Test-retest reliability of segment kinetic energy measures in the golf swing

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

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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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23 *system*

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25

26

Introduction

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 & Marsdhall, 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 (v_{com}) (Equation 1). Rigid body angular KE (KE_{A-RB}) was calculated using

175   their moment of inertia tensor (**I**) and skew-symmetric angular velocity matrix (**ω**) (Equation

176   2).

$$KE_{L-RB} = \frac{1}{2}m.\boldsymbol{v}_{com}{}^2 \tag{1}$$

$$KE_{A-RB} = \frac{1}{2}\boldsymbol{I}.\boldsymbol{\omega}_{com}{}^2 \tag{2}$$

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

$$KE_{L-GS} = \sum_{i=1}^{n}\frac{1}{2}m_i.\widehat{\boldsymbol{v}}_{com}{}^2 \tag{3}$$

178   where m_i is the mass of the ith constituent rigid body, n is the number of constituent rigid

179   bodies and $\widehat{\boldsymbol{v}}_{com}$ 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:

$$KE_{A-GSl} = \sum_{i=1}^{n}\frac{1}{2}\boldsymbol{I}_i.\boldsymbol{\omega}_i{}^2 \tag{4}$$

182   where $\boldsymbol{I}_i$ and $\boldsymbol{\omega}_i$ are the moment of inertia tensor and skew-symmetric angular velocity matrix

183   of the ith 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:

$$KE_{A-GSr} = \sum_{i=1}^{n}\frac{1}{2}m_i.\boldsymbol{v}_{T_i}{}^2 \tag{5}$$

185   where m_i and $\boldsymbol{v}_{T_i}$ are the mass and tangential velocity of ith 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).

$$SEM = SD\sqrt{1 - ICC} \tag{6}$$

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)

$$MD = SEM \times 1.96 \times \sqrt{2} \tag{7}$$

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

Discussion and Implications

267

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

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

Despite good ICCs and the majority of peak segment KE magnitudes being estimated with high reliability, significantly higher magnitudes of peak total (9 iron) and peak linear (5 iron) Lower Body KE were reported in test 1. Closer examination of the results indicated that these differences were caused by significant increases in the magnitude of peak linear thigh 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 (~1/2") and more upright (~1°) 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

390   **References**

392   An, K. N., Jacobsen, M. C., Berglund, L. J., & Chao, E. Y. S. (1988). Application of a

393   magnetic tracking device to kinesiologic studies. *Journal of Biomechanics,* 21 (7), 613 –

394   620.

395   Anderson, B. C., Wright, I. C., & Stefanyshyn, D. J. (2006). Segmental sequencing of kinetic

396   energy in the golf swing. In F. Moritz, & S. Haake, The Engineering of Sport, 6 (1) 167 –

397   172. New York, NY: Springer.

398   Atkinson, G., & Nevill, A. M. (1998). Statistical Methods for assessing measurement error

399   (reliability) in variables relevant to sports medicine. *Sports Medicine,* 26 (4), 217 – 235.

400   Bechard, D. J., Nolte, V., Kedgley, A. E., & Jenkyn, T. R. (2009). Total kinetic energy

401   production of body segments is different between racing and training paces in elite Olympic

402   rowers. *Sports Biomechanics*, 8 (3), 199 – 211.

403   Betzler, N. F., Monk, S. A., Walalce, E. S., & Otto, S. R. (2012). Effects of golf shaft stiffness

404   on strain, clubhead presentation and wrist kinematics. *Sports Biomechanics,* 11 **(2),** 223 –

405   238.

406   Bradshaw, E. J., Keogh, J. W. L., Hume, P. A., Maulder, P. S., Nortje, J., & Marnewick, M.

407   (2009). The effect of biological movement variability on the performance of the golf swing

408   in high- and low-handicapped players. *Research Quarterly for Exercise and Sport*, 80 (2),

409   185 – 196.

410   Burden, A., Grimshaw, P., & Wallace, E. (2001). Hip and shoulder rotations during the golf

411   swing of sub-10 handicap players. *Journal of Sports Sciences*, 16 (2), 165 – 176.

412   Challis, J. H., & Kerwin, D. G. (1996). Quantification of the uncertainties in resultant joint

413   moments computed in a dynamic activity. *Journal of Sports Sciences*, 14 (3), 219 – 231.

414   Cheetham, P. J., Rose, G. A., Hinrichs, R. N., Neal, R. J., Mottram, R. E., Hurrion, P. D.   &

415   Vint, P. F. (2008). Comparison of Kinematic Sequence Parameters between Amateur and

416   Professional Golfers. In D. Crews, & R. Lutz (Eds.), *Proceedings of the 5th World Scientific*

417   *Congress of Golf* (pp. 30 – 36). Phoenix, AZ.

