

Validation of Body Volume Acquisition by Using Elliptical Zone Method

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22 **1 Introduction**

23 Total body volume can be used in the estimation of body composition for assessing obesity
24 levels and associated health risks [24,36] and is also associated with sport performance.
25 From a biomechanical aspect, a higher body fat mass leads to increased demand for energy
26 consumption and has a negative influence on performance [2,11]. Furthermore, body
27 composition can be used to distinguish between athletes at different performance levels
28 and has been suggested to be useful for monitoring training effects [21].

29

30 Segmental volumes provide additional useful information to understand people's physiques
31 and some advanced estimations of fat distribution [7,33]. For example, abdominal volume
32 index [12] and body volume index [23] were used to identify or estimate the amount of
33 central fat and the distribution of adipose tissues. Lee, Freeland-Graves, Pepper, et al. [18]
34 also showed that the segmental volume ratio between thigh and torso and thigh to
35 abdomen-hip were highly related to the visceral adipose tissue deposition. With respect to
36 performance sport, Schranz, Tomkinson, Olds, et al. [28] used 3D photonic scanning
37 technology (3DPS) to extract segmental volume data and used these as the parameters to
38 distinguish performance rowers from the normal population. Moreover, Schranz,
39 Tomkinson, Olds, et al. [29] showed that an anthropometric profile that includes segmental
40 volumes provides more information pertinent to sport performance than a profile that
41 excludes segmental volumes. Estimated segmental volumes can also be used in
42 biomechanics analysis [8,35]. Thus, there is an emerging appreciation by professionals that
43 monitoring and providing feedback on changes in body volume (total body volume and
44 segmental volumes) is beneficial.

45

46 Approaches developed for acquiring both total body volume (body composition) and
47 segmental volumes include manual anthropometry, water and air displacement, medical
48 imaging and bioelectrical impedance (BIA). However, all of those methods have some
49 limitations regarding the frequency and convenience of monitoring body volume changes.
50 Anthropometry, air and water displacement, and medical imaging need specific equipment
51 and expertise to acquire complete body volume data [9,16] and are also time-consuming.
52 Frequent use of medical imaging methods such as dual-energy X-ray absorptiometry (DXA)
53 has associated health risks [26]. Moreover, some groups of participants including the elderly
54 and the very obese may experience difficulties with water displacement, magnetic
55 resonance imaging (MRI), computed tomography (CT) and DXA scanning [26]. The more
56 accessible technique of BIA is highly influenced by factors such as exercise and liquid and
57 food consumption which alter body fluid [22].

58

59 Three-dimensional photonic scanning (3DPS) is an emerging technology that negates several
60 of these limitations. It can acquire multiple measurements in one rapid scan without any
61 health risks [31,32]. Associated software can build an individual 3D human model
62 comprising a mesh of triangles. The 3D human model can then be edited by computer-aided
63 design (CAD) software to obtain the segmental 3D human model. The total body and
64 segmental volumes can be calculated from the triangular meshes.

65

66 Unlike DXA scanning, 3DPS can obtain body volume data directly rather than through
67 indirect calculations which rely on assumptions of body tissue densities of different tissues.
68 3DPS has been compared with water displacement methods and demonstrates comparable

69 accuracy and reliability [6,32]. Moreover, the fast scanning process is efficient and, unlike
70 anthropometric measurement and water displacement, avoids using a range of equipment
71 to measure segmental volumes. 3DPS is also a radiation-free method and can be applied to
72 participants of diverse somatotype [30]. Given these advantages in combination with its
73 accuracy and reliability, 3DPS is suitable as a benchmark with which to compare other
74 methods of obtaining total body and segmental volumes.

75

76 Nevertheless, 3DPS requires non-portable expensive hardware, specific software, and
77 interpretation by specialists in laboratory settings. The post-processing for segmental mesh
78 editing is also time-consuming. Consequently, 3D photonic scanners are not 'user-friendly'
79 for non-expert practitioners, or the general public to monitor body and segmental volume
80 changes.

81

82 A portable, inexpensive and user-friendly method of acquiring total body and segmental
83 volumes is needed for use by researchers, nutritionists, fitness coaches, and health
84 conscious individuals. The Elliptical Zone software (E-Zone) [8] potentially offers a solution.
85 It applies a geometric modelling method of estimating body segment volumes developed by
86 Jensen [15] in which diameters of elliptical 'slices' of the body segments are obtained by
87 digitising two photographs taken from front and side views of the participant (Figure 1). The
88 equipment is inexpensive and portable and 'user friendly' Matlab software enabling
89 digitising, calculation of volumes, and graphical output on a PC has been developed [8]
90 (Figure 2).

