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Test-Retest Reliability of Segment Kinetic Energy Measures in the Golf Swing

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note. research conducted at this institution

1 **Abstract**

2

3 Analyses of segment kinetic energy (KE) can provide the most appropriate means of
4 exploring sequential movements. As the reliability associated with its measurement has not
5 been reported, the aim of this study was to examine the test-retest reliability of segment KE
6 measures in the golf swing. On two occasions, 7 male golfers hit 5 shots with three different
7 clubs. Body segment inertia parameters were estimated for 17 rigid bodies and 3D kinematic
8 data were collected during each swing. The magnitude and timing of peak total, linear and
9 angular kinetic energies were then calculated for each rigid body and for 4 segment groups.
10 Regardless of club type, KE was measured with high reliability for almost all rigid bodies and
11 segment groups. However, significantly larger magnitudes of peak total ($p = 0.039$) and linear
12 ($p = 0.021$) lower body KE were reported in test 2 than in test 1. The high reliability reported
13 in this study provides support for the use of analyses of segment KE. However, practitioners
14 should pay careful attention to the identification of anatomical landmarks which define the
15 thigh, pelvis and thorax as this was the main cause of variability in repeated measures of
16 segment KE.

17

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20

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22 *Proximal-to-distal sequencing, repeatability, inertia parameters, electromagnetic tracking*
23 *system*

24

25

26

27 **Introduction**

28

29 In a system of multiple linked segments, such as that found in the golf swing, it has been
30 suggested that optimal performance is achieved if a proximal-to-distal sequence of body
31 segment movements is produced (Cochran & Stobbs, 1968; Putnam, 1993). As such, the
32 sequencing of body segment movements has become an important theme in golf swing
33 instruction and scientific research articles (Cheetham et al., 2008; Horan & Kavanagh, 2012;
34 Joyce, 2017; Neal, Lumsden, Holland & Mason, 2007; Tinmark, Hellstrom, Halvorsen &
35 Thorstensson, 2010; Vena, Budney, Forest & Carey, 2011a).

36 Segmental sequencing in the golf swing has predominantly been examined in terms of
37 the summation of speed principle using analyses of segment angular velocities (Neal et al.,
38 2007; Tinmark et al., 2010). However, numerous techniques of varying complexity have also
39 been used; from the calculation of segment rotation velocity from the relative angle between
40 two one-dimensional lines (Burden, Grimshaw & Wallace, 2001; Horan & Kavanagh, 2012;
41 Myers et al., 2008) to the calculation of segment angular velocity from a non-stationary
42 instantaneous screw axis (Vena, Budney, Forest & Carey, 2011b). Regardless of technique,
43 the majority of analyses suggest that, for skilled performers, the magnitude of peak angular
44 velocity increases sequentially from the most proximal to the most distal segments (Cheetham
45 et al., 2008; Horan & Kavanagh, 2012; Neal et al., 2007; Tinmark et al., 2010; Vena et al.,
46 2011a). Less conclusive evidence has been provided regarding the timing of peak segment
47 angular velocity. Whilst timing conformed to a proximal-to-distal sequence in some studies
48 (Neal et al., 2007; Tinmark et al., 2010), research has also suggested that the timing of peak
49 angular velocities follows a participant-specific pattern (Cheetham et al., 2008; Vena et al.,
50 2011b).

51 Despite the increasing volume of research into segmental sequencing in the golf
52 swing, there is still little agreement regarding the most appropriate analysis technique. The
53 examination of segment kinetic energy (KE) is increasingly popular in scientific studies to
54 examine the effectiveness of movement patterns (Bechard, Nolte, Kedgley & Jenkyn, 2009;
55 Ferdinands, Kersting & Marsdhal, 2012; Slawinski et al., 2010). It has been suggested that
56 the analysis of segment KE is the most appropriate technique to examine the sequencing of
57 body segments (Anderson, Wright & Stefanyshyn, 2006; Bechard et al., 2009; Ferdinands et
58 al., 2012; Slawinski et al., 2010). As well as incorporating inertial parameters, distal segment
59 speed in striking and throwing movements has frequently been associated with the magnitude,
60 timing and transfer of segment KE (Cole & Grimshaw, 2016; Ferdinands, 2011; Slawinski et
61 al., 2010). It has also been suggested that analyses of segment KE are sensitive to subtle
62 changes in technique (Bechard et al., 2009). For example, during the recovery phase of a
63 rowing stroke, an increase in stroke rate from 18 to 22 stroke/min to 32 to 40 stroke/min
64 caused a significant increase in total KE from 13.5 ± 6.0 J to 83.8 ± 42.7 J (Bechard et al.,
65 2009).

66 The sequencing of segment KE in the golf swing has been examined in two studies
67 (Anderson et al., 2006; Kenny, McCloy, Wallace & Otto, 2008) but neither reported the
68 reliability associated with its measurement. Segment KE is sensitive to even the subtlest
69 changes in technique (Bechard et al., 2009; Ferdinands et al., 2012). This, in addition to the
70 multiple sources of potential error associated with the measurement (collection of 3D linear
71 and angular kinematic data, the definition and computation of body segment axes and the
72 estimation of body segment inertia parameters), mean that before segment KE measurements
73 can be used with confidence, it is important to quantify the associated reliability. Therefore,
74 the aim of this study was to examine the test-retest reliability of measures of the magnitude
75 and timing of peak segment KE in the golf swing. Additionally, the results were also expected

76 to enable subsequent studies and practitioners to determine the meaningfulness of any
77 differences in measures of segment KE (Atkinson & Nevill, 1998). As body segment inertial
78 parameters (Huijbregts, 2002) and 3D linear and angular kinematic golf swing data (Evans,
79 Horan, Neal, Barrett & Mills, 2012) can be measured with high reliability, it was
80 hypothesised that the magnitude and timing of segment KE in the golf swing could be
81 measured with high reliability.

