm$ 0.07 m; mass, 81.4 $\pm$ 13.2 kg). The only inclusion criteria were that the subjects had to be right-handed golfers and have a handicap of $<$10. This handicap range was chosen on the premise that these golfers would be able to produce more consistent swings than golfers of lesser ability. The sample consisted of males and females ($n = 37$ and 3, respectively) covering a wide range of ages (16–72) in order to ensure a broad variety of swing patterns. Informed written consent, in accordance with the specifications of University of Calgary Ethics Committee, was obtained from all subjects prior to testing.

Five Aldila NV55 driver shafts were used as the test shafts in the study. The shafts ranged in stiffness to represent the spectrum of stiffnesses currently available from Aldila: lady flex (L, most flexible), senior flex (A), regular flex (R), stiff flex (S), and extra-stiff flex (X). The Aldila NV55 model was chosen as the properties of this model other than stiffness did not vary substantially. This was verified by measurements taken by a TaylorMade-Adidas Golf technician (Table I). The measured butt flex increased by 61% from the most stiff (X) to the most flexible (L) shaft. Except for frequency, which is related to the bending stiffness, the other shaft parameters varied by $<$9% across shafts.

The methodology used to measure the first five shaft properties presented in Table I is proprietary to TaylorMade-Adidas Golf, and so only general descriptions are provided here. Butt flex was the measured deflection of the shaft when clamped at the butt end subject to a known mass hung from the unclamped end. Frequency was calculated using a laser to measure the oscillations of each shaft when clamped at one end and forcibly perturbed. The ratio of tip to butt flex (tip flex was measured in a similar manner as butt flex, but with the tip of the shaft clamped instead of the butt) gives an indication of the flex profile of the shaft; how the flex changes along the length of the shaft. Torsional deflection was measured as the

Table I. Physical measurements of the Aldila NV55 shafts used in the study.

	Shaft stiffness				
	L	*A*	*R*	*S*	*X*
Butt flex (mm)	112.8	103.2	91.0	80.5	70.0
Frequency (Hz)	217.0	229.0	241.0	253.0	269.0
Ratio of tip to butt flex	1.59	1.56	1.56	1.63	1.62
Torsional deflection (°)	4.9	4.6	4.7	4.6	5.0
Swing weight (g)	24.9	23.5	24.0	24.0	24.1
Length (in)	42 2/16	42 2/16	42 4/16	42 2/16	42 2/16
Mass (g)	51.2	49.0	50.8	51.8	53.0
Inertia ($kg\,m^2$)	0.00503	0.00513	0.00522	0.00534	0.00535

Note: L = lady flex (most flexible), A = senior flex, R = regular flex, S = stiff flex, X = extra-stiff flex (most stiff).

angular deflection of the shaft subject to the application of a known torque. Swing weight is the amount of mass required to add to the butt of the shaft to balance the shaft about a fulcrum 14 inches from the butt end of the shaft. This measure was used in an attempt to quantify the golfer's feel of club 'heaviness' during the swing.

Each of the five shafts was fitted with a removable hosel system such that they could be quickly attached to or removed from a modified TaylorMade 580XD driver head (Figure 1). In this way, the same clubhead was used for all drives performed with each of the five test shafts. The shafts were all visually identical and coded for stiffness (a small numerical code was located on the underside of the butt of the shaft), in order to facilitate a double-blind study design.

Testing took place in a laboratory setting, where each golfer hit tee-shots with maximal effort into a net from an artificial turf mat. The golfers were aligned such that the balls were targeted along a laboratory coordinate system 'target' axis. After a brief warm up, the subjects hit one ball with their own seven-iron, then five balls with the test driver, followed by another one ball with their seven-iron. While the subject was hitting this second seven-iron shot, the shaft of the test driver was changed without the subject's knowledge. The subject then hit five balls with the newly shafted test driver, followed by one ball with their seven-iron, at which point the shaft of the driver was again changed. This process continued until each of the five test shafts were used to hit five balls. The entire test was then repeated, increasing the total number of swings taken with each shaft from 5 to 10. This protocol included the subject's own seven-iron in order to allow them to swing with a familiar club prior to any set of five trials with the test driver. The order in which the shafts were tested was randomized between subjects, and the entire test progressed at each subject's own leisurely pace to minimize any effects of fatigue. Prior to testing, the subjects were instructed to minimally handle the test driver in between trials. They were not permitted to 'waggle' the club or otherwise manually impart a bend in the shaft.

