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considerations for users of geometric modelling methods**

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# **Anatomical and principal axes are not aligned in the torso: considerations for users of geometric modelling methods.**

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# 1 **Abstract**

2 The accuracy and accessibility of methods to calculate body segment inertial parameters are a key concern  
3 for many researchers. It has recently been demonstrated that the magnitude and orientation of principal  
4 moments of inertia are crucial for accurate dynamic models. This is important to consider given that the  
5 orientation of principal axes is fixed for the majority of geometric and regression body models. This paper  
6 quantifies the effect of subject specific geometry on the magnitude and orientation of second moments  
7 of volume in the trunk segment. The torsos of 40 male participants were scanned using a 3D imaging  
8 system and the magnitude and orientation of principal moments of volume were calculated from the  
9 resulting geometry. Principal axes are not aligned with the segment co-ordinate system in the torso  
10 segment, with mean Euler angles of 11.7, 1.9 and 10.3 in the ZXY convention. Researchers using  
11 anatomical modelling techniques should try and account for subject specific geometry and the mis-  
12 alignment of principal axes. This will help to reduce errors in simulation by mitigating the effect of errors  
13 in magnitude of principal moments.

# 14 **Introduction**

15 Body segment inertial parameters (BSIPs) are vital for biomechanical analyses that calculate forward- or  
16 inverse- dynamics of human movement (Hatze, 2002; Nagano et al., 2000) (inverse dynamics are sensitive  
17 to BSIPs primarily in high-acceleration movements such as the golf swing (Domone, 2014)). The accuracy  
18 and accessibility of methods to calculate BSIPs are, therefore, a key concern for many researchers. Medical  
19 imaging technologies that can be used to obtain gold-standard, subject-specific BSIPs (Cheng et al., 2000;  
20 Pearsall et al., 1996; Wicke & Dumas, 2008) remain inaccessible for many researchers. As a result, many  
21 in the community rely on datasets and models to calculate BSIPs from a small number of anthropometric

22 measurements. The methods fall into two categories: 1) regression techniques estimate an individual's  
23 BSIP values through the application of equations to measurements of segment lengths and/or body  
24 weight and/or height (Yeadon & Morlock, 1989), 2) geometric methods approximate segments as a series  
25 of scaled 3D shapes, the BSIPs are then calculated using appropriate mathematical formulae and density  
26 values (Jensen, 1978; Wicke et al., 2009; Yeadon, 1990). Geometric methods better account for individual  
27 variation in volumetric proportion and distribution compared to regression techniques. However, the  
28 datasets on which regression models are based, and on which geometric methods are validated, have  
29 been relatively homogenous in terms of sex and age compared to the variability observed in the total  
30 population. The specifics of BSIP estimations have sustained interest from the research community for  
31 many decades (Challis, 1999; de Leva, 1996; Dumas et al., 2007; Durkin & Dowling, 2003; M. M. Rossi et  
32 al., 2016; Yeadon & Morlock, 1989).

33 This paper focuses on the magnitude of moments of inertia, centre of mass location and orientation of  
34 principal axes. Rossi et al. (M. M. Rossi et al., 2016) recently showed the importance of moments of inertia  
35 and quantified the effect of errors in the magnitude and orientation of principal moments. The motion of  
36 a cylinder was tracked in three dimensions and also simulated using forward dynamics. The simulations  
37 introduced errors of up to 10% in the principal moments and up to 10° of misalignment in the principal  
38 axes. Errors were expressed as angular deviations between the dynamic simulation and recorded motion.  
39 Errors up to 10% in magnitude of principal moments of inertia resulted in root mean squared deviation  
40 angles ranging between 3.2° and 6.6°, and between 5.5° and 7.9° when lumped with errors of 10° in  
41 principal axes of inertia orientation.

42 When calculating BSIPs, errors in the magnitude of moments of inertia have been shown to be  
43 proportionally higher compared to other inertial parameters (mass, centre of mass position) (M. Rossi,  
44 Lytle, & El-Sallam, 2013) and most methods do not allow subject-specific alignment of the principal axes.  
45 In regression-based studies, product moments of inertia are often acknowledged but not included in

46 calculations (Chandler et al., 1975; Zatsiorsky & Seluyanov, 1983). Mcconville and Churchill (McConville et  
47 al., 1980), presented full inertial tensors which were made more applicable by Dumas et al. (Dumas et al.,  
48 2007) through a change in co-ordinate system. We are aware of only one geometric method in which the  
49 principal axes are not implicitly aligned with the anatomical axes (Jensen, 1978). Given the continued use  
50 of regression and geometric models there is a need to quantify the extent to which their use might affect  
51 the accuracy of biomechanical simulation.

52 To better account for individual variations in segment geometry, new methods of calculating BSIPs have  
53 been explored using 3D imaging technology (Bullas et al., 2016; S Clarkson et al., 2014, 2012; Sean  
54 Clarkson et al., 2015; Kordi et al., 2019). While anatomical landmarking and segmentation of the resulting  
55 geometry is not trivial, it promises a cost-effective way to account for individual differences in body shape  
56 and avoid the symmetrical assumptions of traditional geometric methods. However, the technology  
57 cannot determine tissue density and its distribution. Thus, any analysis must either assume a constant  
58 density, use a density profile function or restrict analysis to volumetric parameters. Previous research has  
59 shown that inertial parameters are more sensitive to variations in geometry than variations in density  
60 (Wicke & Dumas, 2010).

61 The study presented in this paper uses a 3D imaging system to quantify the effect of subject specific  
62 geometry on the magnitude and orientation of second moments of volume<sup>1</sup> in the trunk segment. It does  
63 so by making a comparison to a geometric modelling method, putting into context the work of Rossi et al.  
64 (M. M. Rossi et al., 2016). This will allow users of geometric modelling methods to quantify the likely  
65 magnitude of errors resulting from their use in simulation.

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<sup>1</sup> In this paper we will mostly disregard density information and consider the following body segment volume parameters (BSVPs): volume, centre of volume and second moment of volume.

## 66 **Methods**

### 67 **Participants**

68 Forty-one male participants (Mass  $77.3 \pm 9.1$  Kg, stature  $1.81 \pm 0.06$  m, BMI  $23 \pm 2$ ) volunteered to take  
69 part in the study and provided written informed consent. Participants were recreationally active and able  
70 to stand in a stationary, upright position. Ethical approval was granted by our university Research Ethics  
71 Committee.

72 The profile of each participant's torso was obtained using two methods: geometric modelling and 3D  
73 imaging.

74 Yeadon's stadium solids (Yeadon, 1990) were used as the geometric method due to their wide application  
75 and relative complexity. Yeadon's method demonstrated low overall error compared to other methods of  
76 calculating BSIPs (M. Rossi, Lyttle, & El-Sallam, 2013) and is still being developed and utilised by  
77 researchers (Dembia et al., 2015). The regions of interest and corresponding stadium solids are shown in  
78 Figure 2.

### 79 **Imaging system**

80 The 3D imaging system was developed using consumer-level depth cameras and its accuracy and  
81 repeatability has been validated in previous studies (Bullas et al., 2016; Sean Clarkson et al., 2015). It  
82 comprised four depth cameras (Microsoft Kinect version 1, Microsoft Corporation, Redmond, USA)  
83 mounted in a vertical orientation (Figure 1a). The depth cameras were affixed to four tripods, and located  
84 0.8 m from the centre of a 0.4 m x 0.4 m x 1.2 m capture volume.

85 A single computer running custom software (Kinanthroscan, Sheffield Hallam University, UK) was used to  
86 control the depth cameras, perform calibration, and capture scans. The scan time was ~1 second.

## 87 **Manual measurement protocol**

88 Upon arrival, participants were asked to remove clothing from their upper body and change into a pair of  
89 close fitting, non-compressive shorts. The stature and weight of each participant were recorded using a  
90 stadiometer and digital scales. Anatomical landmarks (Figure 2) were palpated and marked by an  
91 International Society for the Advancement of Kinanthropometry (ISAK) level one qualified practitioner.  
92 Girth and breadth measurements were taken at the level of each set of landmarks using anatomical tape  
93 and digital callipers (Kennedy, Leicester, UK), respectively. The length of each segment was also measured  
94 using the digital callipers. Each measurement was repeated three times and mean values taken. These  
95 measurements were used in conjunction with Yeadon's formulae (Yeadon 1990b) to model the three  
96 stadium solids representing the trunk and their related inertial parameters. Throughout the manual  
97 measurement process, the same body control techniques as those used for the scanning process,  
98 discussed below, were adopted by the participant.

## 99 **Imaging protocol**

100 After manual measurement and palpation, participants entered the calibrated scanning volume.  
101 Anatomical markers were used for segmentation and to generate a local segment co-ordinate system.  
102 Each participant was scanned three times. A break of one minute was interspersed between each scan  
103 during which the participant left and re-entered the calibrated volume. Footprint markers in the centre  
104 of the capture volume ensured participants stood in the same location for each scan (Kirby et al., 1987).  
105 Participants were asked to adopt a modified version of the scanning pose defined by ISO 20685-1 (ISO,

106 2018), arms were held out from the torso at an angle of approximately 45° to ensure underarm areas  
107 were visible in the scans.

