Title: Golfer Specific Responses to Shaft Stiffness: Implications for Optimizing Loft during Driver Fitting

Running Title: Golfer Specific Responses to Shaft Stiffness

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Abstract

The purpose of this paper was to demonstrate how individual golfers can mediate the influence of shaft stiffness on loft by systematically changing the orientation of the grip at impact. Two driver shafts, from the same manufacturer, with disparate levels of stiffness (Regular and X-Stiff), but very similar inertial properties, were tested by 33 male golfers representing a range of abilities and clubhead speeds. Shaft deflection data as well as grip and clubhead kinematics were analyzed from 12 out of 14 swings, with each shaft, for each golfer using an optical motion capture system and custom written software. The Regular shaft was associated with significantly more dynamic loft (loft generated solely due to shaft deflection) at impact ($p < .001$); however, there was no significant difference between shafts in the actual delivered loft of the clubhead ($p = .28$). The amount the butt of the club was ahead of the ball, and the amount of club rotation about the longitudinal axis of the shaft, at impact, were significant and meaningful predictors of change in delivered loft due to change in shaft stiffness. How these two variables changed in value between shafts was inconsistent and unpredictable across golfers, unlike the amount of loft added due to shaft deflection, which was always greater for the Regular shaft. While shaft stiffness was found to have a predictable influence on clubhead orientation relative to the grip, shaft stiffness was also found to have an unpredictable influence (across golfers) on how the grip was oriented at impact.

Introduction

Playing golf with a custom fit driver can have a meaningful influence on performance. In particular, there are established physical relationships with delivered clubhead kinematics and carry distance. Consider a typical example of a golfer, Joe, who decides to have his current adjustable driver custom fit. After warming up, Joe hits a dozen balls with his current driver, while being measured on a radar launch monitor, to establish a baseline. The fitter establishes that Joe has a clubhead speed of 100 mph, an attack angle of -2° and a launch monitor reported loft of 9°. Joe's drives have been relatively straight with an average smash factor of 1.48 and an average carry distance of 206 yards. On average, Joe's ball is launching at 6.1° above the horizontal with a backspin of 2500 rpm. By using a combination of fitting experience and the launch monitor's handy software that displays possibilities for increasing Joe's carry distance via trajectory optimization, the fitter decides to try a different shaft in Joe's driver.

The fitter realizes that a more flexible shaft will result in more lead deflection at impact and, theoretically, more loft at impact (MacKenzie & Sprigings, 2009). The increased loft will result in an increased ball launch angle and more backspin (MacKenzie, 2011). The fitter proceeds to have Joe hit drives in blocks of four shots, alternating between Joe's current *stiffer* shaft and a more flexible model, until 12 shots with each shaft have been collected. The fitter's hunch was correct; the flexible shaft increased the reported loft from 9° to 11.5°. Joe's clubhead speed and attack angle remained the same. The additional 2.5° of loft provided by the flexible shaft resulted in a launch angle increase of 2° (from 6.1° to 8.1°) and a backspin increase of 700 rpm (from 2500 rpm to 3200 rpm). These average changes in the initial ball flight parameters resulted in Joe increasing his carry distance by 20 yards (from 206 yards to 226 yards). This is certainly a meaningful increase in performance and Joe leaves the fitting experience as a happy customer.

While the above example is certainly a realistic and, arguably, typical fitting scenario, not every golfer will demonstrate the same relative change in ball flight in response to a change in shaft stiffness.

A golfer does not behave as a golfing robot with, for example, a set pattern of segment angular velocities predefined before the swing begins (e.g., Pingman). At best, from a repeatability standpoint, a golfer may activate each muscle in the same manner during the swing. If the club parameters remained the same, then the kinematics of the entire system would be identical from swing to swing. However, by changing just shaft stiffness, the resulting muscular forces generated by the golfer could change even if the muscle activation pattern remained the same. The different shaft stiffness would result in different reaction forces being applied to the golfer from the club early into the swing. These different reaction forces would result in different golfer kinematics, which would in turn influence the forces generated by the golfer's muscles. This chaotic process could result in meaningful and, in practice, unpredictable changes in grip kinematics at impact. Further complicating the issue is the reality that the golfer may not employ the same muscle activation pattern during the swing as a result of the change in shaft stiffness. The different 'feel' of the club, even at the subconscious level, could result in the golfer generating a different muscle activation pattern as has been suggested in recent research (Osis & Stefanyshyn, 2012).

