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Running Head: Reliability of 3D Scanning for Centres of Mass

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The Effect of Pose Variability and Repeated Reliability of Segmental Centres of Mass Acquisition when Using 3D Photonic Scanning

Abstract

Three-dimensional (3D) photonic scanning is an emerging technique to acquire accurate body segment parameter (BSP) data. This study established the repeated reliability of segmental centres of mass when using 3D photonic scanning (3DPS). Seventeen male participants were scanned twice by a 3D whole-body laser scanner. The same operators conducted the reconstruction and segmentation processes to obtain segmental meshes for calculating the segmental centres of mass. The segmental centres of mass obtained from repeated 3DPS were compared by relative technical error of measurement (TEM). Hypothesis tests were conducted to determine the size of change required for each segment to be determined a true variation. The relative TEMs for all segments were less than 5%. The relative changes in centres of mass at ±1.5% for most segments can be detected ($p<0.05$). The arm segments which are difficult to keep in the same scanning pose generated more error than other segments.

Practitioner Summary

Three-dimensional photonic scanning is an emerging technique to acquire body segment parameter data. This study established the repeated reliability of segmental centres of mass when using 3D photonic scanning and emphasised that the error for arm segments need to be considered while using this technique to acquire centres of mass.

Keywords: Body Segment Parameters; 3D Photonic Scanning; Reliability; Anthropometry; Biomechanics

1 Introduction

Body segment parameter (BSP) data includes segmental masses, segmental centre of mass positions relative to segmental landmarks and segment moments of inertia. These data play important roles in biomechanical studies (Jensen 1989) and ergonomics analysis (Ma et al. 2011a, Ma et al. 2011b). For example, researchers can derive acceleration from segmental centres of mass position time series to quantify the external forces acting on the segments. Several methods can be used to estimate BSP

data including direct measurement techniques, medical scanning approaches, and mathematical modelling. Direct measurements such as water displacement (Dempster 1955) and reaction board (Damavandi et al. 2009, Hansen et al. 2014, Bonnet et al. 2015) enable individual BSP data to be obtained. Medical scanning such as dual energy X-ray absorptiometry (Durkin et al. 2002) , magnetic resonance imaging (Bauer et al. 2007) and computed tomography (Pearsall et al. 1996) have been used to understand the distribution of body tissues and calculate BSP data in conjunction with the assumption of uniform density of body tissues. Mathematical modelling estimates BSP data mathematically from a small number of anthropometric measures obtained manually or extracted from images and 3D scanning results (Hanavan Jr 1964, Jensen 1978, Ma et al. 2011a, Ma et al. 2011b).

However, all these methods contain some limitations which cannot be accounted for easily. Direct measurements usually require complex equipment and time-consuming procedures to acquire the complete set of BSP data for all segments. For instance, specialised tanks for different segments are needed to measure the segmental volumes by water displacement (Drillis, Contini, & Bluestein, 1964). The possibility of health risks associated with medical scanning prevents frequent use of these methods

(Rolland 2012) and mathematical modelling has been criticised as being too simple to represent individual BSP data adequately (Abe et al. 2010, Chen et al. 2011).

Recently, 3D photonic scanning with computer aided design (CAD) software has emerged as a technique which enables fast and accurate acquisition of BSP data (Abe et al. 2010, Ma et al. 2011a). The BSP data can be calculated from the segmental meshes with the assumption of homogeneous density (Ma et al. 2011b). Collins (2006) and Wang et al. (2006) showed that the segmental volume acquired from 3D photonic scanning agreed closely with the segmental volume obtained with the water displacement method.

Although 3D photonic scanning is fast, risk-free, and accurate, the slightly different poses between scanning trials and some humanoid post-processes could affect the reliability of BSP data acquisition. To simplify the tasks for 3D model segmentation, the limbs need to abduct during 3D scanning process (Wang et al. 2006, Ma et al. 2011a). The variability of the lower limbs can be easily controlled by requesting the participants to stand on specific floor markings. By contrast, people cannot keep their upper limbs in identical positions for each scanning trial since no device provides references of direction, and participants have some freedom with respect to the

positions they adopt. This influences the angle of the segmentation planes, leading to some error during the manual post-processing. Therefore, the reliability of BSP data acquired from 3D photonic scanning needs to be quantified.

Previously, Collins (2006) compared the body volume data obtained from repeated 3D scanning trial with manual post-processing by the same operator. The results indicated that the body volume data obtained from 3D photonic scanning was repeatable and with only small effects due to the pose variability and manual post-processing. Ma et al. (2011a) evaluated the effect of different trained operators. The study showed that the result from trained operators remains consistent. Nevertheless, the trained operators processed the same scanning data so the influence of the pose variability between scanning trails was ignored.

