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Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters

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Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters

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Manuscripts

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3 10 **Abstract**
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5 11 The use of multi-segment trunk models to investigate the crunch factor in golf may be
6
7 12 warranted. The first aim of the study was to investigate the relationship between the trunk and
8
9 13 lower trunk for crunch factor related variables (trunk lateral bending and trunk axial rotation
10
11 14 velocity). The second aim was to determine the level of association between crunch factor
12
13 15 related variables with swing (clubhead velocity) and launch (launch angle). Thirty five high
14
15 16 level amateur male golfers (Mean \pm SD: age = 23.8 \pm 2.1 years, registered golfing handicap =
16
17 17 5 \pm 1.9) without low back pain had kinematic data collected from their golf swing using a 10-
18
19 18 camera motion analysis system operating at 500 Hz. Clubhead velocity and launch angle
20
21 19 were collected using a validated real-time launch monitor. A positive relationship was found
22
23 20 between the trunk and lower trunk for axial rotation velocity ($r(35) = .47$, $p < .01$). Cross-
24
25 21 correlation analysis revealed a strong coupling relationship for the crunch factor ($R^2 = 0.98$)
26
27 22 between the trunk and lower trunk. Using generalised linear model analysis, it was evident
28
29 23 that faster clubhead velocities and lower launch angles of the golf ball were related to
30
31 24 reduced lateral bending of the lower trunk.
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25 Introduction

26 Today's high level golfers focus on distance when hitting a driver from the tee (Gluck et al.,
27 2007). This has seen a change from a 'classic' to a 'modern' golf swing, where greater axial
28 rotation of the shoulders relative to the hips (also known as X-factor) is seen at the top of the
29 backswing (Cheetham et al., 2001; McHardy et al., 2006; Gluck et al., 2007). It would seem
30 logical that an increased X-factor at the top of the backswing, will lead to increased axial
31 rotation velocity of the trunk, which will in turn, lead to greater clubhead velocity at ball
32 impact (McLean, 1994; McHardy et al., 2006; Chu et al., 2010). Further, at the point of ball
33 impact, an increase in lateral bending of a line connecting the shoulders relative to the pelvis
34 (i.e. the trunk) on the trailing side is thought to increase the force applied behind the ball
35 (Gluck et al., 2007; Chu et al., 2010). The product of lateral bending and axial rotation
36 velocity is termed the 'crunch factor' (Gluck et al., 2007), and it is believed that this variable
37 is maximised around ball impact and the early stages of follow through (Morgan et al., 1997;
38 Sugaya et al., 1999). It could be argued that the crunch factor may have implications for both
39 performance enhancement and the causation of low back pain.

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41 Investigations have reported dissimilar findings on the relationship between crunch factor and
42 low back pain (Sugaya et al., 1999; Lindsay & Horton, 2002; Glazier, 2010; Cole &
43 Grimshaw, 2014) as well as the magnitude of the X-factor and clubhead velocity (Lephart et
44 al., 2007; Chu et al., 2010). These inconsistent findings may be due to different methods
45 being employed to quantify trunk movement. For example, some studies have used angles
46 determined in the transverse plane (e.g. Chu et al., 2010) whereas other studies have utilised
47 Cardan angles (Joyce et al., 2013; Kwon et al., 2013). The latter method is more anatomically
48 and technically correct when analysing mechanics of the lower back, and this may make the
49 measurement of the crunch factor more anatomically meaningful (Morgan et al., 1997; Cole

