Title: Comparison of Automated Post-processing Techniques for Measurement of Body Surface Area from 3D Photonic Scans

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Comparison of Automated Post-processing Techniques for Measurement of Body Surface Area from 3D Photonic Scans

Abstract

Body surface area (BSA) measurement is important in engineering and medicine fields to determine parameters for various applications. Three-dimensional scanning techniques may be used to acquire the BSA directly. Nevertheless, the raw data obtained from 3D scanning usually requires some manual post-processing which is time-consuming and requires technical expertise. Automated post-processing of 3D scans enables expedient BSA calculation with minimal technical expertise. The purpose of this research was to compare the accuracy and reliability of three different automated post-processing techniques including Stitched Puppet (SP), Poisson surface reconstruction (PSR), and screened Poisson surface reconstruction (SPSR) using manual post-processing as the criterion. Twenty-nine participants were scanned twice, and raw data were processed with the manual operation and automated techniques to acquire BSAs separately. The reliability of BSAs acquired from these approaches was represented by the relative technical error of measurements (TEM). Pearson's regressions were applied to correct BSAs acquired from the automated techniques. The limits of agreement (LOA) were used to quantify the accuracy of BSAs acquired from the automated techniques and corrected by regression models. The reliability (relative TEM) of BSAs obtained from PSR, SPSR and SP were 0.32%, 0.30%, 0.82% respectively. After removing bias with the regression models, the LOA for PSR, SPSR and SP were (-0.0134 m^2, 0.0135 m^2), ±0.0131 m^2, ±0.0573 m^2 respectively. It is concluded that PSR and SPSR are good alternative approaches to manual post-processing for applications that need reliable and accurate measurements of BSAs with large populations.

Introduction

Importance of Body Surface Area

Body surface area (BSA) measurement is important in engineering and medicine fields (Daniell et al. 2012, Yu et al. 2010, Yu et al. 2003) to determine various parameters for quantifying body sizes and shapes (Chen et al. 2010, Katzmarzyk and Leonard 1998), heat transfer (Sørensen and Voigt 2003), calculating medical dose (Chiang et al. 2015, Pinkel 1958, Reagan-Shaw et al. 2008), estimating people's health status (Chen, Chang, Chen and Hsu 2010, Rahman and Adjeroh 2016) and helping to guide the treatment of patients with burns (Yu and Tu 2009). The surface area of the human body, like that of the coastline of an island, is potentially infinite. The accuracy of BSAs obtained from various methods depends on the number of data points used to define it. Therefore, having sufficient points to capture the details of the surface is a critical consideration. Currently, BSAs are typically calculated from mathematical formulae or measured by 3D scanning techniques.

Mathematical formulae and their limitations

Several mathematical formulae using anthropometric measurements such as stature and body mass have been developed to estimate BSAs. These avoid time-consuming and complex measurement (Daniell, Olds and Tomkinson 2012). DuBois and DuBois (1916) presented a model for estimating individual BSAs from stature and body mass lists in the following equation.

$$BSA = Mass^{0.425} \times Stature^{0.725} \times 0.007184 \qquad (1)$$

where BSA is body surface area in m^2, $Mass$ is body mass in kg and Stature in cm.

This model has been used widely for various applications (Verbraecken et al. 2006). Since then, Yu, Lo and Chiou (2003) have used formulae based on stature and body mass to predict BSA of Chinese adults at different ages and sexes. Daniell, Olds and Tomkinson (2012) suggested that the equation of Shuter and Aslani (2000) provided the most accurate BSA estimation (bias: -0.002 m^2; limits of agreement: -0.071 to 0.066 m^2). Similarly, Kuehnapfel et al. (2017) found that Shuter and Aslani (2000) equation had the most accurate BSA estimation (bias: 0.0842 m^2; limits of agreement: -0.0028 to 0.1712m^2). However, because these equations are based only on stature and body mass, these results may not be as accurate for people of different sexes and ethnicity. People's physiques vary due to the ethnicities and heat balance phenomenon. For example, Bergman's Rule shows that the ratio between people's BSAs and volumes changes with geographical latitude (Bergmann 1848). Redlarski et al. (2016) indicated that the results calculated by different mathematical formulae might be variable with the total BSA error being up to 0.5 m^2, which is large relative to the average BSA for men (1.91 m^2) (Sacco et al. 2010). Story and Haase (2008) suggested that the acceptable error for BSAs was 0.1 m^2 and Perini et al. (2005) indicated that the acceptable error of anthropometric measures (e.g. girths, lengths, breadths) for skilful operators was less than 1.0%.

