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# The Effect of Dimple Error on the Horizontal Launch Angle and Side Spin of the Golf Ball During Putting

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## Abstract

This study aimed to examine the effect of the impact point on the golf ball on the horizontal launch angle and side spin during putting with a mechanical putting arm and human participants. Putts of 3.2 m were completed with a mechanical putting arm (four putter-ball combinations, total of 160 trials) and human participants (two putter-ball combinations, total of 337 trials). The centre of the dimple pattern (centroid) was located and the following variables were measured; distance and angle of the impact point from the centroid and surface area of the impact zone. Multiple regression analysis was conducted to identify whether impact variables had significant associations with ball roll variables; horizontal launch angle and side spin. Significant associations were identified between impact variables and horizontal launch angle with the mechanical putting arm but this was not replicated with human participants. The variability caused by 'dimple error' was minimal with the mechanical putting arm and not evident with human participants. Differences between the mechanical putting arm and human participants may be due to the way impulse is imparted on the ball. Therefore it is concluded that variability of impact point on the golf ball has a minimal effect on putting performance.

Words: 199

## Introduction

Based on Professional Golf Association (PGA) Tour statistics during 2014, the putting stroke accounted for approximately 40% of all strokes during tournament rounds (PGA Tour, 2015a; 2015b). This is in accordance with Dorsel & Rotunda (2001) and Alexander and Kern (2005), who identified that putting average was a key contributor to determining earnings on the PGA Tour. A number of factors are considered to influence the success rate of a golf putt, namely, green reading, aim, stroke and ball roll (Karlsen, Smith & Nilsson, 2008). Regarding the putting stroke, Pelz (2000) considered two variables that account for direction variability, face angle at impact (83%) and the putter path (17%). Karlsen et al. (2008) accounted 80% of direction consistency to face angle at impact (0.50° effective variability), 17% to putter path (0.18° effective variability) and 3% to horizontal impact point on the putter (0.09° effective variability). One variable that has not been considered at length within the literature considering direction variability is the impact point on the golf ball.

Golf balls are designed with dimples to reduce the drag of the golf ball when in flight (Aoki, Nakayama, Hayasida, Yamaguti & Sugiura, 1998; Goff, 2013). These dimples, however, may also be a detriment to putting performance. Due to the dimples a golf ball is not perfectly spherical with potential for the golf ball to rebound off the putter during impact at an unexpected angle (Cross & Nathan, 2007). To explain this further, the putter could strike the perimeter of the dimple ‘flat’ allowing the initial roll of the ball to leave in the intended direction towards the target. Or the putter could strike an edge of a dimple causing a deflection of direction off the intended target line (Figure 1). Research has acknowledged that dimples do affect the direction variability during a golf putt, however; only limited data is presented through a simple analysis of the distance that putts have rolled off line (Pelz, 2000). The authors of the current study propose that the direction variability away from the intended target line accountable to the impact point on the golf is termed dimple error. In addition to the horizontal launch angle another variable relatively unexplored is the side spin imparted on the golf ball. Hurrion and Mackay (2012) have identified that side spin imparted on the ball (> 20 rpm) has potential to cause the ball travelling off the intended target line; this is accountable to resultant angle differences between the putter path and face angle. Therefore, could potentially be a contributing factor to missed putts along with the horizontal launch angle.

FIGURE ONE ABOUT HERE

Dimple error will be more prominent when executing shorter golf putts, this is due to greater compression of the golf ball during longer golf putts (Pelz, 2000). Dimple error is likely to have an inverse relationship with the compression of the golf ball, therefore may only be applicable during a shorter golf putt. Cross (2006) demonstrated in a non-golf environment that the golf ball can deflect off at a random angle, whereas a ball bearing bounced symmetrically and vertically. It was suggested that the dimples caused the random deflection (Cross, 2006). This was tested dropping the balls onto a marble surface from a height of 80 cm. There are limitations associated with this experiment, as in a golf situation the ball is the stationary object and the club the moving object. Therefore, Cross (2006) does not accurately replicate the putter-ball impact as it occurs on the putting green. With the initial direction of the golf ball predominantly being determined by the putter face angle (Karlsen et al., 2008), the random deflection will be less significant than observed by Cross (2006). Therefore research is needed to determine whether this mechanism is apparent to any extent in a golf environment.

