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The influence of club-head kinematics on early ball flight characteristics in the golf drive

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Abstract
Despite many coaching and biomechanical texts describing how the kinematics of the club-head at impact lead to distance and accuracy of the ball flight, there is limited quantitative evidence supporting these assertions. The purpose of this study was to quantify the relationships between club-head kinematics and subsequent early ball flight characteristics during the golf drive. An opto-reflective system operating at 400 Hz was used to capture the swings of 21 male golfers using their own drivers. The 3D displacement data permitted the calculation of club-head kinematics at impact, as well as subsequent early ball flight characteristics. Using regression analyses, club-head kinematics at impact (velocity, orientation, path, and centeredness) were used to explain the variability in five dependent variables of early ball flight characteristics (resultant velocity, launch angle, side angle, back spin, and side spin). The results of the study indicated that club-head kinematics at impact explained a significant proportion of early ball flight characteristics (adjusted $r^2 = 0.71-0.82$), even when generalized across individual clubs.

Keywords: *Impact, launch angle, side angle, spin, centeredness, orientation*

Introduction

A number of authors have attempted to explain the determinants of ball flight in the golf swing (Daish, 1972; Hay, 1993; Miura, 2002; Wiren, 1990). These observations have been based on a combination of different physical laws with respect to collisions and projectile motion. Although these laws are unquestionably applicable to the golf swing, there has been little empirical research investigating how these principles interact to influence distance and accuracy in the golf drive. Until quantitative evidence is produced, scientists and coaches are reliant upon information that may not be entirely accurate.

For example, there is a popular belief that a high club-head velocity is the key performance variable in the golf swing (Fradkin, Sherman, & Finch, 2004; Gordon, Moir, Davis, Witmar, & Cummings, 2009; Keogh et al., 2009; Sprigings & Neal, 2000). The justification given for this is that velocity of the club-head at impact is the most influential factor in dictating initial

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ball velocity and, therefore, projected distance of the ball (Hay, 1993). Although it is reasonable that club-head velocity should indeed play a large part in generating ball velocity, it has also been suggested that the location of impact relative to the center of the clubface would also contribute to the ball velocity (Hocknell, 2002; Wiren, 1990). Quantitatively, researchers have established that the location of impact on the club-face has a large effect on club-head orientation, path, and velocity following impact (Ellis, Roberts, & Sanghera, 2010; Williams & Sih, 2002). However, there is currently a lack of understanding of the relative contribution of both club-head velocity and impact location on ball velocity.

There is also some agreement that other key characteristics of ball flight are influenced by more than one kinematic variable of the club-head at impact. For example, the initial direction of the ball in flight is suggested to be the result of both the direction of the velocity vector and the orientation of the club-head at impact (Hay, 1993; Wiren, 1990). What is unclear, however, is which of these is more important and whether other factors, such as centeredness of impact, also have an influence. For instance, the direction of the velocity vector of the club-head at impact may be more important than the club-head orientation in determining the direction of the ball in early ball flight and therefore, is a better predictor of the outcome of the stroke. Determining the relative importance of these club-head variables is important for both scientists and coaches alike. Specifically from a scientific perspective, key performance indicators from the club-head could act as meaningful dependent variables for comparative investigations, as well as training or intervention research designs. From an applied perspective, identifying the contributions of individual club-head kinematics has the potential to shape teaching methods, as well as influence the fitting of clubs to an individual's swing pattern.

The aim of this study was to quantify the relationships between club-head kinematics and early ball flight characteristics, across a group of individuals using their own drivers. It was hypothesized that a combination of club-head velocity, orientation, path, and centeredness of impact would explain a significant proportion of the variance in each variable measured during early ball flight.

Methods

Participants

Twenty-one male golfers volunteered to participate in the study. The mean age, height, mass, and handicap were 24.2 ± 5.7 years ($M \pm$ SD), 181.2 ± 8.0 cm, 79.0 ± 7.9 kg, and 5.7 ± 4.2 (range = 1–14), respectively. The protocol used in this study was approved by the University of Western Australia's human research ethics committee.