The motions of three spherical retroreflective markers (1.91-cm diameter) fixed to the driver head were captured during all swings with eight digital high-speed video cameras (Motion Analysis Corp., Santa Rosa, CA, USA) collecting at 600 Hz. The system was calibrated to an average three-dimensional (3D) residual for all cameras of <0.6 mm. Prior to testing, temporary markers were attached to the club to define a clubface-aligned coordinate system. The club was then placed in the capture area and a trial was recorded. Using the method of Soderkvist and Wedin (1993) and Matlab software (MathWorks Inc.,

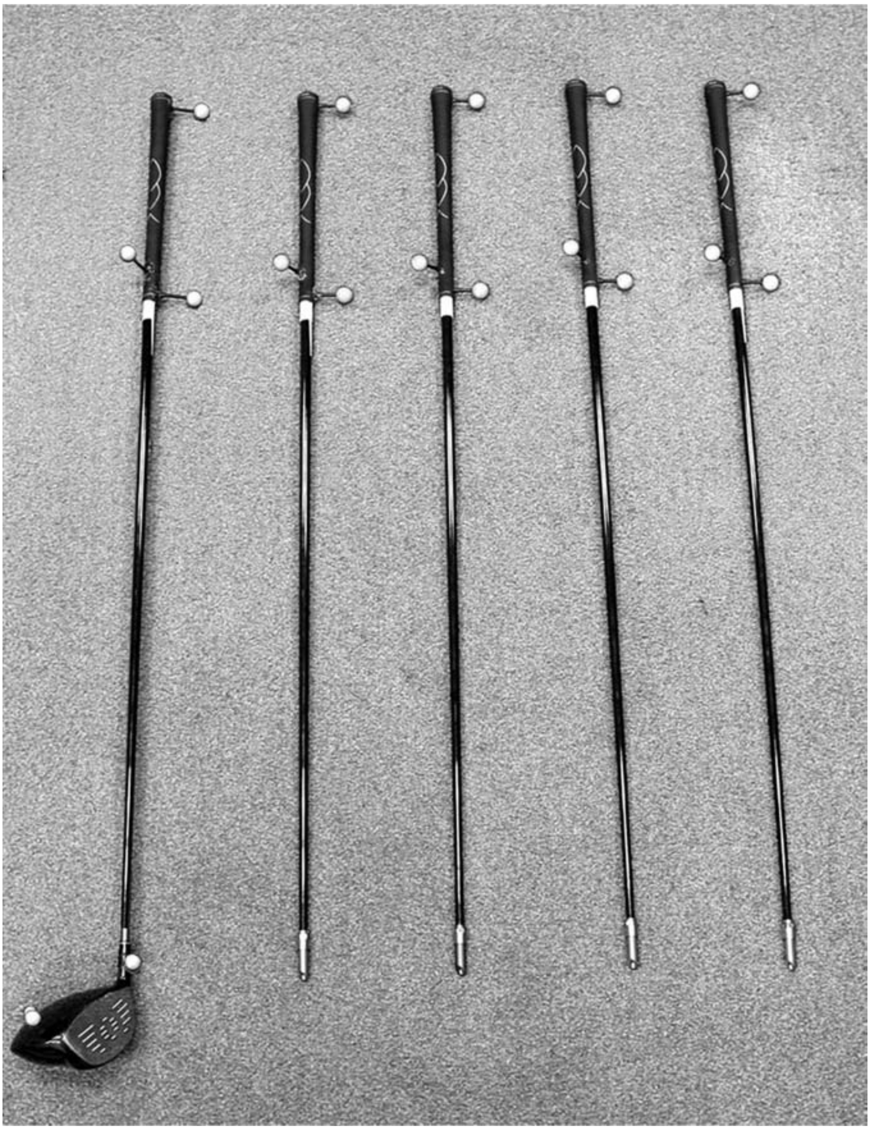

Figure 1. The five Aldila NV55 shafts (*L*, *A*, *R*, *S*, and *X*) and the Taylormade 580XD driver head used in the study.