108 Two tripods were used as hand supports were used to limit involuntary movement during scanning. The  
109 height and position of the supports were adjusted prior to scanning and a goniometer ensured the  
110 participant's arms were at 45°. Participants were asked to hold their breath at the end of the natural  
111 expiration cycle to reduce movement (Schranz et al., 2010).

## 112 **Imaging post processing and volume calculation**

113 After collection, each 3D scan was manually digitised by a single operator using kinanthroscan software.  
114 Four markers were digitised on each scan, both of the ASIS markers and both of the nipple markers. An  
115 anatomical axes system was created in agreement with ISB recommendations (Wu et al., 2005) such that  
116 the x-axis ran posterior-anterior, the y-axis ran inferior-superior and the z-axis ran from the participants'  
117 left-right (figure 3). The system was set-up as follows (referring to figure 3):

- 118 • Two markers were created:  $M1^*$  and  $M4^*$ , as the midpoints of the vectors  $\overline{M1M2}$  and  $\overline{M4M5}$
- 119 • Two horizontal vectors (perpendicular to  $\overline{M1M2}$  and  $\overline{M4M5}$ ) were projected from  $M1^*$  and  $M4^*$ .  
120 The locations at which these vectors intersected the surface of the scan formed markers  $M3$  and  
121  $M6$ .
- 122 • The **origin**  $O$  was located at the midpoint of vector  $\overline{M1^*M3}$
- 123 • The **x-axis**  $X$  was initially defined as the vector  $\overline{OM1^*}$
- 124 • The **y-axis**  $Y$  was defined as the vector from the origin to the midpoint of  $\overline{M4^*M6}$
- 125 • The **z-axis**  $Z$  was defined as the cross product of  $X$  and  $Y$ :  $Z = X \times Y$



126 • The **x-axis** was re-defined (to ensure an orthogonal co-ordinate set) as the cross product of Y and  
 127 Z:  $X = Y \times Z$

128 Volume, centre of volume position and second moments of volume were calculated the scan data, which  
 129 consisted of a series of unconnected data points. The scan was constrained to only include data points  
 130 relating to the torso segment. The torso's scan data were split along the y-axis into 2 mm 'slices' ( the  
 131 minimum permissible size to ensure features were accurately represented). A cubic spline was fitted  
 132 through each slice (as a representation of its perimeter) and used to calculate the inertial parameters.

133 **Calculation of volume**

134 The volume of the segment was calculated by summing the volumes of each slice which was calculated  
 135 by multiplying the area within its perimeter by the slice's height (2 mm). The area within a slice's perimeter  
 136 was calculated by dividing the space into 360 triangles with the apex of each located at the centroid -- the  
 137 area of each triangle was summed.

138 **Calculation of the 2<sup>nd</sup> moments of volume**

139 The moments of volume were calculated using Crisco and McGovern's application of Green's Theorem  
 140 (Crisco & McGovern, 1998). The spline representing the perimeter was sampled at 360 points for each of  
 141 the S slices. With the local x, y and z coordinates of each point the moments of inertia can be calculated  
 142 from:

143 
$$I_{xx} = \sum_{s=1}^S dy \times \sum_{p=1}^{360} \left( u(s,p) \cdot y(s)^2 \cdot dz(s,p) - \frac{1}{3} v(s,p)^3 \cdot dx(s,p) \right)$$

144 
$$I_{yy} = \sum_{s=1}^S dy \times \sum_{p=1}^{360} \left( \frac{1}{3} u(s,p)^3 \cdot dz(s,p) - \frac{1}{3} v(s,p)^3 \cdot dx(s,p) \right)$$

145 
$$I_{zz} = \sum_{s=1}^S dy \times \sum_{p=1}^{360} \left( \frac{1}{3} u(s,p)^3 \cdot dz(s,p) - y(s)^2 \cdot v(s,p) \cdot dx(s,p) \right)$$

146 where  $u(s,p) = \frac{x(s,p+1)+x(s,p)}{2}$ ,  $v(s,p) = \frac{z(s,p+1)+z(s,p)}{2}$

147  $y(s) = 0.002(s - 1) + 0.001$

148  $dx(s,p) = x(s,p + 1) - x(s,p)$ ;  $dy = 0.002$ ;  $dz(s,p) = z(s,p + 1) - z(s,p)$

149 The y co-ordinate was set to the midpoint position of the slice being analysed.

150 **Calculation of centre of volume position**

151 In a similar way, the centre of volume location was calculated in the local x, y, and z directions by:

152 
$$c_x \cdot V = \sum_{p=1}^{360} \left( \frac{1}{2} u(s,p)^2 \cdot dz(s,p) \right)$$

153 
$$c_y \cdot V = \sum_{p=1}^{360} \left( \frac{1}{2} u(s,p) \cdot dz(s,p) - \frac{1}{2} v(s,p) \cdot dx(s,p) \right)$$

154 
$$c_z \cdot V = - \sum_{p=1}^{360} \left( \frac{1}{2} v(s,p)^2 \cdot dx(s,p) \right)$$

155 Equivalent inertial parameters were obtained from the geometric representations using the manual  
 156 measurements in conjunction with Yeadon’s formulae (Yeadon 1990b). Yeadon’s original paper details  
 157 the equations so they aren’t repeated here, they have also recently been implemented in Python code  
 158 that is available as open source (Dembia et al., 2015). It should be noted that density was disregarded in  
 159 our calculations (the equivalent of setting  $\rho=1$ ). The parallel axis theorem was used to combine the  
 160 separate stadium solids and to translate the origin to the centre of the lower face of the lower segment  
 161 (the equivalent position to the 3D imaged torso). When calculating geometric parameters the height of

162 the upper and lower trunk were adjusted so that the overall height of the torso matched that of the 3D  
163 scan. This was to prevent differences in a single dimension dominating differences in volumetric  
164 parameters.

## 165 **Data analysis**

166 The agreement between volume and second moments of volume estimates were assessed using limits of  
167 agreement (LOA) (Bland & Altman 1986). The repeatability of measurement of each technique was  
168 assessed by calculating the repeatability coefficient (Bland & Altman, 2003) for volume, centre of volume  
169 and second moment of volume.

170 Geometric differences between each technique were assessed by calculating the relative orientations of  
171 the principal axes, calculated as 'ZXY' Euler angles.

## 172 **Simulation**

173 To assess the effect of the differences in inertial properties, simulations were set-up in Opensim (v. 4.1,  
174 simtk.org, Stanford, CA) via the Matlab (v. 9.9.0, The Math Works, Natick, Massachusetts) Application  
175 Programming Interface (API).

176 We simulated a single, unconnected and rigid segment in two separate movements: a free and a driven  
177 motion. In the free motion the segment was freely supported and rotated at a speed of  $2\pi$  rad/s about  
178 the z-axis. In the driven motion a torque of 1 Nm acted about the segment's y-axis for 0.1 s. The segment  
179 was fixed with a ball-joint at its anatomical origin (the lower extremity).

180 Inertial properties were calculated by multiplying volumetric parameters by a density value of 0.97. This  
181 is an average of the values used by Yeadon (Yeadon, 1990) for the thorax and abdomen (0.92 and 1.01

182 respectively) that were originally taken from Dempster (Dempster, 1955). This resulted in two sets of data,  
183 a set of parameters obtained using the geometric method and a set of parameters obtained using the 3D  
184 imaging method.

185 Both scenarios were run with each set of inertial parameters, angular positions and velocities of the  
186 geometric data set were compared with those of the 3D imaging data set. This was done for each  
187 participant, resulting in 160 simulations in total. The following comparisons were made:

188 1) The free motion simulations were run for 1 second. The angular deviation (from an axis-angle  
189 representation) between segment orientations (geometric and 3D imaging) were assessed for each  
190 participant.

191 2) The driven motion simulations were run for 0.1 seconds to assess:

192 a) differences in rotational speed between geometric and 3D imaging segments for each  
193 participant.

194 b) the angle between the axes of rotation for geometric and 3D imaging segments for each  
195 participant.

## 196 **Results**

197 Due to problems during data collection, data relating to one participant were removed from this study.  
198 Therefore, the results relate to forty participants. The mean volume, centre of volume and principal  
199 moments for each participant are provided as supplementary material (with repeatability coefficients)  
200 and are summarised in table 1.

## 201 **Agreement between methods**

202 Figure 4 shows the agreement between scan-derived and Yeadon-derived volume, assessed using limits  
203 of agreement (accounting for the fact three repeats were taken for each participant rather than single  
204 measurements (Bland & Altman, 1999)).

205 The volume calculated using the scan method agreed with the geometric method to  $-0.22 \pm 1.58$  litres.  
206 Limits of agreement were  $-1.80$  litres and  $1.35$  litres or  $-9.96\%$  and  $7.39\%$  of average torso volume. Volume  
207 estimates calculated using the geometric method tend to be  $0.22$  litres higher than using the geometric  
208 method but this systematic difference is small compared to the random differences between them. A  
209 systematic difference of  $-1.3\%$  and a mean absolute difference of  $3.2\%$  was observed.

