

The influence of 5-iron clubhead mass distribution on clubhead presentation and initial ball launch conditions – Part I: Golf robot tests.

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Abstract

It is well accepted that iron clubhead properties affect shot outcomes in golf. However, the mechanisms that contribute to this relationship have not received recent scientific study. The purpose of this study was to determine how the different clubhead mass distributions in a blade 5-iron and a cavity-back 5-iron affect clubhead presentation and ball launch conditions. Nine clubhead presentation variables and four ball launch variables were measured for ten discrete impact locations and five face angles during swings using a golf robot. Group means were analysed statistically using an independent samples approach to identify differences and linear regression was used to indicate relationships between key launch variables. The cavity-back showed higher effective clubhead loft with greater total ball spin than the blade, despite having matched static lofts, whilst also providing more consistent launch outcomes across a range of impact locations. Evidence of the phenomenon known as the ‘gear effect’ was found for the cavity-back, but not the blade, suggesting that the threshold at which the clubhead’s centre of gravity (CG) is deep enough to detect the gear effect lies between the CGs of the two 5-iron types. These novel robot test findings lend support to the perceived performance benefits of perimeter-weighted irons; whether these effects translate to human golfer swings is reported in Part II of this paper.

Keywords

5-iron, clubhead, perimeter-weighting, launch conditions, golf, robot

1. Introduction

The design of golf clubs generally followed an evolutionary process until the 1960's, when the principle of 'perimeter-weighting' of iron clubs was implemented in a range of commercial iron club design and manufacturing processes. Perimeter-weighting refers to the process whereby clubhead mass is re-distributed to the outer borders of the clubhead [1], usually creating an indentation or 'cavity' in the rear of the clubhead and giving rise to the nomenclature 'cavity-back' for this clubhead design. The effect of this mass re-distribution is to increase the moment of inertia (MOI) of the clubhead, thus rendering it less prone to rotations arising from off-centre hits that may result in changes to ball launch conditions. Irons without such a cavity, as was the norm prior to the 1960's, are commonly referred to as 'blades'. Today, blade and cavity-back clubs are widely used, along with their counterparts in the continuum between them.

In the popular golfing literature, the blade clubhead is deemed appropriate for better ball strikers, whilst the cavity-back is better suited for higher handicap players. The cavity-back, which has a wide sole, large cavity and more significant perimeter weighting at the heel and toe, is often seen as a 'game improvement' club. A survey investigating perceptions of differences between blade and cavity-back irons [2] suggested that golfers consider cavity-backs to be 'easier-to-hit' and more 'forgiving' than blades. 'Forgiveness' concerned the degree to which the club's performance (e.g. shot distance or direction) depended on impact location and an 'easy-to-hit' club was considered to make a desired ball flight more achievable with greater regularity. Numerous additional subjective factors were also apparent in players' perceptions of these two club types, for example, prejudice by some players

against cavity-back aesthetics and a support for the view expressed above that blade irons are better suited to more skilled golfers.

Early research used computer modelling to demonstrate the extent to which the inertia properties of iron clubheads could be affected by relocating discretionary mass [3, 4], whilst later efforts used idealised blade and cavity-back models to predict the effect on shot outcome [5]. Smaller changes in distance and direction effects were noted for the cavity-back relative to the blade when impact was away from the projection of the centre of gravity (CG) location on to the club face. One robot study [6] has investigated the effects of different weight distributions on club performance in 5-iron clubheads with constant shape and weight. Ball impacts were always on the same spot in the middle of the club face, whilst the horizontal and vertical CG location of the irons were experimentally varied by inserting weights at various ports around the head perimeter. The authors concluded that a lower CG generates higher launch and spin resulting in higher ball flight, whilst shot direction was affected by horizontal CG location. However, the results were based on limited testing and details of the CG locations and methodology were not reported.

Studies using driver clubs have shown that clubheads with a higher MOI have more consistent initial ball velocity and spin characteristics when impact location is varied across the club face [7,8]. These findings could also be inferred from the modelled and experimental results comparing shot distance of blade and cavity-back irons in the studies referred to above. Research using putters noted that increasing MOI about relevant axes had a more noticeable effect on putt distance (also quantified by initial velocity) than putt direction [9,10].

Relocating mass within a clubhead to achieve more advantageous inertia properties is also likely to influence the location of the clubhead's CG; an

interdependency that has been observed previously [4, 6, 7]. The effect of moving the location of the CG can be considered relative to both the impact point and the shaft axis. The CG location of a typical golf clubhead is ‘behind’ the shaft axis (i.e. away from the target) and ‘above’ the shaft axis (i.e. away from the golfer) relative to the golfer at the address position (Fig. 1).

**** Figure 1 near here ****

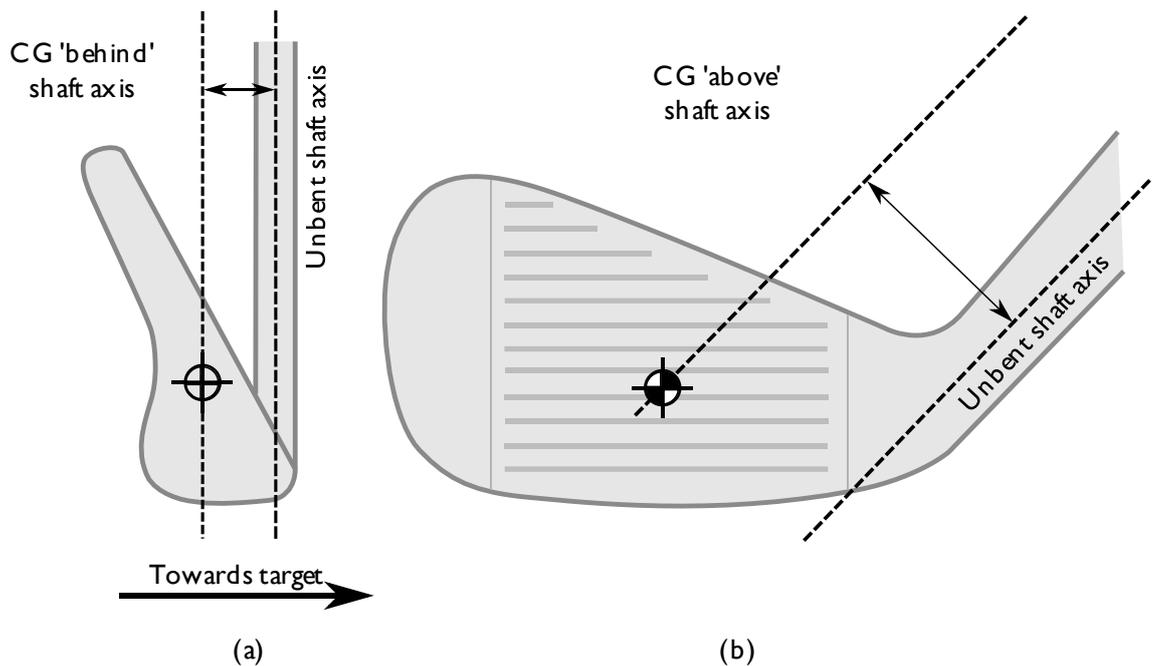


Figure 1. Nominal location of iron clubhead CG relative to the shaft axis as viewed in the frontal (a) and sagittal (b) plane of the golfer's address position. (CG location not positioned to scale).

