Automated body volume acquisitions from 3D structured-light scanning

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Abstract

Whole-body volumes and segmental volumes are highly related to the health and medical condition of individuals. However, the traditional manual post-processing of raw 3D scanned data is time-consuming and needs technical expertise. The purpose of this study was to develop bespoke software for obtaining whole-body volumes and segmental volumes from raw 3D scanned data automatically and to establish its accuracy and reliability. The bespoke software applied Stitched Puppet model fitting techniques to deform template models to fit the 3D raw scanned data to identify the segmental endpoints and determine their locations. Finally, the bespoke software used the location information of segmental endpoints to set segmental boundaries on the reconstructed meshes and to calculate body volume. The whole-body volumes and segmental volumes (head & neck, torso, arms, and legs) of 29 participants processed by the traditional manual operation were regarded as the references and compared to the measurements obtained with the bespoke software using the intra-method and inter-method relative technical errors of measurement. The results showed that the errors in whole-body volumes and most segmental volumes acquired from the bespoke software were less than 5%. Overall, the bespoke software developed in this study can complete the post-processing tasks without any technical expertise, and the obtained whole-body volumes and segmental volumes can achieve good accuracy for some applications in health and medicine.

Keywords: Volumetric Analysis; Segmental Volumes; 3D Structured-light Scanning; Model Fitting

1 Introduction

Body volume data, including whole-body volumes and segmental volumes, are highly related to the health and medical condition of individuals. Whole-body volume measured from underwater weighing, air displacement, and 3D structured-light scanning together with body mass can be used to calculate body density and to estimate body composition [1]. Lee, Freeland-Graves, Pepper, Yu and Xu [2] found that the segmental volumes were related to the segmental body composition. Ng, Hinton, Fan, Kanaya and Shepherd [3] developed mathematical models which enable the estimation of segmental body-fat percentage from segmental volume data and girth measurements. Furthermore, measuring and monitoring body volume data enable the diagnosis of some disease such as lymphedemas [4] and understanding the treatment effect [5]. Segmental volume can also be used to understand health risk, for example of diabetes and mortality [6]. In addition to whole-body and segmental volumes, researchers applied 3D scanning techniques to calculate body volume of certain features such as wounds for improving the patient-care [7, 8].

Traditionally, body volume has been obtained from underwater weighing, water or air displacement, and medical methods. However, underwater weighing and air displacement usually require non-portable equipment and can only measure whole-body volumes [9]. A number of specific containers for water displacement were required to measure the body volume of different segments [10]. Medical methods such as computed tomography or magnetic resonance imaging contain some health risk (e.g. radiation exposure) [9].

Three-dimensional (3D) structured-light scanning can obtain body volume data (both whole-body volumes and segmental volumes) within a short test session non-invasively [9, 11, 12]. Traditionally, the 3D structured-light scanners project single or multiple stripes on the participants and the cameras in the scanners capture the deformation of the projected patterns [13]. The corresponding software of the scanner applies triangulation techniques to reconstruct the 3D raw data as shown in Figure 1 (a). The 3D raw data can be processed by manual operation to complete the reconstruction tasks (e.g. hole-filling, noise reduction and mesh smoothing) and mesh segmentation [14] as shown in Figure 1 (b) and (c). After the reconstruction tasks and mesh segmentation, the body volume data including whole-body meshes and segmental meshes can be obtained.

By comparing with underwater weighing and water displacement, Collins [15] showed that body volume acquired from 3D structured-light scanning with manual post-processing is accurate. Recently, 3D structured-light scanning was regarded as the reference method to obtain body volume data in various studies. This method has been used for a variety of applications including extracting segmental volume data to distinguish performance rowers from the normal population [16], somatotype cluster analysis [17] and investigating the variation of segmental volumes of participants with different body mass indexes [18].