So, while a change in shaft flex may result in a relatively predictable change in shaft bending at impact, how the grip end of club will be positioned is not so evident. This could affect the actual delivered loft of the club at impact, which is what really matters to the ball. Therefore, the purpose of this paper was to demonstrate how certain golfers mediate the influence of shaft stiffness on loft by systematically changing the orientation of the grip at impact. This information will facilitate club fitters' understanding of why ball flight might not change in a predictable manner with changes in shaft flex.

Methods

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.

Procedures

Participants performed a standardized golf warm-up consisting of dynamic stretches and swings of increasing intensity, which lasted approximately 5 minutes. 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 onto a projection screen. The projection screen was approximately 8 m in the target direction from the tee. A FlightScope X2 Doppler radar launch monitor, in conjunction with the software, was used to display the trajectory of the shot on the projection screen immediately after contact. A system of lasers was used to ensure that the launch monitor, tee, and projection system were oriented such that a ball measured to have a 0 deg horizontal launch and no spin axis tilt (no "side spin") would strike an image of the target line on the projection screen and have a simulated trajectory along the target line.

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 (Regular) and PWR 65 Tour X-Stiff (X-Stiff). 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 two assembled clubs were matched for mass and moment of inertia (MOI) by placing 6 grams 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 center of pressure movements and, following testing, each participant acknowledged that they were unware 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.

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 clubhead 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 a face reference frame. 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 2nd reference frame indicated how the face would be positioned and oriented if the shaft were perfectly rigid. The three-dimensional (3D) coordinates of the golf ball for each drive were determined by applying a calibration procedure involving tracking markers rigidly fixed to the corners of a section of hitting mat and a golf ball covered in reflective tape placed on a tee, which was securely inserted to a set-depth into the mat. The same tee height was used by all players for every shot. The same researcher teed-up every ball throughout the study. A metal plate was secured to the underside of the mat, so that a consistent tee height could be achieved across every shot. Camera shutter speeds were set to 3000 Hz, and data were sampled at 500 Hz. The software application Cortex (version 5.3, Motion Analysis Corporation, Santa Rosa, CA, USA) was used to generate and export the 3D coordinate data for each marker. A bespoke software program was written in MatLab (version R2010a, MathWorks, Natick, MA, USA) to process the 3D coordinate data and generate variables of interest (Table 1).

Table 1. Operational definitions for the kinematic variables calculated and analyzed in this study

Variable Name	Definition
Delivered Loft (°)	The angle between a vector, which was normal to the center of the clubface, and the horizontal plane at the moment of ball contact.
Dynamic Loft (°)	The change in the loft of the club due to shaft deflection. This was determined by finding the actual Delivered Loft from the clubhead markers and subtracting the "Delivered Loft" of the virtual clubface as determined from the shaft markers.
ButtX (mm)	The location of the butt end of the club, along the target line (X-axis), relative to the location of the ball at impact. If the butt of the club is closer to the target than the ball, then this value is negative.
Grip Twist (°)	Rotation of the club about the long axis of the shaft. In the address position, with the face square to the target line, Grip Twist would be zero. A positive Grip Twist value would be associated with an 'open' clubface and higher Delivered Loft.

Statistical Analysis

Each participant executed 14 drives with each shaft. The top 12 swings per shaft, based on clubhead speed, were used for the statistical analysis. Paired t-tests were used to compare the effects of the two levels of shaft stiffness on specific dependent variables related to the loft of the club at impact. Since there were 12 data points per condition for each participant, it was possible to make reasonable inferences at the individual participant level using t-tests as well. Multiple linear regression techniques were used to understand the relationship between changes in the loft of the club at impact between shafts and changes in other club kinematic variables at impact (Tabachnick & Fidell, 2001). Statistical significance was set at $p < .05$ for all tests. Statistical analyses were performed using SPSS V22.0 for Windows (IBM Co., NY, USA).