418   Cochran, A., & Stobbs, J. (1968). The search for the perfect swing. Philadephia, PA:

419   Lippincott (pp 48 – 53).

420   Cohen, J. (1988). Statistical power analysis for the behavioural sciences (2nd ed.). Hillsdale,

421   NJ: Lawrence Erlbaum Associates (pp. 20 – 27).

422   Cole, M.H. & Grimshaw, P. N. (2016). The biomechanics of the modern golf swing:

423   Implications for lower back injuries. *Sports Medicine,* 46, 339 – 351.

424   Dempster, W.T. (1955). Space requirements of the seated operator. WADC Technical Report

425   (TR-55-159). Wright-Patterson Air Force Base.

426   Evans, K., Horan, S. A., Neal, R. J., Barrett, R. S., & Mills, P. M. (2012). Repeatability of

427   three-dimensional thorax and pelvis kinematics in the golf swing measured using a field-

428   based motion capture system. *Sports Biomechanics,* 11 (2), 262 – 272.

429   Ferber, R., MClay Davis, I., Williams, D. S., & Laughton, C. (2002). A comparison of within-

430   and between-day reliability of discrete 3D lower extremity variables in runners. *Journal of*

431   *Orthopaedic Research,* 20 (6), 1139 – 1145.

432   Ferdinands, R. E. D. (2011). Analysis of segmental kinetic energy in cricket bowling. In A.

433   Subic, F. K. Fuss, F. Alam, & P. Clifton (5th Eds.). Proceedings of the *Asia-Pacific Congress*

434   *on Sports Technology (APCST)* (pp. 246 – 251). Melbourne, Aus: Procedia Engineering.

435   Ferdinands, R. E. D., Kersting, U. G., & Marshall, R. (2012). Kinematic and kinetic energy

436   analysis of segmental sequencing in cricket fast bowling. *Sports Technology,* 6 (1), 10 –21.

437　Gittoes, M. J., Bezodis, I. N., & Wilson, C. (2009). An image-based approach to obtaining

438　　anthropometric measurements for inertia modelling. *Journal of Applied Biomechanics,* 25

439　　(3), 265 – 270.

440　Grood, E. S. & Suntay, W. J. (1983). A joint coordinate system for the clinical description of

441　　three-dimensional motions: Application to the knee. *Journal of Biomechanical Engineering,*

442　　105 (2), 652 -656.

443　Holgrem. U., & Waling, K. (2008). Inter-examiner reliability of four static palpation tests

444　　used for assessing pelvic dysfunction. *Manual Therapy,* 13 (1), 50 - 56.

445　Horan, S. A., Evans, K., Morris, N. R., & Kavanagh, J. J. (2010). Thorax and pelvis

446　　kinematics during the downswing of male and female skilled golfers. *Journal of*

447　　*Biomechanics,* 43 (8), 1456 – 1462.

448　Horan, S. A., & Kavanagh, J. J. (2012). The control of upper body segment speed and

449　　velocity during the golf swing. *Sports Biomechanics,* **11** (2), 165 – 174.

450　Huijbregts, P.A. (2002). Spinal motion palpation: A review of reliability studies. *The Journal*

451　　*of Manual and Manipulative Therapy,* 10 (1), 24 – 39.

452　Joyce, C. (2017). The most important 'factor' in producing clubhead speed in golf. *Human*

453　　*Movement Science,* 55, 138 – 144.

454　Kenny, I. C., McCloy, A. J., Wallace, E. S., & Otto, S. R. (2008). Segmental sequencing　of

455　　kinetic energy in a computer-simulated golf swing. *Sports Engineering*, 11 (1), 37 – 45.

456　Li, L., & Caldwell, G.E. (1999). Coefficient of cross correlation and the time domain

457　　correspondence. *Journal of Electromyography and Kinesiology,* 9 (6), 385 – 389.

458　MacKenzie, S., & Sprigings, E. (2009). Understanding the role of shaft stiffness in the golf

459　　swing. *Sports Engineering,* 12, 13 – 19.

460   McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-

461   dimensional kinematic gait measurements: A systematic review. *Gait & Posture*, 29 (3), 360

462   – 369.

463   McTeigue, M., Lamb, S. R., & Mottram, R. (1994). Spine and hip motion analysis during the

464   golf swing. In A. J. Cochran, & M. R. Farrally (Eds.). *Science and golf III: Proceedings of*

465   *the World Scientific Congress on Golf* (pp. 50 – 58). Champaign, IL: Human Kinetics.