210 Figure 5 shows the agreement between scan-derived and Yeadon-derived second moments of volume  
211 along the principal axes. Along the first principal axis the scan method agreed with the geometric method  
212 to  $-0.87 \pm 2.76 \text{ m}^5 \times 10^{-5}$ . The limits of agreement were  $-3.63 \text{ m}^5 \times 10^{-5}$  to  $1.89 \text{ m}^5 \times 10^{-5}$ . Along the second  
213 principal axis the scan method agreed with the geometric method to  $-1.68 \pm 2.80 \text{ m}^5 \times 10^{-5}$ . The limits of  
214 agreement were  $-4.48 \text{ m}^5 \times 10^{-5}$  to  $1.12 \text{ m}^5 \times 10^{-5}$ . Along the third principal axis the scan method agreed with  
215 the geometric method to  $0.34 \pm 2.39 \text{ m}^5 \times 10^{-5}$ . The limits of agreement were  $-2.05 \text{ m}^5 \times 10^{-5}$  to  $2.73 \text{ m}^5 \times 10^{-5}$ .  
216 Systematic differences of  $-3.2\%$ ,  $-7.7\%$  and  $1.9\%$  and mean absolute differences of  $3.9\%$ ,  $8.6\%$  and  $5.7\%$   
217 around the first, second and third principal axes were observed between the two methods.

218

## 219 **Repeatability of Measurement**

220 The geometric method was marginally more repeatable than the scanning method regarding volume, with  
221 a 95% probability that 2 measurements will be within  $0.96$  litres as opposed to  $1.12$  litres with scanning.

222 Repeatability of the second moment of volume was similar in magnitude around the second principal axis  
223 for both methods. The geometric method had better repeatability around the first and third principal  
224 axes. Coefficients of repeatability were 3.00, 2.60 and 1.80  $m^5 \times 10^5$  (10.7%, 11.8% and 10.0% of mean  
225 values) for scanning compared to 2.36, 2.62 and 1.19  $m^5 \times 10^5$  (8.8%, 12.6% and 6.26% of mean values) for  
226 the geometric method.

## 227 **Centre of Volume**

228 In the scan method, the centre of volume was positioned anterior to the origin of the local coordinate  
229 system in all cases (mean = 22.2 mm, range 11.2-29.8 mm). The scanned segments were approximately  
230 symmetrical in the frontal plane (with a mean medio-lateral (z) position of 0.5 mm, range -7.3-4.7 mm).  
231 Mean centre of mass position along the y-axis was similar between scanning and geometric methods  
232 (159.2 and 160.1 mm for scanning and geometric methods respectively).

## 233 **Principal Axes**

234 In the geometric method the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> principal moments were, by default, aligned with the sagittal  
235 (x), transverse (z) and vertical (y) axes respectively. With the scanning method, the principal moments  
236 were not restricted by the calculation method and alignment could vary from with the anatomical axes-  
237 system. The discrepancy in alignment between the two methods was expressed as Euler angles in the ZXY  
238 convention (table 2). The first Euler angle was, on average 11.8° which reflects the tendency of the third  
239 principal axis to be directed towards the superior anterior aspect of the torso when using the 3D imaging  
240 method. The third Euler angle had a mean of 10.3° but a median of 4.3° due to a small number of large  
241 values. In two participants the 1<sup>st</sup> and 2<sup>nd</sup> principal moments were switched in comparison to the  
242 geometric method, this corresponded to a third Euler angle of around 90 degrees. The repeatability

243 coefficient of the third Euler angle had a mean of 13.3° but a median of 4.5°. This discrepancy is due to  
244 three individuals having very poor repeatability (14, 22, 35).

## 245 **Simulation Results**

246 Figure 6 shows the range of differences obtained during rigid body simulation and the relationship with  
247 inertial properties.

248 As the difference in moment of inertia about the local y-axis increased (between the geometric and 3D  
249 imaging methods) the rotational speed of the segment in the driven motion decreased, figure 6a ( $r = -$   
250 0.99). The magnitude of differences in  $I_y$  observed in this study resulted in differences of angular velocity  
251 between -16.2% and 21.0%.

252 Scanned centre of mass locations away from a segment's y-axis resulted in differences in the angular  
253 velocity vector orientation (compared to the geometric simulation). Angular difference increased as the  
254 centre of mass moved away from the y-axis (in the local x-direction,  $r = 0.92$ ) as shown in figure 6b. The  
255 centre of mass locations observed in this study resulted in deviations in the angular velocity vector  
256 between 4.3° and 9.6°.

257 The presence of product moments of inertia (a misalignment between the principal axes and anatomical  
258 axes) resulted in off-axis rotations during the free rotation. Deviation angles between geometric and 3D  
259 imaging segments are illustrated in figure 6c and they are correlated with the magnitude of product  
260 moments of inertia (specifically,  $I_{xz}$  and  $I_{yz}$  as the initial rotation is about the local z-axis,  $r = 0.81$ ). The  
261 inertial properties observed in this study resulted in deviation angles between 0.6° and 27.3°.

262

## 263 Discussion

264 Geometric modelling methods use a series of anthropometric measurements to create a (most often  
265 symmetrical) representation of the torso. In reality, the presence of off-centre mass violates symmetrical  
266 assumptions –no individual’s principal and anatomical axes were aligned in our study, with mean Euler  
267 angles (ZXY) of 11.65, 1.93 and 10.31° between the two. The torso segment was chosen in this study as it  
268 is large and central to many biomechanical analyses (MacKenzie & Sprigings, 2009; Nesbit, 2005; Ren et  
269 al., 2008; Winter, 1995). As a segment, it is also likely to violate symmetrical assumptions due to varying  
270 amounts of off-centre mass in the form of adipose tissue. Future studies that adopt a similar approach  
271 should consider using the acromion process of the shoulders as opposed to the nipples for anatomical  
272 markers – this will allow the research include female participants.

273 Many geometric modelling methods have been developed and assessed using young, athletic participants  
274 (M. Rossi, Lyttle, & El-Sallam, 2013; Yeadon, 1990). This study is similar, with a mean BMI of 23 (full range  
275 19 – 29). All users of modelling methods should assume that principal and anatomical axes do not align in  
276 the torso segment, regardless of the participant population. However, biomechanical analyses considering  
277 overweight populations should pay particular attention to the method used to calculate individual BSIPs.  
278 The presence of atypical geometry that presents off-centre mass is more likely and researchers should  
279 anticipate larger deviations than those presented here. Given the random variation in orientation and  
280 magnitude differences observed in this study, systematically correcting principal moments is not possible  
281 and users should aim to use more sophisticated methods than geometric modelling for obtaining BSIPs of  
282 the torso segment.

283 The simulated motions were included to highlight how differences in the magnitudes of principal  
284 moments of inertia, a centre of mass lying away from the segments’ y-axis and a mis-alignment between



285 principal and anatomical axes manifest in altered dynamic behaviour. In reality, the simulations will be  
286 more complex than the simple cases presented here. While the simulated motions are illustrative, the  
287 differences in inertial properties between methods are representative because they are based on the  
288 results presented in this study. It should be noted that during the simulation we used a single, uniform  
289 density for all cases. Future studies with sophisticated models assessing representative motions should  
290 aim to use realistic density profiles.

291 Of the three comparisons made in figure 6, the position of the centre of mass should be considered  
292 carefully, it is the only one of three comparisons which does not have differences in simulation close to  
293 zero. Even with participants that may be close to the 'geometric ideal' off centre mass is always present  
294 and results in differences in simulation that shouldn't be dismissed. If researchers have the opportunity  
295 or means, they should attempt to account for centre of mass position as a priority.

296 Future work should attempt to fully quantify the effect of errors in BSIP errors in a realistic simulation –  
297 for example, in a high-acceleration driven motion such as a golf-swing or a free aerial motion such as a  
298 front flip.

299 Agreement in volume between the two methods was good, with a low ( $\approx 1\%$  of mean) systematic error  
300 and limits of agreement within 10% of the mean volume; mean differences were similar to other  
301 agreement studies examining the Yeadon method (M. Rossi, Lyttle, El-Sallam, et al., 2013). While the  
302 strength of agreement was lower with second moments of volume, the mean errors in this study are lower  
303 than those recorded previously when comparing geometric methods against techniques using dual X-ray  
304 absorptiometry (DXA) (M. Rossi, Lyttle, & El-Sallam, 2013). A major difference in the previous study (M.  
305 Rossi, Lyttle, & El-Sallam, 2013) was the specific density profiles afforded by the DXA scan (compared to  
306 the uniform density of the Yeadon model). In addition, realistic body models should contain non-rigid  
307 elements. This study assumed rigid bodies. The effects of geometry on inertial (volumetric) properties was

308 the primary focus of this paper and non-rigid modelling was beyond the scope of this work. Future work  
309 would benefit from combining the realistic geometries obtained by 3D imaging with non-rigid modelling.  
310 This could help to quantify the magnitude of off-centre masses in the abdomen and predict how it may  
311 deform under load.