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3 50 & Grimshaw, 2014). Furthermore, when examining lower back movement, the trunk should
4
5 51 be modelled with multiple segments (trunk and lower trunk) rather than a single segment due
6
7 52 to the varying kinematics of these segments. This may also avoid ambiguous measures of the
8
9 53 crunch factor (Joyce et al., 2010; Kwon et al., 2013; Cole & Grimshaw, 2014). The
10
11 54 interaction of multiple trunk segments, including proximal to distal segment sequencing has
12
13 55 been shown to be important in producing clubhead velocity (Tinmark et al., 2010; Horan &
14
15 56 Kavanagh, 2012). Using cross-correlation analyses it has been found that strong ‘coupling’,
16
17 57 or relationships exists between the torso and pelvis segments in the golf swing (Horan et al.,
18
19 58 2012). However, the consideration of multiple trunk segments when analysing the crunch
20
21 59 factor has not previously been investigated. It is also unknown if a between-segment
22
23 60 relationship exists for crunch factor variables, i.e. is axial rotation velocity of the trunk
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25 61 related to that of the lower trunk.
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34 63 Investigations into the crunch factor have predominantly focused on its association with low
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36 64 back pain (Hosea & Gatt, 1996; Cole & Grimshaw; 2008). However, the effect of crunch
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38 65 factor on swing (clubhead velocity) and launch (launch angle of the ball) parameters have yet
39
40 66 to be investigated. It was previously suggested that an increase in lateral bending of the
41
42 67 trailing side results in more force being applied into the ball at impact (Gluck et al., 2007).
43
44 68 However, despite experimental investigations using projected angles in the transverse plane
45
46 69 reporting an association between X-factor, axial rotation velocity and clubhead velocity
47
48 70 (Lephart et al., 2007; Chu et al., 2010), none have shown a positive association between
49
50 71 increased lateral bending of the trailing side with clubhead velocity (Chu et al., 2010; Joyce
51
52 72 et al., 2013). It has also been disputed anecdotally that an increase in lateral bending of the
53
54 73 trailing side will facilitate ‘hitting-up’ on the ball, promoting higher launch angles (Foley,
55
56 74 2012). While it has been reported that although lateral bending of the trunk’s trailing side
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3 75 helps to increase the upward path of the clubhead towards impact, excessive trunk lateral
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5 76 bending will restrict trunk rotation velocity and thus, reduce the magnitude of the crunch
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7 77 factor (Chu et al., 2010). However, the effect of crunch factor in isolation on launch angle of
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9 78 the golf ball has not previously been investigated.
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14 80 The first aim of the study was to investigate the relationship between the trunk and lower
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16 81 trunk for axial rotation velocity and lateral bending (crunch factor variables). The
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18 82 coordination between the trunk and lower trunk segments was also examined. The second
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20 83 aim of the study was to determine the level of association between axial rotation velocity and
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22 84 lateral bending of the trunk and lower trunk with swing (clubhead velocity) and launch
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24 85 (launch angle) parameters. These aims were investigated in a group of high level amateur
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26 86 male golfers using their own driver.
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30 31 32 88 **Methods**

33 34 89 *Participants & Experimental Protocol*

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36 90 Thirty five high level amateur male golfers (Mean \pm SD: age = 23.8 \pm 2.1 years, registered
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38 91 golfing handicap = 5 \pm 1.9) were recruited for this study. Each participant was given a
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40 92 modified Nordic Low Back Pain questionnaire (Kuorinka et al., 1987) to confirm an absence
41
42 93 of back pain within the last 12 months. All participants utilised a 'modern' rather than a
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44 94 'classic' swing (Gluck et al., 2007) and this was confirmed via a qualitative video analysis of
45
46 95 each participant's swing. This analysis was performed independently by two Australian
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48 96 Professional Golfers Association teaching professionals. Presence of factors associated with a
49
50 97 classic golf swing, i.e. heel raise and pelvic movement, resulted in exclusion from the study.
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52 98 On the basis of these criteria five of the originally screened 40 participants were excluded.
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3 100 The experimental protocol of this study involved each participant hitting five shots with their
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5 101 own driver using the same leading brand of golf ball. During testing, participants wore
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7 102 bicycle shorts, their own golf glove and golf shoes, and hit off a tee positioned on an artificial
8
9 103 turf surface into a net positioned **five metres** in front of the hitting area. This study was
10
11 104 undertaken in an indoor biomechanics laboratory. Ethical approval to conduct the study was
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13 105 provided by the Institutional Human Research Ethics Committee.
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18 107 ***Data Collection***