Shaft flexibility and the inertial properties of the club cause the CG of the clubhead to tend to move towards the unbent shaft axis during the downswing, which results in the club being presented to the ball with more loft and in a more toe-down position than when the club was static at address [11]. These effects are referred to as ‘lead’ and ‘droop’ deflections, respectively, and typically increase in magnitude as the CG of the clubhead at address is located further from the shaft axis. Lead deflection can also create torque about the shaft axis, resulting in a more

closed dynamic position of the club face at impact relative to its static position at address [11].

The relationship between the impact point and the clubhead's CG location on ball launch has been studied more extensively for drivers. Contact on the face above the CG location causes this point to effectively rotate backwards during impact, increasing the club's effective loft, and vice versa for low impacts. The same can be applied to toe/heel impacts and opening/closing of the club face. In the case of most drivers, an additional mechanism known as the 'gear effect' [1,12] causes tangential motion of the clubface to influence the spin characteristics of the golf ball, such that an eccentric impact (i.e. away from the projection of the CG on to the club face) will cause the clubhead to rotate, with friction subsequently causing the contact surface of the ball to rotate in the opposite direction. The conventions for drivers are such that impacts above/below the CG will decrease/increase backspin, respectively, whilst toe/heel shots cause the ball to spin, such that the flight curves to the left/right, respectively (for a right-handed golfer) [7,8]. It remains contentious as to whether or not the 'gear effect' is present in iron shots, although it has long been considered that if a clubhead's CG is not deep enough (i.e. located close to the impact point), the gear effect will not be evident [1,10]. 'Traditional' blade irons have CG locations on the shallow side of this threshold and thus the gear effect is not expected to be evident; it is not clear if the more recessed features and resultant CG location of cavity-back clubs permit the gear effect to be observed.

No additional published papers have been uncovered on the effects of perimeter-weighting in irons since the paper by Chou et al. [6]. The dearth of scientific knowledge pertaining to shot outcomes with different iron clubhead

designs warrants further investigation, especially considering the significance of iron play in golf. Recent statistical investigations at both amateur and elite levels of the game suggest that the importance of tee-to-green play in relation to a player's average score has been underestimated relative to putting [13]. In tee-to-green play, approach shots which are further than 100 yards (91.4 m) from the green have the greatest impact on scoring [14].

Considering the lack of scientific performance findings for perimeter weighted iron clubs, the aim of this study in Part I was to determine how clubhead mass distribution in a cavity-back 5-iron versus a blade 5-iron affects clubhead presentation and ball launch conditions for different ball impact locations at different face angles for swings using a golf robot.

2. Methods

2.1 Test clubs

Two commercially available clubheads, one 'blade' and one 'cavity-back' 5-iron, from the same manufacturer were chosen for the study. The choice of the blade was based on having a clubhead that had different key properties to the cavity-back, yet would not be perceived as an 'extreme' blade by the high handicap players that participated in the later player tests (Part II of this paper). Thus, whilst the blade had a small cavity in the back, this was much smaller and less pronounced than the cavity in the cavity-back club, which was amongst the more extreme cavity-back models available (Fig. 2). The club face areas were the same for both clubheads, whilst in addition to the larger cavity, the cavity-back also had a wider sole along its length.

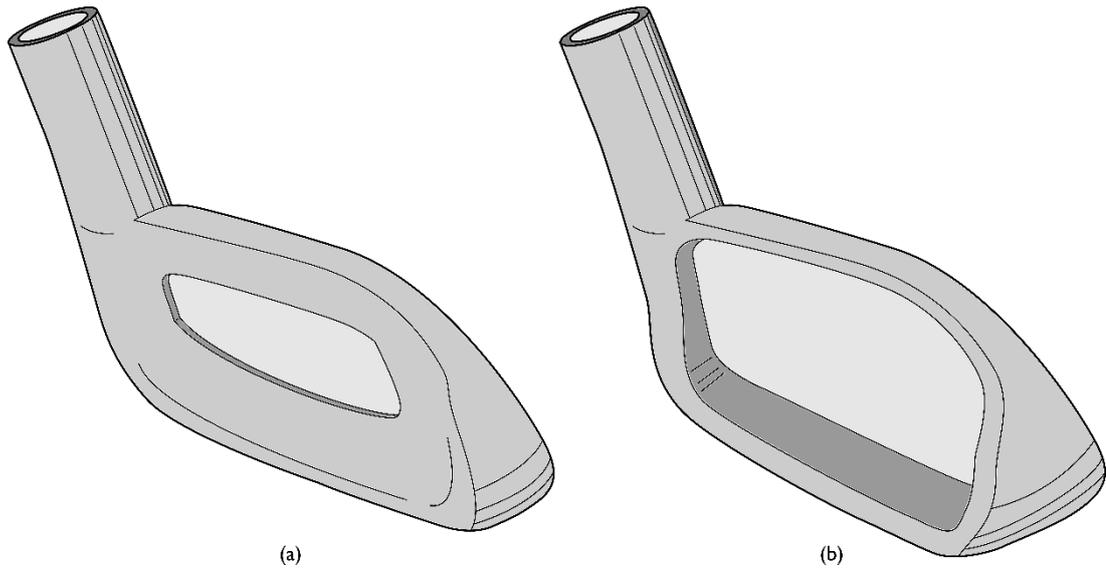


Figure 2. Representation of the extent of ‘cavity’ in the chosen blade (a) and cavity-back (b) clubheads (not to scale).

The clubheads were closely matched for clubhead mass, static loft and static lie (Table 1), whilst the CG location was closer to the hosel (X_f), lower (Y_f) and further behind the face (Z_f) for the cavity-back, which also had a higher moment of inertia (I).