Results

For each participant, the Regular shaft resulted in more Dynamic Loft at impact in comparison to the X-Stiff shaft (Figure 1). The average difference in Dynamic Loft of 1.98° was statistically significant ($t(32) = 12.9$, $p < .001$). At the individual participant level, all golfers generated significantly more Dynamic Loft with the Regular shaft. Several participants added upwards of 8° to the static loft of the driver solely based on how the shaft was bent at impact.

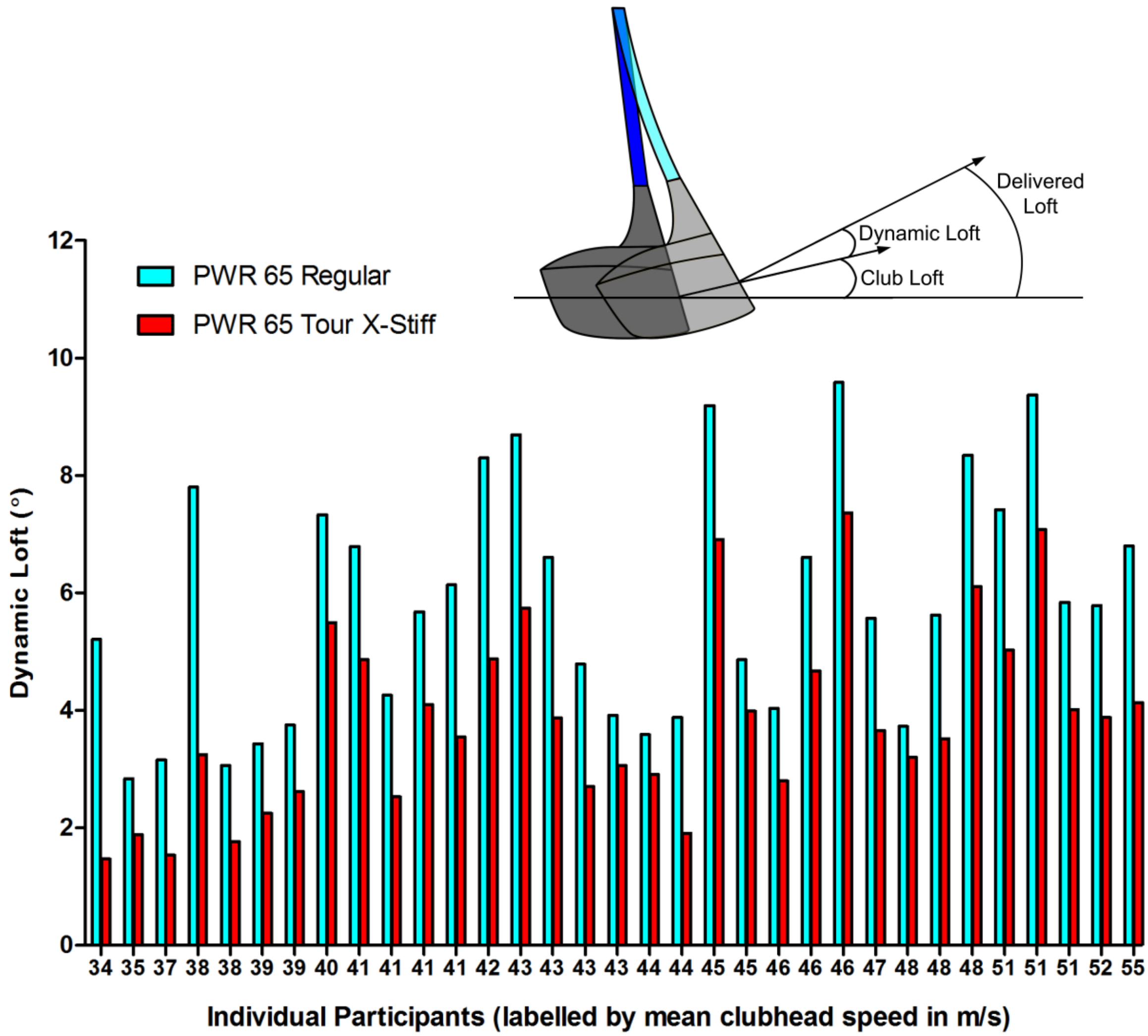

Figure 1. Dynamic Loft for both the Regular and X-Stiff shafts is plotted for each participant separately. These are average values for the top 12 swings with each shaft based on clubhead speed. Participants are sorted from left to right based on average clubhead speed.