Procedures

A standardized 5-min warm up that involved hitting balls at increasingly higher intensities with sequentially longer clubs was carried out by all participants. The collection procedure was then broken up into two parts to enable the most accurate collection of early ball flight characteristics. In part 1, golf ball resultant velocity, side angle (direction of velocity vector in the transverse plane), and launch angle (direction of the velocity vector in the sagittal plane) (Figure 1A—C) were tracked using a 12-camera Vicon MX opto-reflective motion analysis system (ViconPeak, Oxford Metrics, Oxford, UK), operating at 400 Hz. In part 2 of the study, back spin and side spin of the ball (Figure 1D, E) were tracked using a Vector Pro 2 (Accusport, Winston-Salem, NC, USA). Both parts 1 and 2 involved participants using their own driver to hit 10 drives off a rubber tee into a net situated 4 m in front of the contact

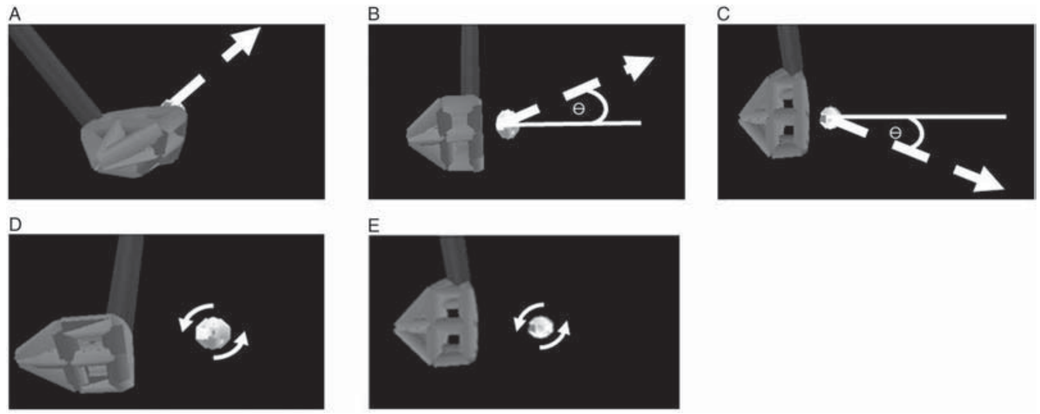

Figure 1. Golf ball variables measured: (A) Golf ball resultant velocity (m/s), (B) Golf ball launch angle (°), (C) Golf ball side angle (°), (D) Golf ball back spin (rev/s) and (E) Golf ball side spin (rev/s).

position. Participants were instructed to use their normal swing to hit the ball straight for maximum distance. All drivers had a club-head volume of 460 cc and comparable club-face sizes.

In part 1, Titleist NXT golf balls were covered in reflective tape. Any effect of covering the ball in tape was considered to be minimal as early ball flight characteristics, such as velocity and launch angle, were similar to that noted in previous research (e.g., Wallace et al., 2007). Furthermore, the players anecdotally reported feeling no difference around the time of impact.

At the completion of part 1, the first eight participants were asked to carry out part 2 of the study. For these trials, the Vector Pro 2 calculated initial back spin and side spin of the ball by tracking two circular marks drawn on the ball in accordance with the Vector Pro 2 manufacturer's recommendations. The Vector Pro 2 has been shown to be accurate and reliable when measuring the initial velocity and direction of the ball (Sweeney, Alderson, Mills, & Elliott, 2009). The manufacturer also reports that the system can accurately measure back spin and side spin to within 150 rpm.