Natick, MA, USA), this information was used to establish a clubhead relevant orthogonal coordinate system with the origin embedded at the center face and with axes normal to the club face, parallel to the score lines, and perpendicular to the score lines (Figure 2).

The raw 3D position data of the clubhead coordinate system origin were first differentiated to calculate clubhead speed. This was used to identify the time of ball impact, which occurred when there was a dramatic and sudden decrease in clubhead speed. The raw position data were then clipped at this time point, and filtered using a 60 Hz low-pass filter. As the last data point of these filtered signals was divergent, the last two data points were clipped off, and the remaining curves were extrapolated up to the time of ball impact. This procedure produced filtered curves with robust end points. This was verified by plotting

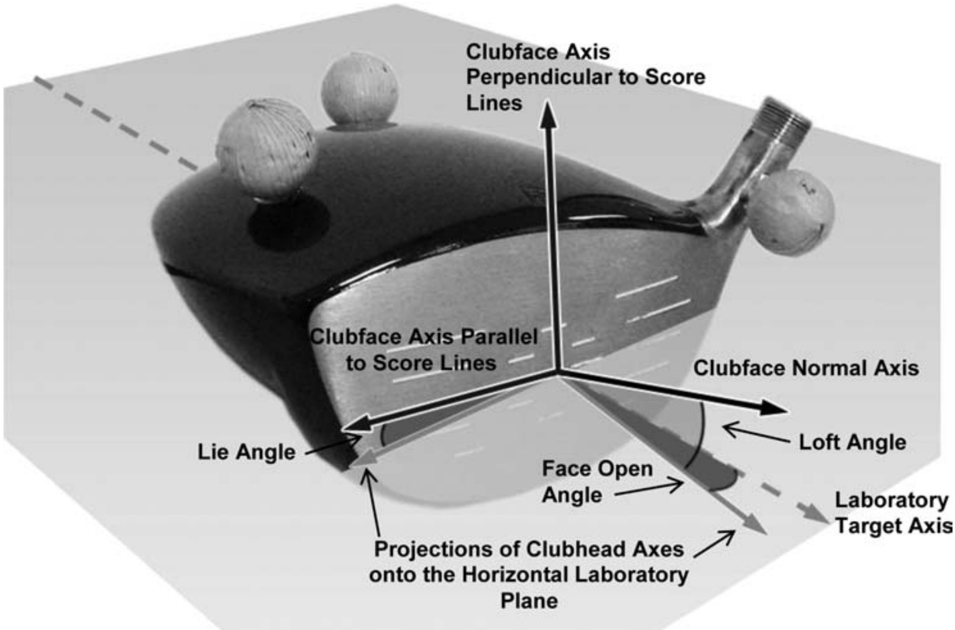

Figure 2. The test driver head, reflective markers, orthogonal clubhead coordinate system, and clubhead orientation angles.

every differentiated filtered curve over the corresponding differentiated raw trace and visually inspecting to ensure that the end points of the filtered curve lay centrally within the noise band of the raw trace.

The analyzed variables of interest were clubhead speed, loft angle, face open angle, lie angle, in to out path angle, and attack angle, all at time of ball impact. The clubhead orientation angles were calculated relative to the laboratory coordinate system (Figure 2): loft angle (the angle between the face normal axis and the horizontal laboratory plane), face open angle (the angle between the face normal axis and the laboratory 'target' axis in the horizontal laboratory plane; positive indicating an open face), and lie angle (the angle between the clubhead axis parallel to the groove lines and the horizontal laboratory plane; positive indicating a 'toe up' orientation). Clubhead speed was defined as the magnitude of the velocity vector of the clubhead coordinate system origin. In to out path angle and attack angle were defined as the angles between this velocity vector and the laboratory 'target' axis in the horizontal laboratory plane, and between the velocity vector and the horizontal laboratory plane, respectively (positive indicating outward and upward trajectories).

For each subject, the 10 trials with each shaft flex were averaged for each variable of interest. Repeated measures ANOVAs were used to detect any overall influence of shaft flex on the variables across all players, and one-way ANOVAs were used to detect any differences between shafts within each of the players. Where necessary, Bonferroni post-hoc tests were used to identify the shafts in which the differences occurred. The level of significance was set at $\alpha = 0.05$.