## 312 **Conclusions**

- 313 • The participant specific advantages of geometric modelling methods are lost when symmetric  
314 assumptions are violated. Off-set mass was observed for every participant in this study.
- 315 • One should expect principal axes to be misaligned with anatomical axes when assessing the torso  
316 segment.
- 317 • Low-cost 3D scanning techniques offer a potential solution when more sophisticated medical  
318 imaging (such as DXA) is unavailable, however, the effect of variable density is still not accounted  
319 for.

## 320 **Conflicts of Interest**

321 The authors declare they have no conflicts of interest.

322

# References

- 324 Bland, J. M., & Altman, D. G. (1999). Measuring agreement in method comparison studies - Statistical  
 325 Methods in Medical Research | SwetsWise Online Content. *Statistical Methods in Medical Research*,  
 326 8, 135–160. [https://www-swetswise-com.libproxy.ucl.ac.uk/swoc-](https://www-swetswise-com.libproxy.ucl.ac.uk/swoc-web/linkingDetails.html?openURL=false&issn=0962-2802&eissn=0962-2802&volume=8&issue=2&page=135)  
 327 [web/linkingDetails.html?openURL=false&issn=0962-2802&eissn=0962-](https://www-swetswise-com.libproxy.ucl.ac.uk/swoc-web/linkingDetails.html?openURL=false&issn=0962-2802&eissn=0962-2802&volume=8&issue=2&page=135)  
 328 [2802&volume=8&issue=2&page=135](https://www-swetswise-com.libproxy.ucl.ac.uk/swoc-web/linkingDetails.html?openURL=false&issn=0962-2802&eissn=0962-2802&volume=8&issue=2&page=135)
- 329 Bland, J. M., & Altman, D. G. (2003). Applying the right statistics: Analyses of measurement studies.  
 330 *Ultrasound in Obstetrics and Gynecology*, 22(1), 85–93. <https://doi.org/10.1002/uog.122>
- 331 Bullas, A. M., Choppin, S., Heller, B., & Wheat, J. (2016). Validity and repeatability of a depth camera-based  
 332 surface imaging system for thigh volume measurement. *Journal of Sports Sciences*, 34(20), 1998–  
 333 2004. <https://doi.org/10.1080/02640414.2016.1149604>
- 334 Challis, J. H. (1999). Precision of the Estimation of Human Limb Inertial Parameters. *Journal of Applied*  
 335 *Biomechanics*, 15(4), 418–428. <https://doi.org/10.1123/jab.15.4.418>
- 336 Chandler, R. F., Clauser, C. E., McConville, J. T., Reynolds, H. M., & Young, J. W. (1975). Investigation of  
 337 inertial properties of the human body. In *National Highway Traffic Safety Administration*.  
 338 <https://doi.org/10.1017/CBO9781107415324.004>
- 339 Cheng, C. K., Chen, H. H., Chen, C. S., Lee, C. L., & Chen, C. Y. (2000). Segment inertial properties of Chinese  
 340 adults determined from magnetic resonance imaging. *Clinical Biomechanics*, 15, 559–566.  
 341 [https://doi.org/10.1016/S0268-0033\(00\)00016-4](https://doi.org/10.1016/S0268-0033(00)00016-4)
- 342 Clarkson, S, Choppin, S. B., Hart, J., Heller, B., & Wheat, J. S. (2012). Calculating Body Segment Inertia  
 343 Parameters from a Single Rapid Scan Using the Microsoft Kinect. *3rd International Conference and*  
 344 *Exhibition on 3D Body Scanning, October*, 153–163.
- 345 Clarkson, S, Wheat, J. S., Heller, B., & Choppin, S. B. (2014). Assessing the Suitability of the Microsoft Kinect  
 346 for Calculating Person Specific Body Segment Parameters. *4th IEEE Workshop on Consumer Depth*  
 347 *Cameras for Computer Vision*.
- 348 Clarkson, S, Wheat, J. S., Heller, B., Webster, J., & Choppin, S. B. (2013). Distortion Correction of Depth  
 349 Data from Consumer Depth Cameras. In N. D’Apuzzo (Ed.), *4th International Conference and*  
 350 *Exhibition on 3D Body Scanning*.
- 351 Clarkson, Sean, Wheat, J., Heller, B., & Choppin, S. (2015). Assessment of a Microsoft Kinect-based 3D  
 352 scanning system for taking body segment girth measurements: a comparison to ISAK and ISO  
 353 standards. *Journal of Sports Sciences*, 1–9. <https://doi.org/10.1080/02640414.2015.1085075>
- 354 Crisco, J. J., & McGovern, R. D. (1998). Efficient calculation of mass moments of inertia for segmented  
 355 homogeneous three-dimensional objects. *Journal of Biomechanics*, 31(1), 97–101.  
 356 <http://www.ncbi.nlm.nih.gov/pubmed/9596545>
- 357 de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov’s segment inertia parameters. *Journal of*  
 358 *Biomechanics*, 29(9), 1223–1230. [https://doi.org/10.1016/0021-9290\(95\)00178-6](https://doi.org/10.1016/0021-9290(95)00178-6)
- 359 Dembia, C., Moore, J. K., & Hubbard, M. (2015). An object oriented implementation of the Yeadon human  
 360 inertia model. *F1000Research*, 3, 223. <https://doi.org/10.12688/f1000research.5292.2>

361 Dempster, W. T. (1955). Space requirements of the seated operator. *WADC Technical Report 55159*,  
362 55(WADC-55-159, AD-087-892), 55–159. [http://www.mendeley.com/research/space-](http://www.mendeley.com/research/space-requirements-of-the-seated-operator/)  
363 [requirements-of-the-seated-operator/](http://www.mendeley.com/research/space-requirements-of-the-seated-operator/)

364 Domone, S. (2014). *Validation and uncertainty of inverse dynamics analysis applied to high acceleration*  
365 *movements* [Sheffield Hallam University]. <http://shura.shu.ac.uk/23508/1/10760405.pdf>

366 Dumas, R., Chèze, L., & Verriest, J. P. (2007). Adjustments to McConville et al. and Young et al. body  
367 segment inertial parameters. *Journal of Biomechanics*, 40(3), 543–553.  
368 <https://doi.org/10.1016/j.jbiomech.2006.02.013>

369 Durkin, J. L., & Dowling, J. J. (2003). Analysis of Body Segment Parameter Differences Between Four Human  
370 Populations and the Estimation Errors of Four Popular Mathematical Models. *Journal of*  
371 *Biomechanical Engineering*, 125(4), 515. <https://doi.org/10.1115/1.1590359>

372 Hatze, H. (2002). The fundamental problem of myoskeletal inverse dynamics and its implications. *Journal*  
373 *of Biomechanics*, 35(1), 109–115. <http://www.ncbi.nlm.nih.gov/pubmed/11747889>

374 ISO. (2018). *3-D scanning methodologies for internationally compatible anthropometric databases*.

375 Jensen, R. K. (1978). Estimation of the biomechanical properties of three body types using a  
376 photogrammetric method. *Journal of Biomechanics*, 11(8–9), 349–358.  
377 [https://doi.org/10.1016/0021-9290\(78\)90069-6](https://doi.org/10.1016/0021-9290(78)90069-6)

378 Kirby, R. L., Price, N. A., & MacLeod, D. A. (1987). The influence of foot position on standing balance.  
379 *Journal of Biomechanics*, 20(4), 423–427. [https://doi.org/10.1016/0021-9290\(87\)90049-2](https://doi.org/10.1016/0021-9290(87)90049-2)

380 Kordi, M., Haralabidis, N., Huby, M., Barratt, P. R., Howatson, G., & Wheat, J. S. (2019). Reliability and  
381 validity of depth camera 3D scanning to determine thigh volume. *Journal of Sports Sciences*, 37(1),  
382 36–41. <https://doi.org/10.1080/02640414.2018.1480857>

383 MacKenzie, S. J., & Sprigings, E. J. (2009). A Three-Dimensional Forward Dynamics Model of the Golf Swing.  
384 *Sports Engineering*, 11, 165–175.

385 McConville, J. T., Clauser, C. E., Churchill, T. D., Cuzzi, J., & Kaleps, I. (1980). Anthropometric Relationships  
386 of Body and Body Segment Moments of Inertia. In *Report*.  
387 <https://doi.org/10.1073/pnas.0710346105>

388 Nagano, a, Gerritsen, K. G., & Fukashiro, S. (2000). A sensitivity analysis of the calculation of mechanical  
389 output through inverse dynamics: a computer simulation study. *Journal of Biomechanics*, 33(10),  
390 1313–1318. <http://www.ncbi.nlm.nih.gov/pubmed/10899342>

391 Nesbit, S. (2005). A three dimensional kinematic and kinetic study of the golf swing. *Journal of Sports*  
392 *Science and Medicine*, 4, 499–519. <http://jsportscimed.org/vol4/n4/17/v4n4-17pdf.pdf>

393 Pearsall, D. J., Reid, J. G., & Livingston, L. A. (1996). Segmental inertial parameters of the human trunk as  
394 determined from computed tomography. *Annals of Biomedical Engineering*, 24(2), 198–210.  
395 <https://doi.org/10.1007/BF02667349>

396 Ren, L., Jones, R. K., & Howard, D. (2008). Whole body inverse dynamics over a complete gait cycle based  
397 only on measured kinematics. *Journal of Biomechanics*, 41, 2750–2759.  
398 <https://doi.org/10.1016/j.jbiomech.2008.06.001>

399 Rossi, M., Lyttle, A., & El-Sallam, A. (2013). Body segment inertial parameters of elite swimmers using DXA  
400 and indirect methods. *Journal of Sports Science and Medicine*, 12, 761–775.  
401 <http://jssm.org/vol12/n4/19/v12n4-19pdf.pdf>

402 Rossi, M., Lyttle, A., El-Sallam, A., Benjanuvatra, N., & Blanksby, B. (2013). Body segment inertial  
403 parameters of elite swimmers using DXA and indirect methods. *Journal of Sports Science and*  
404 *Medicine*, *12*(4), 761–775.