Although the 3D scanning process is quick, the manual post-processing is time-consuming and needs some technical expertise. Gessner, Staniek and Bartkowiak [19] indicated that manual marking was required to calculate of object volumes from 3D scan for engineer applications. Kleiner, Munkelt, Thorhallsson, Notni, Kühmstedt and Schneider [20] and Zhang, Han, Dong and El Saddik [21] developed handheld and robot-driven 3D scanning devices which can capture data from various directions and minimize the requirement of manual post-processing. However, these devices cannot capture data from various directions simultaneously, so operators usually have to move around the human participants during the scanning session. Consequently, the testing time for using these devices on human participants is much longer than for the process of full-body scanning.

A small number of companies have developed algorithms for completing the post-processing tasks of full-body scanning data automatically. For example, the corresponding software, BodyLine Manager of Hamamatsu (http://www.hamamatsu.com/) or CySize or DigiSize Software of Cyberware (http://cyberware.com/) scanners can complete the post-processing tasks and obtain body volume data without manual operation [22]. Wang, Gallagher, Thornton, Yu, Horlick and Pi-Sunyer [9] showed that the accuracy of the body volume acquired from the 3D structured-light scanning with the automated post-processing techniques is high. However, the validation of segmental volume was based on a single small mannequin that was not similar to the body shape of adults. The size difference might not reflect the true accuracy of the segmental volume obtained with automated post-processing techniques [23]. Furthermore, the definitions of segmental boundaries on the mannequin might be different from the one applied on human participants since no palpation can be conducted on the mannequin to identify the location of body landmarks. The definitions of segmental boundaries used in the software (BodyLine Manager or DigiSize) differ between the manufactures (Hamamatsu or Cyberware) and have not been revealed. Use of this kind of software might yield results that differ from those obtained from manual operation.

In Engineering, some automatic post-processing techniques have been developed for acquiring 3D data. For instance, Overby, Bodum, Kjems and Iisoe [24], Huang and Menq [25] and Vanegas, Aliaga and Benes [26] developed automatic methods to identify geometric features from 3D scan data for noise removal, mesh segmentation, and mesh reconstruction. Nevertheless, these techniques could not be applied on 3D full-body scanning data as the geometry of humans are more complicated and variable than the objects used in those studies (e.g. buildings, cars, golf clubs) [24-26].

Model fitting is another technique for automated post-processing techniques of 3D data. This kind of technique can fill the holes by deforming the template models to match the 3D raw scanned data. Previously, these techniques have been used to identified body landmarks and measure traditional anthropometric parameters such as breadth, height and girth measures [27]. Robert, Leborgne, Beurier and Dumas [28] applied model fitting techniques to obtained body segment data. Nevertheless, no validation data for body volume acquisition has been published in previous research. Furthermore, time-consuming processes and technical expertise might be required to place body landmarks on participant's body and identify them on the 3D scanning data manually while applying this approach.

Recently, Zuffi and Black [29] developed a novel model fitting technique, Stitched Puppet, which can avoid any marker placing and showed very good performance in mesh alignment between the deformed template models and the 3D raw scanned data as shown in Figure 2 (a), (b) and (c). Because the vertex orders of the deformed template models are identical, more complex body landmarks such as radiales can be identified by indicating the specific vertex index without any requirement of technical expertise as shown in Figure 2 (g). The body landmarks detected from the deformed Stitched Puppet template models can be used for the process of mesh segmentation for setting the segmental boundaries to obtain segmental models for volume calculation as shown in Figure 2 (g) and (h).

Nevertheless, no corresponding software has been developed for calculating body volume data automatically from the deformed Stitched Puppet template models. The deformed Stitched Puppet template models sometimes contained some abnormal faces (e.g. interior faces) which might cause some error in mesh segmentation and volume calculation as shown in Figure 2(d). Consequently, it remains necessary for users to identify body landmarks on 3D data manually and operate specific software for completing the 'traditional manual processes' including the noise reduction, mesh smoothing, mesh segmentation and volume calculation [14]. These repeated manual operations are time-consuming and need some expertise in specific software operation. Furthermore, the accuracy and reliability of body volume data obtained with the

Stitched Puppet template matching techniques are unknown. Therefore, the purpose of this study was to apply the Stitched Puppet template matching techniques to develop bespoke software for obtaining whole-body volumes and segmental volumes from raw 3D scanned data automatically and establish its accuracy and reliability.