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20 108 A 10-camera MX-F20 Vicon-Peak Motion Analysis System (Oxford Metrics, Oxford, UK)
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22 109 operating at 500 Hz was used to capture 3D coordinates from retro-reflective markers during
23
24 110 the golf swing. A previously validated multi-segment trunk model (Joyce et al., 2010) was
25
26 111 used to create three anatomical reference frames for the trunk, lower trunk and pelvis (Table
27
28 112 I). The top of the backswing was defined as the frame where the two club markers changed
29
30 113 direction to initiate the downswing (Lephart et al., 2007). A small piece of retro-reflective
31
32 114 tape attached to the golf ball was used to identify ball impact. Ball impact was defined as the
33
34 115 frame immediately before the ball was first seen to move after contact with the driver (Joyce
35
36 116 et al., 2013). A validated real-time launch monitor (PureLaunch™, Zelosity, USA) was
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38 117 positioned at a distance of 3m adjacent to the participant's target line to determine clubhead
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40 118 velocity and launch angle at ball impact (Joyce et al., 2014).
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122 122 ***Data Analysis***

123 123 From the five trials recorded for each driver, **the trials with the fastest and slowest clubhead**
124 **velocity were removed, and the remaining three trials were averaged, assuming that there**

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2
3 125 was; minimal retro-reflective marker drop out, the ball landed within a predicted 37 m wide
4
5 126 fairway (from the launch monitor), and where the participant felt that improper contact had
6
7 127 been made were analysed. All kinematic trials were smoothed using a Woltring filter with a
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9
10 128 mean square error of 20mm² (Woltring, 1986).

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14 130 The multi-segment model used in this study was developed using Vicon BodyBuilder V.3.6.1
15
16 131 (Oxford, UK) and used in Vicon Nexus V.1.7.1 (Oxford, UK) to obtain all kinematic
17
18 132 variables (as described below). Cardan angles reported for the trunk were reduced from the
19
20 133 joint coordinate system of the shoulders relative to the joint coordinate system of the pelvis,
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22
23 134 and lower trunk Cardan angles reduced from the joint coordinate system of the lower thorax
24
25 135 relative to the joint coordinate system of the pelvis (i.e. 0,0,0 indicates the shoulder or lower
26
27 136 thorax reference frame is relative to the pelvis reference frame). In order to calculate the
28
29 137 rotations relative to the pelvis, cardan angles for each segment were reported using a ZYX
30
31 138 (lateral bending, flexion / extension, axial rotation) order of rotation, followed by derivation
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33
34 139 of axial rotation velocity using finite difference calculations. With previous research (Morgan
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36 140 et al., 1997) and pilot work in this study indicating that the crunch factor is maximised at ball
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38 141 impact, all kinematic variables (and launch monitor variables) were determined at this point.
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40 142 Eight kinematic variables relating to the trunk and lower trunk segments, in addition to two
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42 143 variables collected from the launch monitor (clubhead velocity and launch angle), were
43
44 144 analysed in this study (see Table II). Ensemble averages for the crunch factor determined for
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46 145 the trunk and lower trunk from the top of the backswing to ball impact were created. All data
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48 146 were time normalised (0-100%) using cubic spline interpolation.

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54 148 Cross-correlation analysis was used to investigate the coordination between the trunk and
55
56 149 lower trunk segments for the crunch factor variable. Specifically, the lag, or phase difference
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3 150 between the two wave forms was examined (from the data shown in Figure I). A maximum
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5 151 phase difference of 50 samples was examined to ensure at least half the data were
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7 152 overlapping (101 time-normalised downswing data points). As the magnitude of the crunch
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9 153 factor for the trunk and lower trunk differed, a normalised cross-correlation coefficient was
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11 154 obtained (-1 to 1) (Derrick & Thomas, 2004). For R^2 values > 0.8 these were defined as high,
12
13 155 0.7 – 0.8 moderate, and < 0.7 low (Vincent, 2005). As cross-correlation values are not
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15 156 normally distributed, a Fisher Z-transformation of the normalised cross-correlation coefficient
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17 157 was performed (Derrick & Thomas, 2004).
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22 23 159 *Statistical Analysis*