405 Rossi, M. M., Alderson, J., El-Sallam, A., Dowling, J., Reinbolt, J., & Donnelly, C. J. (2016). A new validation  
406 technique for estimations of body segment inertia tensors: Principal axes of inertia do matter.  
407 *Journal of Biomechanics*, *49*(16), 4119–4123. <https://doi.org/10.1016/j.jbiomech.2016.10.006>

408 Schranz, N., Tomkinson, G., Olds, T., & Daniell, N. (2010). Three-dimensional anthropometric analysis:  
409 Differences between elite Australian rowers and the general population. *Journal of Sports Sciences*,  
410 *28*(5), 459–469. <https://doi.org/10.1080/02640411003663284>

411 Stewart, A., Marfell-Jones, M., Olds, T., & de Ridder, H. (2011). *International Standards for Anthropometric*  
412 *Assessment*.

413 Wicke, J., & Dumas, G. A. (2008). Estimating Segment Inertial Parameters Using Fan-Beam DXA. *Journal of*  
414 *Applied Biomechanics*, *24*(2), 180–184. <https://doi.org/10.1123/jab.24.2.180>

415 Wicke, J., Dumas, G. A., & Costigan, P. A. (2009). A comparison between a new model and current models  
416 for estimating trunk segment inertial parameters. *Journal of Biomechanics*, *42*(1), 55–60.  
417 <https://doi.org/10.1016/j.jbiomech.2008.10.003>

418 Wicke, J., & Dumas, G. a. (2010). Influence of the volume and density functions within geometric models  
419 for estimating trunk inertial parameters. *Journal of Applied Biomechanics*, *26*(1), 26–31.  
420 <http://www.ncbi.nlm.nih.gov/pubmed/20147755>

421 Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait and Posture*,  
422 *3*, 193–214. [https://doi.org/10.1016/0966-6362\(96\)82849-9](https://doi.org/10.1016/0966-6362(96)82849-9)

423 Wu, G., Vanderhelm, F., Dirkjanveeger, H., Makhsous, M., Vanroy, P., Anglin, C., Nagels, J., Karduna, A.,  
424 Mcquade, K., & Wang, X. (2005). ISB recommendation on definitions of joint coordinate systems of  
425 various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand.  
426 *Journal of Biomechanics*, *38*(5), 981–992. <https://doi.org/10.1016/j.jbiomech.2004.05.042>

427 Yeadon, M. R. (1990). The simulation of aerial movement--II. A mathematical inertia model of the human  
428 body. *Journal of Biomechanics*, *23*(1), 67–74. <http://www.ncbi.nlm.nih.gov/pubmed/2307693>

429 Yeadon, M. R., & Morlock, M. (1989). The appropriate use of regression equations for the estimation of  
430 segmental inertia parameters. *Journal of Biomechanics*, *22*(6–7), 683–689.  
431 [https://doi.org/10.1016/0021-9290\(89\)90018-3](https://doi.org/10.1016/0021-9290(89)90018-3)

432 Zatsiorsky, V., & Seluyanov, V. (1983). The mass and inertia characteristics of the main segments of the  
433 human body. In H. Matsui & K. Kobayashi (Eds.), *Biomechanics VIII B* (Vol. 4B, pp. 1152–1159). Human  
434 Kinetics.  
435 <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+mass+and+inertia+characte>  
436 [ristics+of+the+main+segments+of+the+human+body.#0](http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+mass+and+inertia+characte)

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Figures:

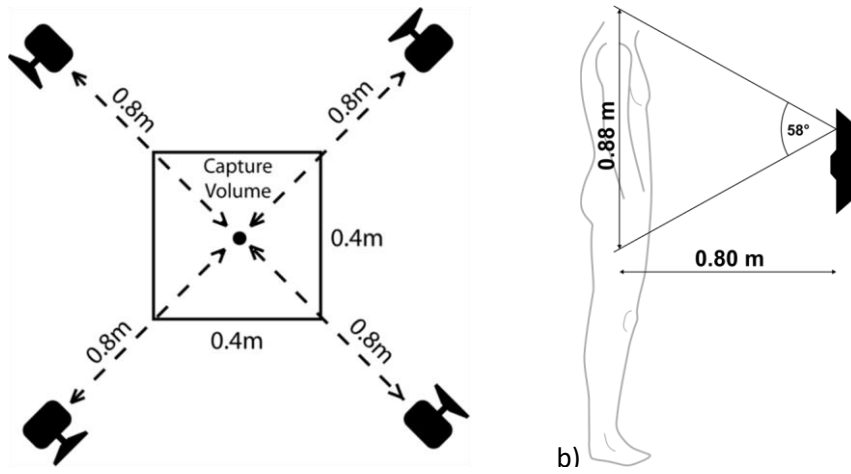


Figure 1. Overview of the Kinect scanning system; a) Layout of the scanning system; b) Scanning field of view.

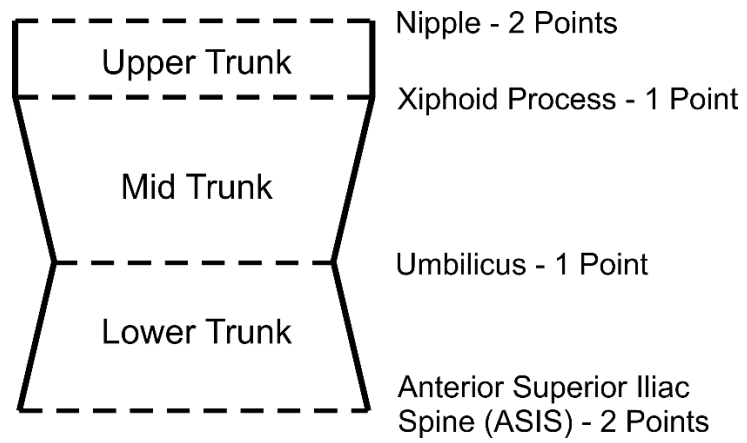


Figure 2. Anatomical landmarks and the segmentation process of the trunk.

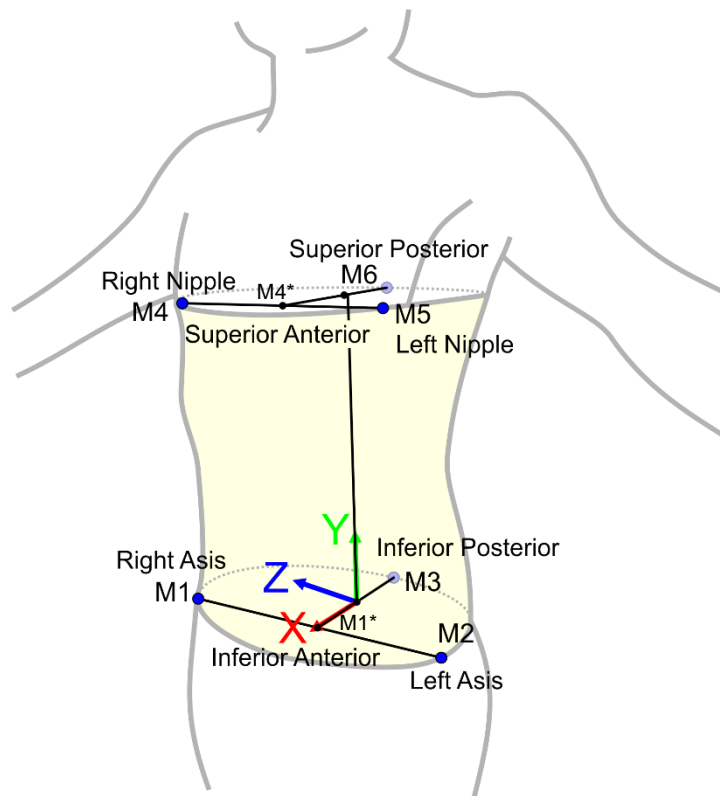


Figure 3. The marker set created for the 3D imaging as used to segment the torso and create a local co-ordinate system