Inaccurate BSAs might lead to miscalculations that are untenable in some applications. For example, miscalculations could cause underestimation in chemotherapy dosing for a cancer patient (Gurney 2002) or overestimation with consequent increased cost of drugs (Sacco, Botten, Macbeth, Bagust and Clark 2010). Accurate BSA measurement in conjunction with

other body dimensions is important to distinguish anthropometric characteristics of individuals within general populations as well as individuals within specific populations, e.g. professional athletes (Schranz et al. 2010). For instance, Schranz, Tomkinson, Olds and Daniell (2010) indicated that female heavyweight and lightweight rowers usually have BSA characteristics that differ from norms of the general population.

Three-dimensional Scanning Techniques

Three-dimensional scanning techniques may be used to acquire the BSA directly. Therefore, it has been regarded as the reference method for previous studies (Daniell, Olds and Tomkinson 2012, Kuehnapfel, Ahnert, Loeffler and Scholz 2017, Yu, Lo and Chiou 2003). Nevertheless, the raw data obtained from 3D scanning usually requires some manual post-processing to fill the 'holes', reduce 'noise', and smooth meshes as shown in Figure 1 (a) and 1 (b) (Daniell, Olds and Tomkinson 2012, Ma et al. 2011). Collins (2006) indicated manual post-processing time is typically around 30 minutes for four raw scanning results. However, the manual post-processing speed depends on the operator's experience. An operator with little experience might need more than 20 minutes to process raw scan data of one person. In other words, manual post-processing is time-consuming and requires technical expertise, thereby reducing the feasibility of measuring large samples. For some applications in sports and health, it is necessary to measure anthropometric characteristics, including BSAs, of a large number of individuals to understand their sports performance, obesity level and health risk. For instance, Schranz, Tomkinson, Olds and Daniell (2010) obtained anthropometric data (including BSAs) of 666 elite Australian rowers and 1498 participants from the general population by 3D scanning techniques to identify differences between elite athletes and the general population.

Kuehnapfel, Ahnert, Loeffler and Scholz (2017) used the commercial software, ANTHROSCAN VITUS XXL, to complete the post-processing tasks automatically for a sample of more than 1000 participants. However, the software represents a 'black box', since its algorithms have not been published in the public domain (Kuehnapfel, Ahnert, Loeffler and Scholz 2017). The software algorithms for this kind of commercial software were usually built as binary files and cannot easily to access by other developers. Therefore, researchers without this software cannot implement this method to measure BSA of large samples without a large investment of time.

Template Model Fitting Techniques for 3D Scanning

Currently, two main categories of automated post-processing have been presented. The first is the template model fitting technique, which deforms a template model to fit the raw 3D scanning data as shown in Figure 2. 'Stitch Puppet' (SP) (Zuffi and Black 2015) is an advanced template model fitting technique. The SP template model is composed of 16 body parts. Each body part can be deformed to different shapes and poses to align with the raw 3D scanning data successfully without needing to place any markers on the participants or digitise the anatomical landmarks. An example output of the SP technique is shown in Figure 1 (c). Therefore, using SP can complete post-processing without the technical expertise required in other template model fitting methods.

Template-free Post-processing Techniques for 3D Scanning

The second category of automated post-processing is the template-free technique, which reconstructs a surface from an oriented point set (vertices extracted from raw 3D scanning data) by solving specific mathematical equations. Poisson surface reconstruction (PSR) (Hoppe 2008) is a popular approach of this category of automated post-processing. PSR has been used widely in various applications (Roth et al. 2015) such as human modelling (Li et al.