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25 160 All statistical analyses were performed using SPSS V22.0 for Windows (IBM Co., NY,
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27 161 USA). The average of three trials were used for each variable for each participant, with
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29 162 intraclass correlation coefficients [ICC (3,1)] and standard error of mean (SEM) statistics
30
31 163 used to determine within-trial reliability of all variables listed in Table II. All data were
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33 164 screened to assess normality, and 95% confidence intervals for crunch factor and launch
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35 165 monitor variables are reported. Bivariate Pearson Product-Moment Correlation analyses were
36
37 166 performed to investigate relationships for all kinematic variables between the trunk and lower
38
39 167 trunk. Pearson correlation coefficient values between 0.2 and 0.4 were considered as weak
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41 168 associations, values between 0.4 and 0.7 were considered as moderate and values above 0.7
42
43 169 as strong (Johnson, 2000).
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50 171 Two generalised linear models (GLM) were used to determine which kinematic variables
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52 172 were associated with clubhead velocity and launch angle. All eight variables were entered
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54 173 into each model then non-significant variables were removed one at a time until only
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56 174 significant variables remained in the final model. The GLM was not used for the first aim, as
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175 multicollinearity of the kinematic variables; crunch factor, lateral bending and axial rotation
176 velocity would cause the information matrix to become ill-conditioned and cause difficulty
177 with the reliability of the estimates of the model parameters, e.g. inflated standard errors
178 (Alin, 2010).

179

180 Results

181 Kinematic variables with 95% confidence intervals are described in Table II. Figure I shows
182 the ensemble average of crunch factor for both the trunk and lower trunk segments from top
183 of backswing to ball impact. This figure shows that the crunch factor of the trunk (and
184 shoulder) movement is of a higher magnitude in the latter part of the downswing, than that of
185 the lower trunk. Maximum crunch factor was found to occur 0.032 s (± 0.045 s) and 0.015 s
186 (± 0.070 s) after ball impact for the trunk and lower trunk, respectively. Pearson correlation
187 analysis revealed a moderate and positive relationship for axial rotation velocity ($r(35) = .47$,
188 $p < .01$) between the trunk and lower trunk although, no correlation was reported for lateral
189 bending ($r(35) = .14$, $p > .05$) and thus, crunch factor ($r(35) = .12$, $p > .05$). Cross-correlation
190 analysis of crunch factor between the trunk and lower trunk revealed a high normalised R^2
191 value of 0.98 (2.27 Fisher Z-score). It was also reported that no lag (phase difference) was
192 present for crunch factor between the trunk and lower trunk.

193

194 **INSERT TABLE II ABOUT HERE**

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196 The two GLMs are shown in Table III. The GLM for clubhead velocity reported trunk crunch
197 factor ($p < .01$), lower trunk axial rotation ($p < .01$), lower trunk axial rotation velocity ($p < .05$)
198 and lower trunk crunch factor ($p < .05$) as a significantly associated variables ($p < .05$) with
199 faster clubhead velocity, $b = .00$, $t(35) = 22.23$, $p < .01$, $b = .16$, $t(35) = 6.68$, $p < .01$, $b = -.02$,

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3 200 $t(35) = 4.61, p < .05$, and $b = -.00, t(35) = 6.41, p < .05$, respectively. The GLM for clubhead
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5 201 velocity can be described by the following equation:
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10 203 *Clubhead velocity (predicted) = intercept + Trunk crunch factor \bar{x} (0.001) + Lower trunk*
11
12 204 *axial rotation \bar{x} (0.163) + Lower trunk axial rotation velocity \bar{x} (-0.017) + Lower trunk*
13
14 205 *crunch factor \bar{x} (-0.001)*
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17 206
18 207 The model estimates and statistics are depicted in Table III. By interchanging estimates into
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20 208 the equation, predicted clubhead velocity can be determined for any individual, dependent
21
22 209 upon the four associated variables. For example, for an individual with a trunk crunch factor
23
24 210 of 9486.0 deg²/s, a lower trunk axial rotation of 13.6°, a lower trunk axial rotation velocity of
25
26 211 123.9 deg/s and a lower trunk crunch factor of 1002.2 deg²/s, would have a predicted
27
28 212 clubhead velocity of 51.9 m/s. The GLM for launch angle resulted in trunk axial rotation ($p <$
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30 213 .01) and lower trunk lateral bending ($p < .05$) as being significantly associated with clubhead
31
32 214 velocity, $b = -.19, t(35) = 31.39, p < .01$ and $b = -.13, t(35) = 5.69, p < .05$, respectively. The
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34 215 model found that as trunk axial rotation and lower truck lateral bending increased, the launch
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36 216 angle decreased. The final model for launch angle can be described by the following
37
38 217 equation:
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43 218
44 219 *Launch angle (predicted) = intercept + Trunk axial rotation \bar{x} (-0.189) + Lower trunk*
45
46 220 *lateral bending \bar{x} (-0.130)*
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50 221
51 222 The model estimates and statistics are depicted in Table III. By interchanging estimates into
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53 223 the equation, predicted launch angle can be determined for any individual dependent upon
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55 224 trunk axial rotation and lower trunk lateral bending. For example, for an individual with a
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225 trunk axial rotation of 24.9° and a lower trunk lateral bending of 8.5°, would have a predicted
226 launch angle of 8.0°.