The results for Delivered Loft did not show the same systematic response as with Dynamic Loft (Figure 2). The majority of participants (21/33) contacted the ball with more Delivered Loft using the Regular shaft; however, this increase was only statistically significant for seven of those golfers. A meaningful number (12/33) produced more Delivered Loft with the X-Stiff shaft and this increase was statistically significant for three of those golfers. Considering all participants, the Regular shaft was associated a relatively small average increase in Delivered Loft (0.39°) over the X-Stiff shaft, which was not statistically significant (t(32) = 1.1, p = .28). Across all swings for all participants the average Delivered Loft was 17.9°.

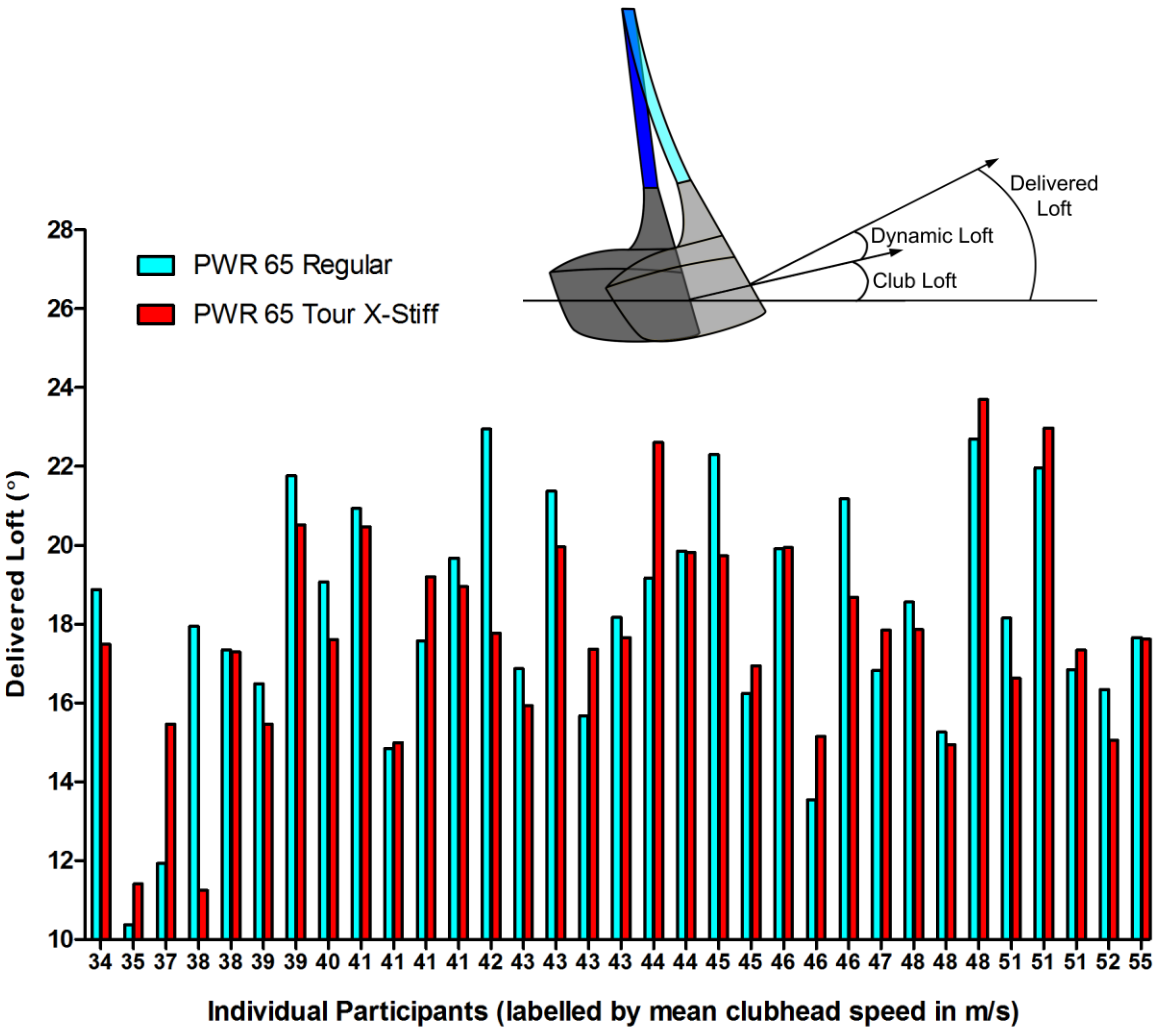

Figure 2. Delivered Loft for both the Regular and X-Stiff shafts is plotted for each participant separately. These are average values for the top 12 swings with each shaft based on clubhead speed. Participants are sorted from left to right based on average clubhead speed.

Five participants were selected to demonstrate how Dynamic Loft, ButtX, and Grip Twist interact to influence Delivered Loft (Figure 3). Participant 4 had approximately 4° more Dynamic Loft with the Regular shaft in comparison to the X-stiff, while the other four participants hovered around approximately 2° of additional loft with the Regular shaft (Figure 3(A)). While these five participants had similar, and predictable, Δ Dynamic Loft values, their ButtX and Grip Twist values were inconsistent between shafts. To be clear, while each golfer demonstrated a reliable response to the change in shaft stiffness, the nature of the response (magnitude and direction) was very different across golfers.