For both parts of the study, the opto-reflective motion analysis system was used to track club-head kinematics. Three retro-reflective markers, all of which were 16 mm in diameter, were affixed to the top of the club-head as shown in Figure 2A. These markers created a technical coordinate system, which was used to reference four virtual points on the club-face (Figure 2B). These four points were originally marked with pen and corresponded to the mid-point on the center-most groove on the club-face, two points 4 cm to each side of the mid-point along the same groove, and the most inferior part of the club-face perpendicular to a line created by the first three points. Using a spherical pointer method, similar to that used by Cappozzo, Catani, Croce, and Leardini (1995) these four points created the club-head anatomical coordinate system. This anatomical coordinate system was then transferred to the laboratory-based coordinate system to enable global club-head kinematics to be defined. All club-head and early ball flight characteristics that were calculated are displayed in Figures 1 and 3.

Treatment of data

Marker coordinate data were labeled and broken trajectories were interpolated using a cubic spline. To remove the influence of the club-ball collision, a method similar to that of Williams

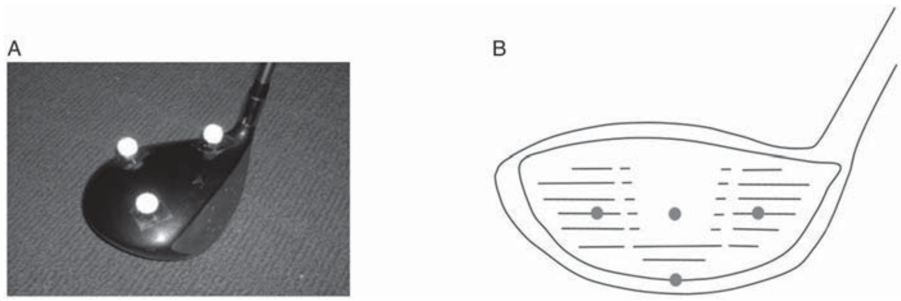

Figure 2. (A) Reflective markers on club-head, (B) four key points on club-face identified in the calibration procedure to identify club-head coordinate system.

and Sih (2002) was used. Specifically, raw data collected after impact were ignored. Instead, a second-order polynomial based on five data points prior to impact was used to create marker coordinates for the following 10 frames, representing a period of 0.0225 s. To ascertain more precise readings at impact, a further 101-point interpolation was carried out on the four frames where the club-face and virtual ball were closest to each other. 'Virtual impact' was defined as the point where the center of the club-face was closest to the ball in the forward direction of the laboratory (toward the target).

Variables

In part 1, raw coordinate data for the golf ball were used to calculate the resultant velocity, side angle, and launch angle during early ball flight (Figure 1). Seven kinematic variables of interest were also calculated from raw coordinate data of the club-head at 'virtual impact' (Figure 3). Resultant club-head velocity was derived from the resultant velocity of the center of the club-face. Both the vertical and lateral velocity vectors were calculated and used to represent the path of the club-head (Williams & Sih, 2002). Club-head 'loft' and 'rotation' angles represented the orientation of the club-face with respect to the global coordinate