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228 **INSERT TABLE III ABOUT HERE**

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230 Discussion

231 Dissimilar findings on the relationship between crunch factor and low back pain (Sugaya et
232 al., 1999; Lindsay & Horton, 2002; Glazier, 2010; Cole & Grimshaw, 2014) may possibly be
233 due to the use of ambiguous three dimensional methods. The use of multi-segment trunk
234 models which have been used to further understand segment interaction when producing
235 clubhead velocity (Tinmark et al., 2010; Horan & Kavanagh, 2012; Joyce et al., 2013), may
236 make crunch factor more anatomically meaningful (Morgan et al., 1997; Cole & Grimshaw,
237 2014).

238

239 The first aim of the study was to investigate the relationship for crunch factor between the
240 trunk and lower trunk. Pearson correlation analysis revealed a moderate and positive
241 relationship for axial rotation velocity between the trunk and lower trunk although, no
242 correlation was reported for lateral bending and thus, crunch factor. This agrees with previous
243 experimental research that lateral bending is probably not as important as axial rotation
244 velocity when maximising clubhead speed (Chu et al., 2010; Joyce et al., 2013). This would
245 then suggest that during the downswing, faster axial rotation of the lower trunk transfers to
246 the trunk through the summation of segments seen in the golf swing (Tinmark et al., 2010;
247 Horan & Kavanagh, 2012). Figure I shows the interaction between the trunk and lower trunk
248 for crunch factor during the downswing from the top of the backswing to ball impact.

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3 250 The use of cross-correlation analysis revealed a high correlation for crunch factor wave forms
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5 251 between the trunk and lower trunk, with no lag or, phase difference being evident. The
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7 252 instance of maximum crunch factor was in agreement with previous research with this
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10 253 variable being maximised just after ball impact for both the trunk and lower trunk segments
11
12 254 (Morgan et al., 1997; Sugaya et al., 1999). However, both axial rotation velocity and lateral
13
14 255 bending of the trunk at ball impact were larger than that of the lower trunk which suggests the
15
16 256 trunk segment is more active during the downswing. This is also supported by the steepness
17
18 257 of the ensemble average curve for the trunk (Figure I). This slope links with the cross-
19
20 258 correlation findings for segment-coupling reported by Horan & Kavanagh (2012) where, the
21
22 259 thorax-pelvis coupling reports a strong R^2 value, and the motion of the thorax during the
23
24 260 downswing assists in producing clubhead speed at ball impact.
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31 262 **INSERT FIGURE I ABOUT HERE**
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34 264 The second aim of the study was to investigate the effect of crunch factor variables on swing
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36 265 (clubhead velocity) and launch (launch angle) parameters. Firstly, for clubhead velocity the
37
38 266 GLM showed that significant associations with trunk crunch factor ($p < .01$), lower trunk axial
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40 267 rotation ($p < .01$), lower trunk axial rotation velocity ($p < .05$), and lower trunk crunch factor
41
42 268 ($p < .05$) were evident. Positive beta coefficients for trunk crunch factor and lower trunk axial
43
44 269 rotation indicated that to increase clubhead velocity, these values are increased. Trunk crunch
45
46 270 factor had the largest F -value of the four variables (22.23), indicating the strongest
47
48 271 association with clubhead speed. The methods used in this study therefore suggest that
49
50 272 increased crunch factor produces faster clubhead speeds, similar to that of the X-factor
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52 273 (Lephart et al., 2007; Chu et al., 2010). Despite previous research suggesting low back pain is
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54 274 associated with crunch factor (Hosea & Gatt, 1996; Cole & Grimshaw, 2008), no research
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3 275 has investigated crunch factor from a performance perspective. Negative beta coefficients for
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5 276 lower trunk axial rotation velocity and lower trunk crunch factor indicate that to increase
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7 277 clubhead velocity, these values are decreased. It would suggest that lower trunk crunch factor
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10 278 variables (crunch factor itself and axial rotation velocity) are not important in producing
11
12 279 faster clubhead velocities. This supports the data and findings related to Figure I, that the
13
14 280 trunk segment is more active in the downswing. These findings also support the kinematics
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16 281 which are seen in the modern golf swing, which was previously described as greater shoulder
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18 282 turn, and reduced hip movement at the top of the backswing (Gluck et al., 2007).