Different types of putter face have previously been compared (Hurrion & Hurrion, 2002; Brouillette, 2010), however, putting remains to date an under researched area. Additionally, focus has predominantly been on the effect of topspin imparted on the golf ball rather than the initial direction of the golf ball, which is clearly an important factor of whether a putt is successful or not. Contrasting results were however observed, whereby Hurrion and Hurrion (2002) observed improved topspin in trials completed with a grooved faced putter whereas Brouillette (2010) did not report improved topspin between a grooved faced and traditional faced putter. This provides rationale to test putters with different face inserts however, neither considered the effect of the variability of the impact point on the golf ball.

The aim of this study was to investigate the effects of impact point on the golf ball on the resulting horizontal launch angle (initial direction) and side spin of the golf ball. This will be investigated using a mechanical putting arm and human participants. It was hypothesised that significant associations between the variance of the kinematic variables (horizontal launch angle and side spin) and the impact point on the golf ball would exist.

## Methods

### Participants

A total of 22 right handed golfers participated in the study (age 42 ± 12 years; handicap 13.6 ± 7.4 (handicap range 0 – 24); height 1.76 ± 0.21 metres; mass 88.6 ± 23.8 kg). All golfers were free of musculoskeletal injury for the previous three months and played a minimum of once a week. During testing participants wore their own personal golfing attire and golf shoes. All participants provided written informed consent and the study was approved by the institutional ethics committee of University of Hertfordshire.

### Experimental set-up

Two testing sessions were completed to establish the association between the impact point on the golf ball and the initial direction of the golf putt. Firstly, with a mechanical putting arm where the putting stroke parameters putter face angle, putter path and impact point on the putter were standardised and secondly with human participants to determine whether results are applicable in a practical setting.

A mechanical putting arm was setup to reproduce a putt of 3.2 metres on an artificial putting surface registering 12 on the stimpmeter (The United States Golf Association, Far Hills, NJ, USA). A square to square swing path was selected to ensure a square club face at impact, referring to a single horizontal axis that was perpendicular to the putting line. Human participants completed a level straight 3.2 metre putt on a Huxley Golf (Huxley Golf, Hampshire, UK) artificial putting green (3.66 x 4.27 metres) registering 11 on the stimpmeter.

The putters used for both testing sessions were the grooved faced GEL® Vicis (GEL GOLF., Wan Chai, Hong Kong) and traditional faced Odyssey White Hot #3 (Callaway Golf Europe Ltd., Surrey, UK). Both putters had a standardised 69° lie and 2.5° loft. Srixon Z-STAR golf balls (Srixon Sports Europe LTD., Hampshire, UK) and Titleist Pro V1 golf balls (Acushnet Europe Ltd., Cambridgeshire, UK) were aligned using two Superline 2D line lasers (Property Perspective Ltd., Warwick, UK). Ball placement during testing with the mechanical putting arm was standardised by placing one laser directly behind the golf ball and the second 90° perpendicular to the path of the golf ball. Dimples were then orientated by ensuring the visual aid printed on the golf ball was intersected with both lasers. Participants testing were completed with only the Srixon golf ball; these were aligned in the manner as the mechanical putting arm to ensure the same placement of the golf ball across trials.

To record the horizontal launch angle (degree to which the ball deviates (°) from the original putting line) and side spin (the amount of side spin (rpm) placed on the ball at impact) of the golf ball, a Quintic (Quintic Consultancy Ltd., Coventry, UK) high speed camera (UI-5220RE) sampling at 220 Hz was positioned perpendicular to the putting line.  The Quintic Ball Roll v2.4 launch monitor software was used to analyse the recorded videos. A Quintic GigE high speed camera sampling at 220 Hz was positioned vertically (1.8 m above putting surface) to validate the horizontal launch angle values during testing with the mechanical putting arm. A Canon (Canon Europe Ltd, Tokyo, Japan) EOS 1000d camera was placed on a tripod away from the putting line where it did not disturb the view of the participant during the trial or impede the mechanical putting arm. This camera took images of the impact point of the golf ball post trial.