*** Table 1 – near here ***

Table 1. Clubhead properties of blade and cavity-back models. Hosel, face and playing coordinate systems are illustrated in Figure 3.

	Mass (g)	Loft (°)	Lie (°)	CG_{hosel} (mm)			CG_{face} (mm)			I_{hosel} (kg.cm ²)			$I_{playing}$ (kg.cm ²)		
				X_h	Y_h	Z_h	X_f	Y_f	Z_f	X_h	Y_h	Z_h	X_p	Y_p	Z_p
				Blade	252.4	25.7	60.4	37.3	8.3	66.9	-1.8	-4.0	-10.0	12.6	17.6
Cavity	252.2	26.0	60.3	41.8	14.7	68.0	1.1	-5.3	-12.6	13.8	19.6	7.2	1.6	3.6	2.3

**** Figure 3 – near here ****

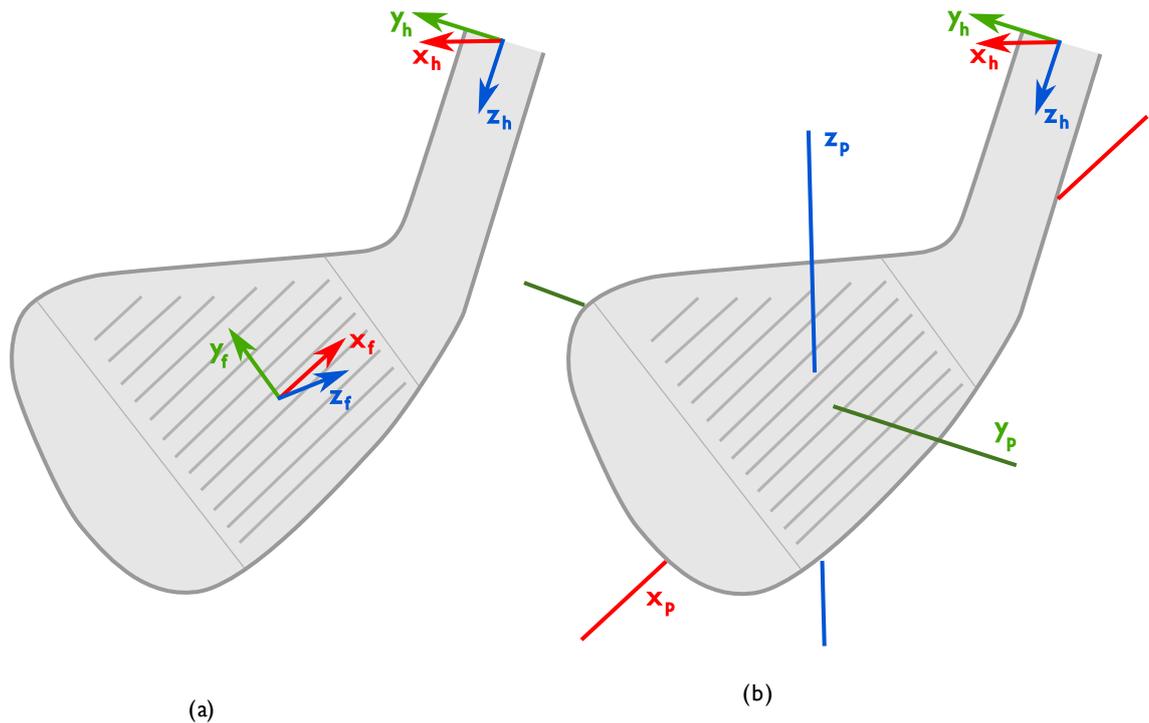


Figure 3. Hosel and club face coordinate systems for CG location measurement (a) and hosel and playing position axes for MOI measurement (b). All playing position inertia axes pass through the CG location.

Loft and lie angles were measured using a mechanical loft-lie machine and the CG locations were measured using an Auditor CGM (Technorama Co. Ltd., Ta-liao, Taiwan). This machine uses several measurements in different orientations to determine CG location in the hosel coordinate system (Fig. 3). The measurements were transformed into the face coordinate system (Fig. 3) using the bespoke clubhead tracking program, described previously [15]. An Auditor Inertia Chronograph (Technorama Co. Ltd., Ta-liao, Taiwan) measured the inertia properties of the clubheads, again in the hosel coordinate system. This machine calculates the MOI from multiple measurements of torque and acceleration while the clubhead is rotating about specified axes [16]. The inertia matrix was then transformed into the playing position coordinate system (Fig. 3).

The clubheads were fitted to two regular stiffness shafts with the same corded grip and a gripped length of 0.965 m (38 in). There was a small difference in swingweight due to the more distal clubhead CG location of the cavity-back clubhead (blade: D1, cavity-back: D2), as measured on the traditional lorythmic scale [17], despite matching clubhead mass. Matching clubhead mass was preferable as research has shown that small differences in swingweight (around three points or less) are unlikely to be detected by a golfer [18]. Similarly, no attempt was made to more closely match clubhead lofts, as to do so would have involved bending one club, which could have affected its properties. Furthermore, no attempt was made to match clubhead inertia properties or CG location, as these are affected by the clubhead design and are interdependent, as noted previously [4,7].

Retroreflective markers were attached to both clubs as required by the clubhead tracking program [15]. The mass of these markers, approximately 10 g, did not meaningfully affect any of the club properties previously described.

2.2 Procedures

A robot (Golf Laboratories Inc., San Diego, CA), featuring a powered ‘arm’ and a free, geared wrist joint, was used to swing the test clubs. Robot testing permitted precise control over clubhead presentation with high levels of repeatability, neither of which would be achievable with player testing. The magnitude of the applied torque was fixed for all trials, whilst the torque profile, along with mechanical adjustments of the ‘wrist joint’, were made to give the desired face angles. The ball impact position was systematically altered by moving the teeing position, whilst keeping all other aspects of clubhead presentation consistent. All testing used Tour standard urethane-covered golf balls.

Three passive marker motion capture cameras (Oqus 300+, Qualisys AB, Gothenburg, Sweden), fitted with 50 mm (focal length) lenses, measured the position of the retroreflective markers attached to the clubheads and the clubhead tracking program [15] was used to calculate clubhead presentation. Mechanical adjustments to impact position and face angle were verified using these measurements. A stereoscopic launch monitor measured the initial launch conditions of the golf ball (Fig. 4).