82

83 **Methods**

84

85 *Participants*

86

87 Seven male golfers (age: 31 ± 12 years; stature: 1.86 ± 0.05 m; body mass 85.0 ± 5.5 kg;
88 handicap 9.3 ± 8.0 strokes) volunteered to take part in this study. At the time of testing the
89 golfers were injury free and playing or practising golf at least once a week. Ethical approval
90 was granted by the Faculty of Health and Wellbeing Research Ethics Committee at Sheffield
91 Hallam University and each participant provided written informed consent.

92

93 *Instrumentation*

94

95 A 16-channel Polhemus Liberty electromagnetic tracking system (Polhemus, Inc., Colchester,
96 VT, USA) sampling at 240 Hz was used to collect 3D position and orientation kinematic data.
97 The electromagnetic transmitter (origin of the global coordinate system) was positioned
98 approximately 0.4 m behind the golfer on a custom-built non-metallic stand with +x directed
99 anteriorly, +y vertically upwards and +z directed away from the target, parallel to the target
100 line.

101 A custom designed suit comprising a base layer jacket with adjustable straps was used
102 to attach twelve electromagnetic sensors to golfers at the following anatomical locations:
103 posteriorly to the upper trunk at the level of T3, posteriorly to the mid-trunk at the level of T6,
104 posteriorly at the mid-point of each upper arm, thigh and lower leg and laterally on the right
105 side of the lower trunk at the mid-point between the anterior superior iliac spine and greater
106 trochanter (Figure 1). Sensors were also attached to the back of each hand using modified golf
107 gloves and to the right side of the head behind the ear using a cap.

108

109 *Segment inertial parameter estimation*

110

111 Body segment inertia parameters were estimated for 17 rigid bodies using a geometric model
112 comprising 28 geometric shapes. It has been reported that segment inertia parameters can be
113 reliably estimated using this model (Outram, Domeone and & Wheat, 2012). The feet, lower
114 legs, thighs, upper arms and forearms were modelled using elliptical solids, the trunk and
115 neck using stadium solids and the cranium using a semi-ellipsoid (Yeadon, 1990). The hand
116 was modelled using an approach adapted from Challis and Kerwin (1996) whereby the base
117 of the hand and fingers were modelled using a stadium solid and segment of a hollow
118 cylinder, respectively (Figure 2).

119 The geometric model segmented the body into geometric shapes using planes
120 perpendicular to the long axes of the rigid bodies at specified boundary levels. The geometry
121 and volume of these shapes were calculated using width, height and depth measurements
122 taken directly from each participant (Gittoes, Bezodis, & Wilson, 2009; Yeadon, 1990). The
123 position of 78 anatomical landmarks (Yeadon, 1990) was identified by one examiner using
124 the Polhemus system's digital stylus. Anatomical landmarks were identified on the right limbs
125 with the participants in the anatomical position, standing upright with their arms by their

126 sides, fist clenched and thumbs pointing forwards. The left and right limbs were assumed to
127 be symmetrical (Yeadon, 1990).

128 The inertial parameters - segment mass, centre of mass location and principal
129 moments of inertia (I_{xx} , I_{yy} and I_{zz}) - were calculated using the equations defined by Yeadon
130 (1990), assuming uniform density (Dempster, 1955). In accordance with the International
131 Society of Biomechanics (ISB) guidelines, all local coordinate systems were defined such that
132 the x, y and z axes were predominantly sagittal, longitudinal and frontal directions,
133 respectively.

134 Club segment geometry and inertial parameters were based on measurements made by
135 a non-contact laser scanner (Model Maker D100 non-contact laser scanner, Metris, Leuven,
136 Belgium) and the known densities of the steel clubhead and shaft. The club segment was
137 assumed to be a rigid body and position and orientation during swing trials were directly
138 obtained from a sensor securely fixed to the shaft just below the grip.

139

140 *Data Collection*

141

142 All trials were performed in a biomechanics laboratory. On two occasions, approximately one
143 week apart, body segment inertia parameters were calculated before golfers hit 15 'good' shots
144 from an artificial mat into a net 5 meters away; 5 with a driver, 5-iron and 9-iron. To establish
145 quality, each shot was qualitatively rated on a ten-point scale with a 1 representing a shot the
146 player was completely unsatisfied with and 10 representing their interpretation of an ideal
147 shot. Shots rated as less than seven were discounted and another shot was hit. When required,
148 ball flight data from a radar tracking device (Trackman A/S, Denmark) set-up in accordance
149 with manufacturer recommendations were also considered. Furthermore, to provide an
150 assessment of golf swing performance in both testing sessions, clubhead characteristics

151 (clubhead speed, face angle, club path and attack angle) and ball flight data (ball speed, carry
152 distance, side carry distance and spin rate) were recorded.