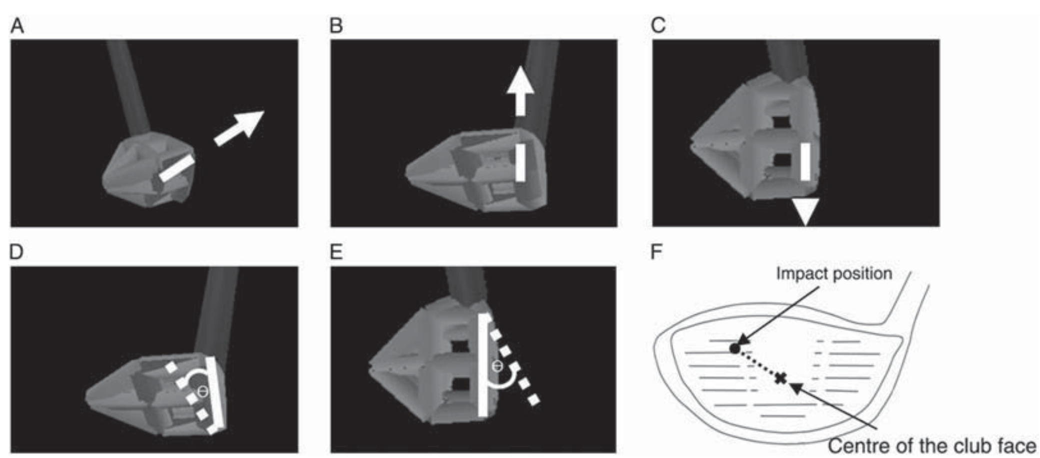

Figure 3. Club-head variables measured: (A) club-head resultant velocity (m/s), (B) club-head vertical velocity (m/s), (C) club-head lateral velocity (m/s), (D) club-head loft angle (°), (E) club-head rotation angle (°), and (F) centeredness of impact (mm).

system. Specifically, club-head loft corresponded to a backward tilt (relative to the direction of the swing) in the sagittal plane, whereas club-head rotation corresponded to the longitudinal axis rotation of the club-face in the transverse plane. Finally, the vertical and horizontal distance between the ball impact position on the club-face and the center of the club-face was calculated to represent the centeredness of impact.

During part 2, two kinematic variables (side spin and back spin—Figure 1) were calculated from the raw coordinate data of the golf ball. Additionally, two kinematic variables were calculated from the raw coordinates of the club-head at 'virtual impact.' The first was calculated from the offset between the direction of the vertical velocity vector and the loft angle of the club-head. The second was calculated from the offset between the direction of the horizontal velocity vector and the rotation angle of the club-head.

Data analysis

A statistical program (SPSS, v14) was used to average all 10 trials for each participant for both parts of the study, and a subsequent check for normality was performed. Five separate forward stepwise regressions were performed to assess the ability of club-head kinematics to predict the resultant ball velocity, ball side angle, ball launch angle, ball side spin, and ball back spin. Prior to performing these regression analyses, all assumptions were taken into account (Vincent, 1999). In particular, linear regression analyses are exposed to inaccuracies stemming from the heterogeneity of the sample, and/or a potential misidentification of nonlinear relationships. However, caution was taken to avoid these during the analyses, with individual relationships qualitatively assessed for linearity as well as the possible effect of sample heterogeneity. As an example, Figure 4 shows the strongest relationships of the study, all of which show clear linearity and appear to be without influence from sample heterogeneity. The dependent and independent variables involved in each regression are displayed in Figure 5. For each stepwise regression, significance was set at $p < 0.01$.

Results

Means and standard deviations for all club-head and early ball flight characteristics are shown in Table I. A number of club-head variables contributed significantly to the prediction of early ball flight characteristics (Table II). These included centeredness of impact in addition to the resultant velocity, loft, rotation, and vertical velocity of the club-head.

The first stepwise regression analysis from part 1 revealed that, together, resultant club-head velocity at impact and centeredness of impact accounted for 82% ($F = 44.8$) of the variance in peak resultant ball velocity across all participants. In addition, step 1 of the analysis revealed that resultant club-head velocity alone explained 75% ($F = 62.3$) of the variance in peak resultant golf ball velocity.

With respect to the direction of the ball, the three independent variables (club-head velocity vector, orientation, and centeredness of impact) all significantly contributed to explaining the variance in launch angle of the ball in part 1. Together, vertical velocity of the club-head, loft of the club-head, and the vertical centeredness of impact on the club-face accounted for 81% ($F = 28.5$) of the variance in golf ball launch angle. The only independent variable that significantly explained the variance in side angle was the club-head rotation in the transverse plane, which explained 82% ($F = 90.2$) of the variance.