**** Figure 4 – near here ****

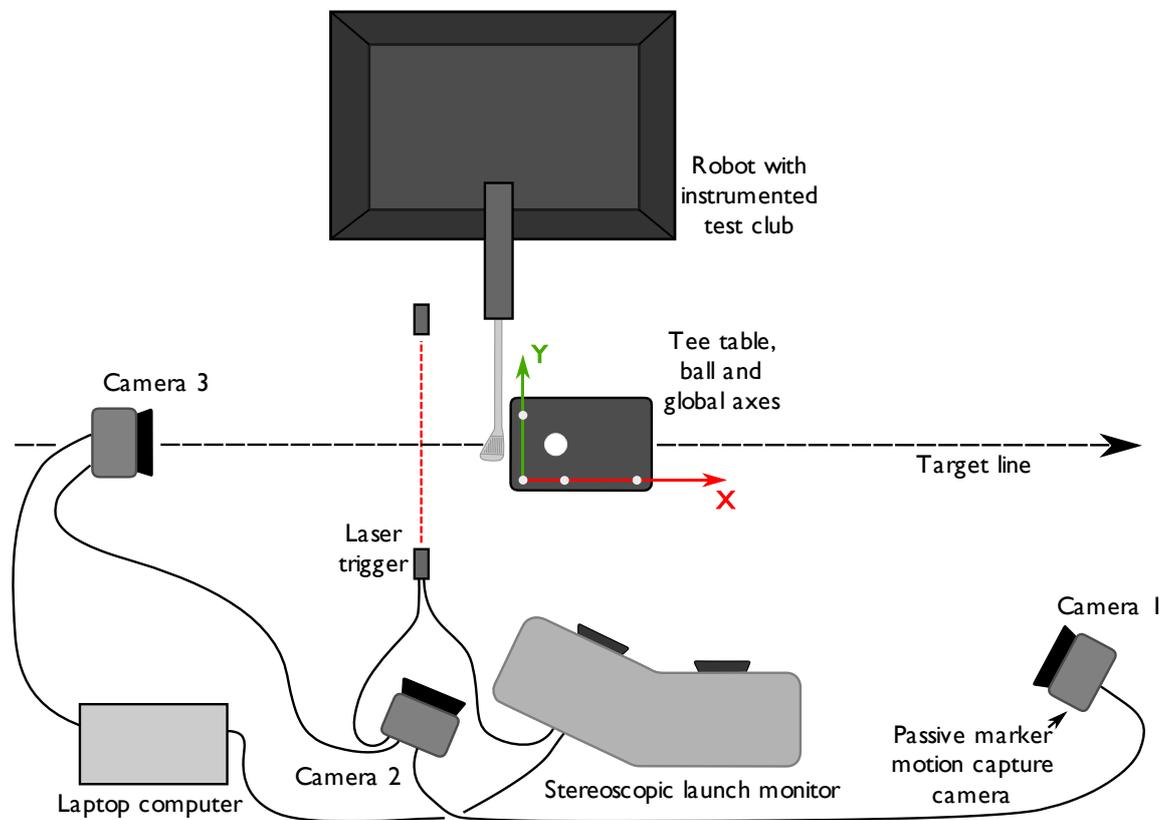


Figure 4. Schematic diagram of experimental setup and camera placement for robot testing. Cameras positioned on fixtures at a height of approximately 3.5 m. Global Z-axis (not shown) is mutually perpendicular to the other two axes.

The robot swing was set to produce launch conditions representative of an elite male amateur golfer swinging a 5-iron [19] (ball speed: $56.0 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$, $125.3 \pm 0.5 \text{ mph}$, launch angle: $16.7 \pm 0.5^\circ$, total spin: $5200 \pm 120 \text{ rpm}$). Elite amateur launch conditions were chosen because these were easier to define than those of a

higher handicap golfer due to the lower variability in elite golfers. These launch conditions were achieved with a central impact with the blade club (horizontal impact location: 0.0 ± 1.0 mm, vertical impact location: -10.0 ± 1.0 mm, relative to the geometric face centre), square club face (face-path: $0.0 \pm 0.5^\circ$) and with horizontal groove alignment (effective lie: $0.0 \pm 1.0^\circ$) (Fig. 5). Other than mechanical adjustments ensuring that the impact location and face angle were appropriate, no changes were made to the swing for the cavity-back club.

**** Figure 5 – near here ****

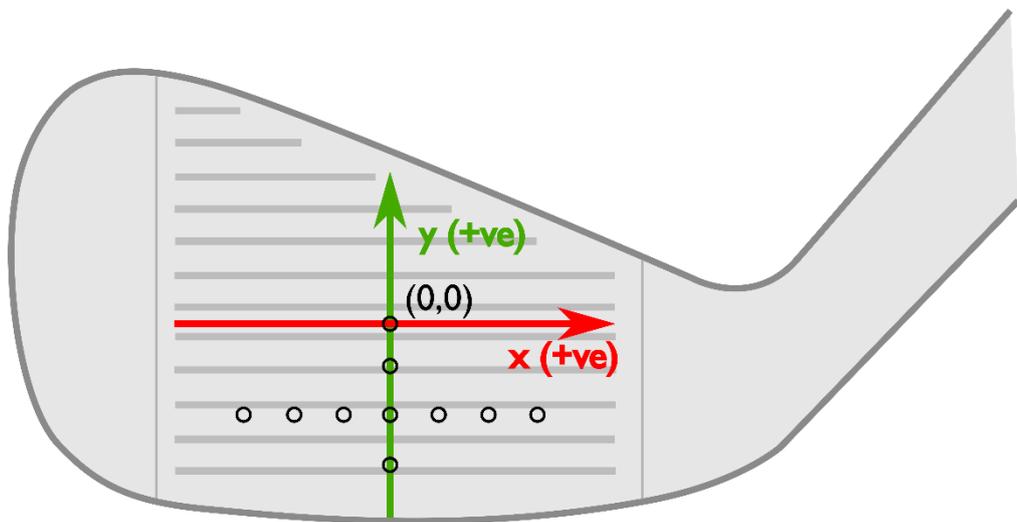


Figure 5. Club face coordinate system with impact locations indicated by black circles (not to scale).

Intervals and ranges of impact location and face angle were based on pilot player testing data: based on a Category 1 golfer (handicap < 6) hitting twelve shots; ± 1.5 cm and $\pm 6^\circ$ fell within ± 3 standard deviations. A row of seven horizontal impacts with a tolerance of ± 1.0 mm was performed at $y = -10.0$ mm, ranging from $x = -15.0$ mm to $x = 15.0$ mm in 5.0 mm intervals. Four additional impact locations with a tolerance of ± 1.0 mm were spaced downwards from the face centre ($x = 0.0$ mm), between $y = 0.0$ mm and $y = -15.0$ mm at 5.0 mm intervals. The impact location (0.0, -10.0) was common to both vertical and horizontal directions (Fig. 5). These 11 impact locations were tested at five prescribed face angles with a tolerance

of $\pm 0.5^\circ$ from -6° (closed) to 6° (open) in 3° increments. Six shots were repeated at each impact location, totaling 330 shots for each club.