2 Methods

2.1 Participants

Ethics approval for this study was given by the ethics committee at the university. Participants were recruited through e-mail or bulletin advertising. Sixteen male and 13 female volunteers who completed all the test sessions for data collection were analysed. Table 1 showed the participants' characters in this study. Before conducting the tests, all participants signed the informed consent forms. Participants were requested to wear a polyester swimming cap to cover their hair as much as possible and dress in close fitting suits for the period of data collection.

2.2 Data Collection

A calibrated body scanner (Vitus^{smart} XXL, Human Solutions GmbH) was used to collected 3D data from each individual repeatedly. The lens and magnification of the 3D scanner were set at the default setting and calibrated in accordance with the manufacturer's instructions. Each participant was scanned twice. Examples of the image and video of 3D scans can be found on the following websites provided by the other institute and the commercial company, VITRONIC:

https://scientificservices.eu/item/optical-measurement-device---3d-body-scanner/959, https://www.youtube.com/watch?v=T7cWD2_uUpA. The first and second scanning trials were completed in succession and were finished in 15 minutes. Participants were requested to stand with the assigned pose shown in Figure 1 which is the standard scanning pose adopted in previous studies [15]. Before the 3D scanning, the physical markers were placed on the participants' Adam's Apple and Acromiales by an accredited anthropometrist (OP1, first author) to identify the segmental boundaries between head & neck and torso, and arms and torso while applying manual operation for post-processing. The segmentation protocols were adapted from the literature of Ma, Lee, Li and Kwon [30] as shown in Figure 3. To decrease the breathing effect on shape variation and body volume acquisition, all participants were guided to expel to end tidal volume before the commencement of scanning and hold their breath until the process finished. Participants were not sedated but were asked to keep still during the scanning to minimise the muscle movements. The scanning process for each trial lasted about 10 seconds.

After scanning, the corresponding software of the 3D scanner was used to complete initial reconstruction tasks and generate the raw 3D data after the scanning as shown in Figure 1 (a).

The quality of the 3D scanning data was examined to ensure it is good for post-processing. Baby powder was available to be applied on the skin if required to minimize reflections and eliminate problems relating to fringe contrast. However, no serious fringe contrast issues were found in this study, so no participants required the application of baby powder. Each participant's raw 3D data (two files obtained from the two scanning trials) were processed with manual operation and the model fitting technique separately to obtain the whole-body and segmental volume data for comparison purposes. In total, there were two sets of body volume data obtained with manual operation and two sets of body volume data acquired with the model fitting technique. The following two sections illustrate the detail of the manual and automated post-processing techniques.

2.3 Manual Operation for Post-processing

A well-trained operator (OP2, second author) used the 3D mesh editing software (Cyslice, Headus 3D) to complete all the reconstruction tasks, including noise reduction, hole filling, and mesh smoothing with the 3D raw scanned data. The procedure of the reconstruction for manual post-processing referred to the illustration presented by Collins [15]. After the manual operation conducted by OP2, the reconstructed 3D meshes were obtained in the Stanford Triangle Formats (Polygon File Format; PLY) for the subsequent steps of mesh segmentation and volume calculation as shown in Figure 1 (b).

After obtaining the reconstructed PLY mesh, OP1 who have extensive experience in 3D mesh processing used another 3D software, Blender (https://www.blender.org/), to identify the body landmarks and complete the tasks of mesh segmentation. The definition of the segmental plane as shown in Figure 3, which was adapted to the literature of Ma, Lee, Li and Kwon [30]. OP1 identified the position of physical markers placed on the participants' Adam's Apple and Acromiales and estimated the position of public bone manually. After that, customized Blender script was used to find the location of armpits (i.e. the critical points with local maximum) and apply Boolean functions to segment reconstructed meshes. Totally, one whole-body mesh and six segmental meshes (head & neck, torso, right arm, left arm, right leg, left leg) were acquired from each reconstructed 3D mesh. Figure 1 (c) shows the example of the right arm segmental mesh.