To our knowledge, the effect of pose variability on the segmental centres of mass obtained from 3D photonic scanning has not been addressed. Therefore, the purpose of this study was to examine the effect of pose variability and establish the repeated reliability of the segmental centres of mass acquisition by using 3D photonic scanning.

2 Methods

2.1 Participants

In this study, 17 male participants (age: 35.59±10.16 years old, body mass: 81.35±9.33 kg, height: 181.53±7.59 cm) with diverse somatotypes were recruited through email and bulletin advertising. All participants signed the informed consent form. All participants were requested to wear close fitting suits such as triathlon pants and a polyester swimming cap during the tests.

2.2 Experiment Protocol

Before scanning, specific markers were placed on each participant's body to indicate the segmental boundaries defined in the E-Zone method (Deffeyes and Sanders 2005) as shown in Table 1. All markers were placed by an accredited anthropometrist (OP1, first author).

Participants were requested to stand with the assigned pose as shown in Figure 1 referred to in previous studies (Collins 2006, Wang et al. 2006). To ensure participants can reduce the pose variability, three steps were followed. First, the participants were asked to stand on 'footprints' marked on the floor of the scanner to

ensure that the positions of lower limb segments remained similar in repeated scanning trials. Second, the participants were asked to put their hands on the sides of their hips and keep the finger pointing to the floor. Finally, the participants were instructed to keep the upper arm angles and change the direction of lower arm and hand such that these two segments can be perpendicular to the floor, and hand segment can be separated from the trunk. Each participant was scanned twice on the same day by a calibrated Vitus^{smart} XXL 3D body scanner (Human Solutions GmbH). To avoid the effect of breathing on chest volume, posture, and body motion, participants were asked to expel the air in their lungs to end tidal volume before the commencement of scanning and hold their breath until the test process finished (approximately 10 seconds). Since it is very difficult to check whether the participants expelled the air in their lungs to end tidal volume during the 3D scanning, participants were requested to do some breathing practice before the scanning tests. During the scanning, unexperienced participants can hear the sound of the operator's verbal commands for guiding their breathing and the experienced participants (who have receive similar scanning tests) can hear the sound of the motors in the 3D scanner as a cue for timing the breath. These helped participants to expel the air maximally and to hold the remaining volume steady.

The 3D human models obtained from the 3D scanner were processed by the 3D mesh edit software Cyslice (Headus 3D) to complete the reconstruction works including noise deleting, 'hole filling', and mesh smoothing in the manner established by Collins (2006). The homogeneous density assumptions were applied. That is, the centre of volume of each segment was regarded as the centre of mass. To lessen the effect of subjective interpretation, the operator (OP2, second author) who is familiar with the use of specific software completed all humanoid processing for reconstruction of the 3D scanning data in this study. After the process by OP2, the 3D mesh files were exported to Polygon File Format (Stanford Triangle Format, PLY) files as shown in Figure 1.

Another trained operator (OP1, first author) completed the segmentation works from the mesh processed by OP2 (the PLY files) and calculated the segment centres of mass. To achieve this, computer software, Blender (https://www.blender.org/), was used to segment the whole-body meshes (the PLY files) and obtain a mesh of body segments including head, neck, upper torso, lower torso, right thigh, right shank, right foot, right upper arm, right lower arm, right hand. The centre of volume (centre of mass) for each segment was calculated by using the MeshLab (MeshLab) functions which apply the methods developed by Mirtich (1996). The centre of mass of each

segment was represented by the percentage of segmental length as shown in Figure 2 which was referred to previous literatures (Ma et al. 2011a, Ma et al. 2011b).

2.3 Statistics Analysis

Two values of centre of mass ($COM_{s,i}^{scan1}$, $COM_{s,i}^{scan2}$) were acquired for each (ith) participant's segment ($s \in \{\text{head, neck, upper torso, lower torso, thigh, shank, foot, upper arm, lower arm, hand}\}$) in repeated trials ($scan1$ and $scan2$). Absolute technical error of measurement (absolute TEM, ATEM) and relative technical error of measurement (relative TEM, %TEM) were used to determine the reliability of segmental centres of mass acquisition by using 3D photonic scanning. The following equations illustrate the calculation of the absolute TEM and relative TEM.

$$Absolute\ TEM = \sqrt{\frac{\sum_{i=1}^{N}\left(COM_{s,i}^{scan1} - COM_{s,i}^{scan2}\right)^2}{2 * N}}$$

$$Relative\ TEM = \frac{Absolute\ TEM}{\frac{\sum_{i=1}^{N}\left(COM_{s,i}^{scan1} + COM_{s,i}^{scan2}\right)}{2 * N}} \times 100\%$$

Where N is representative of the number of participants, $COM_{s,i}^{scan1}$ and $COM_{s,i}^{scan2}$ denote the repeated measurements of the segmental centre of mass obtained

for the i^{th} participant in separate trial. The absolute TEMs and relative TEMs for repeated reliability were calculated by Microsoft® Excel function.