2.3 Data analysis

Position data from the clubhead motion capture system were exported and processed using previously described methods to calculate clubhead presentation [15,20]. Ball launch measurements were exported into .xlsx format and all data were collated in MATLAB for data analysis (MATLAB 2019b, Mathworks, Natick, MA).

Several variables were calculated to help understand differences in clubhead presentation between the two clubs: mean value for the blade club over all shots (\bar{x}_{blade}), difference in means between the two clubs ($\bar{x}_{blade-cavity}$), pooled standard

deviation ($s = \sqrt{\frac{(n_B-1)s_B^2 + (n_C-1)s_C^2}{n_B+n_C-2}}$), and Cohen's d effect size of this difference.

Effect sizes less than 0.2 were considered small, whilst those greater than 0.8 were considered large. Since the number of shots was large, two sample t-tests (9 tests in total) with a Bonferroni adjusted significance level of 0.006 (0.05/9) were used to assess the statistical significance of differences. Due to the consistency of robot testing and the associated likelihood that small differences may be statistically significant, the mean differences were prioritised when assessing the practical significance of differences.

A relationship between face angle and effective loft was observed during testing as a consequence of the mechanical method used to make changes to the face angle. A linear regression with face angle as input and effective loft as output was calculated to characterise this relationship.

Multiple linear regression was used to indicate the relationship between clubhead design (mass distribution) and ball launch for the two clubs. Specifically, a

comparison of ‘forgiveness’ (in terms of iron play) for the two clubs was represented by multiple linear regression of impact locations and three key launch variables (Table 2). Only data from the seven impact locations where horizontal impact location was varied were included in the regression when horizontal impact location was the input variable. Similarly, only four impact locations were included when vertical impact location was the input variable. Each of the linear regression relationships calculated included the nominal face angle and club as categorical predictors in the form: $y = m \cdot x + m_{cavity} \cdot x + m_{face} \cdot x + c + c_{cavity} + c_{face}$. The reference categories were the blade club and a face angle of zero, and the regression equation in this case would take the more recognized form as shown in Eq. (1):

$$y = m \cdot x + c \tag{1}$$

Table 2. Relationships reflecting the forgiveness of the two clubs considered using linear regression.

*** Table 2 – near here ***

Input (x)	Output (y)
Horizontal impact location (mm)	Initial launch direction (side angle, °)
Horizontal impact location (mm)	Spin axis angle (°)
Vertical impact location (mm)	Total spin rate (rpm)

Not including interaction terms (between club and face angle, for example) was a simplification made to limit the number of terms in the model. The range of the output variable for each club, calculated between the maximum and minimum average of six shots (for the impact locations and face angles included in each regression), was determined to understand whether this simplification was justified.

The relationship between impact location and efficiency (the ratio of clubhead speed and ball speed) was assessed using a linear regression with the form shown in Eq. (2):

$$Efficiency = a \cdot x^2 + b \cdot y^2 + c \cdot x + d \cdot y + e \quad (2)$$

where x and y are the horizontal and vertical impact locations, and a , b , c , d and e are the regression coefficients. Nominal face angle and club were included as categorical predictors as above. The decision to include the quadratic term was based on previous work using driver clubs [21].

3. Results

3.1 Differences in clubhead presentation

Non-significant differences between the clubs across all swings for horizontal ($p = 0.66$) and vertical ($p = 0.41$) impact locations (Table 3) confirmed that the robot delivered the clubs to the same impact locations consistently. There were statistically significant differences between the clubs for other clubhead presentation variables (Table 3), several of which were ‘moderate’ to ‘large’ standardised effects. These differences reflect differences in shaft bending due to differences in the clubheads centre of gravity (with unchanged swing parameters). However, considering the small size of the differences and the consistency of the robot (which will inflate the standardized effect size), most were not considered to be meaningful in terms of resultant shot outcomes. The exceptions to this interpretation are the effective loft (mean difference between clubs of -1.8°) and face angle rate of change (mean difference between clubs of $28^\circ \cdot s^{-1}$), both of which are considered as having a material effect on shot outcomes.

The gradient of the linear fit between the face angle and effective loft was 0.75 ($R^2 = 0.93$, $p < 0.01$), indicating that opening the club face by 1.00° resulted in an increase in effective loft of 0.75° .

Table 3. Clubhead presentation for the two clubs, averaged over all shots.

*** Table 3 – near here ***

	\bar{x}_{blade}	$\bar{x}_{blade-cavity}$	Cohen's d	Pooled standard deviation	p
Clubhead speed ($m \cdot s^{-1}$)	40.0	-0.4	-5.43	0.08	< 0.001
Face angle ($^\circ$)	1.5	-0.8	-0.19	4.29	0.031
Face angle rate of change ($^\circ \cdot s^{-1}$)	2208	28	0.94	30	< 0.001
Path angle ($^\circ$)	2.0	-0.1	-0.72	0.13	< 0.001
Attack angle ($^\circ$)	-2.1	0.1	0.64	0.16	< 0.001
Effective loft ($^\circ$)	21.6	-1.8	-0.55	3.22	< 0.001
Effective lie ($^\circ$)	-1.2	0.6	0.89	0.68	< 0.001
Horizontal impact location (mm)	0.2	0.3	0.04	8.26	0.657
Vertical impact location (mm)	-9.5	-0.3	-0.07	3.64	0.410

Statistically significant p values are highlighted in bold.

3.2 Effect of impact location on ball launch

Figure 6 shows the effect of horizontal impact location on initial launch direction (side angle) for each of the five face angles. For both club types, a closed face (negative face angle) results in negative side angles (ball launch to the left) and vice versa. For example, the cavity-back club at a face angle of -6° and a central strike would have a predicted side angle of -3.0° ($c + c_{(cavity)} + c_{(face=-6)}$; Table 4). That the zero face angle condition results in a positive side angle (positive c and $c + c_{(cavity)}$) shows that the shot was a slight push. Table 4 shows the coefficients of this regression ($R^2 = 0.99$, $p < 0.01$) and indicates that there was a statistically significant difference between the two clubs: the cavity-back launching slightly further to the

right on average ($c = 0.86^\circ$, $c + c_{(cavity)} = 1.38^\circ$) and being less affected by changes to impact position ($m = -0.04^\circ \cdot \text{mm}^{-1}$, $m + m_{(cavity)} = -0.02^\circ \cdot \text{mm}^{-1}$).