## Procedure

During testing with the mechanical putting arm, each putter was held securely within a clamping mechanism. A putting arm block was placed at an appropriate distance behind the golf putter to produce the desired length of putt, and the putting arm was released by deactivating an electromagnet. Before each trial a thin layer of pigmented emollient was applied to the putter face and smoothed. The golf ball was then aligned using the Superline lasers dissecting the ball into four equal sections, ensuring the same position for each trial. Forty trials were completed with each putter-ball combination (GEL®-Srixon, GEL®-Titleist, Odyssey-Srixon and Odyssey-Titleist). Trials were filmed with the Quintic Ball Roll software. Additionally, after each trial a picture was taken of the golf ball placed in a pre identified position (50 cm away from the camera) (identifying the pigmented emollient imprint on the ball) with the Canon EOS 1000d camera.

During testing with human participants, an initial period of habituation was allowed with the first putter that had been randomly selected. This habituation period was repeated for the second putter when swapped during the protocol. During both habituation periods the participant was informed of the initial ball velocity threshold (2.10 – 2.28 m/s). This was to ensure a similar pace of putt between participants and during habituation subjects found it relatively easy to satisfy this criteria. After habituation, the investigator lined up the putt with the Superline lasers. This process was completed until six successful (holed) putts had been completed with each putter; however, missed putts were included within the analysis. Six successful putts were selected as criteria, due to procedural limitations (time of analysis) whilst still giving a suitable number of trials.

## Data Processing

Using Adobe Photoshop CS5 (Adobe Systems Incorporated., CA, USA) a 0, 0 coordinate was identified as the centre of the dimple pattern. This was defined as the centroid location (Figure 2; centre of the pentagon and where lines A) and B) join). All impact measurements were then made from this 0, 0 coordinate. For the Srixon golf ball an equilateral triangle drawing was overlaid on the image identifying the centroid location of three dimples. The Titleist ball had two different sized dimples; therefore a pentagon drawing was placed on the image identifying the centroid location of one smaller dimple surrounded by five larger dimples.

The contact made between the putter and ball during the impact was termed the impact zone. To determine the length (mm) and angle (direction of impact from the centroid location (°)) the centre of the impact zone had to be calculated. To complete this a polygon was drawn at the outermost edges of the impact zone and intersected from the four corners, giving a centre point (Figure 2; end of line A) away from centroid location). From this, differences in length (Figure 2; of line A)) and angle (Figure 2; angle between line A) and B) between the standardised centroid location and impact point were measured. The surface area of the impact zone (area of contact between the putter and ball) was measured using ImageJ (National Institutes of Health, Bethesda, Maryland, USA). Using the polygon selection tool the edges of the impact zone were connected giving an output ($mm^2$) of surface area (Figure 2; area of grey shading within white outline). A more detailed explanation of how the data were processed is presented in Richardson, Mitchell and Hughes (2015).

FIGURE TWO ABOUT HERE

**Data Analysis**

The impact variables measured were the length of the impact point from the centroid location, angle of the impact point from the centroid location and surface area of the impact zone, which was used for the multiple regression analysis. The dependent variables were the horizontal launch angle (the degree to which the ball deviates from the original putting line) measured in degrees and side spin (the amount of cut or hook spin (rpm) placed on the ball during impact). Data were exported to statistical software packages SPSS v21 (SPSS Inc, Chicago, USA) for analysis.

The linearity of the data was first assessed by examining residual plots (standardised residuals as a function of standardised predicted values) (Pedhazur, 1997). Then the data were analysed for normality by assessing histogram and box-plot graphs, kurtosis and skewness values. If kurtosis or skewness values were found to be > ± 1, the data set was identified as highly skewed or kurtosed, between ± 0.5 and ± 1 the data set was identified as moderately skewed or kurtosed, and between 0 and ± 0.5 the data was considered to be approximately symmetrical (Bulmer, 1979) and therefore displaying normality. Any data sets that were found to be highly skewed or displaying high kurtosis was transformed logarithmically (log) in order to increase uniformity to a normal distribution curve (Atkinson & Nevill, 1998; Hopkins, Marshall, Batterham & Hanin, 2009). The only data set that required log transforming was the Odyssey-Titleist group (tested with the mechanical putting arm). Descriptive data of the log-transformed data sets are presented in their absolute form. Box-plots were used to identify outliers within the data set; if an outlier was identified for one impact variable the entire trial was removed from analysis.