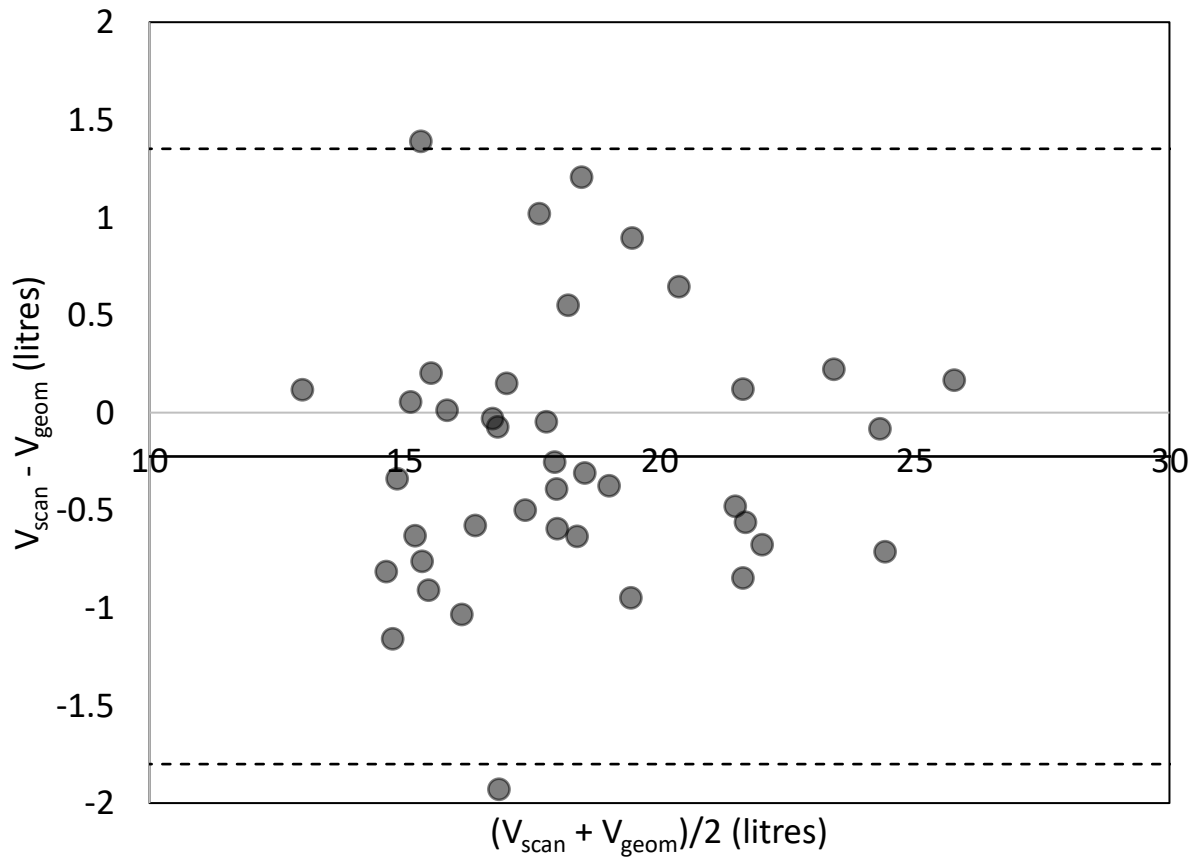


Figure 4. Limits of agreement between scan-derived volume and Yeadon-derived volume.

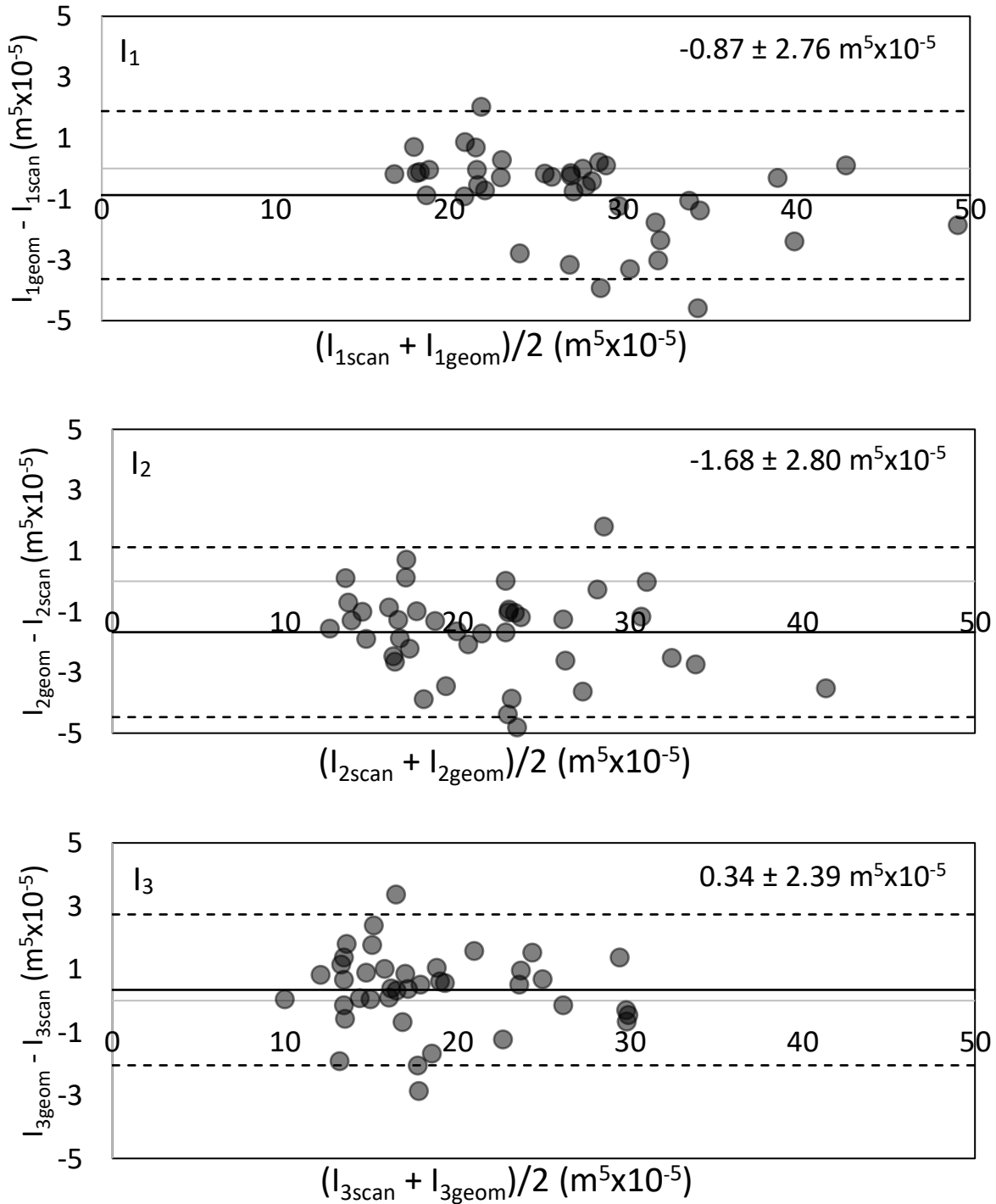


Figure 5. Agreement in Principal moments of volume between scanning and geometric modelling. The limits of agreement are not included on the plot due to their relatively large size compared to individual plot points.