2013, Tong et al. 2012), 3D object scanning (Cui et al. 2013, Gallo et al. 2014) and building 3D databases (Singh et al. 2014). However, the mesh reconstructed by PSR sometimes 'over smooth' which leads to details of the mesh being 'flattened' and the BSAs being underestimated. Screened Poisson surface reconstruction (SPSR) (Kazhdan and Hoppe 2013) is an improved approach of PSR which can avoid 'over smoothing'. The SPSR reconstructed hand mesh (Figure 1 (e)) shows more detail (e.g. finger outlines) than the PSR reconstructed hand mesh Figure 1 (d).

Advantage of Automated Post-processing These automated post-processing methods obtain measurements similar to those obtained by manual post-processing models. The reconstruction techniques can reduce the cost of human resource for post-processing. Moreover, parallel computing approaches can expedite processing raw 3D scanning data of large samples

Purpose

Although SP, PSR, and SPSR can complete the post-processing tasks automatically, the reliability and accuracy of calculating BSA acquired from the 3D models generated with these techniques are unknown. Differences in the number of points used to describe the surface topography might yield different BSA estimates. For example, the meshes generated by SP with around 10,000 data points could yield a different BSA from one processed with PSR or SPSR with approximately 500,000 data points. Until the reliability and accuracy are known, the advanced techniques cannot be applied with confidence. Thus, the purpose of this research was to compare the accuracy and reliability of automated post-processing techniques including Stitched Puppet (SP), Poisson surface reconstruction (PSR), and screened Poisson surface reconstruction (SPSR) using manual post-processing as the criterion.

Material and Methods

Participants

The study was approved by School of Education Ethics Sub-Committee at the University of Edinburgh. In this study, 16 male and 13 female participants (body mass: 54.6-102.9 kg, stature: 162.8-189.5 cm) with various body shapes were recruited through email and bulletin advertising. All participants provided informed consent for the data collection and the usage in scientific publication before the test started. During the data collection, participants wore close fitting clothing (e.g. Lycra cycle shorts, sports tops, etc) and a polyester swimming cap to minimize the effect of dress and possibility of occlusion.

Experiment protocol

Participants were requested to stand with the pose shown in Figure 1 which is the standard pose adopted in previous studies (Daniell, Olds and Tomkinson 2012) to minimise the possibility of occlusion and consequent need for additional post-processing processes including hole-filling and noise reduction. A calibrated Vitus^{smart} XXL 3D body scanner (Human Solutions GmbH) was used to scan each participant. Participants were scanned twice in one test session to enable repeated reliability to be determined. In order to avoid the effect of breathing on shape variation, participants were requested to expel the air in their lungs to the end of tidal volume before the commencement of scanning and to hold their breath until the test process finished (approximately 10 seconds). After scanning, raw 3D scan data were obtained as shown in Figure 1 and processed with manual operation, template-free techniques (PSR, SPSR) and the SP template model fitting technique.

For manual post-processing, the 3D software Cyslice (Headus 3D) was used to edit the meshes for 'noise reduction', 'hole-filling' and 'mesh smoothing' with the 3D human models

obtained from the 3D scanner. The manual procedure referred to the illustration presented by Daniell, Olds and Tomkinson (2012). Ma, Kwon, Mao, Lee, Li and Chung (2011) indicated trained operators can minimize inter-operator differences and enable accurate body measurement from 3D scanning. To lessen the effect of subjective interpretation, a well-trained operator (OP, second author) completed all manual processing for reconstruction of the 3D scanning data in this study. After the manual post-processing by OP, the edited 3D smooth meshes without noise and holes were obtained as shown in Figure 1 (b).

SP (Zuffi and Black 2015) was used to align the raw data obtained from the 3D scanning as shown in Figure 1 (c). The SP presented a parametric model which consisted of 16 body parts including head & neck, torso, right shoulder, left shoulder, right upper arm, left upper arm, right lower arm, left lower arm, right hand, left hand, right upper leg, left upper leg, right lower leg, left lower leg, right foot, left foot. The model can align with 3D human scanning data in different shapes and poses by applying diverse particle max-product algorithms (Pacheco et al. 2014) to alter its parameters. The detail of the SP technique can be found in the paper presented by Zuffi and Black (2015).