Bivariate analysis was undertaken for the independent and dependent variables to ensure multicollinearity was avoided. Correlations were identified as very high if $r \geq 0.90$ (Ntoumanis, 2001). Additionaly, collinearity diagnostics, variance inflation factor (VIF) and the tolerance statistic were used to assess multicollinearity. A VIF greater than 10, was identified as a cause of concern (Bowerman & O'Connell, 1990; Myers, 1990) and a tolerance below 0.2 indicated a problem (Menard, 1995). Multiple regression analysis was then completed. The independent variables length from the centroid location (mm), angle from the centroid location (°) and surface area ($mm^2$) were the predictors used to assess whether the impact point on the golf ball effected side spin and horizontal launch angle. Level of significance was set at $\alpha < 0.05$.

## Results

### Horizontal Launch Angle with the mechanical putting arm

Mean and standard deviations for the independent variables length, angle and surface area are presented in Table 1. The multiple regression model was found to be a significant predictor of horizontal launch angle for the GEL®-Titleist ($p = 0.001$), GEL®-Srixon ($p = 0.001$) and Odyssey-Srixon ($p = 0.03$) groups, but not for the Odyssey-Titleist group ($p = 0.18$) (Table 2). The impact variables accounted for 34% of the variability of horizontal launch angle for the GEL®-Titleist group, 44% for the GEL®-Srixon group and 21% of the variability for the Odyssey-Srixon group. The range of results observed for the horizontal launch angle were -1.00 to 0.71°.

TABLE ONE ABOUT HERE

TABLE TWO ABOUT HERE

**Horizontal Launch Angle with human participants**

The multiple regression model was not a significant predictor of horizontal launch angle for either the GEL®-Srixon ($p$ = 0.52) or Odyssey-Srixon ($p$ = 0.49) combinations (Table 3). Although not significant, the variability accountable to the impact (predictor) variables would have been negligible at 2% (0.03°) and 1% (0.02°) for the GEL®-Srixon and Odyssey-Srixon groups respectively. Figure 3 demonstrates the different variance in the impact points on the golf ball between the mechanical putting arm and human participants, where increased variance is observed in the latter.

TABLE TWO ABOUT HERE

**Side spin with the mechanical putting arm**

Significant association was found between side spin with all predictors (length, angle and surface area) coupled for the Odyssey-Srixon combination ($p$ = 0.04). The impact variables accounted for 20% (2.8 rpm) of the variation within this group (Table 4). There were no significant associations between the impact variables and kinematic variables for the other three putter-ball combinations.

TABLE THREE ABOUT HERE

**Side spin with human participants**

The multiple regression model was found to be a significant predictor of side spin (Table 5) for the GEL® putter ($p$ = 0.04) but not for the Odyssey putter ($p$

= 0.93). The impact variables accounted for 6% of variation observed in side spin (1.54 rpm) for the GEL® putter

TABLE FOUR ABOUT HERE

## Discussion

This is the first study to have measured and analysed the effects of the impact point on the golf ball on subsequent ball roll kinematics. It was hypothesised that significant associations would exist between the variance of the horizontal launch angle and impact point variables. This were accepted with the mechanical putting arm but rejected with human participants. Regarding side spin, the hypothesis can be rejected with the mechanical putting arm and partially accepted with human participants. The variance of the horizontal launch angle with the mechanical putting arm was minimal. This however can be attributed to dimple error during putting, with the dimple orientation, putter face angle and path being controlled during the experiment. With no significant associations identified with human participants, dimple error is unlikely to have any implications on putting performance. This is also apparent with side spin where only 20% of variance was accountable for one putter-ball combination.

Pelz (2000) states that the larger the golf ball dimples, the more likely contact made on the edge of a dimple will affect the horizontal launch angle, as each dimple is covering a larger surface area. However, the smaller the dimple, the increased number of dimples there will be covering the ball, therefore increasing the chance of making contact with the edge of a dimple. Although a golf ball with larger dimples has less chance of contact being made to a dimple edge, the horizontal deviation caused by impact may increase. This was not observed in the current study. Dimple circumferences of 12.4 mm (Titleist Pro V1) and 12.9 mm (Srixon Z-STAR) were measured, indicating more variability was expected for the Srixon golf ball. More variance was however observed for the Titleist ball (GEL®-Titleist = 0.15°, Odyssey-Titleist = 0.06°) in comparison to the Srixon (GEL®-Srixon = 0.13°, Odyssey-Srixon = 0.04°). Differences are marginal between each group, however, based on these results, it seems the different putters used in testing had more influence on the horizontal launch angle (and therefore success rate of a putt), rather than the impact point on the golf ball when using a mechanical putting arm with standardised stroke kinematics. This is based on the differences in variance of the horizontal launch angle being observed between putters rather than golf balls.