Results

Mean values of all the variables of interest for each shaft flex are given in Table II. Each mean is the average of all 40 subjects. Mean intra-golfer *SDs* for each variable are also shown in

Table II. Mean (±mean intra-golfer *SD*) clubhead kinematic variables at impact for each of the shaft stiffnesses.

	Shaft stiffness				
	L	*A*	*R*	*S*	*X*
Clubhead speed (m/s)	43.5 ± 0.4	43.5 ± 0.6	43.4 ± 0.5	43.4 ± 0.5	43.3 ± 0.5
Loft angle (°)	14.1 ± 2.0	14.3 ± 2.1	14.2 ± 2.1	14.3 ± 2.2	14.1 ± 2.1
Face angle (°)	6.3 ± 3.2	6.2 ± 3.0	6.3 ± 3.1	6.1 ± 2.8	6.1 ± 2.9
Lie angle (°)	1.0 ± 0.9*	1.4 ± 1.0*	1.6 ± 0.8*	2.1 ± 1.0*	2.4 ± 0.8*
In to out path angle (°)	3.0 ± 1.7	2.9 ± 1.5	3.1 ± 1.3	3.0 ± 1.4	3.1 ± 1.6
Attack angle (°)	0.2 ± 1.5	0.2 ± 1.5	0.3 ± 1.4	0.1 ± 1.5	0.2 ± 1.6

Note: *L* = lady flex (most flexible), *A* = senior flex, *R* = regular flex, *S* = stiff flex, *X* = extra-stiff flex (most stiff). *indicates statistically significant differences between consecutive shaft stiffnesses.

Table II. These values represent the average swing-to-swing variability, not the variability between subjects or between test shafts.

Clubhead speed data for an example subject are shown in Figure 3. The 10 bars on the left side of the graph present the data in the manner in which they were collected: each bar is the average of five trials, and the shafts are ordered in the repeating sequence by which they were tested. The five bars on the right side of the graph are the averages of the 10 trials of each shaft flex, ordered in increasing stiffness from left to right. This presentation illustrates the repeatability of the clubhead speed data, as the general trend from flex to flex was repeated within the two sets of five conditions. Furthermore, as the clubhead speed did not consistently decrease from the first shaft tested to the last, any effects of fatigue appear to be insubstantial.

Shaft flex did not have an overall systematic effect on clubhead speed for all subjects, as the average values for each shaft were not statistically different. However, subject-specific differences were found with shaft flex having a statistically significant effect on clubhead

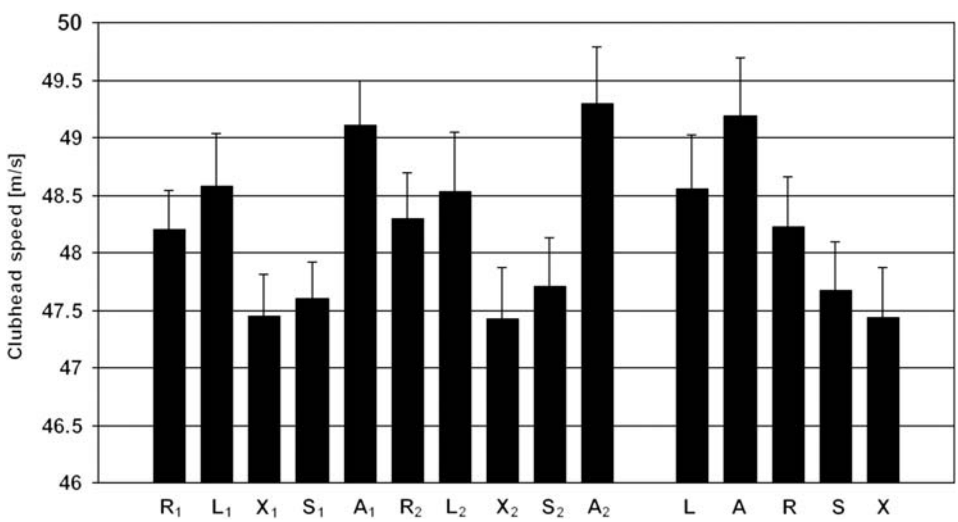

Figure 3. Clubhead speed data for an example subject. The 10 bars on the left are averages (with *SDs*) of five swings per shaft listed in the order in which they were tested. The five bars on the right are averages (with *SDs*) of all 10 swings taken with each of the five shafts, ordered in increasing stiffness from left to right. *L* = lady flex, *A* = senior flex, *R* = regular flex, *S* = stiff flex, and *X* = extra-stiff flex.

speed in 27 out of the 40 subjects. For these 27 subjects, the average difference in clubhead speed between the flexes with the highest and lowest clubhead speed was 2.6% (1.5%–5.0%). When the flex with the highest clubhead speed value for each subject was identified, a visible trend did occur (*L*: 10, *A*: 7, *R*: 6, *S*: 2, and *X*: 2), more players tending to have their highest clubhead speed with a more flexible shaft.

