

The effect of dimple error on the horizontal launch angle and side spin of the golf ball during putting

Richardson, Ashley K., Mitchel, Andrew C. S. and Hughes, Gerwyn
2016

This is the accepted manuscript of an article published by Taylor & Francis in the *Journal of Sports Sciences* on 16 March 2016 available online: <http://dx.doi.org/10.1080/02640414.2016.1161213>

1 **The effect of dimple error on the horizontal launch angle and side spin**
2 **of the golf ball during putting**

3

4 **Abstract**

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

23 Words: 199

24

25

26 **Introduction**

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

42

43 Golf balls are designed with dimples to reduce the drag of the golf ball when
44 in flight (Aoki, Nakayama, Hayasida, Yamaguti & Sugiura, 1998; Goff, 2013).
45 These dimples, however, may also be a detriment to putting performance.
46 Due to the dimples a golf ball is not perfectly spherical with potential for the
47 golf ball to rebound off the putter during impact at an unexpected angle
48 (Cross & Nathan, 2007). To explain this further, the putter could strike the
49 perimeter of the dimple 'flat' allowing the initial roll of the ball to leave in the
50 intended direction towards the target. Or the putter could strike an edge of a

51 dimple causing a deflection of direction off the intended target line (Figure 1).
52 Research has acknowledged that dimples do affect the direction variability
53 during a golf putt, however; only limited data is presented through a simple
54 analysis of the distance that putts have rolled off line (Pelz, 2000). The
55 authors of the current study propose that the direction variability away from
56 the intended target line accountable to the impact point on the golf is termed
57 dimple error. In addition to the horizontal launch angle another variable
58 relatively unexplored is the side spin imparted on the golf ball. Hurrion and
59 Mackay (2012) have identified that side spin imparted on the ball (> 20 rpm)
60 has potential to cause the ball travelling off the intended target line; this is
61 accountable to resultant angle differences between the putter path and face
62 angle. Therefore, could potentially be a contributing factor to missed putts
63 along with the horizontal launch angle.

64

65 FIGURE ONE ABOUT HERE

66

67 Dimple error will be more prominent when executing shorter golf putts, this is
68 due to greater compression of the golf ball during longer golf putts (Pelz,
69 2000). Dimple error is likely to have an inverse relationship with the
70 compression of the golf ball, therefore may only be applicable during a
71 shorter golf putt. Cross (2006) demonstrated in a non-golf environment that
72 the golf ball can deflect off at a random angle, whereas a ball bearing
73 bounced symmetrically and vertically. It was suggested that the dimples
74 caused the random deflection (Cross, 2006). This was tested dropping the
75 balls onto a marble surface from a height of 80 cm. There are limitations

76 associated with this experiment, as in a golf situation the ball is the stationary
77 object and the club the moving object. Therefore, Cross (2006) does not
78 accurately replicate the putter-ball impact as it occurs on the putting green.
79 With the initial direction of the golf ball predominantly being determined by
80 the putter face angle (Karlsen et al., 2008), the random deflection will be less
81 significant than observed by Cross (2006). Therefore research is needed to
82 determine whether this mechanism is apparent to any extent in a golf
83 environment.

84

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

96

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

101 between the variance of the kinematic variables (horizontal launch angle and
102 side spin) and the impact point on the golf ball would exist.

103

104 **Methods**

105

106 **Participants**

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

114

115 **Experimental set-up**

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

122

123 A mechanical putting arm was setup to reproduce a putt of 3.2 metres on an
124 artificial putting surface registering 12 on the stimpmeter (The United States
125 Golf Association, Far Hills, NJ, USA). A square to square swing path was

126 selected to ensure a square club face at impact, referring to a single
127 horizontal axis that was perpendicular to the putting line. Human participants
128 completed a level straight 3.2 metre putt on a Huxley Golf (Huxley Golf,
129 Hampshire, UK) artificial putting green (3.66 x 4.27 metres) registering 11 on
130 the stimpmeter.