PSR (Hoppe 2008) and SPSR (Kazhdan and Hoppe 2013) were also used to process the raw 3D scan data. The 'Reconstruction' filter of the open source software, Meshlab (version: 1.3.4 beta; (Visual Computing Lab - ISTI - CRN 2014)) and the code from the website (https://github.com/mkazhdan/PoissonRecon; version: 9.011; (Poisson Surface Reconstruction 2017)) were applied to implement PSR and SPSR separately. Examples of processed results by PSR, and SPSR are shown in Figure 1 (d) and (e) respectively.

After the post-processing conducted by manual operation, SP, PSR, and SPSR, the complete 3D meshes without noise and holes were obtained in Polygon File Format (PLY). The 'Compute Geometric Measures' filter of the open source software, Meshlab (version: 1.3.4 beta; (Visual Computing Lab - ISTI - CRN 2014)), was used to calculate the BSA for each of the 3D human models from the exported PLY files.

Statistics analysis

After BSA calculations, eight BSA values were acquired for each participant. $BSA_{i,1}^{Manual}$ and $BSA_{i,2}^{Manual}$ were acquired from the repeated 3D scanning with manual post-processing; $BSA_{i,1}^{SP}$ and $BSA_{i,2}^{SP}$ were acquired from the repeated 3D scanning with SP; $BSA_{i,1}^{PSR}$ and $BSA_{i,2}^{PSR}$ were acquired from the repeated 3D scanning with PSR; $BSA_{i,1}^{SPSR}$, and $BSA_{i,2}^{SPSR}$ were acquired from the repeated 3D scanning with SPSR.

The repeated reliability was quantified by relative technical error of measurements ($TEMs$). The relative TEMs were obtained by using the following equation (Perini, Oliveira, Ornellas and Oliveira 2005):

$$Relative\ TEM = \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(BSA_{i,1}^{T} - BSA_{i,2}^{T}\right)^2}{2*N}}}{\frac{\sum_{i=1}^{N}\left(BSA_{i,1}^{T} + BSA_{i,2}^{T}\right)}{2*N}} * 100\% \qquad (2)$$

where N is representative of the number of participants, $BSA_{i,1}^{T}$ and $BSA_{i,2}^{T}$ denotes BSA measured by the specific technique (T $\in \{Manual, SP, PSR, SPSR\}$) for the ith participants. The error margin for repeated measurement accepted in ISAK Level 2 should be less than 1.0% (http://www.isakonline.com). Therefore, the value of relative TEMs lower than 1.0%

could be categorized as good reliability. The relative TEM was calculated with Microsoft Excel (version 2016; Microsoft®, Redmond, USA).

To compare the accuracy of BSA measurement obtained from the automated post-processing techniques, the means of repeated BSA measurements with the manual post-processing ($MBSA_i^{Manual}$) and the automated post-processing techniques ($MBSA_i^{SP}$, $MBSA_i^{PSR}$, $MBSA_i^{SPSR}$) were calculated. Bland-Altman analysis (Bland and Altman 1986) was applied to determine the difference between the BSA acquired with manual and automated post-processing techniques ($MBSA_i^{Manual} - MBSA_i^{SP}$, $MBSA_i^{Manual} - MBSA_i^{PSR}$, $MBSA_i^{Manual} - MBSA_i^{SPSR}$). The means of repeated BSA measurements with the manual post-processing and the automated post-processing techniques were entered as scores for the analyses. Pearson's regression analysis conducted with Microsoft Excel (Microsoft®) was also conducted to understand the relationship between the BSA acquired with manual post-processing and the automated techniques. The regression equations were represented as following equation:

$$CBSA_i^T = \beta \cdot MBSA_i^T + \varepsilon \qquad (2)$$

Bland-Altman analysis was also applied to examine the difference between the BSA acquired with manual operations and the BSA corrected by regression equations ($MBSA_i^{Manual} - CBSA_i^{SP}$, $MBSA_i^{Manual} - CBSA_i^{PSR}$, $MBSA_i^{Manual} - CBSA_i^{SPSR}$). The Pearson's regression analysis and Bland-Altman analysis were also conducted with Microsoft Excel (Microsoft®). Matlab (Mathwork®) was used to plot the Bland-Altman limits of agreement.