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23 284 For launch angle, the GLM reported significant associations with trunk axial rotation ($p < .01$)
24
25 285 and lower trunk lateral bending ($p < .05$). Beta coefficients for both these variables were
26
27 286 negative, indicating a reduced axial rotation of the trunk as well as lower trunk lateral
28
29 287 bending resulted in an increased launch angle. Negative correlations for trunk axial rotation
30
31 288 and driver clubhead velocity have previously been reported at ball impact (Kwon et al.,
32
33 289 2013), possibly to return the body and clubhead to a position required for straight driver
34
35 290 shots. This is also supported by Hume et al. (2005), who stated in their narrative review that
36
37 291 at ball impact, hip rotation is greater than shoulder rotation. This also supports the finding
38
39 292 from the GLM for clubhead velocity where lower trunk axial rotation had a positive beta
40
41 293 coefficient. With reduced lower trunk lateral bending shown to increase launch angle, this
42
43 294 was found both anecdotally, where 'hitting-up' on the ball was reported not to produce higher
44
45 295 launch angles (however, lateral bending of the trunk was not reported in the GLM) (Foley,
46
47 296 2012), and experimentally, where excessive lateral bending restricts rotation velocity and
48
49 297 thus, the magnitude of crunch factor (Chu et al., 2010). Interestingly, lower trunk crunch
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51 298 factor was found to be negatively associated with faster clubhead velocities, and may support
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53 299 the previous finding for the launch angle GLM. With respect to both GLMs, the optimal
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3 300 launch conditions for highly skilled golfers report that faster clubhead velocities are
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5 301 associated with lower launch angles when optimising distance (Wallace et al., 2007; Wishon,
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7 302 2013). The crunch factor variables reported by each GLM would support body positioning at
8
9 303 ball impact to produce these optimal launch conditions.
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14 305 Previous authors have reported excessive spinal loading and the potential for injury at ball
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16 306 impact where, trunk lateral bending coupled with fast trunk axial rotation velocity are
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18 307 required to produce faster clubhead velocity (Gluck et al., 2007; Sato et al., 2013). It is
19
20 308 important to note that the golfers who participated in this study all reported no incidence of
21
22 309 low back pain within the last 12 months. Based on the variables selected for both GLMs, this
23
24 310 could suggest that the golfers in this study avoid crunch factor related low back injury by
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26 311 minimising the amount of lateral bending at ball impact, so that trunk and lower trunk
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28 312 segment axial rotation and axial rotation velocity are not restricted during the downswing and
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30 313 maximise clubhead velocity (Chu et al., 2010). It has been found that low level amateur
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32 314 golfers (who display high variability in their golf swings) exhibit 80 % greater peak lateral
33
34 315 bending of the trunk, leading to increased shear loads on the lower back, than that of
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36 316 professionals (Hosea & Gatt, 1996; Metz, 1999). This could explain why lateral bending was
37
38 317 not shown to be important for both aims of this study, based on the cohort used.
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45 319 A limitation of the study was the use of only kinematic variables related to crunch factor
46
47 320 when explaining swing (clubhead velocity) and launch (launch angle) parameters in the
48
49 321 GLMs. Despite crunch factor variables showing significant associations for both clubhead
50
51 322 velocity and launch angle models, the addition of other kinematic variables (e.g. wrist
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53 323 kinematics) may have given further explanation of the summation of segments in producing
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55 324 each parameter (Chu et al., 2010; Tinmark et al., 2010; Horan & Kavanagh, 2012). Another
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3 325 limitation was that while the 3D methods used were more anatomically meaningful than that
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5 326 of reporting plane-projected angles, the use of acromion markers does not lead to the
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7 327 definition of a solid trunk segment. Finally, it is possible that skin movement artefact may
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9 328 have affected the reported kinematics (Leardini et al., 2009).