131

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

146

147 To record the horizontal launch angle (degree to which the ball deviates (°)
148 from the original putting line) and side spin (the amount of side spin (rpm)
149 placed on the ball at impact) of the golf ball, a Quintic (Quintic Consultancy
150 Ltd., Coventry, UK) high speed camera (UI-5220RE) sampling at 220 Hz was

151 positioned perpendicular to the putting line. The Quintic Ball Roll v2.4 launch
152 monitor software was used to analyse the recorded videos. A Quintic GigE
153 high speed camera sampling at 220 Hz was positioned vertically (1.8 m
154 above putting surface) to validate the horizontal launch angle values during
155 testing with the mechanical putting arm. A Canon (Canon Europe Ltd, Tokyo,
156 Japan) EOS 1000d camera was placed on a tripod away from the putting line
157 where it did not disturb the view of the participant during the trial or impede
158 the mechanical putting arm. This camera took images of the impact point of
159 the golf ball post trial.

160

161 **Procedure**

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

175

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

188

189 **Data Processing**

190 Using Adobe Photoshop CS5 (Adobe Systems Incorporated., CA, USA) a 0,
191 0 coordinate was identified as the centre of the dimple pattern. This was
192 defined as the centroid location (Figure 2; centre of the pentagon and where
193 lines A) and B) join). All impact measurements were then made from this 0, 0
194 coordinate. For the Srixon golf ball an equilateral triangle drawing was
195 overlaid on the image identifying the centroid location of three dimples. The
196 Titleist ball had two different sized dimples; therefore a pentagon drawing
197 was placed on the image identifying the centroid location of one smaller
198 dimple surrounded by five larger dimples.

199

200 The contact made between the putter and ball during the impact was termed
201 the impact zone. To determine the length (mm) and angle (direction of
202 impact from the centroid location (°)) the centre of the impact zone had to be
203 calculated. To complete this a polygon was drawn at the outermost edges of
204 the impact zone and intersected from the four corners, giving a centre point
205 (Figure 2; end of line A) away from centroid location). From this, differences
206 in length (Figure 2; of line A)) and angle (Figure 2; angle between line A) and
207 B) between the standardised centroid location and impact point were
208 measured. The surface area of the impact zone (area of contact between the
209 putter and ball) was measured using ImageJ (National Institutes of Health,
210 Bethesda, Maryland, USA). Using the polygon selection tool the edges of the
211 impact zone were connected giving an output (mm²) of surface area (Figure
212 2; area of grey shading within white outline). A more detailed explanation of
213 how the data were processed is presented in Richardson, Mitchell and
214 Hughes (2015).

215

216 FIGURE TWO ABOUT HERE

217

218 **Data Analysis**

219 The impact variables measured were the length of the impact point from the
220 centroid location, angle of the impact point from the centroid location and
221 surface area of the impact zone, which was used for the multiple regression
222 analysis. The dependent variables were the horizontal launch angle (the
223 degree to which the ball deviates from the original putting line) measured in
224 degrees and side spin (the amount of cut or hook spin (rpm) placed on the

225 ball during impact). Data were exported to statistical software packages
226 SPSS v21 (SPSS Inc, Chicago, USA) for analysis.

227

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

245

246 Bivariate analysis was undertaken for the independent and dependent
247 variables to ensure multicollinearity was avoided. Correlations were
248 identified as very high if $r \geq 0.90$ (Ntoumanis, 2001). Additionally, collinearity
249 diagnostics, variance inflation factor (VIF) and the tolerance statistic were

250 used to assess multicollinearity. A VIF greater than 10, was identified as a
251 cause of concern (Bowerman & O'Connell, 1990; Myers, 1990) and a
252 tolerance below 0.2 indicated a problem (Menard, 1995). Multiple regression
253 analysis was then completed. The independent variables length from the
254 centroid location (mm), angle from the centroid location ($^{\circ}$) and surface area
255 (mm^2) were the predictors used to assess whether the impact point on the
256 golf ball effected side spin and horizontal launch angle. Level of significance
257 was set at $\alpha < 0.05$.

258

259 **Results**

260 **Horizontal Launch Angle with the mechanical putting arm**

261 Mean and standard deviations for the independent variables length, angle
262 and surface area are presented in Table 1. The multiple regression model
263 was found to be a significant predictor of horizontal launch angle for the
264 GEL[®]-Titleist ($p = 0.001$), GEL[®]-Srixon ($p = 0.001$) and Odyssey-Srixon ($p =$
265 0.03) groups, but not for the Odyssey-Titleist group ($p = 0.18$) (Table 2). The
266 impact variables accounted for 34% of the variability of horizontal launch
267 angle for the GEL[®]-Titleist group, 44% for the GEL[®]-Srixon group and 21%
268 of the variability for the Odyssey-Srixon group. The range of results
269 observed for the horizontal launch angle were -1.00 to 0.71° .