One of the main reasons for establishing the effect of pose on the reliability of the measurements is to help one assess whether differences in centres of mass positions following interventions, for example a dietary or exercise intervention that might change body shape and composition, are actual changes or possibly due to measurement error associated with changes in pose. Therefore, hypothesis tests were conducted to determine the size of change required for each body segment to be confident at ($p<0.05$) that a change has occurred. The alpha and 1-beta (power) were obtained for simulated changes with magnitudes ±1.5%, ±2.5% and ±5%. All the hypothesis tests with their corresponding power analyses were conducted with Microsoft® Excel function and free software, R (https://www.r-project.org/). The simulations to obtain power (the likelihood of a type 2 error) for particular magnitudes of change were based on the method described by Hinton (2004) with the mean of the means of the two pose variations of each body segment being used as the mean of the known distribution. The standard errors were based on the differences between the poses found in this study and the associated critical t values based on a

simulated intervention with 17 participants (the same as used in this study) with the significance level set at p=0.05.

3 Results

The repeated reliability of segmental centres of mass acquired from 3D photonic scanning is represented with absolute TEMs and relative TEMs as shown in

Table 2. The absolute TEMs for all segments were less than 2.5%. The absolute TEMs for hand segments (absolute TEM=2.20%) and upper arm segments (absolute TEM=1.85%) were higher than other segments (absolute TEMs<1.6%). Similarly, the relative TEMs for all segments were less than 5%. The relative TEMs for the upper arm segments (relative TEM=4.65%) and hand segments (relative TEM=3.46%) were higher than other segments (relative TEMs<3%).

The results of the hypothesis tests are as shown in Table 3. The relative changes of ±1.5% had a small chance of both type 1 and type 2 errors for the head, upper and lower torso, and all lower limbs. However a greater percentage change is required for the neck and upper limbs to be confident of avoiding type 1 and type 2 errors.

4 Discussion

The purpose of this study was to determine the repeated reliability of the segmental centres of mass acquired from 3D photonic scanning. The relative TEMs for all segmental centres of mass were less than an error margin of 5% which has been used as a useful criterion for reporting overall reliability in accordance with convention (Sanders et al., 2015). Ma et al. (2011a) established the inter-processer reliability of segmental centres of mass acquisition by comparing different operators' results for acquiring segmental centre of mass from the same scanning data. The results

presented by Ma et al. (2011a) and in this study shows that inter-processer and intra-processer reliability of segmental centres of mass acquisition of hand and upper arm was poorer than those of the other segments. It might be that it is difficult for participants to maintain a fixed arm orientation during scanning. The repeated reliability of most segmental centres of mass positions was poorer than the inter-processer reliability of segmental centres of mass acquisition (Ma et al. 2011a). The possible reason might be that the trained operators can maintain consistency of the manual post-processing but there is some error due to the variability of the scanning poses. In other words, the pose variability between each scanning truly affects the precision of segmental centre of mass estimated by 3D photonic scanning.

It is important to determine the changes from the test-retest observation since it can help researchers understand whether their interventions such as dietary and exercise interventions change the position of segmental centres of mass. Based on the results of the hypothesis testing it is apparent that a change of more than 1.5% can be interpreted confidently as having little chance of type 1 or type 2 error for all body segments except the neck and upper limbs. At ±2.5% change, only the hand and upper arm retains a substantial risk of type 2 error. However, the hand is small and centre of mass position is not likely to have much clinical importance either with respect to the

hand itself or its influence on derived kinematics and kinetics of whole body motion. The relatively low power (0.46) for the upper arm at ±2.5% change is of some concern as it is a major limb with clinical importance and influence on derived kinematics and kinetics of whole body motion. This result reflects the greater sensitivity to pose of the upper arm segments than the other segments when conducting 3D photonic scanning to acquire segmental centre of mass.