91

92 The accuracy of using elliptical models to approximate body volume has been assessed in
93 some studies. Durkin and Dowling [10] used DXA to examine the accuracy of elliptical
94 models built from anthropometric measurements and found that the lower leg volume can
95 be estimated accurately by elliptical models. Abe, Yokozawa, Takamatsu, et al. [1] compared
96 the body volume acquired by 3DPS and the results estimated from elliptical models and
97 expressed the view that the elliptical assumption may be too simple to approximate the
98 body volume data. Nevertheless, this study [1] did not indicate which segment volumes
99 could not be estimated accurately. These studies conducted by Durkin and Dowling [10] and
100 Abe, Yokozawa, Takamatsu, et al. [1] were both based on the elliptical models built from
101 data obtained by manual anthropometry or 3D scanning, rather than the methods
102 developed by Deffeyes and Sanders [8] and so did not measure the accuracy of E-Zone
103 directly.

104

105 The E-Zone software developed by Deffeyes and Sanders [8] provides an advanced method
106 that can avoid time-consuming manual anthropometry and expensive 3D scanning. Intra-
107 assessor and inter-assessor reliability for the acquisition of body volume data has been
108 demonstrated to be within 5% error for the main body segments [27]. However, to date, no
109 research has been conducted to examine the accuracy of E-Zone for obtaining complete
110 body volume data including total body volume and all segmental volumes.

111

112 Therefore, the purpose of this research was to assess the accuracy of obtaining total body
113 and segmental volumes using E-Zone by comparing it with the reference 3DPS.

114

115 **2 Method**

116 ***2.1 Participants***

117 In this study, 17 male participants (age: 35.59 ± 10.16 years old, body mass: 81.4 ± 9.3 kg,
118 stature: 181.5 ± 7.6 cm, Endomorphy: 3 males; Mesomorphy: 12 males; Ectomorphy: 2 males)
119 were recruited through email or bulletin advertising. All participants signed the informed
120 consent form. Ethics approval was given by Moray House School of Education Ethics
121 Committee at the University of Edinburgh. This study meets the ethical standard of
122 International Journal of Sports Medicine [13]. Somatotype was determined according to the
123 Heath-Carter anthropometric method [4]. The intra technical error of measurements (intra
124 TEMs) used for somatotype determination were less than 5% and 1% for skinfolds and other
125 manual anthropometry respectively. All measures were undertaken by the International
126 Society for the Advancement of Kinanthropometry accredited anthropometrist (first author)
127 in order to reduce the location error [5] and resultant error in anthropometric measurement
128 [14]. All participants were requested to wear close fitting suits such as triathlon pants and a
129 polyester swimming cap during the tests (Figure 1).

130

131 ***2.2 Experiment Design***

132 Each participant was scanned twice on the same day by a 3D whole-body laser scanner and
133 photographed twice for the E-Zone analysis. The mean of body volume data acquired from
134 repeated 3D laser scanning results was regarded as the reference to validate the mean of
135 body volume data acquired by E-Zone from the two sets of photos.

136

137 ***2.3 Acquiring Body Volume from 3D Photonic Scanning***

138 Before scanning, specific markers were placed on each participant's body to indicate the
139 segmental boundaries defined in the E-Zone [8] as shown in Table 1. To ensure that all the
140 markers could be seen from the body scanning results, triangular marks were placed on the
141 acromiales. This avoided the possibility that the flat marks on the horizontal shoulder could
142 not be detected. All markers were placed by an accredited anthropometrist (first author).

143

144 A calibrated Vitus^{smart} XXL 3D body scanner (Human Solutions GmbH) was used to obtain
145 individual 3D human models. Participants were requested to stand with the assigned pose
146 referred to in previous studies [6,32]. To avoid the effect of breathing on volume of the
147 trunk, participants were asked to expel the air in their lungs to end tidal level before the
148 commencement of scanning and to hold their breath until the test process finished
149 (approximately 10 seconds).

150

151 The 3D human models obtained from the 3D scanner were processed by the 3D mesh edit
152 software Cycleslice (Headus 3D) to delete noise, 'fill the holes', and smooth the mesh in the
153 manner established by Collins [6]. To lessen the effect of subjective interpretation, the
154 operator (OP1, second author) who is familiar with the use of the specific software
155 completed all manual processing for 3D scanning data in this study. After the processing by
156 the second author, the 3D mesh files were exported to Polygon File Format (Stanford
157 Triangle Format, PLY) files.

