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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Abstract

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

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

Introduction

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

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

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

The sequencing of segment KE in the golf swing has been examined in two studies (Anderson et al., 2006; Kenny, McCloy, Wallace & Otto, 2008) but neither reported the reliability associated with its measurement. Segment KE is sensitive to even the subtlest changes in technique (Bechard et al., 2009; Ferdinands et al., 2012). This, in addition to the multiple sources of potential error associated with the measurement (collection of 3D linear and angular kinematic data, the definition and computation of body segment axes and the estimation of body segment inertia parameters), mean that before segment KE measurements can be used with confidence, it is important to quantify the associated reliability. Therefore, the aim of this study was to examine the test-retest reliability of measures of the magnitude and timing of peak segment KE in the golf swing. Additionally, the results were also expected to enable subsequent studies and practitioners to determine the meaningfulness of any differences in measures of segment KE (Atkinson & Nevill, 1998). As body segment inertial parameters (Huijbregts, 2002) and 3D linear and angular kinematic golf swing data (Evans, Horan, Neal, Barrett & Mills, 2012) can be measured with high reliability, it was hypothesised that the magnitude and timing of segment KE in the golf swing could be measured with high reliability.

Methods

Participants

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

Instrumentation

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

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

Segment inertial parameter estimation

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

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

The inertial parameters - segment mass, centre of mass location and principal moments of inertia (Ixx, Iyy and Izz) - were calculated using the equations defined by Yeadon (1990), assuming uniform density (Dempster, 1955). In accordance with the International Society of Biomechanics (ISB) guidelines, all local coordinate systems were defined such that the x, y and z axes were predominantly sagittal, longitudinal and frontal directions, respectively.

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

Data Collection

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

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

Data Analysis

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

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

Linear KE ($KE_{L\text{-}RB}$) of each rigid body was calculated using their mass (m) and centre of mass velocity ($\mathbf{v}_{com}$) (Equation 1). Rigid body angular KE ($KE_{A\text{-}RB}$) was calculated using their moment of inertia tensor (**I**) and skew-symmetric angular velocity matrix (**ω**) (Equation 2).

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

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

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

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

where m_i is the mass of the ith constituent rigid body, n is the number of constituent rigid bodies and $\widehat{\boldsymbol{v}}_{com}$ is the segment group's centre of mass linear velocity.

Two forms of angular KE were calculated for each segment group (Outram, 2015). Segment group local angular KE ($KE_{A\text{-}GSl}$) was calculated using equation 4:

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

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

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

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

where m_i and $\boldsymbol{v}_{\boldsymbol{T}_i}$ are the mass and tangential velocity of ith constituent rigid body and n is the number of constituent rigid bodies. The tangential velocity of constituent rigid bodies was calculated as the component of the relative velocity vector between the rigid body centre of mass and the segment group centre of mass, perpendicular to the relative position vector.

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

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

Statistical analysis

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

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

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

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

where SD is the standard deviation for all participants.

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

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

Results

Clubhead and ball flight characteristics

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

Magnitude of peak segment kinetic energy

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

With the driver (Table 2) and 5 iron, acceptable reliability was achieved for the measurement of peak total Lower Body KE. However, with the 9 iron, significantly larger magnitudes of peak total Lower Body KE ($t(6) = 2.50$, $p = 0.039$, $d = 0.39$) were reported in test 1 (20.5 ± 3.6 J) compared with test 2 (18.0 ± 4.8 J). Despite a good ICC (0.945), the magnitude of peak linear Lower Body KE was also significantly larger (t(6) = 3.02, p = 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.

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

Timing of peak segment kinetic energy

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

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

Discussion and Implications

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

For the majority of segments and rigid bodies, the timing of peak segment KE was highly reliable, as similar mean times, low effect sizes and good ICCs were reported. Similar to the findings presented in previous examinations of total segment KE for the Driver, body segment (LB, UB and Arms) KE peaked simultaneously at approximately 74% relative downswing time whilst total Club KE peaked just before impact (Anderson et al., 2006; Kenny et al., 2008). As changes in the timing of peak segment KE are primarily caused by changes in the measurement of linear and angular velocities these results also support the notion that electromagnetic tracking systems are capable of measuring 3D movements with acceptable reliability (An, Jacobsen, Berglund & Chao, 1988; Evans et al., 2012; Horan, Evans, Morris & Kavanagh, 2010).

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

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

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

Although support has been presented for the reliability of segment KE measures in the golf swing some limitations of this study should be noted. The study analysed a limited sample of seven participants of varying ability. Although this sample is reflective of golfers who typically undertake 3D analysis it is likely that the measures of absolute reliability may be conservative for a group of highly skilled players who typically produce less variable golf swings (Cheetham et al., 2007; Mills et al., 2007). Furthermore, to enable accurate club modelling, the same Ping G15 driver and Ping i15 irons with standard length and standard lie angles were used. Golfers with the physical characteristics of those included in this study are likely to require clubs with an increased shaft length (~1/2") and more upright (~1°) lie angle. These alterations in club fit along with changes in swing weight and moment of inertia caused by using standardised clubs may have affected the perceived feel of these clubs by the golfer and subsequently produced altered swing mechanics (Wallace, Otto & Nevill, 2007). However, it has been suggested that club properties have only marginal effects on clubhead characteristics and shot outcome (Betzler, Monk, Wallace & Otto; 2012; MacKenzie & Sprigings, 2009). Therefore, it is anticipated that, as the same clubs were used in both conditions and unlimited familiarisation trials were allowed, club characteristics would have had a minimal effect on the results of this study.

Conclusion

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

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Tables

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)

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)

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

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)

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

Figure Captions

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

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