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14 330 In conclusion, the purpose of this study was to firstly investigate the relationship of crunch
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16 331 factor variables between the trunk and lower trunk, then secondly, to see what crunch factor
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18 332 variables are associated with swing (clubhead velocity) and launch (launch angle) parameters.
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20 333 Firstly, a relationship was reported for axial rotation velocity, but no correlation for lateral
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22 334 bending and thus, crunch factor was reported, using a Pearson correlation analysis. Cross-
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24 335 correlation analysis revealed a strong coupling relationship for the crunch factor between the
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26 336 trunk and lower trunk. Secondly, reduced lateral bending at ball impact was shown to be
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28 337 related to faster driver clubhead velocities and a lower launch angle. These findings have
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30 338 implications for both injury prevention and improved golf performance.
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2 448 **Tables & Figure**

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4 450 **Table I** Anatomical placement of the retro-reflective markers.

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6 452 **Table II** Crunch factor variables reported for the trunk and lower trunk segments and swing and
7 453 launch parameters (Mean \pm SD). The 95% confidence intervals are reported, along with indices of
8 454 reliability.

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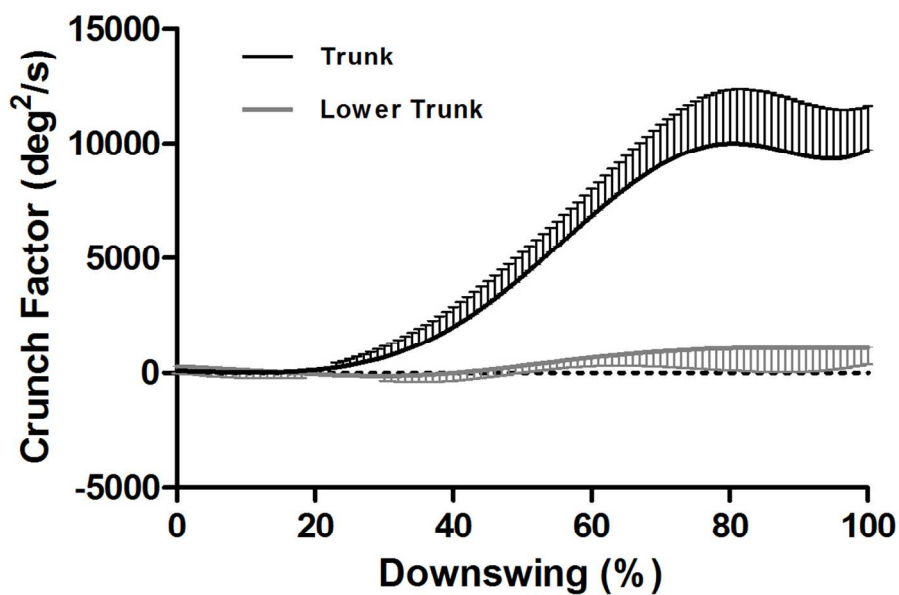
10 456 **Table III** Final generalised linear model estimates for clubhead velocity and launch angle.

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13 457 **Figure I** Ensemble averages of crunch factor data reported for the trunk and lower trunk segments
14 458 from the top of the backswing (0 %) to ball impact (100 %). Shaded areas represent one standard
15 459 deviation from the mean.

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Ensemble averages of crunch factor data reported for the trunk and lower trunk segments from the top of the backswing (0 %) to ball impact (100 %). Shaded areas represent one standard deviation from the mean.