153 A Ping (Ping, Phoenix, Arizona) G15 Driver and Ping i15 irons with regular graphite
154 shafts, standard lengths and standard lie angles were used by all golfers. In the first session,
155 the order in which each participant was given each club was randomised but this order was
156 maintained for the second session. Sufficient time was given for golfers to perform their usual
157 pre-game warm-up routine and adequate practice trials were allowed to ensure that golfers
158 were familiar with the clubs, the laboratory environment and the data collection protocol.

159

160 *Data Analysis*

161

162 Using anatomical landmarks identified in the geometric modelling process and 12 additional
163 anatomical landmarks identified on the left limbs, linear and angular velocity data were
164 obtained for 17 rigid bodies during each golf swing. The centre of mass of each rigid body
165 was defined as the origin of each local coordinate system and translations and rotations were
166 calculated with regard to the global system in a manner consistent with the recommendations
167 of the ISB (Grood & Suntay, 1983; Wu & Cavanagh, 1995).

168 Using raw kinematic data, KE was calculated for the 17 rigid bodies of the geometric
169 model as well as four segment groups; Lower Body (comprising foot, lower leg, thigh and
170 pelvis), Upper Body (comprising mid-trunk, upper trunk, neck and head), Arms (comprising
171 left and right upper arms, forearms and hands) and Club (Anderson et al., 2006; Kenny et al.,
172 2008).

173 Linear KE (KE_{L-RB}) of each rigid body was calculated using their mass (m) and centre
174 of mass velocity (\mathbf{v}_{com}) (Equation 1). Rigid body angular KE (KE_{A-RB}) was calculated using

175 their moment of inertia tensor (\mathbf{I}) and skew-symmetric angular velocity matrix ($\boldsymbol{\omega}$) (Equation
176 2).

$$KE_{L-RB} = \frac{1}{2} m \cdot \mathbf{v}_{com}^2 \quad (1)$$

$$KE_{A-RB} = \frac{1}{2} \mathbf{I} \cdot \boldsymbol{\omega}_{com}^2 \quad (2)$$

177 For the segment groups, linear KE (KE_{L-SG}) was calculated using equation 3:

$$KE_{L-GS} = \sum_{i=1}^n \frac{1}{2} m_i \cdot \hat{\mathbf{v}}_{com}^2 \quad (3)$$

178 where m_i is the mass of the i th constituent rigid body, n is the number of constituent rigid
179 bodies and $\hat{\mathbf{v}}_{com}$ is the segment group's centre of mass linear velocity.

180 Two forms of angular KE were calculated for each segment group (Outram, 2015).

181 Segment group local angular KE (KE_{A-GSl}) was calculated using equation 4:

$$KE_{A-GSl} = \sum_{i=1}^n \frac{1}{2} \mathbf{I}_i \cdot \boldsymbol{\omega}_i^2 \quad (4)$$

182 where \mathbf{I}_i and $\boldsymbol{\omega}_i$ are the moment of inertia tensor and skew-symmetric angular velocity matrix
183 of the i th constituent rigid body, respectively, and n is the number of constituent rigid bodies.

184 Segment group remote angular KE (KE_{A-GSr}) was calculated using equation 5:

$$KE_{A-GSr} = \sum_{i=1}^n \frac{1}{2} m_i \cdot \mathbf{v}_{T_i}^2 \quad (5)$$

185 where m_i and \mathbf{v}_{T_i} are the mass and tangential velocity of i th constituent rigid body and n is the
186 number of constituent rigid bodies. The tangential velocity of constituent rigid bodies was
187 calculated as the component of the relative velocity vector between the rigid body centre of
188 mass and the segment group centre of mass, perpendicular to the relative position vector.

189 The magnitude and timing of peak segment and peak rigid body kinetic energies were
190 calculated for the downswing phase of the golf swing, using custom written Matlab scripts. The
191 downswing was defined as the time between the top of the backswing (TOB) and impact - where

192 TOB represented the point at which the club changed direction at the end of the backswing. The
193 impact was calculated as the time of a sudden increase in the output of an accelerometer attached
194 at the end of the club shaft. The timing of peak KE was then calculated relative to the total
195 downswing time with 0 representing the TOB and 1 representing ball impact.

196

197 *Statistical analysis*

198

199 All data were analysed using SPSS (Version 19.0). The means of the five shots for each club
200 in both data collections were used for statistical analysis. Tests of normality (Shapiro-Wilk)
201 were performed to ensure data sets were appropriate for parametric statistical tests. The
202 relative and absolute reliability of the data were assessed using a variety of statistical
203 techniques (Atkinson & Nevill, 1998). Initially, to ensure that the outcomes of golf swings in
204 both testing sessions were similar and appropriate for inclusion in this study, the reliability of
205 launch monitor data was examined. Subsequently, the reliability of the magnitude and timing
206 of peak segment and peak rigid body KEs were assessed.

207 To compare mean values across repeated measurements, separate paired sample *t*-tests
208 were performed for each club. Alpha was set at 0.05 and Cohen's *d* effect size was calculated
209 (Cohen, 1988). Two-way random model intraclass correlation coefficients (ICCs) with
210 absolute agreement (ICC 2,1) were used to establish test-retest relative reliability (Shrout &
211 Fleiss, 1979). Single measures *r* values were interpreted as: good reliability: 0.8 - 1.00,
212 acceptable reliability: 0.6 - 0.79, poor reliability: <0.6 (Sleivert & Wenger, 1994).