During testing with the mechanical putting arm, all 160 trials would have resulted in a successful putt (holed), even with the variation observed with the horizontal launch angle and side spin. Therefore, the variation accountable to the impact variables can be considered negligible for a simulated putt. This is in accordance with Karlsen et al. (2008) who stated that variables of the putting stroke including the putter face angle, putter path and horizontal impact point on the putter face (standardised in mechanical putting arm protocol) only have a minor influence on the direction consistency in golf putting in elite players. Karlsen et al. (2008) accounted

3% of direction consistency to the impact point on the putter face. This variability may not just be due to the variability on the putter face but also the impact point on the golf ball, as demonstrated by the results in the current study with the mechanical putting arm. This minor variation will not affect success rate from 12 feet. As Hurrion and Mackay (2012) state that for a putt to be successful from this distance a horizontal launch angle threshold of 0.75° would need to be exceeded. Results in the current study were within this threshold whilst using the mechanical putting arm.

Along with the mechanical putting arm, dimple error can additionally be considered inconsequential for golfers, with no significant associations identified (Table 3). Differences in significant associations between the mechanical putting arm and human participants may be due to human participants' differences in stroke kinematics such as the face angle and putter path trial to trial as previously identified within the literature (Karlsen et al., 2008; Pelz, 2000). Whilst no measurements were made of the putter face angle and putter path the authors consider this to be a reasonable assumption. The magnitude of the effects of the variation in putter face angle and putter path may render the effects of dimple error statistically negligible. For example, if the left hand side of a dimple was struck by the putter, for dimple error to potentially affect the horizontal launch angle the putter face would also have to be slightly open. However, natural variation will occur in clubface angle at impact which may have contributed to the larger variation observed in golfers in comparison to the mechanical putting arm (Figure 3). Additionally, with a large range of handicaps observed in the current study (handicap: 13.6 ± 7.4), golfers with a higher handicap will demonstrate a wider range of natural variation in the face angle and putter path. Therefore, these factors will have an increased effect, rendering dimple error even less important regarding putting performance.

For a putt of 12 feet, Hurrion and Mackay (2012) state a putt with an initial horizontal launch angle of within 0.75° would be successful which would be produced with a putter face angle of 0.69° based on the putter face angle determining 92% of the direction of the putt. Based on results with the mechanical putting arm (Table 2), the addition of dimple error could reduce the chance of a successful putt. However, with results not being reproduced with golfers it can be considered that dimple error is not a problem a golfer should be concerned about, particularly considering the difficulty in controlling for it.

No literature to date has explored the initial phase of skid and side spin and has focused on when the ball enters a state of pure rolling (Alessandri, 1995; Hurrion & Hurrion, 2002; Lorensen & Yamrom, 1992; Penner, 2002). It has been stated that friction between the ball and the green removes all spin in approximately the first 20% of the roll (Pelz, 2000), therefore it may be possible that friction between the stationary ball and green contributes towards the side spin initially along with the small amounts of rotation during impact. Potentially explaining a portion of the large variability observed in human participants (Table 5).

The practical implications of this study are that golfers should not be overly concerned with dimple error, as the effects are very small and it would be very difficult to control for. Dimple error has the potential to reduce the success rates of putts by taking a putt over the initial horizontal launch angle ‘threshold’ of a holed putt. Despite being identified as statistically not significant in the current study, dimple error may add to the direction error along with larger contributions of the putter face angle and putter path. However, as this can be considered negligible at most, therefore golfers training and practice focus should remain on factors known to affect the variability of the horizontal launch angle, with particular emphasis on the putter face angle.

## Conclusion

Significant associations were identified between the horizontal launch angle and the point of impact on the golf ball when using a mechanical putting arm with standardised parameters. This, however, was not replicated with golfers where no significant associations were identified. The differences may be accountable to the variance across trials of the putter face angle and path with the human participants. The practical implications of this study are that golfers should not be concerned with dimple error during the putting activity and should instead focus on other elements that contribute to a successful golf putt, such as focusing on the putter face angle, which has previously been found to significantly contribute to the direction of a golf putt.