The whole-body mesh and the six segmental meshes were exported as OBJ file format and the segmental volume data were calculated with the polyhedral volume calculation techniques [31] by using the Python Module (trimesh; https://trimsh.org/index.html). Totally, one whole-body and six segmental volumes (head & neck volume, torso volume, right arm volume, left arm volume, right leg volume, left leg volume) obtained with the manual operation from each 3D scanning trial.

2.4 Automated Post-processing Techniques

In this study, the bespoke software was developed for completing the post-processing tasks automatically. The developed software combined different algorithms including Stitched Puppet model fitting techniques [29], screen Poisson reconstruction techniques [32], mesh Boolean techniques [33] and polyhedral volume calculation techniques [31]. Figure 4 shows the flowchart of the developed software. The following paragraphs describe how to use these techniques in our software. Detail of these algorithms can be found in previous literature [29, 31, 32] or its source code (https://code.google.com/archive/p/carve/).

First, the bespoke software applied the Stitched Puppet model fitting techniques [29] to match the raw data obtained from the 3D scanning as shown in Figure 2 (b). Stitched Puppet model fitting techniques deformed the template models by the mathematical optimization algorithm to match the shape of 3D raw scanning data [29]. After the model fitting process, the deformed Stitched Puppet template models were exported in PLY file format. Then, the screened Poisson reconstruction techniques [32] were implemented on the raw data by cleaning, repairing and smoothing the meshes as shown in Figure 2 (f). The screen Poisson reconstruction techniques [32] applied the screen Poisson equation to reconstruct the mesh surfaces from the 3D points of the raw data in two resolutions (high-resolution: around 700000 points; mid-resolution: around 50000 points). The mid-resolution meshes can increase the speed of mesh segmentation and avoid software problems. The deformed Stitched Puppet template models aligned with the mid-resolution meshes and used to identify the segmental endpoints and determine their locations. Then, the bespoke software used the location information of segmental endpoints to set segmental boundaries on the reconstructed meshes (mid-resolution ones) as shown in Figure 2 (g).

The Boolean function of Blender was applied to obtain segmental meshes without manual operation as shown in Figure 2 (h). Carve library (https://code.google.com/archive/p/carve/) was used to implement the Blender Boolean function [33], which segmented the 3D whole-body meshes (i.e. the reconstructed human models in mid-resolution) with the indicated planes. Totally, the bespoke software obtained one whole-body (the reconstructed mesh in high-resolution) and six segmental meshes in the same manner as manual operation from each raw scanning mesh and exported them in 3D model file formats (OBJ). The segmental volume data were calculated with the polyhedral volume calculation techniques [31] by using the Python Module (trimesh; https://trimsh.org/index.html). The polyhedral volume calculation techniques [31] calculated the sum of volumes by Green's Theorem for estimating the total volumes of the segment meshes. Totally, one whole-body volume and six segmental volumes (head & neck volume, torso volume, right arm volume, left arm volume, right leg volume, left leg volume) obtained with the automated post-processing from each 3D scanning trial.

2.5 Statistical Analysis

Four sets of body volume data (BV_i^{M1}, BV_i^{M2}, BV_i^{T1} and BV_i^{T2}) were acquired for each (i th) participant from 3D structured-light scanning with the two different post-processing approaches in separate trials (manual operation 1, manual operation 2, automated post-processing 1 and automated post-processing 2). The reliability of the manual operation and the bespoke software was quantified by calculating the root mean square error, the intra-method relative technical error of measurement (intra-TEM), and the Pearson correlation coefficients between BV_i^{M1} and BV_i^{M2}, and BV_i^{T1} and BV_i^{T2} respectively [34].

M_i^M are the mean segmental volumes of BV_i^{M1} and BV_i^{M2} obtained from manual operation. M_i^T are the mean segmental volumes of BV_i^{T1} and BV_i^{T2} acquired from automated post-processing respectively. In this study, M_i^M were regarded as the reference values and compared to M_i^T. The inter-method relative technical error of measurement (inter-TEM, [34]), the root mean square error (RMSE) were used to quantify the differences between M_i^M and M_i^T. The Pearson correlation coefficients were also computed to understand the relationship between M_i^M and M_i^T. The statistical analyses were conducted with Microsoft® Excel.