213 To calculate absolute reliability and express measurement error in the original units of
214 measurement the standard error of measurement (SEM) was calculated for each variable
215 (equation 6). The minimum detectable difference (MD) was also calculated using equation 7
216 (Weir, Therapy & Moines, 2005).

$$SEM = SD\sqrt{1 - ICC} \quad (6)$$

217 where SD is the standard deviation for all participants.

218 The minimum difference to be considered real (MD) was also calculated using
219 equation 7 (Weir et al., 2005)

$$MD = SEM \times 1.96 \times \sqrt{2} \quad (7)$$

220

221 **Results**

222

223 *Clubhead and ball flight characteristics*

224

225 In both testing sessions, similar clubhead and ball flight characteristics were produced (Table
226 1). For all three clubs, similar means and acceptable-good ICCs were reported, demonstrating
227 that the outcomes of the golf swings were reliable and appropriate for inclusion in this study.

228

229 *Magnitude of peak segment kinetic energy*

230

231 In general, the magnitude of peak total segment KE was estimated with good reliability
232 (Table 2). For the Upper Body, Arms and Club segments small effect sizes and good ICCs
233 were reported for repeated measures of the magnitude of peak total KE for all clubs.
234 Furthermore, regardless of club type, the magnitudes of peak linear as well as local and
235 remote angular Upper Body, Arms and Club kinetic energies were also measured with
236 acceptable reliability.

237 With the driver (Table 2) and 5 iron, acceptable reliability was achieved for the
238 measurement of peak total Lower Body KE. However, with the 9 iron, significantly larger
239 magnitudes of peak total Lower Body KE ($t(6) = 2.50, p = 0.039, d = 0.39$) were reported in

240 test 1 (20.5 ± 3.6 J) compared with test 2 (18.0 ± 4.8 J). Despite a good ICC (0.945), the
241 magnitude of peak linear Lower Body KE was also significantly larger ($t(6) = 3.02$, $p =$
242 0.021 , $d = 0.37$) in test 1 (7.4 ± 3.1 J) than in test 2 (6.3 ± 2.6 J) with the 5 iron.

243 The majority of peak total, linear and angular rigid body kinetic energies were
244 measured with high reliability. However, with the 5 and 9 irons, questionable reliability was
245 reported for the repeated measures of peak total thigh KE. Significantly greater peak total
246 thigh KE was reported in test 1 for the 5 iron ($t(6) = 3.22$, $p = 0.018$, $d = 0.29$) and 9 iron
247 ($t(6) = 2.82$, $p = 0.030$, $d = 0.38$). Furthermore, significantly larger peak linear thigh KE was
248 also reported in test 1 compared to test 2 with the 5 iron ($t(6) = 2.05$, $p = 0.047$, $d = 0.25$) and
249 9 iron ($t(6) = 2.584$, $p = 0.042$, $d = 0.51$).

250

251 *Timing of peak segment kinetic energy*

252

253 The timing of peak total segment KE was measured with high reliability. For all repeated
254 measures of peak total KE acceptable ICC values and similar mean times were reported
255 (Table 3). Furthermore, the timing of peak linear, local angular and remote angular KE was
256 also estimated with high reliability (Table 3).

257 Despite a non-significant difference, a medium effect size ($t(6) = 1.39$, $p = 0.213$, $d =$
258 0.59) was reported for the timing of peak total Lower Body KE with the Driver (Table 3).
259 Medium effect sizes were also reported for the timing of peak total Upper Body KE with the 9
260 iron (0.68), and peak local angular and remote angular Upper Body KE with the 5 iron (0.72)
261 and 9 iron (0.70) respectively. Although the timing of peak total, linear, local angular and
262 remote angular kinetic energies were also measured with acceptable reliability for the
263 majority of rigid bodies a medium effect size ($t(6) = 2.018$, $p = 0.090$, $d = 0.57$) was reported
264 for the timing of peak linear upper trunk KE with the driver.

265

266 **Discussion and Implications**

267

268 The reliability of measures of segment KE in the golf swing was generally very good.
269 Regardless of reliability statistic (t-test or ICC) all measures of the timing of peak total, linear,
270 local angular and remote angular KE were highly reliable. The majority of measures of the
271 magnitude of peak segment KE were also made with good reliability. However, with the 5
272 and 9 irons significant differences were observed for some measures of peak total and peak
273 linear Lower Body and thigh KE.

274 For the majority of segments and rigid bodies, the magnitude of peak total, linear,
275 local angular and remote angular KE was highly reliable. The magnitudes of peak segment
276 KE with the Driver were also similar to those reported in previous studies of KE in the golf
277 swing (Anderson et al., 2006; Kenny et al., 2008). In all analyses, mean peak total Club KE
278 exceeded 200 J and mean peak total Upper Body (~34 J) and Lower Body (~24 J) kinetic
279 energies also demonstrated good agreement. The largest variance between results (~40 J) was
280 apparent between measures of mean peak total Arms KE. This was most likely caused by the
281 inclusion of higher handicap players in this study compared with only scratch players in
282 others (Anderson et al., 2006; Kenny et al., 2008). Swing deficiencies exhibited by less skilled
283 players have been attributed to the earlier release of the arms in the downswing and
284 subsequent reduction of peak angular velocities of the arm segments (Zheng, 2008).