There was no significant difference in loft angle between shafts across all subjects. Within subject, there was a significant influence in 11 out of the 40 subjects. The average difference between the flexes with the highest and lowest loft angle within each of these 11 subjects was 2.5° (1.8–3.6°). This influence was not systematic, with some subjects having higher loft angles with the stiffer flexes (*S* or *X*; $n = 7$), and yet others having higher loft angles with softer flexes (*L* or *A*; $n = 4$).

Shaft flex had a statistically significant influence on average lie angle across all subjects. This influence was a consistent increase in lie angle from the *L* to the *X* shaft (Table II). Shaft stiffness was not found to have a statistically significant influence on face angle, in to out path angle, or attack angle, either across all subjects or within each subject.

Discussion and implications

The current understanding of the influence of shaft stiffness on clubhead variables at impact is limited. For instance, although it has been shown that shaft flex can affect ball yardage (Pelz, 1990; Stanbridge et al., 2004), it has not been clearly shown whether this effect is due to a change in clubhead speed, or a change in loft angle. The purpose of this investigation was, therefore, to experimentally quantify clubhead variables at impact of a variety of different shaft flexes.

The average values of the clubhead kinematics presented in Table II are very similar to the experimentally obtained values reported in previous studies (Van Gheluwe et al., 1990; Butler & Winfield, 1994; Horwood, 1994; Masuda & Kojima, 1994; Miao et al., 1998; Wallace & Hubbell, 2001; Lee et al., 2002; Tsujiuchi et al., 2002; Williams & Sih, 2002). The low average swing-to-swing variability in clubhead speed seen within-player within-club (Table II, mean intra-golfer SD) supports the notion of Mather et al. (2000), who stated that even amateur golfers display consistent results.

Shaft flex was found to have a significant influence on clubhead speed, loft angle, and lie angle. The effect on clubhead speed was significant, with changes in clubhead speed found in approximately 67%. This result is contrary to current belief (Milne & Davis, 1992; Wallace & Hubbell 2001; Wishon, 2005; MacKenzie & Sprigings, 2009). Loft angle was only influenced in 25% of the subjects, and not in the manner assumed by previously published studies (Milne & Davis, 1992; Wishon, 2005; MacKenzie & Sprigings, 2009). Lie angle was systematically affected by shaft flex for all subjects. The face open and path angles did not change from flex to flex.

Of the players having a statistically significant change in clubhead speed, their clubhead speed was influenced by shaft flex by 2.6% on average. Assuming consistent launch conditions, it has been estimated that this could lead to an increase in ball carry distance of approximately 10 yards (Cochran & Stobbs, 1968; Quintavalla, 2006). This is not consistent with previous experimental findings (Wallace & Hubbell, 2001) or theoretical (Milne & Davis, 1992; MacKenzie & Sprigings, 2009) conclusions. Wallace and Hubbell (2001) did find a statistically significant change in the clubhead speed of a mid-range iron due to flex; but since this change was small (0.9%), they concluded that it was irrelevant. However, it appears that with the use of a driver, a club with a longer and more flexible shaft, the effect of shaft flex on club head speed is amplified to a relevant degree. As two experimental studies have now shown results contrary to the models of Milne and Davis (1992) and MacKenzie and Sprigings (2009), the validity of these models must be questioned.

Shaft flex influenced clubhead speed in 27 out of the 40 golfers, but for some subjects the clubhead speed was not altered. This ratio of affected golfers is nearly identical to that reported by Stanbridge et al. (2004), where 21 out of 30 golfers realized a change in ball distance with different shaft flexes. Furthermore, there was no overall trend in clubhead speed between shafts among all subjects; although most subjects had higher clubhead speed with the most flexible shaft, some had higher clubhead speeds with the stiffer shafts. This was also the case in the Stanbridge study, as well as in a similar study by Pelz (1990), which both found that the maximum ball distance varied somewhat randomly with the different levels of shaft flex achieved by the players.