*** Figure 6 – near here ***

*** Table 4 – near here ***

Figure 7 shows similar trends in the regression between horizontal impact location and spin axis angle ($R^2 = 0.98$, $p < 0.01$; Table 5). There was a statistically significant difference between the two clubs, but both clubs were equally affected by impact location ($m = -0.001^\circ \cdot \text{mm}^{-1}$, $m + m_{(cavity)} = 0.001^\circ \cdot \text{mm}^{-1}$). The cavity-back displayed a shallower gradient for closed face angles and the blade displayed a shallower gradient for open face angles (Fig. 7). However, the range of spin axis angles displayed across the five face angles, calculated between the averages of the six shot groups, was smaller for the cavity-back (blade = 36.7° , cavity = 31.2° ; Fig. 7), suggesting increased forgiveness to changes in face angle.

*** Figure 7 – near here ***

*** Table 5 – near here ***

The effect of vertical impact location on total ball spin for both clubs is illustrated in Fig. 8 and indicates that the cavity-back club had generally higher spin than the blade club ($c = 5200 \text{ rpm}$, $c + c_{(cavity)} = 5414 \text{ rpm}$). Inspecting the clubs separately, the blade had positive gradients for most face angles, whereas the cavity-back had negative gradients. Thus, a higher impact location was associated with more spin with the blade club, whereas a lower impact location was associated with more spin with the cavity-back club. This relationship is supported by the regression coefficients for the gradient ($c = 9 \text{ rpm} \cdot \text{mm}^{-1}$) and the gradient for the cavity-back club ($c + c_{(cavity)} = -21 \text{ rpm} \cdot \text{mm}^{-1}$; $R^2 = 0.97$, $p < 0.01$; Table 6). The cavity-back club

also had a larger range in total spin across the five face angles, calculated between the averages of the six shot groups (blade = 2274 rpm, cavity = 2718 rpm).

*** Figure 8 – near here ***

*** Table 6 – near here ***

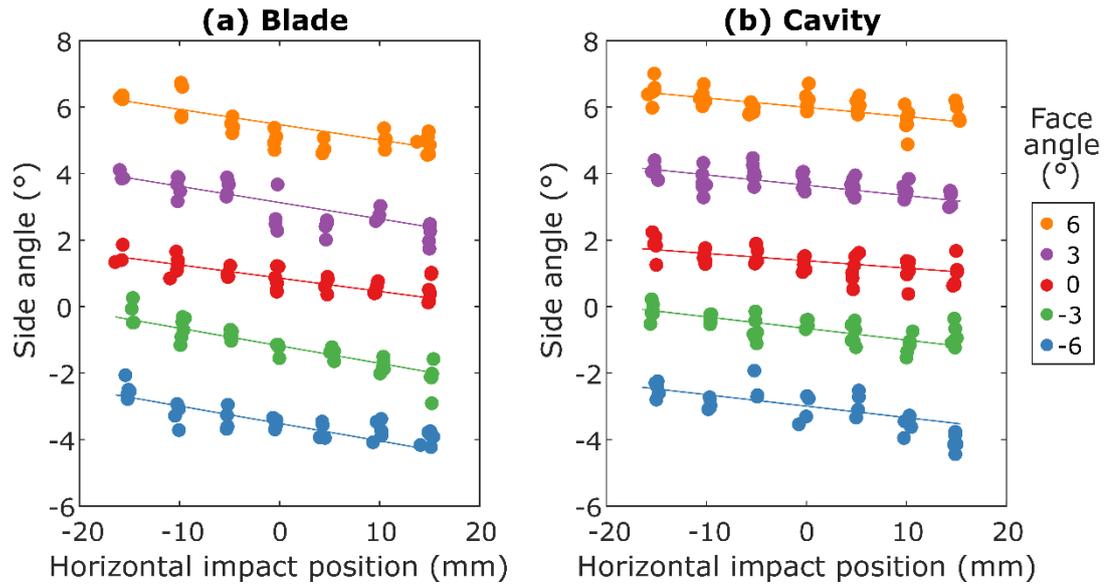


Figure 6. Horizontal impact location (at $y = -1.0$ cm) against side angle for the blade (a) and cavity-back (b) clubs. A positive side angle indicates a ball launching to the right of the target (push) and vice versa.

Table 4. Coefficients (β), standard errors in coefficients (σ_e) and statistical significance for linear regression fit between horizontal impact location and side angle.

	β	σ_e	t	p
c	0.857	0.044	19.6	< 0.01
$c_{(cavity)}$	0.522	0.036	14.6	< 0.01
$c_{(face = -6)}$	-4.373	0.056	-77.6	< 0.01
$c_{(face = -3)}$	-2.036	0.056	-36.6	< 0.01
$c_{(face = 3)}$	2.273	0.056	40.7	< 0.01
$c_{(face = 6)}$	4.617	0.056	82.9	< 0.01
m	-0.040	0.004	-9.2	< 0.01
$m_{(cavity)}$	0.018	0.003	5.1	< 0.01
$m_{(face = -6)}$	-0.013	0.005	-2.3	0.02
$m_{(face = -3)}$	-0.013	0.005	-2.3	0.02
$m_{(face = 3)}$	-0.009	0.006	-1.6	0.11
$m_{(face = 6)}$	-0.006	0.005	-1.1	0.27

The reference level for the regression was the blade club at a face angle of zero degrees. The units for β and σ_e are $^\circ$ for c (the intercept terms) and $^\circ \cdot \text{mm}^{-1}$ for m (the slope terms). The t statistic was calculated prior to rounding.