285 Despite good ICCs and the majority of peak segment KE magnitudes being estimated
286 with high reliability, significantly higher magnitudes of peak total (9 iron) and peak linear (5
287 iron) Lower Body KE were reported in test 1. Closer examination of the results indicated that
288 these differences were caused by significant increases in the magnitude of peak linear thigh
289 KE in test 1. Therefore, this variability was most likely caused by between test differences in

290 the identification of anatomical landmarks which define the thigh and the subsequent effect
291 on the definition of the local coordinate systems and estimation of geometric shape geometry
292 and inertial parameters. This suggestion is supported by additional statistical analysis of thigh
293 length and inertial parameters estimates. Although significant differences were not identified,
294 large and medium effect sizes were reported for estimates of thigh mass ($t(6) = 2.261, p =$
295 $0.064, d = 0.85$) and centre of mass location ($t(6) = 1.171, p = 0.268, d = 0.61$). These effect
296 sizes suggested that lower thigh mass estimates and decreased centre of mass location
297 distances were produced in test 2 (Mass: 10.5 ± 1.0 kg; COM: 26.7 ± 0.8 cm) than in test
298 1 (Mass: 11.2 ± 0.6 kg; COM: 27.4 ± 1.6 cm). This suggestion is consistent with other
299 kinematic studies where marker reapplication and landmark identification errors were
300 considered to be key factors in decreased measurement repeatability (Ferber, McClay, Davis,
301 Williams & Laughton, 2002; McGinley, Baker, Wolfe & Morris, 2009; Mills, Morrison,
302 Lloyd & Barrett, 2007). Inconsistency in the measurement of pelvis forward bend velocity in
303 the golf swing was also associated with variation in anatomical landmark identification
304 between test retest conditions (McGinley, et al., 2009). The increased magnitudes of peak
305 Lower Body KE in test 1 might also have been caused by changes in golf swing technique as
306 golf swings of less skilled players can be affected by movement variability during the
307 downswing (Bradshaw, Keogh, Hume, Maulder, Nortje, Marnewick, 2009; Cheetham et al.,
308 2007; Evans et al., 2012). However, similar shot outcomes were achieved in both tests (Table
309 1) and it has also been reported that golfers of varying skill level (handicap range +2 – 14
310 strokes) are able to closely replicate their kinematics in repeated tests (Bradshaw et al., 2009).
311 Therefore, it is more likely that differences in the identification of the anatomical landmarks
312 which define the thigh segment were responsible.

313 For the majority of segments and rigid bodies, the timing of peak segment KE was
314 highly reliable, as similar mean times, low effect sizes and good ICCs were reported. Similar

315 to the findings presented in previous examinations of total segment KE for the Driver, body
316 segment (LB, UB and Arms) KE peaked simultaneously at approximately 74% relative
317 downswing time whilst total Club KE peaked just before impact (Anderson et al., 2006;
318 Kenny et al., 2008). As changes in the timing of peak segment KE are primarily caused by
319 changes in the measurement of linear and angular velocities these results also support the
320 notion that electromagnetic tracking systems are capable of measuring 3D movements with
321 acceptable reliability (An, Jacobsen, Berglund & Chao, 1988; Evans et al., 2012; Horan,
322 Evans, Morris & Kavanagh, 2010).

323 Despite the majority of timing measures being estimated with high reliability, medium
324 effect sizes were reported for the timing of peak total Lower Body KE (Driver), peak total (9
325 iron), local angular (9 iron) and remote angular (5 iron) Upper Body KE. However, for these
326 measures, other reliability indices suggested that acceptable reliability was achieved;
327 acceptable-good ICC was reported and the measures of absolute reliability (SEM and MD)
328 were smaller than those reported with other clubs. It is possible that the medium effect sizes
329 reported for the timing of peak Lower Body and Upper Body KE were caused by changes in
330 swing mechanics between tests or by errors in the measurement of kinematics caused by
331 movement of the electromagnetic sensor relative to the underlying segment. However,
332 previous investigations have demonstrated that thorax and pelvis kinematics can be acquired
333 in the golf swing using an electromagnetic tracking system with acceptable reliability (Evans
334 et al., 2012). Furthermore, it has been indicated that reductions in the repeatability of thorax
335 and pelvis inertial parameter estimates (Outram, Domone & Wheat, 2012) and kinematics
336 measures in the golf swing (Evans et al., 20012) were attributable to errors associated with
337 inconsistent re-identification of anatomical landmarks. It has also been suggested that the high
338 proportion of trunk segment fat and relative motion of overlying tissue can cause
339 inconsistencies in the identification anatomical landmarks which define the pelvis and thorax

340 (Huijbregts, 2002; Outram, Domone, Hart & Wheat, 2011; Wicke & Dumas, 2010).
341 Therefore, the medium effect sizes were most likely related to errors associated with
342 anatomical landmark identification errors (Ferber et al., 2002) and subsequent estimation of
343 segment COM position and anatomical coordinate systems.