Shaft flex affected loft angle in only 25% of the subjects. This may be due to the statistical analysis, only sensitive enough to detect differences in loft angle of, on average, 2° or more between clubs. However, only four of the subjects had a higher loft angle with the more flexible (*L* or *A*) shafts, and not one of these four exhibited an increasing trend among the five flexes. Although it was based on only one subject, Tsujiuchi et al. (2002) also reported experimental results showing no correlation between flex and loft angle. These findings are contrary to previous models (Milne & Davis, 1992; MacKenzie & Sprigings, 2009), which predicted increasing loft angle with increasing shaft flexibility, as well as the general belief of the golf community (Wishon, 2005).

For both clubhead speed and loft angle, the effects of shaft flex were highly subject-specific. It is known that different players impart different kinetic loading patterns to the club, and as a result exhibit different shaft bending profiles throughout the swing (Butler & Winfield, 1994; Mather & Jowett, 2000; Lee et al., 2002; Ozawa et al., 2002; Tsujiuchi et al., 2002; Nesbit, 2005). It is therefore plausible that if the response of a shaft is dictated by the manner in which it is loaded, then a certain loading pattern may be inherently more suited to a particular shaft flex. Although this might explain the subject-specific influences of shaft flex among the different subjects, it is merely speculation and was not validated in this study.

The lie angle data showed a consistent and systematic trend between flexes, the more flexible shafts orienting the clubhead in a more 'toe-down' position. Conceptually this would be expected, as the stiffer shafts would resist the 'drooping' effect caused by the mass of the clubhead more than the flexible shafts. These results suggest that, unlike loft angle, lie angle is more sensitive to the equipment than to the player's swing.

Shaft flex was not found to influence face angle, in to out path angle, or attack angle, which are consistent with the findings of Wallace and Hubbell (2001). These findings are not surprising, as the five different shafts had very similar torsional resistance values and flex profiles (Table I), and shaft flex has also been purported by professional clubfitters to have a minimal effect on shot accuracy (Wishon, 2005).

The main limitation of the study was the sample of subjects used. Although the subjects did show a high degree of consistency in the clubhead speed data, the sample was made up of single digit amateurs. Professional golfers with negative handicaps may have produced even more consistent data, particularly more consistent loft angle values.

In summary, it has been experimentally shown that shaft flex can have an effect on ball distance achieved (Pelz, 1990; Stanbridge et al., 2004). Although only few studies have investigated the influence of shaft flex, the current belief is that the mechanism by which this occurs is due to a change in loft angle only, not a change in clubhead speed (Milne & Davis, 1992; Wishon, 2005; MacKenzie & Sprigings, 2009). The results of this study do not support this conclusion. Rather, these findings suggest that the mechanism by which shaft flex influences ball distance achieved is more likely to be due to increased clubhead speed than altered loft angle.

Conclusion

Shaft flex was experimentally shown to have an influence on clubhead speed and loft and lie angles at impact. The effect on clubhead speed occurred in 67% of the golfers, but the flex with which maximal clubhead speed was attained was subject-specific. Loft angle was not affected according to the currently believed manner; loft angle did not increase with increasing shaft flexibility. Lie angles were found to change systematically with flex, the lie angle decreasing with decreasing stiffness. Contrary to previous experimental (Wallace & Hubbell, 2001), theoretical (Milne & Davis, 1992; MacKenzie & Sprigings, 2009), and golf industry (Wishon, 2005) publications, the current findings suggest that the likely mechanism by which players produce an increase in ball yardage due to shaft flex is due to increased clubhead speed rather than altered loft angle.

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References

Butler, J. H., & Winfield, D. C. (1994). The dynamic performance of the golf shaft during the downswing. In A. J. Cochran, and M. R. Farrally (Eds.), *Science and golf II. Proceedings of the 1994 World Scientific Congress of Golf* (pp. 259–264). London: E & FN Spon.

Cochran, A., & Stobbs, J. (1968). *The search for the perfect swing*. London: Heinemann.