The variance in both back spin and side spin of the golf ball was able to be significantly explained by the offset between the direction of the velocity vector and the orientation of the

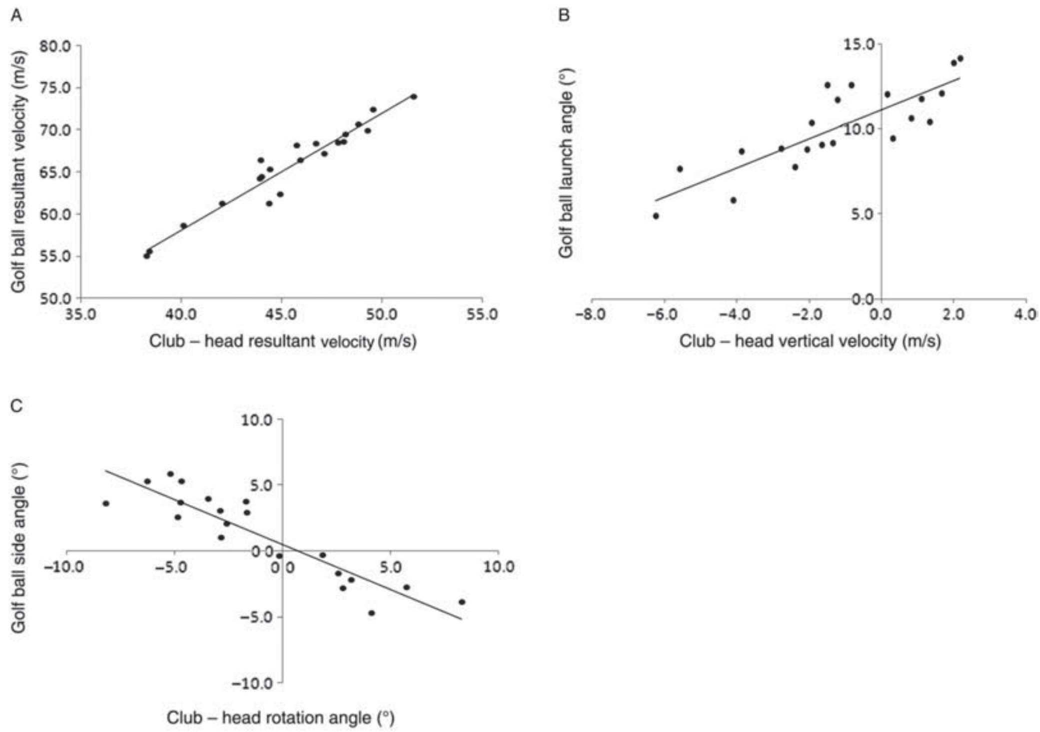

Figure 4. Scatter plots of the three strongest relationships between club-head variables and subsequent ball flight characteristics. These relationships are between (A) club-head resultant velocity and golf ball resultant velocity, (B) club-head vertical velocity and golf ball launch angle, and (C) club-head rotation angle and golf ball side angle.

club. This offset explained 73% ($F = 20.4$) of the variance in back spin and 82% ($F = 33.8$) of the variance in side spin.

Discussion and implications

The primary aim of this study was to explain the variance in golf ball launch kinematics based on club-head kinematics at impact. As hypothesized, for each dependent variable, a large degree of the variance in early ball flight characteristics could be explained by one or more club-head kinematic variables at impact. Although there is unquestionably some interaction between individual club specifications and some of the measures calculated in this study, the results suggest that the relationships between club-head kinematics and the subsequent early ball flight characteristics are consistent across a selection of different drivers and individuals.

Golf ball resultant velocity

Club-head velocity is perhaps the most commonly reported kinematic variable in the golfing scientific literature. It is often used as the sole measure of performance, under the assumption that a higher club-head velocity will produce a higher initial ball velocity and, therefore, greater distance (Gordon et al., 2009; Keogh et al., 2009; Sprigings & Neal, 2000). The results from this study support the notion that club-head velocity is a strong predictor of ball velocity.