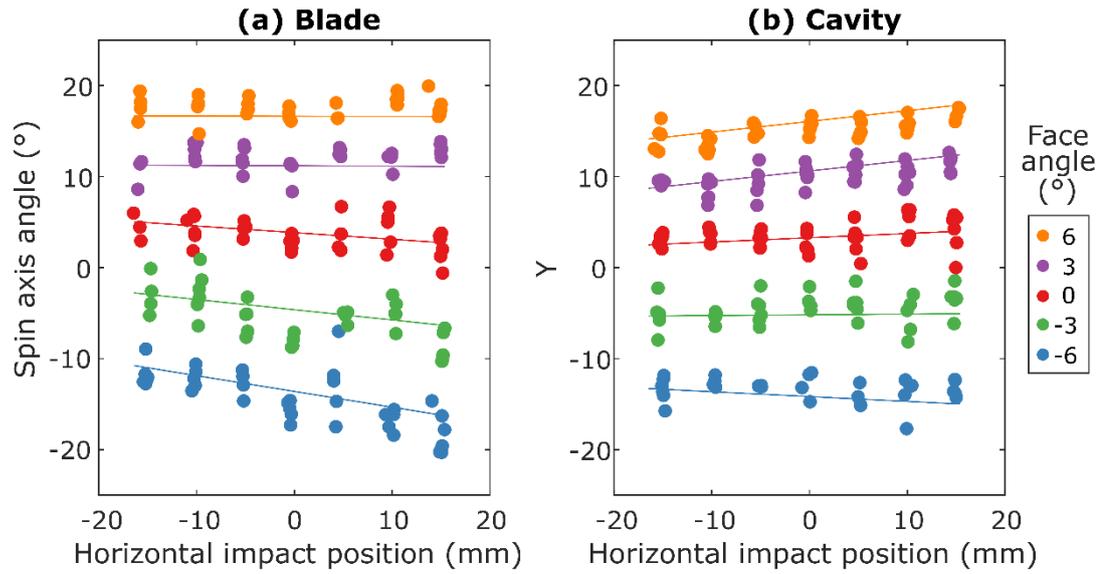


Figure 7. Plot of horizontal impact location (at $y = -1.0$ cm) against spin axis for the blade (a) and cavity-back (b) clubs. Positive spin axis indicates a tilt to the right (fade spin) and vice versa.

Table 5. Coefficients (β), standard errors in coefficients (σ_e) and statistical significance for linear regression fit between horizontal impact location and spin axis angle.

	β	σ_e	t	p
c	3.8	0.2	17.2	< 0.01
$c_{\text{(cavity)}}$	-0.6	0.2	-3.1	< 0.01
$c_{\text{(face = -6)}}$	-17.5	0.3	-60.6	< 0.01
$c_{\text{(face = -3)}}$	-8.5	0.3	-29.8	< 0.01
$c_{\text{(face = 3)}}$	7.3	0.3	25.7	< 0.01
$c_{\text{(face = 6)}}$	12.8	0.3	44.9	< 0.01
m	-0.07	0.02	-3.3	< 0.01
$m_{\text{(cavity)}}$	0.12	0.02	6.7	< 0.01
$m_{\text{(face = -6)}}$	-0.10	0.03	-3.6	< 0.01
$m_{\text{(face = -3)}}$	-0.04	0.03	-1.4	0.16
$m_{\text{(face = 3)}}$	0.07	0.03	2.4	0.02
$m_{\text{(face = 6)}}$	0.07	0.03	2.5	0.01

The reference level for the regression was the blade club at a face angle of zero degrees. The units for β and σ_e are $^\circ$ for c (the intercept terms) and $^\circ \cdot \text{mm}^{-1}$ for m (the slope terms). The t statistic was calculated prior to rounding.

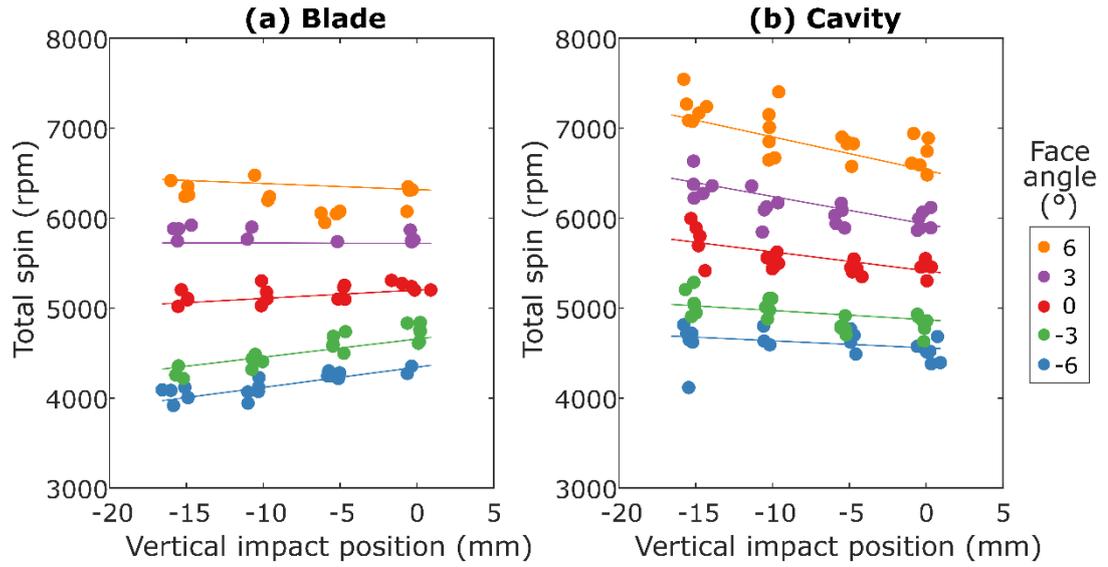


Figure 8. Plot of vertical impact location (at $x = 0$ cm) against total spin for the blade (a) and cavity-back (b) clubs.

Table 6. Coefficients (β), standard errors in coefficients (σ_e) and statistical significance for linear regression fit between vertical impact location and total spin.

	β	σ_e	t	p
c	5200	46	114.0	< 0.01
$c_{\text{(cavity)}}$	214	38	5.7	< 0.01
$c_{\text{(face = -6)}}$	-857	60	-14.4	< 0.01
$c_{\text{(face = -3)}}$	-544	56	-9.7	< 0.01
$c_{\text{(face = 3)}}$	519	60	8.7	< 0.01
$c_{\text{(face = 6)}}$	1118	58	19.2	< 0.01
m	9	5	1.9	0.06
$m_{\text{(cavity)}}$	-30	4	-7.7	< 0.01
$m_{\text{(face = -6)}}$	13	6	2.1	0.03
$m_{\text{(face = -3)}}$	11	6	1.8	0.07
$m_{\text{(face = 3)}}$	-10	6	-1.5	0.13
$m_{\text{(face = 6)}}$	-16	6	-2.6	0.01

The reference level for the regression was the blade club at a face angle of zero degrees. The units for β and σ_e are rpm for c (the intercept terms) and rpm·mm⁻¹ for m (the slope terms). The t statistic was calculated prior to rounding.