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## Tables

Table 1. Mean ± SD for the independent variables used in regression (HP) refers to testing completed by human participants.

| | Length: Mean ± SD (mm) | Angle: Mean ± SD (°) | Surface Area: Mean ± SD ($mm^2$) |
|---|---|---|---|
| GEL®-Titleist | 2.82 ± 0.85 | 140.94 ± 12.38 | 18.88 ± 4.34 |
| GEL®-Srixon | 1.49 ± 0.59 | 122.60 ± 41.06 | 21.36 ± 4.04 |
| Odyssey-Titleist | 3.09 ± 0.74 | 145.37 ± 11.57 | 21.83 ± 4.63 |
| Odyssey-Srixon | 1.59 ± 0.70 | 131.77 ± 54.73 | 23.95 ± 4.72 |
| GEL®-Srixon (HP) | 4.54 ± 2.45 | 152.87 ± 110.41 | 24.86 ± 4.78 |
| Odyssey-Srixon (HP) | 4.46 ± 2.25 | 119.53 ± 82.04 | 26.71 ± 4.98 |

Table 2. Linear regression model, between predictors and the kinematic variable horizontal launch angle, $R^2$ (± standard error normalised as a percentage of the mean (SE%)) and standardised coefficients.

| | GEL®-Titleist | GEL®-Srixon | Odyssey-Titleist | Odyssey-Srixon |
|---|---|---|---|---|
| Mean ± SD (Right (+), Left (-), °) | 0.47 ± 0.43 | 0.31 ± 0.30 | 0.12 ± 0.44 | 0.34 ± 0.18 |
| $R^2$ ± SE% | 0.34 ± 78.7 | 0.44 ± 74.2 | 0.13 ± 350.0 | 0.21 ± 47.1 |
| F-ratio, (*p*-value) | 6.17 (<0.01)* | 9.58 (<0.01)* | 1.71 (0.18) | 3.23 (0.03)* |
| Length (β), (*p*-value) | -0.43 (0.02)* | -0.60 (<0.01)* | -0.22 (0.29) | -0.41 (0.04)* |
| Angle (β), (*p*-value) | 0.76 (<0.01)* | -0.14 (0.30) | 0.21 (0.45) | 0.23 (0.22) |
| Surface Area (β), (*p*-value) | -0.07 (0.72) | 0.42 (<0.01)* | 0.21 (0.36) | -0.23 (0.17) |

*Denotes significance.

Table 3. Linear regression model, between predictors and the kinematic variable horizontal launch angle, $R^2$ and standardised coefficients with human participants

| | GEL®-Srixon | Odyssey-Srixon |
|---|---|---|
| Mean ± SD (Right (+), Left (-), °) | -0.07 ± 1.57 | -0.22 ± 1.50 |
| $R^2$ ± SE | 0.02 (1.58) | 0.01 ± 1.50 |
| F-ratio, (*p*-value) | 0.76 (0.52) | 0.81 (0.49) |
| Length (β), (*p*-value) | -0.04 (0.65) | -0.09 (0.28) |
| Angle (β), (*p*-value) | -0.12 (0.23) | 0.03 (0.67) |
| Surface Area (β), (*p*-value) | 0.02 (0.88) | -0.04 (0.66) |

Table 4. Linear regression model, between predictors and the kinematic variable side spin, $R^2$ and standardised coefficients are reported.

| | GEL®-Titleist | GEL®-Srixon | Odyssey-Titleist | Odyssey-Srixon |
|---|---|---|---|---|
| Mean ± SD (Cut (+), Hook (-), rpm) | -12.62 ± 18.35 | 1.64 ± 15.25 | -13.36 ± 13.76 | 0.86 ± 14.32 |
| $R^2$ ± SE | 0.20 ± 16.50 | 0.17 ± 14.47 | 0.16 ± 13.16 | 0.20 ± 13.31 |
| F-ratio, (*p*-value) | 2.84 (0.052) | 2.43 (0.08) | 2.21 (0.10) | 3.04 (0.04)* |
| Length (β), (*p*-value) | -0.31 (0.10) | -0.32 (0.07) | -0.29 (0.16) | -0.02 (0.93) |
| Angle (β), (*p*-value) | -0.26 (0.24) | -0.14 (0.39) | -0.07 (0.79) | -0.37 (0.052) |
| Surface Area (β), (*p*-value) | 0.10 (0.62) | 0.27 (0.11) | -0.13 (0.56) | -0.16 (0.35) |

*Denotes significance.