Horwood, G. P. (1994). Golf shafts—a technical perspective. In A. J. Cochran, and M. R. Farrally (Eds.), *Science and golf II. Proceedings of the 1994 World Scientific Congress of Golf* (pp. 247–258). London: E & FN Spon.

Lee, N., Erickson, M., & Cherveny, P. (2002). Measurement of the behaviour of a golf club during the golf swing. In E. Thain (Ed.), *Science and golf IV: Proceedings of the World Scientific Congress of Golf* (pp. 374–385). London: Routledge.

MacKenzie, S. J., & Sprigings, E. J. (2009). Understanding the role of shaft stiffness in the golf swing. *Sports Engineering*, *12*, 13–19.

Masuda, M., & Kojima, S. (1994). Kick back effect of club-head at impact. In A. J. Cochran, and M. R. Farrally (Eds.), *Science and golf II. Proceedings of the 1994 World Scientific Congress of Golf* (pp. 284–289). London: E & FN Spon.

Mather, J. S. B., & Jowett, S. (2000). Three dimensional shape of the golf club during the swing. In A. Subic, and S. Haake (Eds.), *The engineering of sport—research development and innovation* (pp. 77–85). London: Blackwell Publishing.

Mather, J. S. B., Smith, M. J., Jowett, S., Gibson, K. A. H., & Moynihan, D. (2000). Application of a photogrammetric technique to golf club evaluation. *Sports Engineering*, *3* (1), 37–47.

Miao, T., Watari, M., Kawaguchi, M., & Ikeda, M. (1998). A study of clubhead speed as a function of grip speed for a variety of shaft flexibility. In M. R. Farrally, and A. J. Cochran (Eds.), *Science and golf III* (pp. 554–561). Leeds: Human Kinetics.

Milne, R. D., & Davis, J. P. (1992). The role of the shaft in the golf swing. *Journal of Biomechanics*, *25* (9), 975–983.

Nesbit, S. M. (2005). A three dimensional kinematic and kinetic study of the golf swing. *Journal of Sports Science and Medicine*, *4*, 499–519.

Ozawa, T., Namiki, H., & Horikawa, N. (2002). A study on clubface direction during a golf swing. In S. Ujihashi, and S. Haake (Eds.), *The engineering of sport 4* (pp. 688–694). Oxford: Blackwell.

Pelz, D. (1990). A simple scientific shaft test: Steel versus graphite. In A. J. Cochran (Ed.), *Science and golf: Proceedings of the World Scientific Congress of Golf* (pp. 264–269). London: Chapman & Hall.

Penner, A. R. (2003). The physics of golf. *Reports on Progress in Physics*, *66* (2), 131–171.

Quintavalla, S. J. (2006). Experimental determination of the effects of clubhead speed on driver launch conditions and the effects on drive distance for balls used by the PGA tour. USGA Technical Report RB/cor2006-01.

Soderkvist, I., & Wedin, P. (1993). Determining the movements of the skeleton using well-configured markers. *Journal of Biomechanics*, *26* (12), 1473–1477.

Stanbridge, K., Jones, R., & Mitchell, S. (2004). The effect of shaft flexibility on junior golfers' performance. *Journal of Sports Sciences*, *22* (5), 457–464.

Tsujiuchi, N., Koizumi, T., & Tomii, Y. (2002). Analysis of the influence of golf club design on the golf swing. In S. Ujihashi, and S. Haake (Eds.), *The engineering of sport 4* (pp. 537–544). Oxford: Blackwell.

Van Gheluwe, B., Deporte, K., & Ballegeer, K. (1990). The influence of the use of graphite shafts on golf performance and swing kinematics. In A. J. Cochran (Ed.), *Science and golf: Proceedings of the World Scientific Congress of Golf* (pp. 258–263). London: Chapman & Hall.

Wallace, E. S., & Hubbell, J. E. (2001). The effect of golf club shaft stiffness on golf performance variables—implications for club-fitting. In F. H. Froes, and S. J. Haake (Eds.), *Materials and science in sports* (pp. 23–35). Warrendale, PA: TMS.

Williams, K. R., & Sih, B. L. (2002). Changes in golf clubface orientation following impact with the ball. *Sports Engineering*, *5*, 65–80.

Wishon, T. (2005). *The search for the perfect golf club*. Ann Arbour, MI: Sports Media Group.