270

271 TABLE ONE ABOUT HERE

272

273 TABLE TWO ABOUT HERE

274

275 **Horizontal Launch Angle with human participants**

276 The multiple regression model was not a significant predictor of horizontal
277 launch angle for either the GEL[®]-Srixon ($p = 0.52$) or Odyssey-Srixon ($p =$
278 0.49) combinations (Table 3). Although not significant, the variability
279 accountable to the impact (predictor) variables would have been negligible at
280 2% (0.03°) and 1% (0.02°) for the GEL[®]-Srixon and Odyssey-Srixon groups
281 respectively. Figure 3 demonstrates the different variance in the impact
282 points on the golf ball between the mechanical putting arm and human
283 participants, where increased variance is observed in the latter.

284

285 TABLE TWO ABOUT HERE

286

287 **Side spin with the mechanical putting arm**

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

294

295 TABLE THREE ABOUT HERE

296

297 **Side spin with human participants**

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

300 = 0.93). The impact variables accounted for 6% of variation observed in side
301 spin (1.54 rpm) for the GEL[®] putter

302

303 TABLE FOUR ABOUT HERE

304

305 **Discussion**

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

320

321 Pelz (2000) states that the larger the golf ball dimples, the more likely contact
322 made on the edge of a dimple will affect the horizontal launch angle, as each
323 dimple is covering a larger surface area. However, the smaller the dimple,
324 the increased number of dimples there will be covering the ball, therefore

325 increasing the chance of making contact with the edge of a dimple. Although
326 a golf ball with larger dimples has less chance of contact being made to a
327 dimple edge, the horizontal deviation caused by impact may increase. This
328 was not observed in the current study. Dimple circumferences of 12.4 mm
329 (Titleist Pro V1) and 12.9 mm (Srixon Z-STAR) were measured, indicating
330 more variability was expected for the Srixon golf ball. More variance was
331 however observed for the Titleist ball (GEL[®]-Titleist = 0.15°, Odyssey-Titleist
332 = 0.06°) in comparison to the Srixon (GEL[®]-Srixon = 0.13°, Odyssey-Srixon
333 = 0.04°). Differences are marginal between each group, however, based on
334 these results, it seems the different putters used in testing had more
335 influence on the horizontal launch angle (and therefore success rate of a
336 putt), rather than the impact point on the golf ball when using a mechanical
337 putting arm with standardised stroke kinematics. This is based on the
338 differences in variance of the horizontal launch angle being observed
339 between putters rather than golf balls.

340

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

350 3% of direction consistency to the impact point on the putter face. This
351 variability may not just be due to the variability on the putter face but also the
352 impact point on the golf ball, as demonstrated by the results in the current
353 study with the mechanical putting arm. This minor variation will not affect
354 success rate from 12 feet. As Hurrion and Mackay (2012) state that for a putt
355 to be successful from this distance a horizontal launch angle threshold of
356 0.75° would need to be exceeded. Results in the current study were within
357 this threshold whilst using the mechanical putting arm.

358

359 Along with the mechanical putting arm, dimple error can additionally be
360 considered inconsequential for golfers, with no significant associations
361 identified (Table 3). Differences in significant associations between the
362 mechanical putting arm and human participants may be due to human
363 participants' differences in stroke kinematics such as the face angle and
364 putter path trial to trial as previously identified within the literature (Karlsen et
365 al., 2008; Pelz, 2000). Whilst no measurements were made of the putter face
366 angle and putter path the authors consider this to be a reasonable
367 assumption. The magnitude of the effects of the variation in putter face angle
368 and putter path may render the effects of dimple error statistically negligible.
369 For example, if the left hand side of a dimple was struck by the putter, for
370 dimple error to potentially affect the horizontal launch angle the putter face
371 would also have to be slightly open. However, natural variation will occur in
372 clubface angle at impact which may have contributed to the larger variation
373 observed in golfers in comparison to the mechanical putting arm (Figure 3).
374 Additionally, with a large range of handicaps observed in the current study

375 (handicap: 13.6 ± 7.4), golfers with a higher handicap will demonstrate a
376 wider range of natural variation in the face angle and putter path. Therefore,
377 these factors will have an increased effect, rendering dimple error even less
378 important regarding putting performance.