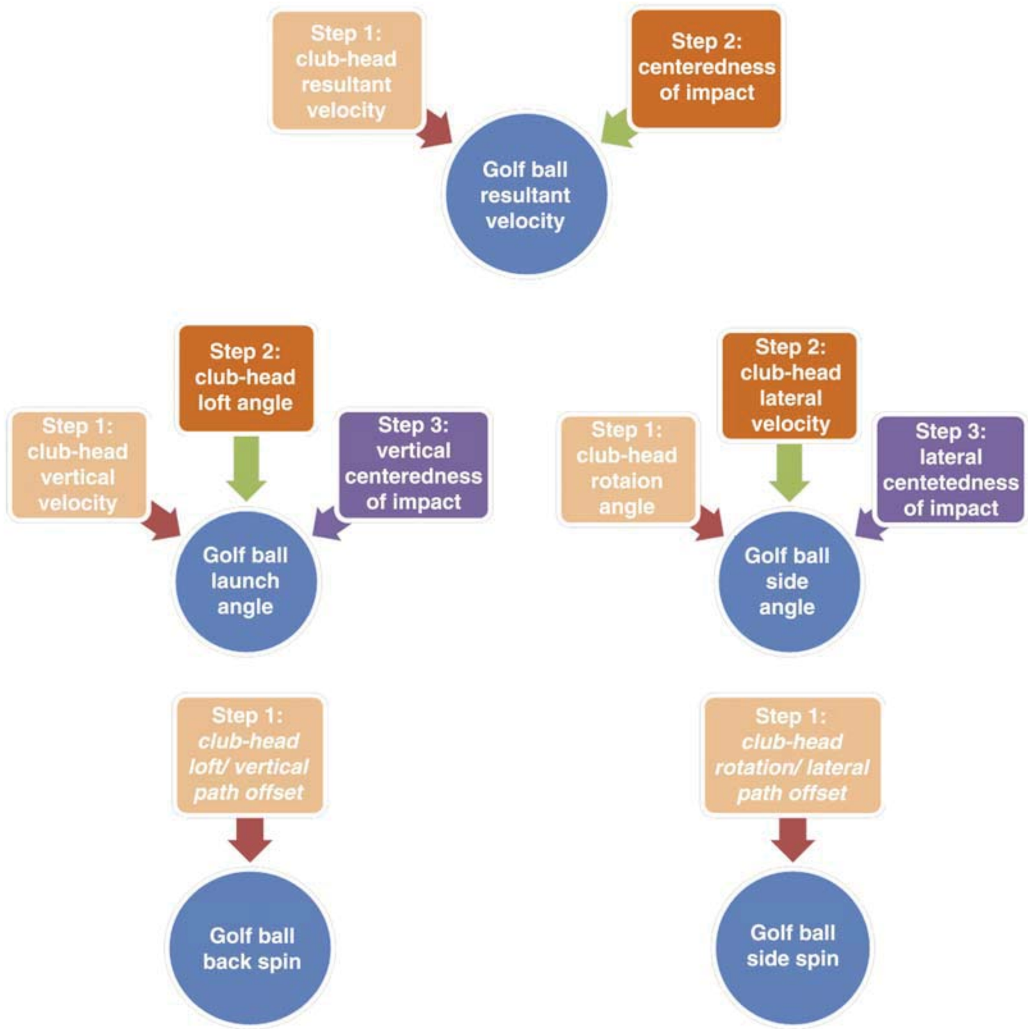

Figure 5. Variables involved in the five stepwise regressions used to explain early ball flight characteristics in the golf.

Although club-head velocity explained the majority of variance in ball velocity, centeredness of impact also contributed significantly. Unlike club-head velocity, the influence of centeredness of impact has, at times, been overlooked in the scientific literature. However, its inclusion as a significant factor in explaining the variance in ball velocity in this study would attest to its importance in allowing players to achieve a maximal driving distance. It seems, therefore, that in addition to the club-head velocity, future investigations into the swing should also take into account centeredness of impact.