344 The implications of these findings for the examination of both the magnitude and
345 timing of peak segment KE are that at least part of any observed differences may be
346 attributable to sources of variability associated with anatomical landmark identification. As
347 such, practitioners should pay particular attention to the identification of anatomical
348 landmarks which define the thigh, pelvis and thorax. Further standardisation of the landmark
349 identification protocol and a detailed review of anatomical reference points have been
350 suggested as ways to improve identification accuracy (Huijbregts, 2002; Wicke & Dumas,
351 2010). Use of alternative landmarks may also improve repeatability but this has the potential
352 to decrease inertial parameter estimation accuracy (Outram, Domone, Hart & Wheat, 2011).
353 Therefore, it is recommended that future studies and practitioners consider the SEM and MD
354 presented here when interpreting the results of analyses of segment KE.

355 Although support has been presented for the reliability of segment KE measures in the
356 golf swing some limitations of this study should be noted. The study analysed a limited
357 sample of seven participants of varying ability. Although this sample is reflective of golfers
358 who typically undertake 3D analysis it is likely that the measures of absolute reliability may
359 be conservative for a group of highly skilled players who typically produce less variable golf
360 swings (Cheetham et al., 2007; Mills et al., 2007). Furthermore, to enable accurate club
361 modelling, the same Ping G15 driver and Ping i15 irons with standard length and standard lie
362 angles were used. Golfers with the physical characteristics of those included in this study are
363 likely to require clubs with an increased shaft length ($\sim 1/2''$) and more upright ($\sim 1^\circ$) lie angle.
364 These alterations in club fit along with changes in swing weight and moment of inertia caused

365 by using standardised clubs may have affected the perceived feel of these clubs by the golfer
366 and subsequently produced altered swing mechanics (Wallace, Otto & Nevill, 2007).
367 However, it has been suggested that club properties have only marginal effects on clubhead
368 characteristics and shot outcome (Betzler, Monk, Wallace & Otto; 2012; MacKenzie &
369 Sprigings, 2009). Therefore, it is anticipated that, as the same clubs were used in both
370 conditions and unlimited familiarisation trials were allowed, club characteristics would have
371 had a minimal effect on the results of this study.

372

373 **Conclusion**

374

375 The magnitude and timing of peak total, linear and angular KE were measured with high
376 reliability for almost all segment groups and rigid bodies. The similar mean values,
377 acceptable-good ICCs and low SEMs provided support for the examination of the proximal-
378 to-distal sequence using analyses of segment KE. However, the magnitude of peak total (9
379 iron) and linear (5 iron) Lower Body KE and timing of peak total (9 iron), local angular (9
380 iron) and remote angular (5 iron) Upper Body KE) were measured with questionable
381 reliability. This variability was most likely associated with the repeated identification of the
382 anatomical landmarks especially for the thigh, pelvis and thorax segments.

383

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385

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520 **Tables**

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Table 1. Reliability of ball flight and clubhead characteristics.

Parameter	Club	Test 1	Test 2	<i>p</i>	ICC	SEM (MD)
Clubhead Speed (m/s)	Driver	44.0 ± 3.1	44.8 ± 3.6	0.540	0.81	0.6 (1.7)
	5 iron	37.5 ± 1.5	39.2 ± 3.0	0.115	0.73	0.6 (1.7)
	9 iron	35.2 ± 2.3	35.5 ± 3.5	0.796	0.85	1.0 (2.8)
Face Angle (°)	Driver	-2.32 ± 1.91	-2.42 ± 2.30	0.892	0.78	0.45 (1.26)
	5 iron	2.06 ± 2.69	1.89 ± 2.31	0.903	0.79	0.54 (1.48)
	9 iron	-1.17 ± 2.12	0.40 ± 1.82	0.116	0.74	1.11 (3.07)
Club Path (°)	Driver	-0.81 ± 1.43	0.44 ± 3.37	0.247	0.65	0.83 (2.30)
	5 iron	-0.84 ± 3.09	-1.62 ± 2.37	0.566	0.80	1.08 (3.00)
	9 iron	0.88 ± 2.72	-1.37 ± 2.67	0.098	0.64	1.50 (4.17)
Attack Angle (°)	Driver	-3.78 ± 2.49	-2.10 ± 1.91	0.088	0.80	0.89 (2.47)
	5 iron	-4.63 ± 1.79	-4.41 ± 1.62	0.385	0.97	0.05 (0.14)
	9 iron	-4.94 ± 2.45	-5.05 ± 2.56	0.919	0.86	0.86 (2.39)
Ball Speed (m/s)	Driver	62.8 ± 4.3	65.4 ± 5.7	0.174	0.74	1.3 (3.6)
	5 iron	51.5 ± 3.9	53.3 ± 5.2	0.130	0.89	0.5 (1.5)
	9 iron	45.3 ± 3.3	44.2 ± 5.0	0.405	0.71	1.2 (3.4)
Carry (yd)	Driver	217.6 ± 14.2	219.6 ± 26.1	0.793	0.76	4.9 (13.5)
	5 iron	169.6 ± 15.7	171.8 ± 16.0	0.284	0.97	0.4 (1.2)
	9 iron	127.7 ± 15.9	128.7 ± 18.1	0.829	0.90	1.8 (4.9)
Side Carry (yd)	Driver	-8.1 ± 5.3	-11.1 ± 5.8	0.288	0.70	1.7 (4.6)
	5 iron	8.1 ± 7.8	9.1 ± 8.1	0.800	0.70	2.4 (6.6)
	9 iron	-3.0 ± 5.0	0.0 ± 3.2	0.126	0.73	1.9 (5.3)
Spin Rate (°/s)	Driver	3573 ± 793	3240 ± 648	0.529	0.76	171 (475)
	5 iron	3949 ± 649	4277 ± 742	0.203	0.74	180 (499)
	9 iron	6848 ± 736	6456 ± 921	0.334	0.76	366 (1015)

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Table 2. Reliability of the magnitude of peak segment KE.