The variable ButtX indicates the location of the butt end of the club, along the target line, relative to the location of the ball at impact (Figure 3(B)). The variable Δ ButtX indicates the difference in ButtX between shafts at impact. For example, on average Participant 4 contacted the ball with the butt end of the club approximately 11 mm further from the target while using the Regular shaft in comparison to the X-Stiff shaft (Figure 3(B)). This would tend to increase the Delivered Loft of the club with the Regular shaft in comparison to the X-Stiff. In contrast, Participant 3 contacted the ball with the butt end of the club approximately 37 mm closer to the target while using the Regular shaft in comparison to the X-Stiff shaft. This would tend to *decrease* the Delivered Loft of the club with the Regular shaft in comparison to the X-Stiff.

The variable Grip Twist indicates how much the club is rotated about its long axis at impact (Figure 3(C)). The variable Δ Grip Twist indicates the difference in Grip Twist between shafts at impact. For example, Participant 4 contacted the ball with the grip twisted approximately 5° more ‘open’ while using the Regular shaft in comparison to the X-Stiff shaft (Figure 3(C)). This would tend to increase the Delivered Loft of the club with the Regular shaft in comparison to the X-Stiff. In contrast, Participant 3 contacted the ball with the grip twisted approximately 2.5° more ‘closed’ while using the Regular shaft in comparison to the X-Stiff shaft. This would tend to *decrease* the Delivered Loft of the club with the Regular shaft in comparison to the X-Stiff.