158

159 Another trained operator (OP2, first author) obtained the body volume data from the mesh
160 processed by OP1 (the PLY files). To achieve this, computer software, Blender, was used to

161 obtain a mesh of each segment. The setting of cutting planes was informed by previous
162 literature [8] as shown in Figure 3. The cutting planes between head and neck, neck and
163 upper torso, upper torso and lower torso, upper leg and lower leg, lower leg and foot were
164 set as horizontal planes. The cutting planes between upper torso and upper arm, upper arm
165 and lower arm, lower arm and hand, lower torso and upper leg were set manually by
166 referring to the locations of markers and body landmarks (e.g. pubic bone; the critical points
167 were identified manually from the images). For instance, the operator identified the
168 location of pubic bone by visually following the diagonal creases between the thighs and
169 lower torso to their intersection and allowing for the soft tissue below the pubic symphysis.
170 Then, the oblique cutting plane was set such that it passed through the points of
171 trochanterion (on right thigh) and pubic bone as shown in Figure 3. Similarly, the oblique
172 cutting planes between upper torso and upper arms were set such that they passed through
173 the points of the markers of ac joint/humerus heads and the critical points of the armpits.
174 The cutting planes between upper arm and lower arm, lower arm and hand were also set
175 manually so they were perpendicular to the long axis of the limbs. The body volume data
176 were calculated from total body mesh and segmental meshes by applying the tetrahedron
177 volume techniques [37].

178

179 ***2.4 Acquiring Body Volume from E-Zone***

180 Colour markers were placed to indicate each participant's body landmarks or segmental
181 boundaries as shown in Table 1. All markers were placed by an accredited anthropometrist
182 (first author).

183

184 Participants' images were captured from the front view and side view by calibrated cameras
 185 (Casio EX-FH100, resolution 2736*3648) as shown in Figure 1. The two cameras were set on
 186 the tripod at a height of about 1 m and at a distance of approximately 12 m for both front
 187 and side view. The axes of the cameras were parallel to the floor and perpendicular to the
 188 participants. Then, OP2 used the E-Zone software [8] to build the 3D elliptical zone models
 189 (Figure 2). The cutting planes were set in a manner similar to that used in the processing of
 190 the 3D scanning data (Figure 3). Since the arms were partially flexed during the scanning,
 191 the oblique cutting plane between upper arm and lower arm was set such that it passed
 192 through the point of the radiale and the point on the fold of inner elbow.

193 **2.5 Statistics Analysis**

194 Four sets of body volume data (BV_i^{scan1} , BV_i^{scan2} , BV_i^{eZone1} and BV_i^{eZone2}) were acquired
 195 for each (*i*th) participant with the two different methods in separate trials (3DPS 1, 3DPS 2,
 196 E-Zone 1 and E-Zone 2). The means of two repeated measurements (total body volume,
 197 head volume, neck volume, upper torso volume, lower torso volume, thigh volume, shank
 198 volume, foot volume, upper arm volume, lower arm volume, hand volume) for each
 199 participant by different methods (M_i^{scan} and M_i^{eZone}) were compared as follows:

$$M_i^{scan} = \frac{BV_i^{scan1} + BV_i^{scan2}}{2}$$

$$M_i^{eZone} = \frac{BV_i^{eZone1} + BV_i^{eZone2}}{2}$$

200 Inter technical error of measurement (inter-TEM or relative TEM), the statistic used by the
 201 World Health Organization [34] and the International Society for the Advancement of
 202 Kinanthropometry [25], was used to determine the accuracy of E-Zone in this study. The
 203 following equations illustrate the calculation of the relative TEM.

$$Absolute\ TEM = \sqrt{\frac{\sum_{i=1}^N (M_i^{scan} - M_i^{eZone})^2}{2 * N}}$$

$$Relative\ TEM = \frac{Absolute\ TEM}{\frac{\sum_{i=1}^N (M_i^{scan} + M_i^{eZone})}{2 * N}} * 100\%$$

204 where N is representative of the number of participants and M_i^{scan} and M_i^{eZone} denote the
 205 mean of repeated measurements obtained for the i^{th} participant with the techniques of 3D
 206 laser scanning and E-Zone accordingly. The relative TEM was calculated by the Microsoft®
 207 Excel function.