Golf ball launch angle

In the golf swing, the horizontal displacement of the ball is influenced directly by its initial launch angle (Hay, 1993). However, the launch angle of the golf ball is a kinematic variable that has received limited attention in the scientific literature. Our findings indicate that the launch angle of the ball is influenced by both the path and orientation of the club-head at

Table I. Variables included in the analyses, across participants in part 1 ($n = 21$) and part 2 ($n = 8$).

Variable	$M \pm$ SD
Peak ball resultant velocity (m/s)	65.6 ± 5.1
Ball launch angle (°)	10.1 ± 2.5
Ball side angle (°)	1.2 ± 3.2
Ball back spin (revs/s)	2383 ± 663
Ball side spin (revs/s)	-148 ± 123
Club-head resultant velocity (m/s)	45.4 ± 3.6
Total off-centeredness of impact (mm)	14.1 ± 4.5
Club-head loft angle (°)	8.8 ± 4.0
Club-head rotation angle (°)	-1.0 ± 4.3
Club-head lateral velocity (m/s)	1.6 ± 2.7
Club-head vertical velocity (m/s)	-1.2 ± 2.4

Note: Golf ball variables are all calculated at peak resultant velocity and club-head variables are all calculated at 'virtual impact.'

impact, in addition to the location of impact on the club-face. The teaching model of Wiren (1990), which is popular among many professional coaches, highlights the importance of the vertical path of the club-head at impact to the vertical trajectory of the ball. That is, the angle formed by the ascending or descending arc of the club-head relative to the slope of the ground will influence the trajectory and distance. This effect is strongly supported by the results of this study, with vertical velocity of the club-head explaining the majority of the variance in the initial launch angle of the ball. However, the results from this investigation suggest other important contributors to the launch angle of the golf ball during the drive.

Also important in predicting the launch angle of the ball was the loft of the club-face at impact. This kinematic measure is a result of both the orientation of the club-head at impact and the degree of loft with which the face of the club sits relative to the club-head. Interestingly, the former of these relationships is almost entirely influenced by the kinematics of the golfer in each swing, whereas the latter can only be manipulated through the design of the club. Therefore, for skilled players who possess kinematics with low variability (Dowlan, Brown, Ball, Best, & Wrigley, 2001; Jobe, Perry, & Pink, 1989), the results of this study highlight the importance of correct club fitting in allowing maximal driving distance to be achieved. For example, a skilled player not achieving an optimal launch angle of the ball may be due to the particular loft angle of the club being inappropriate.

Golf ball side angle

The accuracy of any shot in golf is the result of the ball's initial direction and spin (Miura, 2002). Initial lateral direction is especially important in the drive, where a small error in side angle can cause a large error in lateral position of the ball relative to the target. For example, discounting the effect of air resistance, a 280-m drive miss-hit by 2° will land close to 10-m offline, while a 120-m wedge shot miss-hit by 2° will land around 4-m offline. Hay (1993) suggested that both the orientation of the club at impact and the path along which it is moving play a key role in the direction traveled by the ball. However, our data support Miura's (2002) suggestion that the orientation of the club-head at impact was the most important factor in the initial lateral direction of the ball. In fact, the club-head rotation alone explained 82% of the variance in golf ball side angle and was the only independent variable to achieve significance in the regression analysis. Although it would be difficult to

Table II. Results of five stepwise regressions using club-head kinematics, at impact, to predict ball flight kinematics.

Dependent variable	Independent variables	Adjusted R^2	Direction of relationship	df	F	Significance	SE of estimate
Ball velocity	Club-head velocity	0.75*	Positive	1,19	62.3	0.000	1.97 m/s
	Centeredness of impact	0.82*	Negative	2,18	44.8	0.000	1.71 m/s
Ball launch angle	Club-head vertical velocity	0.68*	Positive	1,19	43.1	0.000	1.4°
	Club-head loft angle	0.74*	Positive	2,18	29.6	0.000	1.3°
	Vertical centeredness of impact	0.81*	Negative	3,17	28.5	0.000	1.1°
Ball side angle	Club-head rotation	0.82*	Positive	1,19	90.2	0.000	1.4°
	Club-head lateral velocity	n.s.					
	Horizontal centeredness of impact	n.s.					
Ball back spin	Offset between club-head loft and vertical path	0.73*	Positive	1,7	20.4	0.004	341 revs/s
Ball side spin	Offset between club-head rotation and lateral path	0.82*	Positive	1,6	33.8	0.001	52 revs/s