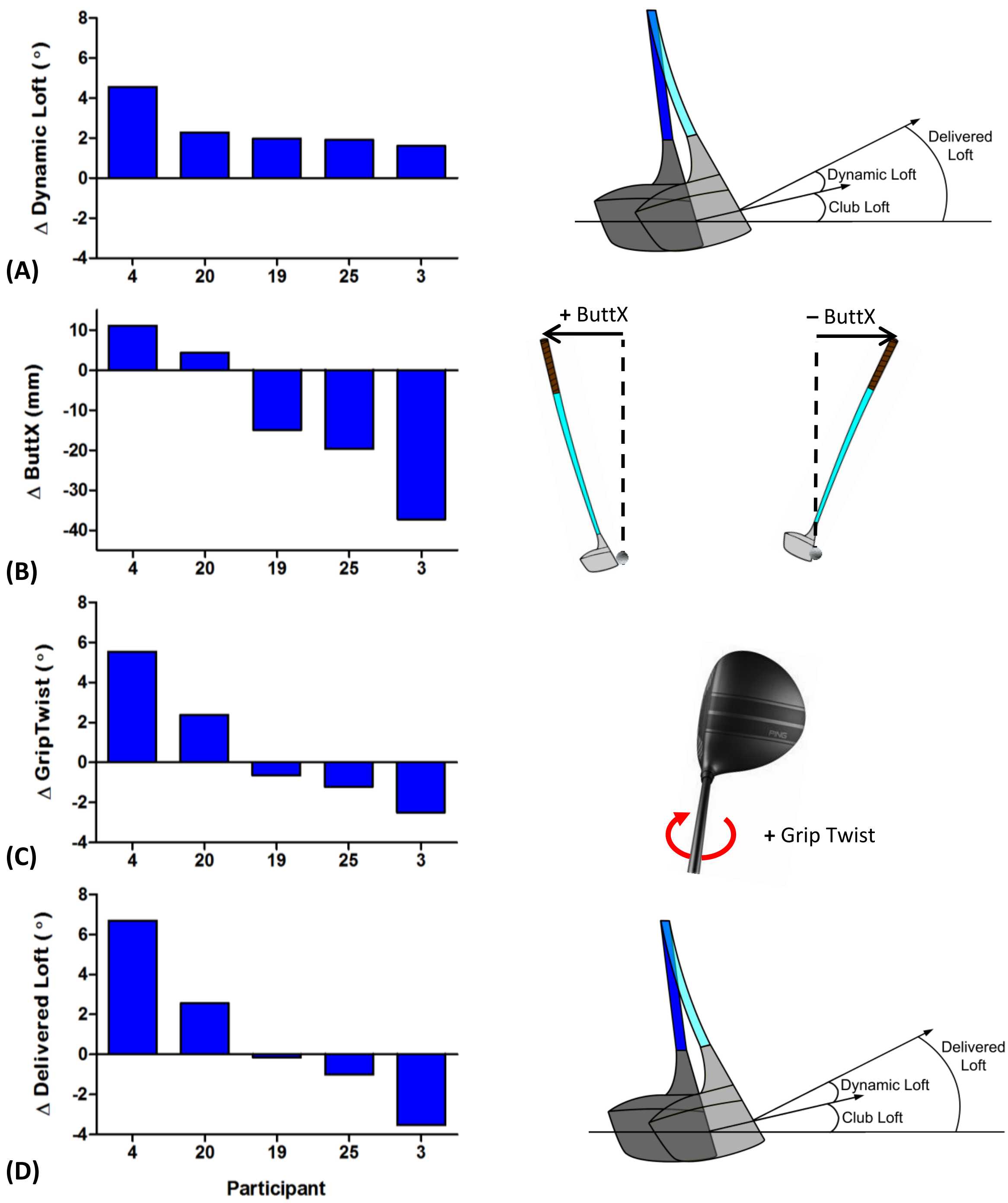

Figure 3. The figure shows differences between the Regular and X-Stiff shaft for five selected participants on four variables at impact. Each figure plots the result of the X-Stiff shaft value *subtracted from* the Regular shaft value. These are average values for the top 12 swings based on clubhead speed. (A) Difference in Dynamic Loft. (B) Difference in the X-coordinate of the butt end of the grip, relative to the ball, at impact. A negative ButtX value would tend to reduce Delivered Loft. (C) Difference in Grip Twist. A positive Grip Twist would tend to increase Delivered Loft. (D) Difference in Delivered Loft.