Results

Table 1 shows the test result in this study. The reliability of BSAs acquired with manual post-processing (0.29%) and the automated post-processing techniques (SP: 0.82%; PSR: 0.32%; SPSR: 0.30%) were all smaller than the error margin for repeated measurement accepted in ISAK Level 2. The intra-operator relative TEM of BSAs acquired with manual post-process (0.29%), the automatic processes PSR (0.32%), and SPSR (0.30%) were less than the relative TEM of BSAs acquired with the SP automated post-processing technique (0.82%).

The Bland and Altman plots are shown in Figure 3. The bias of SP was very near 0 m^2 (-0.0016 m^2). The biases of the template-free techniques were usually underestimated BSAs (bias of PSR = 0.0271 m^2) or overestimated BSAs (bias of PSR = -0.0383 m^2). The limit of agreement of SP was larger than other automated post-processing techniques. After correction by regression models, the biases of BSA measured from PSR and SPSR were eliminated.

The Bland and Altman plots of SP, PSR, and corrected SP showed obvious downward trends for the mean of BSA increased as shown the green lines in Figure 3. The plots of SPSR, correct PSR, and corrected SPSR showed the horizontal trend when the mean of BSA changed. The slopes of the trend for SP, PSR, and corrected SP were larger than 0.01 whereas the slopes of the trend for SPSR, correct PSR, and corrected SPSR were very close to zero.

Discussion

The purpose of this research was to compare the accuracy and reliability of three different automated post-processing techniques including Stitched Puppet (SP), Poisson surface reconstruction (PSR), and screened Poisson surface reconstruction (SPSR) using manual

post-processing as the criterion. Using 3D photonic scanning with manual post-processing has been regarded as a reference method for establishing or examining reliability and validity of simplified mathematical formulae (Daniell, Olds and Tomkinson 2012, Kuehnapfel, Ahnert, Loeffler and Scholz 2017, Yu, Lo and Chiou 2003). SP includes some random initialisations in its model fitting process which might be the reason that the relative TEM of BSAs acquired from the SP is higher than the TEMs obtained from other automated post-processing techniques. Further research should be conducted to assess the effect of the random initialisation and to explore ways to improve the test-retest reliability of the SP post-processing technique. Nevertheless, the test-retest error using SP to measure an individual with the mean BSA for men (1.91 m^2) (Sacco, Botten, Macbeth, Bagust and Clark 2010) would be less than 0.032 m^2 and this could be considered acceptable for monitoring the variation of body sizes and shapes.

The Bland-Altman analysis shows that SP appears more accurate in terms of mean bias than the others (PSR and SPSR). The bulk of this error could be attributed to the missing information on the bottom of foot (Figure 4). In other words, the foot meshes reconstructed by PSR (missing toes) and SPSR (abnormal feet frame) cannot reflect the real shapes. Separate scanning for feet could be applied to improve the scanning quality and the accuracy in BSA estimation while using PSR and SPSR to measure BSAs. Nevertheless, the bias of PSR and SPSR could be eliminated by linear regression.

The limits of agreement of the automated post-processing techniques were smaller than those reported by Daniell et al for mathematical formulae (-0.071 m^2, 0.066 m^2) (Daniell, Olds and Tomkinson 2012). This may not be surprising since the automated post-processing techniques estimated the BSA from realistic 3D human models whereas the mathematical formula used a

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very small number of anthropometric measurements (e.g. stature and mass). The realistic model can allow for the incorporation of several actual anatomic details whereas the mathematical formula methods rely upon many assumptions. In addition, the automated post-processing techniques can measure the BSA directly so that errors due to effects of age or ethnicity associated with the use of mathematical formulae can be avoided.