The mean mesh overlapped distance was also used to determine the accuracy of the proposed automated post-processing techniques. The open source software, CloudCompare [35], was applied to calculate the mean overlapped distance between the reference meshes (obtained from manual operation) and their corresponding meshes that acquired from the automated post-processing.

3 Results

Table 2, Table 3, Figure 5 and Figure 6 show analysis results in this study. The intra-TEMs of whole-body volume acquired with both manual operation and automated post-processing techniques were less than 1%. The intra-TEMs of most segmental volumes (torso volume, right arm volume, left arm volume, right leg volume, left leg volume) acquired with the manual operation were less than 2%. The intra-TEMs of segment volumes obtained with automated post-processing techniques were larger than 2%.

The inter-TEM between of M_i^M and M_i^T for whole-body volumes and most segmental volumes were smaller than 5%. The RMSE for whole-body, head & neck, and arm volumes was less than 1 l. The Pearson correlation coefficients for all segmental volumes were higher than 0.900. The mean of mesh overlapped distances was around 0.06 cm.

4 Discussion

The purpose of this study was to apply the Stitched Puppet template matching techniques to develop bespoke software for obtaining whole-body volumes and segmental volumes from raw 3D scanned data automatically and establish its accuracy and reliability. To achieve this, bespoke software routines were developed for completing the post-processing tasks, including mesh reconstruction, mesh segmentation and volume calculation automatically. Whole-body volumes and segmental volumes acquired from 3D structured-light scanning with the manual operation was compared to that obtained using the automated post-processing technique.

Sanders, Chiu, Gonjo, Thow, Oliveira, Psycharakis, Payton and McCabe [36] referred to some other precedent for setting the 5% error margin as a threshold to determine whether a method has good reliability for certain applications (e.g. body segment parameter acquisition). According to the test results shown in this study, both manual operation and automated post-processing could be used to obtain whole-body volumes and segmental volumes with good reliability for some applications. Moreover, the reliability of whole-body volumes (RMSE < 0.60 l) obtained with the manual operation and the automated post-processing for 3D data in this study was similar to the results shown in previous research [15]. Thus, the automated post-processing could be an alternative method for manual operation to monitor the change of body volumes and body composition.

The variation of scanning pose caused that different test results were obtained in repeated trials [37, 38] since the location of body landmarks, the orientation of segmental planes in repeated trial were different while pose changed. Manual operation can adapt the changes generated by the variation of scanning pose easily to minimize the error in identifying body landmarks. Nevertheless, stitch puppet deformed the template models by altering a limited number of parameters. It might not cover all situations of the scanning pose variation. Consequently, the segmental volumes obtained with manual operation with higher reliability than the data extracted with the bespoke software. The positioning aid device developed by Schwarz-Müller, Marshall and Summerskill [39] should be applied in further studies to improve the reliability of the bespoke software.

Human bodies are non-rigid objects. Slight muscle movement and blood flow during scanning could cause shape deformation and influence the 3D body measurement. For the applications which require detection of small differences such as wound care, further development should be conducted to improve the reliability of post-processing techniques for 3D scanning.

In the past, there has been no research conducted to compare the complete body volume (including whole-body volumes and segmental volumes) acquired with manual operation and automatic post-processing techniques. This study compared whole-body volumes and segmental volumes obtained from two post-processing techniques and utilised inter-TEM and RMSE to quantify the difference between these techniques. The small mean of overlapped distances from the meshes reconstructed by the bespoke software to the reference mesh led to the good accuracy in whole-body volume estimation. The inter-TEM for the whole-body volume acquired with the bespoke software was less than 1% which is lower than the requirement of accuracy for traditional anthropometric measurement [34]. In other words, the whole-body volume obtained with the bespoke software was very close to the result obtained with manual operation.