The cumulative effects of Δ Dynamic Loft, Δ ButtX, and Δ Grip Twist on Δ Delivered Loft were golfer specific (Figure 3(D)). Participant 4 had approximately 4° more Dynamic Loft with the Regular shaft; therefore, it could be expected that Delivered loft would also be approximately 4° higher with the Regular shaft. However, while using the Regular shaft, in comparison to the X-Stiff, Participant 4 added loft by having the butt of the club further from the target and also by twisting the shaft 'open' at impact. For Participant 4, these three variables combined to generate almost 7° more Delivered Loft with the Regular shaft (Figure 3(D)). Participant 19 had approximately 2° more Dynamic Loft with the Regular shaft; therefore, it could be expected that Delivered Loft would also be approximately 2° higher with the Regular shaft. However, while using the Regular shaft, in comparison to the X-Stiff, Participant 19 reduced loft by having the butt of the club closer to the target and also by twisting the shaft 'closed' at impact. For Participant 19, these three variables combined to generate virtually the same amount of Delivered Loft with both shafts (Figure 3(D)). Participant 3 had approximately 2° more Dynamic Loft with the Regular shaft; therefore, it could be expected that Delivered loft would also be approximately 2° higher with the Regular shaft. However, while using the Regular shaft, in comparison to the X-Stiff, Participant 3 reduced loft by having the butt of the club closer to the target and also by twisting the shaft 'closed' at impact. For Participant 3, these three variables combined to generate almost 4° *less* Delivered Loft with the Regular shaft (Figure 3(D)).

A clubfitter may expect to see a *change* in Delivered Loft, and hence ball flight, if a golfer switched to a flexible shaft from a stiff shaft. This *change* in Delivered Loft would likely be in part due to a *change* in Dynamic Loft; however, the *change* in grip orientation at impact would also play an important role as previously demonstrated through the explanation of Figure 3 above. A sequential multiple linear regression analysis, *using all 33 participants*, was performed between change in (Δ) Delivered Loft as the dependent variable and Δ Dynamic Loft, Δ Grip Twist, and Δ ButtX, as independent variables entered in that order (Table 2). All variables were calculated by subtracting the X-Stiff shaft average from the Regular shaft average. The results of the regression indicated that the three predictors explained 94% of the variance in Δ Delivered Loft (R^2 = .94, F(3,29) = 158, p < .001). It was found that all three predictors contributed significantly to the prediction of Δ Delivered Loft with Δ Grip Twist having the largest unique contribution (sr^2 = .453), followed by Δ ButtX (sr^2 = .092), and Δ Dynamic Loft (sr^2 = .046) (Table 2). The three predictors in combination contributed another .35 in shared variability.

Table 2. Results of sequential multiple linear regression of Δ Delivered Loft (dependent variable) with three predictors (Δ Dynamic Loft, Δ Grip Twist, and Δ ButtX).

	Unstandardized Coefficients		Standardized Coefficients						
	B	Std. Error	Beta	R^2 Change	t	p	r	sr^2 Unique	Mean (Std. Dev.)
Constant	-.202	.262			-.77	.447			
Δ Dynamic Loft (°)	.559	.116	.242	.387	4.80	< .001	.622	.046	1.97 (0.88)
Δ Grip Twist (°)	.722	.048	.730	.463	15.08	< .001	.867	.453	-0.50 (2.05)
Δ ButtX (mm)	-.053	.008	-.320	.093	-6.81	< .001	-.496	.092	2.96 (12.3)
Δ Delivered Loft (°)									0.39 (2.03)

Discussion

The purpose of this article was to demonstrate how certain golfers can mediate the influence of shaft deflection (at impact) on the loft of the club by systematically (based on shaft stiffness) changing the orientation of the grip. Based on Figure 1, it would *seem* clear that switching any of the golfers in this study from a stiff to a flexible shaft would result in higher Delivered Loft and thus likely a higher ball launch and more spin. However, what can't be predicted by the fitter is how the golfer will systematically alter the position of the grip at impact, in response to a change in shaft stiffness, and thus influence the actual Delivered Loft of the club. While there are likely other variables that mediate the relationship between Dynamic Loft and Delivered Loft, the amount the butt of the club is ahead of the ball at impact (ButtX) and the amount of rotation about the longitudinal axis of the shaft (Grip Twist) appear to be major influencers.