379

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

389

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

399

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

411

412 **Conclusion**

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

423

424

425 **References**

- 426 Alessandrini, S. M. (1995). A motivational example for the numerical solution
427 of two-point boundary-value problems. *SIAM review*, 37(3), 423-427.
- 428 Alexander, D. L., & Kern, W. (2005). Drive for show and putt for dough? An
429 analysis of the earnings of PGA Tour golfers. *Journal of Sports*
430 *Economics*, 6(1), 46-60.
- 431 Aoki, K., Nakayama, Y., Hayasida, T., Yamaguti, N., & Sugiura, M. (1998).
432 Flow Characteristics of a Golf Ball Using Visualization Techniques.
433 In: Farrally, M. R., & Cochran, A. J., editors. *Science & Golf III:*
434 *Proceedings of the World Scientific Congress of Golf*. Human
435 Kinetics; pp. 446-456.
- 436 Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing
437 measurement error (reliability) in variables relevant to sports
438 medicine. *Sports Medicine*, 26(4), 217-238.
- 439 Bowerman, B. L., & O'Connell, R. T. (1990). *Linear Statistical Models: An*
440 *Applied Approach*. Belmont California: Duxbury Press.
- 441 Brouillette, M. (2010). Putter features that influence the rolling motion of a
442 golf ball. *Procedia Engineering*, 2(2), 3223-3229.
- 443 Bulmer, M. G. (1979). *Principles of Statistics*. Courier Corporation.
- 444 Cross, R., & Nathan, A. M. (2007). Experimental study of the gear effect in
445 ball collisions. *American Journal of Physics*, 75, 658-664.
- 446 Cross, R. (2006). *Physics of golf*. Retrieved Jan 14 2015, from,
447 <http://www.physics.usyd.edu.au/~cross/GOLF/GOLF.htm>

- 448 Debicki, D. B., & Gribble, P. L. (2004). Inter-joint coupling strategy during
449 adaptation to novel viscous loads in human arm movement. *Journal of*
450 *Neurophysiology*, 92(2), 754-765.
- 451 Dorsel, T. N., & Rotunda, R. J. (2001). Low scores, top 10 finishes, and big
452 money: An analysis of professional golf association tour statistics and
453 how these relate to overall performance. *Perceptual and Motor Skills*,
454 92(2), 575-585.
- 455 Goff, J. E. (2013). A review of recent research into aerodynamics of sport
456 projectiles. *Sports Engineering*, 16(3), 137-154.
- 457 Hirashima, M., Kudo, K., & Ohtsuki, T. (2003). Utilization and compensation
458 of interaction torques during ball-throwing movements. *Journal of*
459 *Neurophysiology*, 89(4), 1784-1796.
- 460 Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009).
461 Progressive statistics for studies in sports medicine and exercise
462 science. *Medicine and Science in Sports and Exercise*, 41(1), 3-12.
- 463 Hurrion, P. D., & Hurrion, R. D. (2002). An investigation into the effect of the
464 roll of a golf ball using the C-groove putter. In: Thain, E., editor.
465 *Science and Golf IV: Proceedings of the World Scientific Congress of*
466 *Golf*. London: Routledge; pp. 531-538.
- 467 Hurrion, P. D., & MacKay, J. (2012). A Rolling Brief: *Golf International*, 111,
468 107 – 111.
- 469 Karlsen, J., Smith, G., & Nilsson, J. (2008). The stroke has only a minor
470 influence on direction consistency in golf putting among elite players.
471 *Journal of Sports Sciences*, 26(3), 243-250.

472 Lorensen, W. E., & Yamrom, B. (1992). Golf green visualization. *IEEE*
473 *Computer Graphics and Applications*, 12(4), 35-44.

474 Menard, S. (1995). *Applied logistic regression analysis*. Sage University
475 Paper Series on Quantitative Applications in the Social Sciences, 07-
476 106. Thousand Oaks, California: Sage.

477 Myers, R. (1990). *Classical and Modern Regression with Applications*.
478 Boston: Duxbury Press.

479 Ntoumanis, N. (2001). *A step-by-step guide to SPSS for sport and exercise*
480 *studies*. London: Routledge.

481 Osis, S. T., & Stefanyshyn, D. J. (2012). Golf players exhibit changes to grip
482 speed parameters during club release in response to changes in club
483 stiffness. *Human Movement Science*, 31(1), 91-100.