208

209 The accuracy scores (%TEM) for whole-body and segmental volumes (excluding neck, hand
 210 and foot) were entered into a repeated measures ANOVA and post-hoc analyses (Fisher's
 211 Least Significant Difference) to examine whether the accuracy of the method was affected
 212 by different somatotypes. The reason for excluding neck, hand and foot was that these
 213 inaccurate and unreliable segmental volumes [27] could influence the results
 214 disproportionately relative to their size. The repeated measures ANOVA tests and post-hoc
 215 analyses were conducted by commercial statistical software (IBM SPSS Statistics version 21).
 216

217 **3 Results**

218 The accuracy of the E-Zone is represented with relative technical error of measurement
 219 (%TEM) as shown in Table 2. The relative TEM of total body volume estimations for all
 220 participants was around 3% for E-Zone. E-Zone can estimate the segmental volumes of head,
 221 upper torso, lower torso, thigh, shank, upper arm and lower arm accurately (relative
 222 TEM<10%) for all participants but the accuracies of small segments including neck, hand and

223 foot were poor. E-Zone can estimate the leg volume including thigh and shank with under
224 5% relative TEM for all participants whereas the trunk (upper torso and lower torso) and
225 arm (upper arm and lower arm) volume with a slightly higher error (under 10%).

226

227 An examination of the accuracy between the three different somatotypes revealed that
228 there was a significant effect of somatotype ($p=0.025$) on whole-body and segmental
229 volumes estimation error. Post-hoc analyses revealed that the differences were significant
230 between ectomorphy-mesomorphy ($p=0.008$) but not between ectomorphy-endomorphy
231 ($p=0.122$) or endomorphy-mesomorphy ($p=0.27$). The errors were significantly smaller in
232 ectomorph subjects than mesomorph subjects. The accuracy of whole-body volume and the
233 segmental volumes of upper torso, lower torso, thigh, shank, upper arm and lower arm for
234 the subjects in different somatotypes were all less than 5% and 10% respectively.

235

236 **4 Discussion**

237 The purpose of this study was to determine the accuracy of E-Zone for obtaining individual
238 data of total body volume and segmental volumes. The accuracy of total body volume for E-
239 Zone (<5% error) in this study was similar to previous research [8,15] in which the total body
240 mass calculated from the segmental volume and density assumption were compared against
241 the value of total body mass from weight scales.

242

243 Previous studies [1,10] determined the accuracy of elliptical zone models indirectly by
244 building the models from 3D scanning results and manual anthropometric data accordingly
245 instead of the approaches that used the 2D image approach [8]. The current study

246 established the elliptical models from 2D images and quantified the accuracy directly by
247 comparing the results to that of 3DPS. The accuracy range (error<30%) shown in this study
248 was similar to that shown in the validation test conducted on performance athletes [1] and
249 the accuracy of leg volume (error<5%) was similar to the error shown previously with
250 participants in a different age group (19-30 years and 55+ years)[10]. Thus, this research
251 provided the data for direct validation of E-Zone and showed that the accuracy of the
252 elliptical zone model built from 2D images, manual anthropometry and 3D scanning are
253 similar.

254

255 The accuracy (<5% error in total body volume and <10% error in segmental volumes) for E-
256 Zone might be adequate for general users rather than for clinical examination. However,
257 this research shows the potential of E-Zone. Automatic digitizing might be the principal
258 strategy to improve accuracy. Lin and Wang [19] used the techniques of digital image
259 processing to detect the body boundaries and the anatomical landmarks. Although these
260 techniques can standardize the digitizing process and avoid human error, they require well-
261 controlled light sources and simple contrasting backgrounds [3]. In other words, these
262 techniques can be conducted successfully only in laboratories rather than in the field.

263

264 Different somatotypes affected the accuracy significantly which means E-Zone might need
265 further improvement to estimate the body volume data of the general population for health
266 assessment. For instance, it is possible to use different geometric assumptions to
267 approximate the body shape of subjects in various somatotypes and obtain better results.
268 Nevertheless, the accuracy for whole-body and main segmental volumes estimated by E-
269 Zone was high across the three somatotypes. Therefore, the E-Zone method might be

270 beneficial to provide a general concept of body volume data for people with extreme large
271 size who cannot enter a medical or 3D photonic scanner easily.