The regression analysis conducted in this study can facilitate a practical understanding of how much each predictor influences the dependent variable: Δ Delivered Loft. Standardized coefficients (Beta in Table 2) refer to how many standard deviations a dependent variable will change, per standard deviation change in the predictor variable. For example, Beta for Δ Dynamic Loft was 0.242 and the standard deviation was 0.88° (Table 2). Therefore, if Δ Dynamic Loft increased by 0.88°, then Δ Delivered Loft would be expected to increase by approximately 0.5° (0.242*2.03°). If Δ Grip Twist increased by 2.05°, then Δ Delivered Loft would be expected to increase by approximately 1.5° (0.730*2.03°). If Δ ButtX increased by 12.3 mm, then Δ Delivered Loft would be expected to *decrease* by approximately 0.65° (-0.32*2.03°).

These values seem to indicate that Δ Grip Twist is the most important variable when determining the differences in Delivered Lofts between two shafts. Supporting this, is the fact that Δ Grip Twist had the highest correlation with Δ Delivered Loft ($r = .867$) and also predicted the most unique amount of variance ($sr^2 = .453$). However, unlike Dynamic Loft, in which all participants showed an increase with the Regular shaft, 13 of the participants increased Grip Twist with the Regular shaft, while 20 decreased Grip Twist with the Regular shaft. The finding was similar for ButtX; 13 of the participants increased ButtX with the Regular shaft, while 20 decreased ButtX with the Regular shaft. Interestingly, the 13|20 split for both of these variables was just a coincidence as there was not a significant correlation between Δ Grip Twist and Δ ButtX ($r = -.139$, $p = .221$). In other words, the group of 13 golfers that increased Grip Twist with the Regular shaft was not the same as the group of 13 individuals that increased ButtX with the Regular shaft. So, while a fitter can reliably expect Dynamic Loft to increase with a more flexible shaft, the same is not true for Grip Twist or ButtX.

Previous research supports, and can explain why, a more flexible shaft will lead to an increase in Dynamic Loft ((MacKenzie & Sprigings, 2010). To the contrary, currently, there is no research or available line of reasoning that would allow a fitter to predict how a change in shaft stiffness will influence grip orientation at impact for an individual golfer. It is currently beyond our abilities to determine the root cause of the systematic adjustments in grip orientation due to the change in shaft stiffness in this study. There are a few plausible possibilities. 1. The golfer used the same muscular firing pattern (motor pattern) for each shaft, but each shaft generated different reaction forces onto the golfer, which in turn resulted in altered golfer kinematics. 2. The golfer subconsciously felt a difference between the shafts early in the swing, which resulted in a different motor program being implemented during the remainder of the swing. 3. Although the participants were unaware of the shaft change, it is possible that they were reacting to the feedback from the ball flight throughout the testing period.

Practical Application

So, how does a fitter use this information? Considering the average response from this study, it still makes sense to try a more flexible shaft if you want to increase Delivered Loft with the end goal of increasing ball launch angle and spin. If the response to a more flexible shaft change is less loft, then you can be confident that while the more flexible shaft is still deflecting more in the lead direction at impact (more Dynamic Loft) the golfer has altered (probably unknowingly) the grip orientation at impact. If you really need this golfer to add loft at impact, then use whichever shaft leads to the most beneficial grip orientation for increasing Delivered Loft and couple that with a high lofted driver head.

In most cases it is not necessary for the fitter to be able to predict how the golfer and club will interact. A launch monitor with reliable ball data and a systematic process of trial and error employed by the fitter will work. Paramount to the fitting process is that the golfer is attempting to hit the same shot (e.g., high draw) with the same level effort on each attempt. It is also important that a sufficient number of swings (e.g., 10) are executed with each club configuration as the fitter narrows in on an optimal custom fit. It is easy for a single exceptionally good or bad shot out of a small number of attempts (e.g., 5) to unjustly skew the perception of the fitter and/or golfer (or even a statistical calculation). While a fitter is not necessarily an instructor, there are some important factors that a fitter should check to ensure the golfer is in the best position to maximize the results of just about any driver configuration. First, is the ball relatively forward in the stance? Second, is the ball contacting the driver above the center of the face? It is probably a good idea to have the golfer make these adjustments before fitters work their way through various driver configurations. When reviewing ball launch data after a configuration change, the fitter should be aware of any systematic change in impact spot on the face. In most cases, a suboptimal impact location on the face should not be addressed with a configuration change, but rather by adjusting tee height or ball location relative to the golfer's stance.

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