466   Mills, P. M., Morrison, S., Lloyd, D. G., & Barrett, R. S. (2007). Repeatability of 3D gait

467   kinematics obtained from an electromagnetic tracking system during treadmill locomotion.

468   *Journal of Biomechanics,* 40 (7), 1504 – 1511.

469   Myers, J., Lephart, S., Tsai, Y. S., Sell, T., Smoliga, J., & Jolly, J. (2008). The role of upper

470   torso and pelvis rotation in driving performance during the golf swing. *Journal of Sports*

471   *Sciences,* 26 (2), 181 – 188.

472   Neal, R., Lumsden, R., Holland, M., & Mason, B. (2007). Body segment sequencing and

473   timing in golf. *International Journal of Sports Science and Coaching,* 2 (S1), 25 – 36.

474   Outram, T. (2015) *Sequencing of segment kinetic energy in the golf* (Doctoral dissertation).

475   Sheffield Hallam University, Sheffield, UK.

476   Outram, T., Domone, S., Hart, J. and Wheat, J. (2011, September). The use of geometric

477   shapes in estimating the geometry of human body segments. *Proceedings of the British*

478   *Association of Sport and Exercise Science Conference*, University of Essex, Colchester, UK.

479   Penner, R.A. (2003). The physics of golf. *Reports on Progress in Physics,* 66 (2), 131- 173.

480   Putnam, C. A. (1993). Sequential motions of body segments in striking and throwing skills:

481   descriptions and explanations. *Journal of Biomechanics*, 26 (S1), 125 – 135.

482   Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: Uses in assessing rater reliability.

483   *Psychological Bulletin*, 86 (2), 420 – 428.

484   Slawinski, J., Bonnefoy, A., Ontanon, G., Leveque, J. M., Miller, C., Riquet, A., & Chèze, L.

485   (2010). Segment-interaction in sprint start: Analysis of 3D angular velocity and kinetic

486   energy in elite sprinters. *Journal of Biomechanics*, 43 (8), 1494 – 1502.

487   Sleivert, G. G., & Wenger, H.A. (1994). Reliability of measuring isometric and isokinetic

488   peak torque, rate of torque development, integrated electromyography, and tibial nerve

489   conduction velocity. *Physical Medicine and Rehabilitation,* 75 (12), 1315 – 1321.

490   Tinmark, F., Hellstrom, J., Halvorsen, K., & Thorstensson, A. (2010). Elite golfers' kinematic

491   sequence in full-swing and partial-swing shots. *Sports Biomechanics*, 9 (4), 236 – 244.

492   Vena, A., Budney, D., Forest, T., & Carey, J. P. (2011a). Three-dimensional kinematic

493   analysis of the golf swing using instantaneous screw axis theory, part 1: Methodology and

494   verification. *Sports Engineering*, 13 (3), 105–123.

495   Vena, A., Budney, D., Forest, T., & Carey, J. P. (2011b). Three-dimensional kinematic

496   analysis of the golf swing using instantaneous screw axis theory, Part 2: Golf swing

497   kinematic sequence. *Sports Engineering*, 13 (3), 125 – 133.

498   Wallace, E. S., Otto,S. R., & Nevill, A. (2007). Ball Launch conditions for skilled golfers

499   using drivers of different lengths in an indoor testing facility. *Journal of Sports Sciences,* 25

500   (7), 731 – 737.

501   Weir, J. P., Therapy, P., & Moines, D. (2005). Quantifying test retest reliability using the

502   intraclass correlation coefficient and the SEM. Journal of Strength and *Conditioning*

503   *Research*, 19 (1), 231 – 240.

504   Wicke, J., & Dumas, G. A. (2010). Influence of the volume and density functions within

505   geometric models for estimating trunk inertial parameters. *Journal of Applied Biomechanics,*

506   26 (1), 26 – 31.

507   Wren, T. A. L., Do, P. K., Rethlefsen, S.A., & Healy, B. (2006). Cross-correlation as a

508   method for comparing dynamic electromyography signals during gait. *Journal of*

509   *Biomechanics,* 36 (14), 2714 – 2718.

510   Wu, G., & Cavanagh, P. R. (1995). ISB recommendations for standardisation in the reporting

511   of kinematic data. *Journal of Biomechanics*, 28, 1257–1261.

512   Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., … Stokes, I. (2002).

513   SB recommendation on definitions of joint coordinate system of various joints for the

514   reporting of human joint motion – part I: Ankle, hip and spine. *Journal of Biomechanics*, 35,

515   543–548.

516   Yeadon, M.R. (1990). The simulation of aerial movement II. A mathematical inertia model of

517   the human body. *Journal of Biomechanics*, 23 (1), 67-74.

