Validation of Body Volume Acquisition by Using Elliptical Zone Method

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Abstract

The Elliptical Zone method (E-Zone) can be used to obtain reliable body volume data including total body volume and segmental volumes with inexpensive and portable equipment. The purpose of this research was to assess the accuracy of body volume data obtained from E-Zone by comparing with those acquired from the 3D photonic scanning method (3DPS). Seventeen male participants with diverse somatotypes were recruited. Each participant was scanned twice on the same day by a 3D whole-body scanner and photographed twice for the E-Zone analysis. The body volume data acquired from 3DPS was regarded as the reference against which the accuracy of the E-Zone was assessed. The relative technical error of measurement (TEM) of total body volume estimations was around 3% for E-Zone. E-Zone can estimate the segmental volumes of upper torso, lower torso, thigh, shank, upper arm and lower arm accurately (relative TEM<10%) but the accuracy for small segments including neck, hand and foot were poor. In summary, E-Zone provides a reliable, inexpensive, portable, and simple method to obtain reasonable estimates of total body volume and to indicate segmental volume distribution.

Key words: Body Volume Data, Elliptical Zone Method, 3D Photonic Scanning, Anthropometry

1 Introduction

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

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

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

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

Unlike DXA scanning, 3DPS can obtain body volume data directly rather than through indirect calculations which rely on assumptions of body tissue densities of different tissues. 3DPS has been compared with water displacement methods and demonstrates comparable accuracy and reliability [6,32]. Moreover, the fast scanning process is efficient and, unlike anthropometric measurement and water displacement, avoids using a range of equipment to measure segmental volumes. 3DPS is also a radiation-free method and can be applied to participants of diverse somatotype [30]. Given these advantages in combination with its accuracy and reliability, 3DPS is suitable as a benchmark with which to compare other methods of obtaining total body and segmental volumes.

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

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

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

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

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

2 Method

2.1 Participants

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

2.2 Experiment Design

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

2.3 *Acquiring Body Volume from 3D Photonic Scanning*

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

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

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

Another trained operator (OP2, first author) obtained the body volume data from the mesh processed by OP1 (the PLY files). To achieve this, computer software, Blender, was used to obtain a mesh of each segment. The setting of cutting planes was informed by previous literature [8] as shown in Figure 3. The cutting planes between head and neck, neck and upper torso, upper torso and lower torso, upper leg and lower leg, lower leg and foot were set as horizontal planes. The cutting planes between upper torso and upper arm, upper arm and lower arm, lower arm and hand, lower torso and upper leg were set manually by referring to the locations of markers and body landmarks (e.g. pubic bone; the critical points were identified manually from the images). For instance, the operator identified the location of pubic bone by visually following the diagonal creases between the thighs and lower torso to their intersection and allowing for the soft tissue below the pubic symphysis. Then, the oblique cutting plane was set such that it passed through the points of trochanterion (on right thigh) and pubic bone as shown in Figure 3. Similarly, the oblique cutting planes between upper torso and upper arms were set such that they passed through the points of the markers of ac joint/humerus heads and the critical points of the armpits. The cutting planes between upper arm and lower arm, lower arm and hand were also set manually so they were perpendicular to the long axis of the limbs. The body volume data were calculated from total body mesh and segmental meshes by applying the tetrahedron volume techniques [37].

2.4 Acquiring Body Volume from E-Zone

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

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

2.5 Statistics Analysis

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

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

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

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

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

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

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

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

3 Results

The accuracy of the E-Zone is represented with relative technical error of measurement (%TEM) as shown in Table 2. The relative TEM of total body volume estimations for all participants was around 3% for E-Zone. E-Zone can estimate the segmental volumes of head, upper torso, lower torso, thigh, shank, upper arm and lower arm accurately (relative TEM<10%) for all participants but the accuracies of small segments including neck, hand and foot were poor. E-Zone can estimate the leg volume including thigh and shank with under 5% relative TEM for all participants whereas the trunk (upper torso and lower torso) and arm (upper arm and lower arm) volume with a slightly higher error (under 10%).

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

4 Discussion

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

Previous studies [1,10] determined the accuracy of elliptical zone models indirectly by building the models from 3D scanning results and manual anthropometric data accordingly instead of the approaches that used the 2D image approach [8]. The current study established the elliptical models from 2D images and quantified the accuracy directly by comparing the results to that of 3DPS. The accuracy range (error<30%) shown in this study was similar to that shown in the validation test conducted on performance athletes [1] and the accuracy of leg volume (error<5%) was similar to the error shown previously with participants in a different age group (19-30 years and 55+ years)[10]. Thus, this research provided the data for direct validation of E-Zone and showed that the accuracy of the elliptical zone model built from 2D images, manual anthropometry and 3D scanning are similar.

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

Different somatotypes affected the accuracy significantly which means E-Zone might need further improvement to estimate the body volume data of the general population for health assessment. For instance, it is possible to use different geometric assumptions to approximate the body shape of subjects in various somatotypes and obtain better results. Nevertheless, the accuracy for whole-body and main segmental volumes estimated by E-Zone was high across the three somatotypes. Therefore, the E-Zone method might be beneficial to provide a general concept of body volume data for people with extreme large size who cannot enter a medical or 3D photonic scanner easily.

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

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

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

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

5 Conclusions

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

Conflict of Interest

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

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Table Captions

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

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

Figure Legends

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

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

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