The automatic process of identifying landmarks and segmentation planes might cause the error for segmental volumes so the errors when estimating segmental volumes using the software were greater than the errors for whole-body volumes. Nevertheless, the inter-TEMs were all less than 5% (apart from head & neck) so the bespoke software can provide a general concept for body volume distribution for the applications in health and medicine. The RMSEs for arms were less than 0.2 l so the developed method could be used, for example, for applications such as diagnosis of unilateral arm lymphedema [40]. Nevertheless, some applications need higher accuracy than the 5% error margin (e.g. medical examinations). Further development should be conducted to improve the accuracy of anatomical detection for these applications.

The scanning posture used in this study can minimize occlusion problems during 3D scanning [41]. However, 3D scanning could not detect the body surface accurately for extremely obese patients with large skin folds or saggy skins. Hence, further studies should be conducted to compare the 3D scanning techniques with reference methods such as underwater weighting and or air displacement for correcting the influence of skin folds or saggy skins.

5 Summary

Body volume data including whole-body volumes and segmental volumes are highly related to individual's health and medical conditions, but the manual operation for post-processing 3D scanning data requires technical expertise. There is clearly a need to automate this process if 3D scanning is likely to be used more widely in the respective disciplines. This study applied the Stitched Puppet template matching [29] and screened Poisson reconstruction techniques [32] to develop software which can complete all the post-processing of 3D raw scanned data including mesh reconstruction, mesh segmentation and calculation of whole body and segmental volumes with acceptable levels of reliability and accuracy.

Acknowledgement

The authors would like to thank Ned Brophy-Williams for operating the 3D scanner.

Funding Source

Not applicable.

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Table Captions

Table 1 Participant characteristics (the values were shown in mean ± standard deviation and extracted from manual measurement or traditional 3D scanning techniques).

Table 2 The reliability of the manual operation and automated techniques for post-processing. Inter-TEM: Intra relative technical error of measurement between BV_i^{M1} and BV_i^{M2} or BV_i^{T1} and BV_i^{T2} (%). RMSE: Root mean square error (l). R: Pearson regression coefficient.

Table 3 Comparison of M_i^M and M_i^T . Inter-TEM: Inter relative technical error of measurement between M_i^M and M_i^T (%). RMSE: Root mean square error (l). R: Pearson regression coefficient.

Figure Captions

Figure 1 The manual post-process for obtaining segmental meshes (a) 3D raw data can be obtained from 3D Structured-light scanning, but the data contains many holes. (b) The smooth meshes without any holes can be obtained after manual reconstruction tasks on 3D raw scanned data. (c) The segmental meshes (e.g. right arm mesh) can be obtained from the 3D reconstructed meshes by the mesh segmentation process.

Figure 2 The automated post-processing techniques for obtaining segmental meshes (a) 3D raw data can be obtained from 3D structured-light scanning, but the data contains many holes. (b) The deformed 'Stitched Puppet' template model. (c) The 'Stitched Puppet' template model (blue model) was deformed to fit the shape and the pose of the raw data obtained from the 3D scanning (red model). (d) An example of the deformed Stitched Puppet template model contains some abnormal faces which might generate some error in mesh segmentation and volume calculation. (e) The bespoke software applied screened Poisson reconstruction techniques to reconstruct the 3D raw data. (f) A reconstructed mesh sample of the 3D raw data. (g) The segmental endpoint (the circle with coordinates) can be identified by indicating the corresponding vertex indices, and the segmental boundary (the yellow plane) can be easily set by referring the indicated segmental endpoint. (h) The example of the upper arm segmental mesh obtained from the automated post-process.

Figure 3 The definition of the segmental planes in this study. The blue point is the position placed with physical landmarks. The green points are virtual landmarks which identified from the reconstructed mesh visually (pubic bone) or detected by the customized Blender script (armpit) while applying the manual operation for post-processing.

Figure 4 The flowchart of the developed software.

Figure 5 The reliability of manual and automatic post-processing represented by (a) intra-TEM and (b) RMSE.

Figure 6 The accuracy of the automatic post-processing.