	Driver				5 iron				9 iron			
	Kinetic Energy (J) \pm SD				Kinetic Energy (J) \pm SD				Kinetic Energy (J) \pm SD			
	Test 1	Test 2	ICC	SEM (MD)	Test 1	Test 2	ICC	SEM (MD)	Test 1	Test 2	ICC	SEM (MD)
Total												
LB	23.9 \pm 11.4	23.9 \pm 11.9	0.99	0.8 (2.3)	20.4 \pm 4.6	19.3 \pm 4.8	0.96	1.0 (2.6)	20.5 \pm 3.6	18.0 \pm 4.8	0.90	1.2 (3.6)
UB	30.7 \pm 4.5	32.4 \pm 4.2	0.84	1.8 (4.9)	29.5 \pm 3.7	30.1 \pm 4.7	0.93	1.2 (3.2)	26.8 \pm 3.9	26.3 \pm 5.8	0.72	2.5 (7.0)
Arms	87.2 \pm 19.7	89.3 \pm 21.0	0.97	3.3 (9.1)	83.7 \pm 18.5	81.8 \pm 19.5	0.99	1.6 (4.4)	79.3 \pm 8.0	78.7 \pm 11.2	0.97	1.6 (4.5)
Club	269.1 \pm 36.8	262.8 \pm 26.2	0.92	9.0 (24.8)	259.2 \pm 30.7	255.4 \pm 27.6	0.88	10.0 (27.6)	231.8 \pm 36.1	223.8 \pm 41.3	0.98	5.2 (14.4)
Linear												
LB	10.8 \pm 6.1	11.6 \pm 6.3	0.98	0.8 (2.3)	7.4 \pm 3.1	6.3 \pm 2.6*	0.95	0.6 (1.9)	6.7 \pm 3.9	5.7 \pm 3.0	0.95	0.7 (2.0)
UB	14.4 \pm 4.8	15.0 \pm 4.5	0.95	1.0 (2.9)	12.8 \pm 4.9	13.1 \pm 5.4	0.99	0.5 (1.5)	12.1 \pm 3.9	11.6 \pm 3.7	0.94	1.0 (2.7)
Arms	48.5 \pm 12.9	48.7 \pm 12.9	0.98	1.8 (4.9)	47.6 \pm 12.4	46.1 \pm 12.6	0.99	1.1 (3.1)	45.4 \pm 13.1	44.6 \pm 13.0	0.98	1.8 (5.0)
Club	224.4 \pm 29.2	228.6 \pm 23.7	0.94	6.5 (17.9)	232.0 \pm 35.1	223.6 \pm 25.4	0.91	8.9 (24.6)	194.2 \pm 32.1	190.7 \pm 35.9	0.98	4.3 (11.9)
Local Angular												
LB	7.3 \pm 2.1	7.4 \pm 2.1	0.96	4.2 (1.2)	6.8 \pm 1.3	6.8 \pm 0.9	0.82	0.5 (1.3)	6.8 \pm 1.7	6.1 \pm 1.1	0.88	0.5 (1.3)
UB	16.4 \pm 2.7	17.7 \pm 3.0	0.85	1.1 (3.1)	16.6 \pm 1.9	17.5 \pm 3.4	0.75	1.3 (3.7)	14.8 \pm 1.8	15.3 \pm 3.5	0.81	1.2 (3.2)
Arms	4.9 \pm 1.2	5.1 \pm 1.0	0.95	0.3 (0.7)	4.5 \pm 1.3	5.0 \pm 1.2	0.98	0.2 (0.5)	4.4 \pm 1.3	4.4 \pm 1.0	0.84	0.5 (1.3)
Club	42.2 \pm 4.8	43.2 \pm 4.2	0.89	1.5 (4.3)	39.0 \pm 6.4	38.0 \pm 5.6	0.98	0.9 (2.5)	33.8 \pm 5.4	34.1 \pm 7.2	0.94	1.5 (4.2)
Remote Angular												
LB	8.8 \pm 3.3	8.4 \pm 3.5	0.99	0.3 (0.9)	8.6 \pm 1.5	8.8 \pm 1.1	0.85	0.5 (1.4)	8.6 \pm 1.2	7.8 \pm 1.9	0.73	0.8 (2.2)
UB	2.4 \pm 1.2	2.7 \pm 1.3	0.96	0.2 (0.6)	1.9 \pm 1.0	1.7 \pm 0.9	0.85	0.4 (1.0)	1.8 \pm 0.8	1.6 \pm 0.5	0.71	0.3 (0.9)
Arms	37.7 \pm 8.2	39.9 \pm 9.6	0.96	1.9 (5.3)	35.1 \pm 7.2	34.6 \pm 8.4	0.98	1.0 (2.9)	34.3 \pm 7.7	34.3 (8.4)	0.93	2.2 (6.0)

533 *Notes: * denotes significant different between tests; LB, Lower Body; UB, Upper Body*

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Table 3. Reliability of the timing of peak segment KE.