The reason for the slightly larger error of the upper arm segments than the other segments is most likely because the upper arm segments are difficult to keep in exactly the same pose despite explicit instructions given to participants. The angle of orientation of the shoulder changed more than the angles of orientation of the torso and leg segments between poses. These might affect the humanoid post-processing and influence the result of BSP data acquisition. Hence, it is possible to improve the repeated reliability by 'fixing' the segments. For example, a handle for supporting the arms might be used to enable consistent orientation of the upper arms. Using automatic post-processing to replace the humanoid procedure might be another strategy to improve the repeated reliability. The advanced 3D computer vision techniques (Anguelov et al. 2005, Yinpeng et al. 2013) can be used to complete the post-processing automatically. However, the accuracy of the BSP data obtained with these techniques was not established in previous literature.

A function of the software is to archive the results of reliability in this studies. These results of reliability can then be compared with the results of subsequent scans. Based on the magnitude of the difference between scans an analyst can state whether 3D photonic scanning can be used to obtain repeatable segmental centres of mass. However, the hardware and software for this technology is still expensive. More development might be needed to reduce the barrier of cost. Although some methods (Weiss et al. 2011, Tong et al. 2012) that used low-cost devices, for example Microsoft Kinect, to generate 3D individual models have been developed, the accuracy for BSP data estimation still needs to be established. Furthermore, the homogeneous density assumption for body segments might cause some errors for the estimation of segmental centres of mass. While 3D scanning gives repeatable results, further research is required to ensure that the locations of the segment centres of mass are also accurate.

5 Conclusion

In this study the effect of pose variability and evaluated the repeated reliability of segmental centres of mass acquired from 3D photonic scanning was examined. The relative TEMs of all segmental centres of mass were less than 5% error although the

arm segments have higher errors than other segments. It is suggested to keep the scanning pose fixed in different trials to improve the repeatability. The results of the hypothesis tests showed that by using 3D photonic scanning one can confidently detect the relative changes in centres of mass of greater magnitude than ±1.5% for most segments including head, torso, and lower limbs. Some additional design features such as handles could be used to help participants maintain their arm postures and obtain highly repeatable BSP data.

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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Tables

Table 1 Locations of marks for 3D photonic scanning (adapted from the literature of Deffeyes and Sanders (2005), Ma et al. (2011a) and Ma et al. (2011b)).

Number	Marker	Marker Location
1	C2	Mandible Angle
2	C7	Adam's Apple
3	AC Joint	Acromiale
4	Elbow	Radiale
5	Wrist	Stylion
6	Xiphoid	Base of Sternum
7	Hip	Trochanterion
8	Knee	Tibiale laterale
9	Ankle	Lateral Malleolus of the Fibula

Table 2 Repeat reliability (%) for centre of mass acquisition of each body segment

Segment	Head	Neck	Upper torso	Lower torso	Upper arm	Lower arm	Hand	Upper leg	Lower leg	Foot
ATEM	0.82	0.93	0.70	0.42	1.85	1.58	2.20	0.48	0.13	0.59
%TEM	1.73	1.95	1.53	0.76	4.65	2.87	3.46	0.94	0.23	1.01

Table 3 The results of the hypothesis tests for each segment

Segment	Head	Neck	Upper torso	Lower torso	Upper arm	Lower arm	Hand	Upper leg	Lower leg	Foot
P-value (-5.0%)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Power (-5.0%)	1.00	1.00	1.00	1.00	0.93	1.00	0.99	1.00	1.00	1.00
P-value (-2.5%)	<0.01	<0.01	<0.01	<0.01	0.06	0.01	0.02	<0.01	<0.01	<0.01
Power (-2.5%)	0.99	0.96	1.00	1.00	0.46	0.81	0.67	1.00	1.00	1.00
P-value (-1.5%)	0.01	0.02	0.01	<0.01	0.17	0.07	0.10	<0.01	<0.01	<0.01
Power (-1.5%)	0.76	0.68	0.85	1.00	0.24	0.44	0.35	1.00	1.00	0.99
P-value (+1.5%)	0.01	0.02	0.01	<0.01	0.17	0.07	0.10	<0.01	<0.01	<0.01
Power (+1.5%)	0.76	0.68	0.85	1.00	0.24	0.44	0.35	1.00	1.00	0.99
P-value (+2.5%)	<0.01	<0.01	<0.01	<0.01	0.06	0.01	0.02	<0.01	<0.01	<0.01
Power (+2.5%)	0.99	0.96	1.00	1.00	0.46	0.81	0.67	1.00	1.00	1.00
P-value (+5.0%)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Power (+5.0%)	1.00	1.00	1.00	1.00	0.93	1.00	0.99	1.00	1.00	1.00

Figure Captions

Figure 1 The scanning result after reconstruction.

Figure 2 The centre of mass of each segment was represented by the percentage of segmental length (used left leg segments to represent the right one and this figure is adapted by Ma et al. (2011a)). The numbers of anatomical landmarks refer to Table 1.