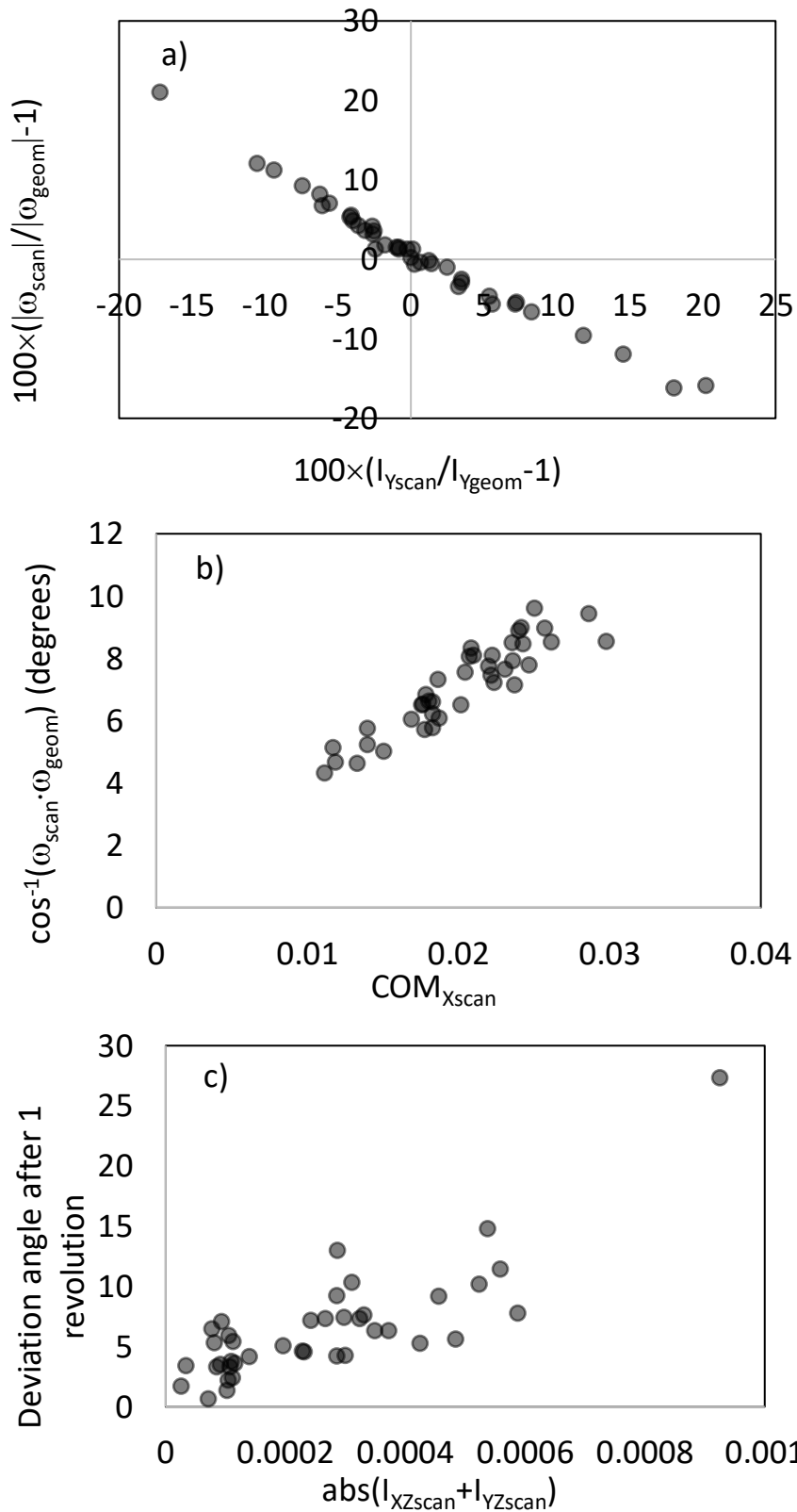


Figure 6. The difference in angular velocity and position during a forced motion (a, b) and free rotation (c). Percentage differences in moments of inertia affect rotational speed (a). The position of the centre of mass in the x-axis affects angular velocity (b). The presence of product moments of inertia causes angular deviations (c).

Tables:

Parameter	Scan			Geometric		
	Mean	Range	C.R	Mean	Range	C.R
Volume (l)	18.15	13.06-25.87	1.12	18.37	12.95-25.71	0.96
Centre of Mass (mm)						
X	20.20	11.15-29.80	3.95	0.00		0.00
Y	159.22	131.45-191.76	7.47	160.12	131.86-191.45	6.47
Z	0.49	-7.28-4.67	2.43	0.00		0.00
Principal Moments of Volume (m <sup>5</sup> x10 <sup>-5</sup> )						
1	28.00	17.00-50.00	3.00	26.81	16.77-48.38	2.36
2	22.00	13.00-43.00	2.60	20.81	11.84-39.62	2.62
3	18.00	10.00-30.00	1.80	19.00	10.00-30.09	1.19

Table 1. A summary comparison of the volumetric parameters calculated using each method.

Euler Angle (ZXY)	Mean	Range	C.R
$\alpha$	11.65	5.67-31.70	2.74
$\beta$	1.93	-2.84-7.51	2.48
$\gamma$	10.31	0.74 – 95.83	13.34

Table 2. A summary of the Euler angles describing the relative orientations of the principal axes as measured by the geometric and 3D scanning method.