484 Pedhazur, E. J. (1997). *Multiple regression in behavioral research:*
485 *Explanation and prediction*. Belmont, California: Wadsworth
486 Publishing Company.

487 Pelz, D. T. (2000). *Dave Pelz's Putting Bible*. New York: Random House.

488 Penner, A. R. (2002). The physics of putting. *Canadian Journal of Physics*,
489 80(3), 83-96.

490 PGA Tour (2015a). *2014 PGA TOUR scoring average (actual)*. Retrieved
491 June 28 2015, from, <http://www.pgatour.com/stats/stat.120.2014.html>.

492 PGA Tour (2015b). *2014 PGA TOUR putts per round*. Retrieved June 28
493 2015, from, <http://www.pgatour.com/stats/stat.119.html>

494 Richardson, A. K., Mitchell, A. C., & Hughes, G. (2015). Reliability of an
495 experimental method to analyse the impact point on a golf ball during
496 putting. *Sports Biomechanics*, (ahead-of-print), 1-10.

497 **Tables**

498 Table 1. Mean \pm SD for the independent variables used in regression (HP)

499 refers to testing completed by human participants.

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

500

501

502

503

504

505

506

507

508

509

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

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

513 *Denotes significance.

514

515

516

517

518

519

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

	GEL [®] -Srixon	Odyssey-Srixon
Mean \pm SD (Right (+), Left (-), °)	-0.07 \pm 1.57	-0.22 \pm 1.50
$R^2 \pm$ SE	0.02 (1.58)	0.01 \pm 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)

523

524

525

526

527

528

529

530

531

532

533

534

535

536

537

538

539

540

541

542 Table 4. Linear regression model, between predictors and the kinematic
 543 variable side spin, R² 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)

544 *Denotes significance.

545

546

547

548

549

550

551

552

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

	GEL [®] -Srixon	Odyssey-Srixon
Mean \pm SD (Cut (+), Hook (-), rpm)	-10.90 \pm 25.69	-8.00 \pm 24.87
$R^2 \pm$ SE	0.06 (20.74)	0.003 \pm 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)

556 *Denotes significance.

557

558

559 **Figure titles**

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

564

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

571

572 Figure 3. X, Y scatterplot graphs demonstrating the variability in the impact
573 point, axes have been adjusted for clarity (a large black circle represents the
574 0, 0 coordinate). Graphs A – D were completed with the mechanical putting
575 arm and E – F were completed with human participants (HP).

Figure 1

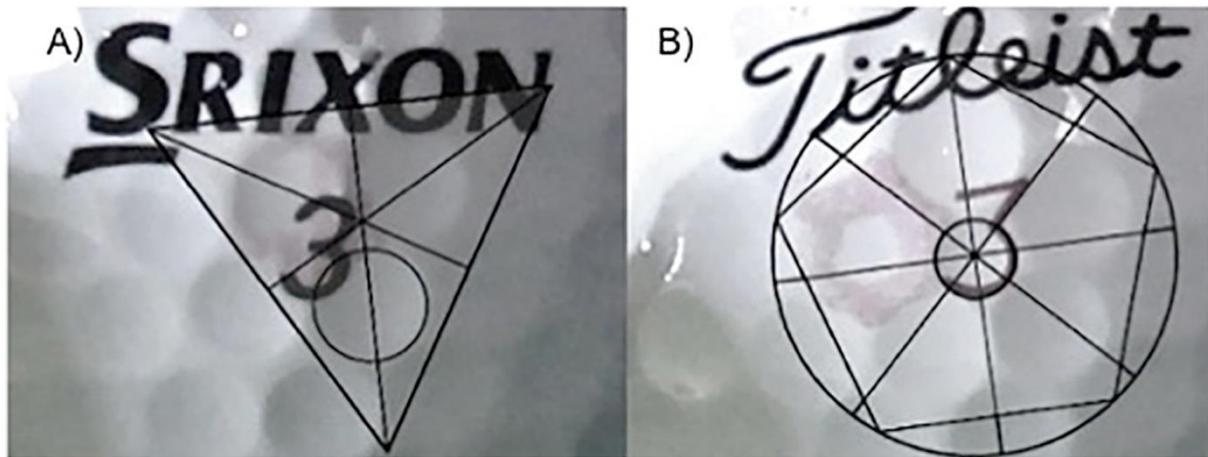


Figure 2



Figure 3