The likely reason for the limits of agreement of PSR and SPSR being smaller than the limit of agreement of SP is that both PSR and SPSR consider all vertices of the 3D scanning results during reconstruction while SP only considers some vertices of the raw 3D scanning during the fitting process. The vertex numbers of PSR and SPSR models (around 500,000) were similar to those of manually operated meshes and larger than the vertex number of SP models (10,777). PSR and SPSR models which used the large number of data points described detail surface topography and generated more accurate results than SP models which estimated human body shape in small number of data points.

The various models generated by manual operation, PSR, SPSR, and SP were not compared by the point-to-point distances in this study as the vertex number of the generated models differed. The reliability and accuracy of other body measurements (e.g. body volume) obtained from these automated post-processing should be compared also. Further studies should be conducted to find the optimal method to quantify and minimize the inter-test error for manual processing. This could deliver a better reference method to examine the accuracy of improving automated post-processing methods.

The trends in Bland and Altman plots with the downward trends indicated that the accuracy of BSA estimation might be affected by the size of BSAs. Thus, the accuracy of BSA might

be different while applying SP, PSR, and corrected SP on the participants with extreme sizes (very small or large BSAs). By contrast, the accuracy of SPSR, corrected PSR, and corrected SPSR could maintain the same levels when applied to the participants with extreme BSAs.

The BSAs obtained from PSR and SPSR yield more reliable BSA measurements than SP. The regression model developed in this study eliminated the bias in BSA estimation by PSR and SPSR. Thus, it is suggested that researchers use PSR or SPSR with the regression models presented in this study to minimise systematic offsets, when measuring and monitoring BSA with large samples.

Conclusions

Body surface area is an important measurement for many applications in engineering and medical fields. The accuracy of the mathematical formula estimations is affected by natural variability in the morphology of humans including the effects of age and ethnicity. This study compared the accuracy and reliability of BSAs acquired from 3D scanning with SP, PSR, SPSR for completing post-processing automatically. The results showed that, after correction of bias using the regression models presented in this study, both PSR and SPSR provide more accurate and reliable estimation of BSAs than SP and mathematical estimation. In addition, SPSR can maintain its accuracy while measuring the participants with different BSAs. Therefore, the PSR and SPSR automated post-processing technique are good alternatives to manual post-processing for applications that need accurate and reliable measurements of BSAs of large populations.

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Declarations of Interest Statement

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

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Table Caption

Table 1 The test results for the automated post-processing techniques

Figure Captions

Figure 1 The raw 3D scanning data and the results after post-processing with manual operation and the automated post-processing techniques. (a) The raw data obtained from 3D scanning with noise and holes. (b) The results after manual post-processing on the raw 3D scanning data. (c) The results after applying Stitch Puppet model fitting technique (SP) on the raw 3D scanning data. (d) The results after applying Poisson surface reconstruction (PSR) on the raw 3D scanning data. (e) The results after applying screen Poisson surface reconstruction (SPSR) on the raw 3D scanning data.

Figure 2 The concept of the template matching techniques. The template model can be deformed by setting parameters with different poses and shapes. While applying template matching techniques, the parameters of the template model are altered to make the deformed model match the raw 3D scanning data. Then the measurements can be obtained from the deformed model.

Figure 3 The Bland and Altman plots in this study (The female with the lowest BSA and the male with highest BSA in this study). (a) $MBSA_i^{Manual} - MBSA_i^{SP}$ (b) $MBSA_i^{Manual} - MBSA_i^{PSR}$ (c) $MBSA_i^{Manual} - MBSA_i^{SPSR}$ (d) $MBSA_i^{Manual} - CBSA_i^{SP}$ (e) $MBSA_i^{Manual} - CBSA_i^{PSR}$ (f) $MBSA_i^{Manual} - CBSA_i^{SPSR}$

Figure 4 The poor foot scanning results caused some error while applying the automated post-processing techniques. (a) The raw data obtained from 3D scanning. (b) The results after manual post-processing. (c) The results after applying SP. (d) The results after applying PSR (missing toes). (e) The results after applying SPSR (abnormal feet frame).