Table 5. Linear regression model, between predictors and the kinematic ball roll variable side spin, $R^2$ and standardised coefficients are reported with human participants.

| | GEL®-Srixon | Odyssey-Srixon |
|---|---|---|
| Mean ± SD (Cut (+), Hook (-), rpm) | -10.90 ± 25.69 | -8.00 ± 24.87 |
| $R^2$ ± SE | 0.06 (20.74) | 0.003 ± 25.04 |
| F-ratio, (*p*-value) | 2.87 (0.04)* | 0.15 (0.93) |
| Length (β), (*p*-value) | -0.10 (0.26) | -0.05 (0.52) |
| Angle (β), (*p*-value) | -0.04 (0.69) | -0.002 (0.98) |
| Surface Area (β), (*p*-value) | 0.21 (0.03)* | 0.007 (0.94) |

*Denotes significance.

## Figure titles

Figure 1. Examples of the two types of contact possible during impact between the putter face and golf ball. Image A) highlighted area shows the square contact with a dimple and Image B) highlighted area shows the contact where an edge of a dimple is struck.

Figure 2. Diagram demonstrating the 2D structure identifying the centroid, the polygon used to identify the centre of impact and impact variables; A) length of the impact point from the centroid, B) line representing 90° (normalised to each image) the angle is represented by the degrees between line A and B and the area surrounded by the solid white line was the surface area of the impact zone.

Figure 3. X, Y scatterplot graphs demonstrating the variability in the impact point, axes have been adjusted for clarity (a large black circle represents the 0, 0 coordinate). Graphs A – D were completed with the mechanical putting arm and E – F were completed with human participants (HP).