Participant	Volume (l)		Centre of Volume (mm)			Principal moments of volume (m <sup>5</sup> x10 <sup>-5</sup> )						Principal axis orientation (°)					
	Scan	Geometric	COV <sub>x</sub>		COV <sub>y</sub>		COV <sub>z</sub>		I1		I2		I3		α	β	γ
			Scan	Geometric	Scan	Geometric	Scan	Geometric	Scan	Geometric	Scan	Geometric	Scan	Geometric	Scan	Scan	Scan
1	19.08(0.29)	17.88(0.25)	18.73(3.34)	175.17(1.51)	170.68(3.91)	2.55(1.56)	30.72(0.83)	26.78(0.69)	25.12(1.18)	20.73(0.61)	19.22(0.43)	16.34(0.29)	10.95(1.87)	-1.37(0.9)	1.98(4.63)		
2	20.71(0.53)	20.07(0.64)	13.99(1.75)	151.78(5.19)	153.38(10)	1.48(2.66)	33.39(1.83)	31.01(2.69)	25.89(1.79)	21.08(1.83)	23.27(0.53)	22.04(0.89)	13.86(2.03)	-1.47(0.71)	4.31(7.8)		
3	17.77(1.25)	17.82(0.85)	24.71(5.54)	175.48(10.06)	178.15(8.98)	1.36(2.14)	28.47(3.63)	28.04(3.31)	24.29(3.74)	23.1(3.11)	16.01(1.47)	16.09(0.81)	5.68(2.34)	0.56(2.07)	0.74(1.72)		
4	25.87(1.33)	25.71(0.88)	29.8(1.87)	191.76(3.14)	191.45(1.8)	0.31(1.5)	50.24(3.69)	48.38(1.45)	43.16(2.93)	39.62(1.14)	30.15(3)	29.48(1.42)	6.94(0.12)	2.65(0.68)	1.11(3.11)		
5	15.62(0.37)	15.42(0.47)	25.72(3.99)	158.66(7.08)	154.13(3.32)	2.28(3.08)	21.37(1.44)	20.44(1.29)	17.55(0.68)	15.07(0.98)	13.8(0.57)	13.22(0.55)	7.55(2.09)	1.81(1.53)	5.64(2.16)		
6	18.49(0.72)	17.94(0.63)	28.65(3.16)	168.69(2.52)	171.3(3.17)	-2.61(3.4)	30.43(1.64)	29.19(1.17)	25.09(1.67)	21.22(0.93)	17.17(1.02)	16.48(0.92)	10.93(0.75)	4.39(0.55)	3.51(4.06)		
7	21.41(0.71)	21.97(0.33)	16.93(3.76)	161.56(6.74)	160.65(4.51)	3.94(5.39)	35.17(2.28)	33.78(1.82)	27.59(1.92)	24.98(0.73)	24.62(1.12)	25.29(0.46)	13.71(2.48)	-1.53(2.83)	3.63(10.43)		
8	19.91(0.43)	19.02(0.23)	23.72(5.38)	185.6(7.49)	188.76(7.57)	-0.05(1.96)	33.58(2.64)	30.55(1.62)	29.1(2.39)	25.47(0.75)	19.37(0.68)	17.69(0.74)	9.81(1.21)	3.17(1.17)	0.92(2.39)		
9	18.16(0.83)	17.14(1.04)	13.33(0.68)	163.12(2.33)	165.9(3.33)	0.16(2.05)	28.57(1.52)	25.39(1.13)	21.09(1.16)	17.63(1.6)	18.73(1.67)	16.67(1.58)	10.51(0.32)	1.89(1.07)	8.4(3.16)		
10	15.16(1.27)	15.1(0.77)	18.65(6.52)	142.23(4.32)	141.48(7.35)	0.54(1.39)	19.16(2.46)	18.28(1.35)	15.67(2.35)	13.78(1.97)	13.5(1.73)	13.35(0.88)	13.47(1.63)	3.1(3.52)	5.48(4.69)		
11	16.02(0.8)	14.64(0.37)	26.17(4.29)	170.7(3.45)	171.92(0.45)	4.66(3.1)	25.48(1.59)	22.69(1.32)	19.99(1.43)	16.1(0.89)	14.15(1.17)	12.23(0.45)	5.67(0.34)	-1.72(0.84)	10.18(2.94)		
12	21.68(0.98)	22.36(1.19)	18.32(3.68)	178.72(6.43)	181.86(3.72)	-2.62(1.94)	39.09(3.03)	38.78(2.94)	31.26(2.64)	30.08(3.61)	23.22(1.64)	24.16(1.56)	7.65(0.77)	4.37(1.63)	4.08(5.32)		
13	24.29(2.96)	24.38(2.24)	23.1(1.62)	168.08(13.73)	166.93(10.97)	3.13(3.65)	41.12(8.75)	38.72(5.2)	33.69(7.4)	31.16(7.83)	30.15(5.34)	29.69(2.99)	12.38(0.64)	1.15(2.66)	8.53(9.98)		
14	21.71(0.87)	21.59(0.4)	24.16(3.57)	146.94(2.3)	145.62(3.16)	-0.19(1.81)	32.11(1.57)	28.79(0.36)	26.76(1.66)	25.5(1.96)	26.21(1.88)	26.05(0.61)	22.16(1.99)	3.33(1.69)	95.83(63.84)		
15	17.79(1.45)	18.19(2.07)	22.24(1.44)	151.44(12.04)	152.28(5.01)	0.39(4.35)	26.08(3.77)	25.79(3.81)	20.8(3.47)	19.14(4.42)	17.63(1.87)	18.12(2.37)	10.99(1.58)	4.62(3.13)	3.97(4.42)		
16	21.25(2.28)	21.73(1.38)	20.2(0.2)	172.89(12.15)	172.18(9.61)	0.66(0.94)	34.36(7.51)	33.3(4.43)	28.26(5.27)	27.99(3.97)	23.35(4.03)	23.85(1.72)	9.4(2.07)	4.91(1.19)	1.61(3.28)		
17	18.97(0.62)	19.92(0.67)	18.32(1.82)	157.04(0.8)	160.96(3.16)	4.09(1.63)	29.02(1.15)	29.12(0.89)	22.81(1.59)	22.81(1.33)	20.19(0.71)	21.76(0.91)	9.26(1.79)	1.81(3.58)	5.68(7.02)		
18	21.22(1.4)	22.07(0.43)	22.02(3.7)	158.87(6.18)	157.07(4.29)	1.02(0.56)	32.79(3.77)	31.01(2.3)	27.63(3.35)	29.41(0.91)	23.59(2.5)	25.1(0.29)	17.22(2.99)	1.04(5.7)	5.81(10.71)		
19	23.54(0.83)	23.32(0.8)	23.59(6.23)	154.32(6.4)	150.34(3.44)	-1.98(5.44)	36.64(1.45)	32.04(1.42)	31.01(2.06)	30.98(4.02)	29.93(1.5)	29.63(1.67)	31.7(8.77)	3.12(8.52)	2.07(4.12)		
20	15.85(1.5)	15.84(1.49)	18.06(4.16)	154.48(16.66)	156.75(13.73)	1.77(2.02)	21.95(4.19)	21.4(4.24)	17.63(3.96)	15.75(3.28)	14.31(1.71)	14.37(1.37)	13.66(3.1)	-0.71(1.82)	1.16(1.85)		
21	17.08(0.29)	16.93(0.75)	17.79(3.32)	174.38(0.54)	178.94(4.76)	1.28(0.51)	27.14(0.2)	26.9(1.16)	22.28(0.41)	20.55(0.93)	14.95(0.39)	14.98(0.94)	5.91(1.49)	-0.83(1.54)	1.2(1.14)		
22	17.7(0.88)	18.3(0.96)	17.57(1.16)	151.19(2.98)	153.76(2.05)	2.25(3.2)	25.62(1.28)	25.45(1.49)	19.38(0.78)	18.06(1.66)	18.29(2.07)	19.33(1.29)	10.65(0.81)	-0.22(3.13)	16.18(29.3)		
23	16.71(0.99)	16.75(0.79)	24(0.99)	150.64(4.3)	153.48(0.42)	2.59(2.52)	22.46(2.35)	21.74(2.19)	18.34(1.84)	16.12(1.86)	16.32(1.52)	16.63(0.83)	16.45(1.94)	1.04(1.28)	6.58(5.82)		
24	16.8(0.3)	16.88(0.3)	21.02(1.55)	142.44(0.53)	144.69(2.19)	0.94(1.88)	23.16(0.33)	22.86(0.76)	17.72(0.34)	15.06(0.45)	16.97(0.67)	17.33(0.4)	11.41(2.43)	-0.19(1.48)	23.76(11.06)		
25	14.24(0.83)	15.06(0.99)	20.86(3.52)	139.53(5.77)	140.92(6.45)	-0.14(1.64)	18.4(1.61)	18.29(1.92)	14.04(1.54)	13.33(1.96)	12.72(1.13)	13.86(1.25)	14.31(2.96)	2.14(0.92)	7.18(5.41)		
26	18.83(0.45)	19.21(0.38)	24.28(1.56)	160.05(2.84)	159.01(0.21)	1.18(2.06)	27.56(1.28)	26.8(0.72)	23.49(0.89)	22.47(1.33)	18.69(0.81)	19.3(0.41)	15.16(0.25)	1.98(1.6)	4.3(1.8)		
27	14.7(0.48)	15.04(0.82)	25.05(5.86)	142.08(7.89)	144.13(7.78)	-0.39(0.41)	18.22(1.38)	18.07(2.22)	15(1.37)	13.99(1.47)	13.11(0.62)	13.77(0.61)	7.68(3.65)	7.51(1.5)	22.22(26.16)		
28	18.39(2.3)	18.7(1.73)	20.48(5.22)	152.96(11.02)	153.88(6.83)	4.67(0.5)	27.11(5.21)	26.96(3.39)	21.68(4.73)	19.59(3.52)	19(3.67)	19.56(2.5)	9.04(3.79)	-1.32(1.93)	3.92(7.05)		
29	14.9(0.72)	15.54(0.27)	22.18(8.96)	167.51(6.65)	166.83(5)	-1.7(1.18)	21.64(1.64)	21.6(1.08)	18.15(1.32)	17.16(0.43)	11.68(0.96)	12.49(0.35)	9.71(1.25)	3.81(1.48)	3.88(2.71)		
30	17.13(0.78)	17.63(0.89)	15.08(2.38)	173.78(6.43)	178.66(3.98)	-3.42(1.25)	27.72(2.4)	27.71(2.3)	23.47(2.12)	22.52(2.41)	14.3(0.99)	15.18(0.84)	7.44(1.05)	4.34(1.07)	5.04(4.06)		
31	14.19(0.47)	15.35(0.26)	14(2.38)	138.48(3.09)	137.86(5.45)	-3.06(0.38)	17.64(1.24)	18.33(0.89)	13.47(1.05)	13.57(0.52)	12.71(0.49)	14.5(0.24)	10.18(0.94)	3.79(1.64)	23.89(13.68)		
32	18.07(0.99)	18.7(1.11)	23.63(4.24)	167.09(4.95)	171.86(5.74)	-2.79(2.96)	28.2(2.84)	27.61(2.65)	23.88(2.75)	22.82(2.69)	16.56(1.18)	17.4(1.33)	10.44(1.29)	4.9(2.1)	4.06(2.66)		
33	24.08(0.76)	24.79(0.59)	18.3(2.59)	175.72(4.32)	173.56(3.8)	-7.28(0.65)	42.82(2.99)	42.91(2.94)	35.2(2.9)	32.45(1.55)	28.73(0.94)	30.09(0.63)	9.62(1.29)	3.4(2.51)	3.68(4.69)		
34	17.82(0.42)	18.08(0.08)	22.39(1.56)	172.87(4.97)	172.27(5.9)	1.09(2.24)	28.55(1.55)	28.74(1.61)	23.66(1.27)	21.97(1.07)	15.98(0.46)	16.36(0.09)	8.06(0.68)	0.95(1.21)	1.21(0.89)		
35	15.02(1.32)	15.93(0.95)	11.72(6.31)	131.45(11.86)	131.86(12.39)	-0.22(0.68)	18.9(2.75)	18.85(2.89)	14.52(1.99)	13.23(1.98)	13.97(2.26)	16.34(1.18)	25.43(8.4)	0.92(0.65)	90.46(15.08)		
36	15.61(1.61)	16.65(0.91)	17.67(2.67)	151.99(10.94)	152.65(9.35)	0.94(2.21)	21.22(3.66)	21.89(1.46)	16.97(3.3)	17.08(5.81)	14.2(2.1)	15.95(0.7)	10.94(1.53)	2.69(0.86)	2.38(3.5)		
37	15.9(0.59)	17.83(0.7)	20.73(5.45)	142.14(6.42)	143.28(1.37)	-0.66(1.84)	20.84(1.32)	22.87(0.92)	16.71(0.75)	17.41(1.55)	14.79(0.98)	18.14(1.17)	10.35(4.79)	4.48(4.41)	7.59(2.91)		
38	13.06(0.82)	12.95(0.67)	17.88(4.73)	147.3(3.07)	151.25(5.38)	-1.13(2.85)	16.97(1.48)	16.77(1.12)	13.41(1.45)	11.84(1.01)	9.99(0.93)	10.03(0.72)	8.93(1.25)	-2.84(0.84)	3.42(8.73)		
39	16.11(0.74)	16.69(0.77)	11.9(1.15)	148.73(7.2)	150.83(6.49)	2.74(3.99)	22.91(1.94)	23.19(2.27)	17.22(1.76)	15.94(1.82)	15.28(0.9)	16.28(0.71)	11.04(1.61)	3.33(2.21)	9.25(8.56)		
40	14.98(1.51)	15.74(1.72)	11.15(5.84)	151.01(15.36)	153.17(13.68)	1.85(0.74)	20.49(4.03)	21.36(4.42)	16.47(3.78)	15.6(4.29)	12.77(1.57)	14.12(1.57)	11.09(3.53)	0.78(1.29)	4.3(2.1)		
Mean	18.15(1.12)	18.37(0.96)	20.20(3.95)	159.22(7.47)	160.12(6.47)	0.49(2.43)	28.00(3.00)	26.81(2.36)	22.00(2.60)	20.81(2.62)	18.00(1.80)	19.00(3.20)	11.65(2.74)	1.93(2.48)	10.48(13.34)		

Table Supp1. The volumetric parameters for all participants, as measured using the geometric and 3D scanning methods. Shown as: mean(C.R) of 3 repeats.