	Driver				5 Iron				9 Iron			
	Kinetic Energy (J) ± SD				Kinetic Energy (J) ± SD				Kinetic Energy (J) ± SD			
	Test 1	Test 2	ICC	SEM (MD)	Test 1	Test 2	ICC	SEM (MD)	Test 1	Test 2	ICC	SEM (MD)
Total												
LB	0.755 ± 0.097	0.812 ± 0.094	0.91	0.029 (0.079)	0.742 ± 0.052	0.756 ± 0.088	0.84	0.028 (0.077)	0.759 ± 0.075	0.758 ± 0.060	0.79	0.031 (0.086)
UB	0.692 ± 0.062	0.680 ± 0.128	0.83	0.023 (0.063)	0.720 ± 0.037	0.706 ± 0.072	0.71	0.029 (0.081)	0.746 ± 0.040	0.719 ± 0.039	0.92	0.011 (0.031)
Arms	0.718 ± 0.073	0.732 ± 0.051	0.95	0.014 (0.038)	0.725 ± 0.045	0.760 ± 0.096	0.72	0.038 (0.104)	0.739 ± 0.058	0.745 ± 0.062	0.96	0.012 (0.033)
Club	0.959 ± 0.064	0.978 ± 0.013	0.92	0.011 (0.030)	0.989 ± 0.006	0.982 ± 0.013	0.84	0.004 (0.011)	0.988 ± 0.011	0.988 ± 0.008	0.91	0.003 (0.008)
Linear												
LB	0.813 ± 0.102	0.849 ± 0.085	0.95	0.021 (0.059)	0.735 ± 0.153	0.761 ± 0.173	0.92	0.047 (0.129)	0.713 ± 0.131	0.732 ± 0.164	0.88	0.052 (0.143)
UB	0.730 ± 0.097	0.743 ± 0.102	0.91	0.031 (0.066)	0.710 ± 0.057	0.712 ± 0.059	0.79	0.026 (0.073)	0.729 ± 0.099	0.757 ± 0.114	0.93	0.028 (0.079)
Arms	0.693 ± 0.068	0.696 ± 0.044	0.87	0.020 (0.056)	0.687 ± 0.028	0.692 ± 0.027	0.76	0.013 (0.037)	0.693 ± 0.032	0.706 ± 0.033	0.87	0.012 (0.033)
Club	0.961 ± 0.064	0.979 ± 0.013	0.94	0.010 (0.027)	0.990 ± 0.007	0.982 ± 0.013	0.88	0.003 (0.009)	0.989 ± 0.010	0.988 ± 0.008	0.92	0.003 (0.007)
Local Angular												
LB	0.693 ± 0.030	0.691 ± 0.074	0.76	0.038 (0.097)	0.690 ± 0.080	0.726 ± 0.075	0.85	0.030 (0.083)	0.751 ± 0.071	0.741 ± 0.071	0.80	0.032 (0.087)
UB	0.652 ± 0.053	0.669 ± 0.097	0.94	0.018 (0.051)	0.707 ± 0.019	0.703 ± 0.030	0.80	0.011 (0.031)	0.723 ± 0.030	0.696 ± 0.040	0.71	0.019 (0.052)
Arms	0.763 ± 0.068	0.790 ± 0.052	0.84	0.022 (0.063)	0.816 ± 0.091	0.896 ± 0.078	0.82	0.036 (0.099)	0.897 ± 0.062	0.885 ± 0.104	0.89	0.028 (0.077)
Club	0.959 ± 0.064	0.973 ± 0.016	0.98	0.006 (0.016)	0.988 ± 0.007	0.980 ± 0.012	0.95	0.002 (0.006)	0.982 ± 0.021	0.986 ± 0.011	0.98	0.002 (0.006)
Remote Angular												
LB	0.710 ± 0.172	0.688 ± 0.116	0.95	0.045 (0.126)	0.764 ± 0.115	0.752 ± 0.140	0.99	0.016 (0.043)	0.788 ± 0.108	0.786 ± 0.105	0.99	0.011 (0.031)
UB	0.828 ± 0.104	0.858 ± 0.151	0.78	0.060 (0.167)	0.860 ± 0.158	0.760 ± 0.195	0.73	0.092 (0.256)	0.832 ± 0.158	0.757 ± 0.157	0.80	0.070 (0.193)
Arms	0.820 ± 0.093	0.845 ± 0.084	0.89	0.029 (0.082)	0.814 ± 0.073	0.848 ± 0.089	0.90	0.026 (0.072)	0.857 ± 0.076	0.845 ± 0.099	0.96	0.018 (0.051)

538 *Notes: * denotes significant difference between tests; LB, Lower Body; UB, Upper Body*

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Figure Captions

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Figure 1 - Electromagnetic sensors attached using a baselayer jacket with adjustable straps and adjustable leg straps.

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Figure 2 - A segment of a hollow cylinder used to represent the fingers holding a gold club.