Figure 1

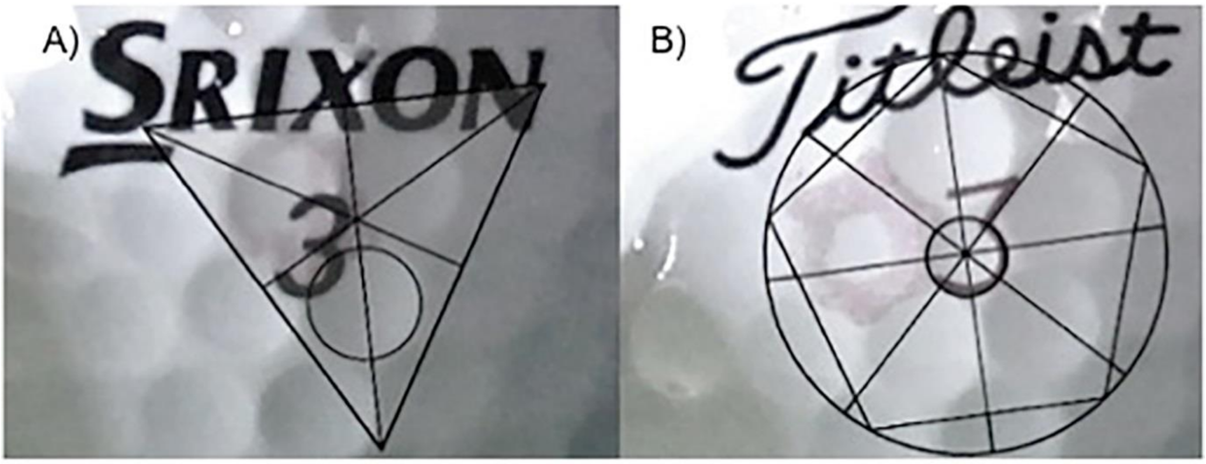


Figure 2

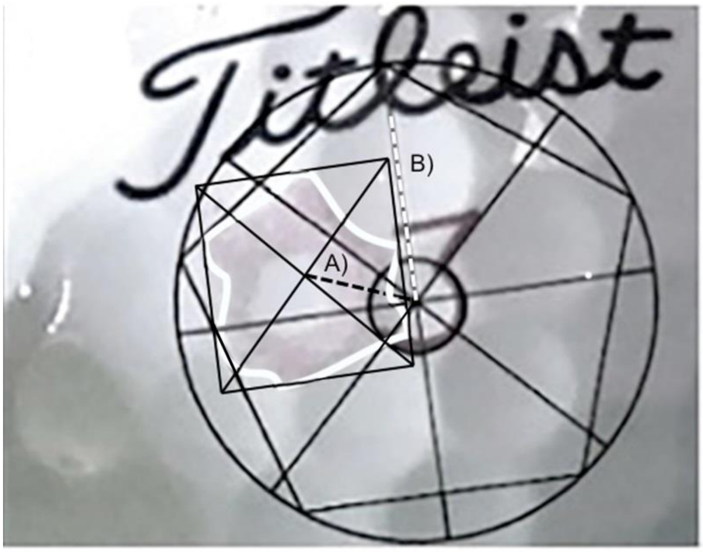
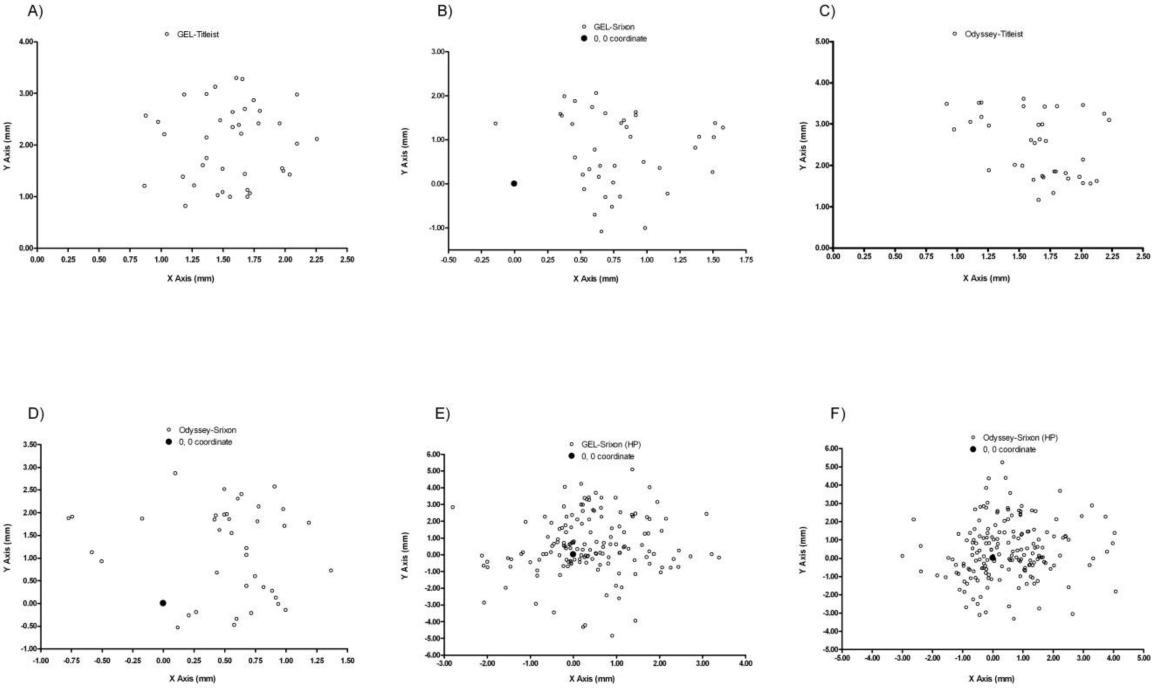


Figure 3


A)
GEL-Titleist
Y Axis (mm)
4.00
3.00
2.00
1.00
0.00
X Axis (mm)
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50
B)
GEL-Srixon
0, 0 coordinate
Y Axis (mm)
3.00
2.00
1.00
0.00
-1.00
X Axis (mm)
-0.50 -0.25 0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75
C)
Odyssey-Titleist
Y Axis (mm)
5.00
4.00
3.00
2.00
1.00
0.00
X Axis (mm)
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50
D)
Odyssey-Srixon
0, 0 coordinate
Y Axis (mm)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
X Axis (mm)
-1.00 -0.75 -0.50 -0.25 0.00 0.25 0.50 0.75 1.00 1.25 1.50
E)
GEL-Srixon (HP)
0, 0 coordinate
Y Axis (mm)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
X Axis (mm)
-3.00 -2.00 -1.00 0.00 1.00 2.00 3.00 4.00
F)
Odyssey-Srixon (HP)
0, 0 coordinate
Y Axis (mm)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
X Axis (mm)
-5.00 -4.00 -3.00 -2.00 -1.00 0.00 1.00 2.00 3.00 4.00 5.00