272

273 In this study, the results obtained from 3DPS were extrapolated to be equal to the actual
274 value and were regarded as the reference with which to validate E-Zone. The accuracy of
275 the 3DPS used in this study was not calibrated with water displacement or examined using
276 the protocol illustrated in previous literature [17]. Compared with the volume data obtained
277 from water displacement techniques, the results acquired from 3DPS has been shown to
278 contained some errors [6,32]. Hence, the difference between water displacement and E-
279 Zone is still unknown. Further research should be conducted with a manikin with detachable
280 limbs in E-Zone assigned pose in order to complete the validation with water displacement.

281

282 In this study, a cutting plane was set by using less than three markers. Manually identifying
283 critical points or assumptions that the most segments can have horizontal cutting planes
284 might lead to some inconsistencies in segmental volume estimation. However, previous
285 research [20,27] has indicated that experienced operators are likely to achieve high
286 reliability (error less than 5% for main segments) while applying manual digitizing and
287 assuming horizontal cutting planes to calculate segmental masses that are calculated from
288 segmental volumes with presumed densities. Thus, the validation results shown in this study
289 reflect the accuracy of E-Zone. The automatic segmentation approach could reduce human
290 error in validation. Nevertheless, most automatic segmentation approaches for 3DPS are
291 limited to the calculation of regional volumes (combined segmental volumes). Further
292 research should be conducted to develop an automatic approach to obtain segmental

293 meshes accurately and reliably. After that, researchers can use this approach to validate
294 other simplified methods (e.g. E-Zone) precisely.

295

296 Compared with current methods including water displacement, anthropometry, medical
297 image methods, DXA and 3D photonic scanning, using E-Zone to obtain personalised body
298 volume data would appear to be a good choice at the current stage of technological
299 development of body volume measuring systems. E-Zone uses standard digital cameras
300 which provide a more portable and inexpensive method than water displacement,
301 anthropometry, medical image methods and DXA. Moreover, the 2D image capturing
302 process of E-Zone can be conducted by untrained practitioners without any technical
303 expertise. Although some technical expertise for placing markers and manual digitizing is
304 still needed in the E-Zone process, it is possible to complete these tasks automatically by
305 further development of advanced computer vision techniques [3,19]. By contrast,
306 anthropometry, medical imaging methods, DXA and 3D photonic scanning require trained
307 people to operate equipment or machinery. E-Zone is a non-invasive method so it can avoid
308 the health risks associated with medical imaging methods and DXA. Although BIA is also
309 portable and free of health risks, the accuracy of BIA for obtaining segmental volumes has
310 yet to be determined.

311

312 The results from this study show that the accuracy of E-Zone is generally good. Furthermore,
313 the reasonable reliability of E-Zone can help individuals to measure changes in body shape
314 longitudinally [27]. However, further development for automatic detection anatomical
315 landmarks and the body boundaries in 2D images is needed for improving accuracy and the

316 automation of E-Zone. The further development for improving the automation of E-Zone
317 should aim for better accuracy than the results shown in this study.

318

319 **5 Conclusions**

320 In this study the total body volumes and segmental body volumes obtained from 3D
321 photonic scanning and E-Zone were compared. According to the results of the statistical
322 analysis, E-Zone can provide reasonable estimates of body volume distribution and total
323 body volume. However, improvements in accuracy through future development would be
324 desirable for applications in which accurate volumes are required. Although E-Zone is not as
325 accurate as other commercial solutions such as medical scanners and DXA, it provides an
326 inexpensive and portable method which enables people to understand their obesity level
327 easily without any health risks.

328

329 **Conflict of Interest**

330 The authors declare that there is no conflict of interest with regard to this paper for any
331 author.

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438
- 439
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- 441

442 **Table Captions**

443 Table 1 Segmental endpoints for 3D photonic scanning (adapted from the literature of
444 Deffeyes and Sanders [8]) and E-Zone (adapted from Deffeyes and Sanders [8]). The markers
445 for head, hand and foot were not placed in this study since they can be easily identified
446 from both the 3D scanning and images captures for E-Zone.

447 Table 2 The body volume data (Mean \pm Standard Deviation in litre) measured by the
448 traditional 3DPS and E-Zone, the accuracy of E-Zone (relative TEMs, %)

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452 **Figure Legends**

453 Figure 1 Front view and side view images captured for E-Zone.

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455 Figure 2 Each body segment can be approximated by a series of elliptical cylinders.

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457 Figure 3 The setting of the cutting planes applied on obtaining segmental volumes for 3DPS
458 and E-Zone.

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