518   Zheng, N. E. (2008). Kinematic analysis of the swing in pro and amateur golfers.

519   *International Journal of Sports Medicine*, 29, 487 - 493.

520   **Tables**

521

522   **Table 1.** Reliability of ball flight and clubhead characteristics.

Parameter	Club	Test 1	Test 2	*p*	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) ± 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	23.9 ± 11.4	23.9 ± 11.9	0.99	0.8 (2.3)	20.4 ± 4.6	19.3 ± 4.8	0.96	1.0 (2.6)	20.5 ± 3.6	18.0 ± 4.8	0.90	1.2 (3.6)
UB	30.7 ± 4.5	32.4 ± 4.2	0.84	1.8 (4.9)	29.5 ± 3.7	30.1 ± 4.7	0.93	1.2 (3.2)	26.8 ± 3.9	26.3 ± 5.8	0.72	2.5 (7.0)
Arms	87.2 ± 19.7	89.3 ± 21.0	0.97	3.3 (9.1)	83.7 ± 18.5	81.8 ± 19.5	0.99	1.6 (4.4)	79.3 ± 8.0	78.7 ± 11.2	0.97	1.6 (4.5)
Club	269.1 ± 36.8	262.8 ± 26.2	0.92	9.0 (24.8)	259.2 ± 30.7	255.4 ± 27.6	0.88	10.0 (27.6)	231.8 ± 36.1	223.8 ± 41.3	0.98	5.2 (14.4)
Linear												
LB	10.8 ± 6.1	11.6 ± 6.3	0.98	0.8 (2.3)	**7.4 ± 3.1**	**6.3 ± 2.6***	0.95	0.6 (1.9)	6.7 ± 3.9	5.7 ± 3.0	0.95	0.7 (2.0)
UB	14.4 ± 4.8	15.0 ± 4.5	0.95	1.0 (2.9)	12.8 ± 4.9	13.1 ± 5.4	0.99	0.5 (1.5)	12.1 ± 3.9	11.6 ± 3.7	0.94	1.0 (2.7)
Arms	48.5 ± 12.9	48.7 ± 12.9	0.98	1.8 (4.9)	47.6 ± 12.4	46.1 ± 12.6	0.99	1.1 (3.1)	45.4 ± 13.1	44.6 ± 13.0	0.98	1.8 (5.0)
Club	224.4 ± 29.2	228.6 ± 23.7	0.94	6.5 (17.9)	232.0 ± 35.1	223.6 ± 25.4	0.91	8.9 (24.6)	194.2 ± 32.1	190.7 ± 35.9	0.98	4.3 (11.9)
Local Angular												
LB	7.3 ± 2.1	7.4 ± 2.1	0.96	4.2 (1.2)	6.8 ±1.3	6.8 ± 0.9	0.82	0.5 (1.3)	6.8 ± 1.7	6.1 ± 1.1	0.88	0.5 (1.3)
UB	16.4 ± 2.7	17.7 ± 3.0	0.85	1.1 (3.1)	16.6 ± 1.9	17.5 ± 3.4	0.75	1.3 (3.7)	14.8 ± 1.8	15.3 ± 3.5	0.81	1.2 (3.2)
Arms	4.9 ± 1.2	5.1 ± 1.0	0.95	0.3 (0.7)	4.5 ± 1.3	5.0 ± 1.2	0.98	0.2 (0.5)	4.4 ± 1.3	4.4 ± 1.0	0.84	0.5 (1.3)
Club	42.2 ± 4.8	43.2 ± 4.2	0.89	1.5 (4.3)	39.0 ± 6.4	38.0 ± 5.6	0.98	0.9 (2.5)	33.8 ± 5.4	34.1 ± 7.2	0.94	1.5 (4.2)
Remote Angular												
LB	8.8 ± 3.3	8.4 ± 3.5	0.99	0.3 (0.9)	8.6 ± 1.5	8.8 ± 1.1	0.85	0.5 (1.4)	8.6 ± 1.2	7.8 ± 1.9	0.73	0.8 (2.2)
UB	2.4 ± 1.2	2.7 ± 1.3	0.96	0.2 (0.6)	1.9 ± 1.0	1.7 ± 0.9	0.85	0.4 (1.0)	1.8 ± 0.8	1.6 ± 0.5	0.71	0.3 (0.9)
Arms	37.7 ± 8.2	39.9 ± 9.6	0.96	1.9 (5.3)	35.1 ± 7.2	34.6 ± 8.4	0.98	1.0 (2.9)	34.3 ± 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 Kinetic Energy (J) ± SD				5 Iron Kinetic Energy (J) ± SD				9 Iron 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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540 **Figure Captions**

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

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