110x73mm (300 x 300 DPI)

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Table 2

Reference Frame	Anatomical Marker Placement	Defined Joint Coordinate System
Shoulders¹	Left Acromion Process (LACRM) Right Acromion Process (RACRM) Tenth Thoracic Spinous Process (T10)	Mid-acromion, then T10 mid-point (origin). Mid-acromion, unit vector pointing right (X vector). A distal unit vector perpendicular to X from the origin (Y-temp vector). Common perpendicular of X and Y-temp, proximal unit vector, perpendicular to X (Z vector). Cross-product of X and Z, a unit vector perpendicular and anterior to X.
Lower Thorax²	Xiphoid Process, distal end of the Sternum Tenth Thoracic Spinous Process (T10) First Lumbar Spinous Process (L1)	Mid-L1 and T10, then mid-sternum (origin). Mid-L1 and T10, unit vector pointing right (X vector). A distal unit vector perpendicular to X from the origin (Y-temp vector). Common perpendicular of X and Y-temp, proximal unit vector, perpendicular to X (Z vector). Cross-product of X and Z, a unit vector perpendicular and anterior to X.
Pelvis²	Left Anterior Superior Iliac Spine (LASIS) Right Anterior Superior Iliac Spine (RASIS) Left Posterior Superior Iliac Spine (LPSIS) Right Posterior Superior Iliac Spine (RPSIS)	Mid-point of mid-ASIS and mid-PSIS (origin). Unit vector pointing right from the origin (X vector). A distal unit vector perpendicular to X from the origin (Y-temp vector). Common perpendicular of X and Y-temp, proximal unit vector, perpendicular to X (Z vector). Cross-product of X and Z, a unit vector perpendicular and anterior to X.
Golf Club	1/3 length of shaft from grip 2/3 length of shaft from grip	None

¹ – Trunk, ² – Lower Trunk. Joint coordinate systems defined from anatomical position perspective.

Table II Crunch factor variables reported for the trunk and lower trunk segments and swing and launch parameters (Mean \pm SD). The 95 % confidence intervals are reported, along with indices of reliability.

Variable	Segment	Mean (\pm SD)	95% Lower – Upper CI	ICC	SEM
Crunch factor (deg ² /s)	Trunk	9486.0 (\pm 1945.6)	9109.5 – 9862.6	0.978	288.6
	Lower trunk	1002.2 (\pm 618.8)	882.5 – 1122.0	0.970	107.2
Lateral bending (deg)	Trunk	30.6 (\pm 4.9)	29.6 – 31.5	0.991	0.5
	Lower trunk	8.5 (\pm 4.7)	7.6 – 9.5	0.970	0.8
Axial rotation (deg)	Trunk	24.9 (\pm 7.6)	23.5 – 26.4	0.979	1.1
	Lower trunk	13.6 (\pm 4.1)	12.8 – 14.4	0.965	0.8
Axial rotation velocity (deg/s)	Trunk	317.4 (\pm 38.2)	310.0 – 324.7	0.885	13.0
	Lower trunk	123.9 (\pm 34.7)	117.2 – 130.6	0.910	10.4
Clubhead velocity (m/s)		48.1 (\pm 3.0)	47.5 – 48.7	0.969	0.5
Launch angle (deg)		8.0 (\pm 2.7)	7.4 – 8.5	0.825	1.1

CI – Confidence intervals, ICC – intra-class correlation coefficient, SEM – standard error of measurement

Table III Final generalised linear model estimates for clubhead velocity and launch angle.

Model	Variables	β – coefficient	Standard error	p – value
Clubhead velocity	<i>Intercept</i>	43.254	1.927	0.000
	Trunk crunch factor	0.001	0.000	0.000
	Lower trunk axial rotation	0.163	0.063	0.010
	Lower trunk axial rotation velocity	-0.017	0.008	0.032
	Lower trunk crunch factor	-0.001	0.000	0.011
Launch angle	<i>Intercept</i>	13.791	1.146	0.000
	Trunk axial rotation	-0.189	0.034	0.000
	Lower trunk lateral bending	-0.130	0.054	0.017