The two irons produced a similar peak efficiency (clubhead speed : ball speed) at locations close to their CG location: blade = 1.44 at (-3.1, -3.6 mm), cavity-back = 1.44 at (0.1, -6.3 mm). The regression model ($R^2 = 0.89$, $p < 0.01$) indicated that the cavity-back was slightly more forgiving than the blade in the horizontal direction, but slightly less forgiving in the vertical direction. At a clubhead speed of $40 \text{ m}\cdot\text{s}^{-1}$, moving 5 mm in the vertical direction would result in a loss in ball speed of $0.74 \text{ m}\cdot\text{s}^{-1}$ for the cavity-back and $0.50 \text{ m}\cdot\text{s}^{-1}$ for the blade. In the horizontal direction the loss in ball speed for a 5 mm shift was $0.19 \text{ m}\cdot\text{s}^{-1}$ and $0.23 \text{ m}\cdot\text{s}^{-1}$, respectively.

4. Discussion

The observed difference in effective loft (Table 3) is consistent with previous findings regarding ‘lead’ deflection [11]. The deeper CG location of the cavity-back iron, relative to the blade, would result in more lead deflection and more effective loft at impact, as observed. Despite not being meaningful differences, the observed differences in effective lie angle and clubhead speed are also consistent with this relationship, whilst the slower face angle rate of change (ROC) of the cavity-back club also agrees with previous research. More distal CG location [6] and greater MOI [4] relative to the shaft axis (Table I, CG_{hosel} x -axis, and I_{hosel} z -axis, respectively) would necessitate an increase in torque to close the face at the same rate. Whilst this demonstrates small differences in clubhead presentation between the clubs, the clubhead presentation was controlled as much as feasibly possible. It is believed that even though these differences are small, meaningful insights can still be drawn from the data.

The two irons were found to produce equal peak efficiency at 1.4 mm and 1.6 mm away from their CG location in the face coordinate system for the blade and

cavity-back, respectively. Differences in efficiency between the clubs when moving away from each club's peak were relatively small.

The effects shown in Fig. 6 support the hypothesis of perimeter weighting [1]. The greater MOI (about the z -axis in the playing position; Table 1) of the cavity-back clubhead results in a smaller difference in initial direction between toe and heel shots, likely caused by slower clubhead rotation during these impacts. The difference in initial direction (side angle) between impacts 15 mm towards the toe and heel would be 1.20° for the blade (slope of $-0.040^\circ \cdot \text{mm}^{-1}$), but only 0.66° for the cavity-back (slope of $-0.022^\circ \cdot \text{mm}^{-1}$).

Figure 7 shows opposing gradients for the blade and cavity-back clubs at different face angles. Considering only the square-faced shots (face angle = 0°), the positive gradient is suggestive of the 'gear effect', more commonly associated with drivers [7, 8]. In an off-centre strike, the impact force will cause the clubhead to rotate. This rotation of the clubhead will, in turn, cause the ball to rotate in the opposite direction (like a pair of gears). For an impact on the toe of the club, the rotation of the clubhead (an opening of the face) will impart anti-clockwise side spin and result in a more negative spin axis angle. The positive gradient of the cavity-back club ($m + m_{\text{cavity}} = 0.001^\circ \cdot \text{mm}^{-1}$) is consistent with this description of gear effect (a more negative spin axis for toe impacts than heel impacts), although the magnitude of the effect appears to be small. The distance of the clubs CG from the impact point is supposed to affect the magnitude of the 'gear effect' [1,10] with the implication being that the CG of traditional irons is too close to the impact point for this effect to be observed. The differences between the cavity-back and the blade, whose negative gradient does not agree with the physics of the gear effect (Fig. 7), support this claim.

Figure 8 offers a clearer suggestion that the ‘gear effect’ is indeed evident in the cavity-back club. Whilst gear effect is more typically associated with strikes toward the toe and heel, the gear effect also occurs in the vertical direction. As impacts move higher on the clubface, the clubhead rotates backwards and imparts an opposite spin on the ball, reducing the back spin and total spin, with backspin as the primary component. Again, considering only the square-faced shots (face angle = 0°), this relationship is visible in the cavity-back club (strikes lower on the face have more spin; $m + m_{\text{(cavity)}} = -21$, $p < 0.06$). The underlying physics has previously been shown with driver clubs [7, 8], but was not thought to occur in irons. Again, this effect is not observable for the blade club ($m = 9$, $p = 0.06$) and it follows that the distance of the CG behind the face limits the gear effect in ‘blade’ type irons, but not ‘cavity-backs’. The lower range in total spin for the blade club (at different face angles) may indicate that this club could offer a golfer greater control over the spin of the ball. This would primarily be a concern of better golfers and as such agrees with the perceived benefits of the club.

The effect of impact location and club type on ball launch are measurable, but these effects are much smaller than the effect due to face angle and effective loft. Face angle is the most important factor for determining side angle (Fig. 6) and spin axis angle (Fig. 7), and is also an important factor for the total spin (Fig. 8). However, there was a relationship between face angle and effective loft, and it is hypothesised that these differences are mostly due to changes in effective loft, not face angle. A club opened by 3° with an associated increase in effective loft of 2.25° was found to reduce efficiency by 0.02 and resulted in a decrease in ball speed of $0.93 \text{ m}\cdot\text{s}^{-1}$ for a $40 \text{ m}\cdot\text{s}^{-1}$ swing. The same decrease would require 10.3 mm and 6.5 mm shifts in horizontal and vertical impact position, respectively, for the blade club.

Thus, the horizontal impact location appears less important than the face angle and vertical impact location for maintaining ball speed.

5. Conclusions

This research is the most comprehensive scientific study to quantify performance differences between blade and cavity-back 5-irons for consistent swings. Robot testing permitted systematic manipulation of impact location and face angle to discern differences in clubhead presentation and initial ball launch conditions between a cavity-back and a blade 5-iron. For matched robot swings, the cavity-back showed a lower face angle rate of change and a higher effective loft, which were presumably due to differences in shaft deflection caused by the clubheads' centre of gravity location. The ball launch parameters showed a reduced effect of off-centre impacts on initial launch direction and spin axis angle with the cavity-back club. These findings support the perceived benefits of perimeter-weighting associated with cavity-back clubs. The location of the CG in the cavity-back (further from the face) resulted in observations consistent with the 'gear effect' in this club, whilst its higher effective loft generated the higher launch angle and greater spin compared to the blade. Whilst these robot test findings are novel and will inform Part II of this paper involving human players, there was a limitation with the study. As noted above, the blade club used in the study had some perimeter-weighting, but much less than the cavity-back, as indicated by the clear differences in the CG locations and moment of inertia between the two test clubs. Other blade clubs with no perimeter-weighting may have shown greater performance differences between the two club types.

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