argue that the path of the club-head at impact and centeredness of impact have no influence on the lateral direction of the ball during its flight, it would appear that these do not play an important enough role to achieve significance in statistical analysis.

Golf ball spin

In addition to the initial direction of the ball, the spin imparted on the golf ball will largely dictate both distance and accuracy achieved in the drive (Hay, 1993). Miura (2002) reported that a shot resulting in a 'hook' or a 'slice' is caused by excessive spin about the vertical axis, resulting from a misalignment between the position of the club-face and the path of the club at impact. That is, if the club-face is not aligned perpendicular to the direction that the club-head is traveling at impact, the rotation of the ball will occur during flight due to an off-center impact. This appears to be quantitatively supported by the analyses performed in the present investigation. The variance in both side spin and back spin produced in the drive appears to be best explained by the alignment between club-head orientation and path. This also supports the popular coaching recommendation of keeping the club-head 'square' at impact to reduce the possibility of a hook or a slice.

Further implications

For the purpose of this investigation, the early flight of the ball was broken into separate variables. What should not be ignored, however, is the interaction of these variables and their possible combined influence on the outcome of the stroke. For example, it is important to be aware that certain club-head kinematics may influence different determinants of distance in the drive such as ball velocity, launch angle, and back spin (Chou, 2004). In recognition of the major role that launch angle can play in achieving optimal distance, a number of articles in the popular golfing literature have focused on the potential benefit of using a club with an increased loft angle, within the narrow range of $10°–14°$ (e.g., Johnson, 2006; Masters, 2010; Statchura & Wilson, 2003). Although results from the present study would indicate that this may well increase the ball launch angle, these also suggests that a disparity between the loft of the club and the vertical path of the club may result in greater back spin. This increased back spin can reduce distance in a drive and may, therefore, negate any potential benefit achieved by increasing the launch angle of the ball. It is evident that although the results of this study provide a better understanding of the influence of club-head kinematics at impact on specific launch kinematics of the ball, researchers and coaches should be mindful of the interaction effect between these variables.

Although this study ensured a high external validity by allowing golfers to use their own driver, it is likely that design differences across clubs would have had some effect on early ball flight characteristics in the golf drive. Although this acted as a limitation of this study, early ball flight characteristics were still significantly explained by the club-head kinematics at impact. A further limitation of this study was the use of linear regression analyses. Despite the caution taken, the possibility of some error deriving from sample heterogeneity and nonlinearity of statistical relationships should be considered when interpreting the current research.

Future research could take into account the influence of specific design differences, such as the size of the 'sweet spot,' club-face composition, and shaft specifications and their effect on performance. Research in this vein would allow valuable insight into the influence of club design and specifications on the interaction between the variables explored in this study.

Conclusion

This study has identified strong relationships between club-head kinematics at impact and subsequent ball flight characteristics. Each component of initial ball flight (resultant velocity, launch angle, side angle, back spin, and side spin) was well explained by the kinematics of the club-head at impact. In summary, resultant ball velocity seemed to be largely determined by the velocity of the club-head at impact, as well as the centeredness of this impact on the club-face. Although the launch angle of the ball during early flight was explained by the orientation, path, and centeredness of the club-head at impact, only the orientation of the club-head significantly explained the variance in the side angle. Finally, it was evident that the majority of variance in both back spin and side spin can be explained by the misalignment between the orientation and the path of the club-head at impact. These results allow both researchers and coaches to have a better understanding of the key club-head kinematics that are required to produce optimal early ball flight characteristics.

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