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Original Article

A multi-method comparison of body volume and body fat in healthy adults: source of caution for interchangeability of techniques

[1]Njoku, C.O.; [2]Besong, E.E.; [3]Stewart, A.D.

Abstract

BACKGROUND AND AIM: The interchangeability of different techniques for volume measurements makes it important to cross-calibrate volumes from different scanning systems against a gold standard Air Displacement Plethysmography (ADP), and identify possible causes of the differences.

MATERIALS AND METHODS: A sample of 121 adults (78 males and 43 females, aged 18 – 44 y underwent body volume measurement via ADP (Bodpod system, Cosmed, Rome, Italy) and 3D scanning using portable scanner (Artec L, Artec Luxembourg) and fixed laser scanner (Hamamatsu BLS, Hamamatsu, Japan). Duplicate measurements were undertaken in 12 participants.

RESULTS: Measurements were highly correlated between techniques for volume (R=0.989; 0.977 and 0.979; P<0.0001) and inter-technique errors for volumes and girths were <1% technical error of measurement. Bland and Altman analysis revealed volume measurements differed between Hamamatsu and both Artec and Bodpod (P<0.05), but were similar between Artec and Bodpod (P>0.05) and these patterns remained when volumes were converted into %fat. There were no significant differences between anthropometric and 3DS-extracted waist and hip girths for either scanner type (P>0.05).

CONCLUSION: Despite their comparability for extracted waist and hip girth, the scanners are not interchangeable for volume and %fat estimation.

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[1]*Department of Anatomy, Faculty of Basic Medical Sciences, Ebonyi State University, Abakaliki, Nigeria;* [2]*Department of Physiology, Faculty of Basic Medical Sciences, Ebonyi State University, Abakaliki, Nigeria;* [3]*School of Health Sciences, Robert Gordon University, Aberdeen, UK.*

Address for Correspondence:
Njoku, C.O.
Department of Anatomy, Faculty of Basic Medical Sciences, Ebonyi State University, Abakaliki, Nigeria.
clintonnjoku76@gmail.com

INTRODUCTION

Body composition is of interest to anatomists, physiologists, nutritionists, sports scientists and other researchers because it shows how proportionate components of human body are interdependent for optimal health and function. Humans, arguably the best adapted animal for 'feast and famine', too little or too much excess fat carries a penalty in terms of impaired function (Maffetone *et al*., 2017), even when this might not imminently threaten survival.

For the 2-compartment model, body volume (BV) has traditionally been the cornerstone for developing human body composition models in human subjects via two methods: hydrodensitometry (underwater weighing [UWW]) and air displacement plethymography (ADP) (Heymsfield, 2005). Apart from UWW and ADP, 3D scanners also capture volume. 3-D scanning technology was initially developed for the automotive and textile industries in the 1990s (Horiguchi, 1998; Jones *et al*., 1995). These are of different types and have different principles in capturing body topology. Daanen and van de Water (1998), Treleaven and Wells (2007), and Carter and Stewart (2012) described many types of 3D scanners and their working modalities, ranging from Hamamatsu photonic scanners, InSpeck and Artec series, and millimetre wave-based 3D scanners.

Traditionally, densitometry method involves UWW and ADP is the considered a gold standard at 2 compartment model. This method principally involves a determination of body volume, and calculation of body density [mass / volume] and subsequent conversion to % fat via formula produced from empirical observation ((Brožek *et al.*, 1963; Siri, 1956). Because lipid displays specific gravity lower than 1.0 (for water) it is buoyant, whereas all other bodily constituents have specific gravity exceeding this value (Rushal, 2007; Byard, 2017). Hence, an increase in fatness increases body buoyancy.

Since it is difficult for two or more techniques to provide an unequivocally correct measurement, it becomes imperative to assess the degree of agreement between techniques. Hence the quest

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for accurate body composition measurements necessitated that each newer technique be validated against the gold standard.

As reviewed by Ackland *et al*. (2012), assumptions in both the two component models and multi-component models create scope for affordable laboratory and field methods of body composition that are both practicable and accurate. 3D body scanning can not only yield whole body volumetric measures, but also linear, areal and segmental volumes which have the capacity to describe 3D shape in an unprecedented way. While comparison of traditional laser scanners for volume and girth measurements have been made (Wang et al., 2006), no published study has compared portable scanners with plethysmographically-determined volume. As a result, it is unknown whether portable scanners will be comparable with either Bod pod or traditional scanners for estimating body fatness. The aim of this study is to determine if this is the case.

Materials and Methods

Participants

A sample of 121 adults (78 males and 43 females), aged between 18 and 44 years (at the last birthday) was recruited via poster advertisement to participate in a single session of body composition measurements. The participants were drawn from various ethnicities (Caucasians, Black Africans, and Asians). All participants were instructed to avoid meals for at least 3 hours before the measurements were taken. To ensure that the participants were fully hydrated, they were required to drink at least 60 cL water 20 minutes before the commencement of the measurements.

Measurements were carried out during the day, under standard lighting conditions, according scanning protocols pertaining to the Hamamatsu scanner. The time for the Bod pod measurement was 20 s, while the time duration for Hamamatsu and portable Artec measurements were 10s and 45s, respectively. All those who wished to participate gave their consent to participate by signing the consent form. The university ethics committee approved the study.

Inclusion criteria. Only apparently healthy adults within the age range of 18 – 60 y were allowed to participate in the research. However, the accessible age range was 18 – 44 y, which it was decided to implement, as there was an abundance of available individuals within this range. Such individuals are more likely to be healthy than older individuals (who might otherwise have skewed the data).

Exclusion criteria. Owing to hormonal changes during pregnancy and the consequence on altered tissue masses, distribution and densities, pregnant women were excluded. Pregnant women self-identified verbally.

As a precaution for using structured light with portable scanner, each participant was screened for epilepsy (photo-sensitive epilepsy which is known to affect approximately 1 in 2000 people). This was done by administering a screening form to all participants investigating individuals who had suffered from epilepsy or had anyone with a family history of epilepsy.

Apparel for the measurements

Owing to the fact that the surface area of clothing and body hair affect volume measurements by encapsulating entrapped air, all male participants wore form-fitting shorts and females additionally wore sports tops that exposed a region of the abdomen for landmarking for digital anthropometry. Each wore a swim cap and removed all jewelries, shoes, stockings, and wrist watches.

Methods for Measurements and Data Extraction

Procedure for Bod pod measurements (ADP)

All participants [121 adults (78 males and 43 females)] involved in this research took part in the air displacement plethysmography measurements. A double chamber calibration was performed when the chamber was empty using a standard 50 Litres cylinder.

Each participant, in the required clothing, was asked to sit in the chamber for volume measurement after which the door of the Bod pod was closed (fig. 1). Following the manufacturer's instructions, the 20 s volume measurement commenced with the participant relaxed and breathing normally. Two trials were performed on each participant and the average of the two measured volumes was taken as the participant's volume as per the manufacturer's instructions. Rarely, if the two trials did not meet the reproducibility criteria, then a third trial was performed and the two closest volumes averaged. However, if none of the measurements agreed with each other (within 150 mL, that is equivalent to 0.2%), then the whole system was recalibrated and the measurements repeated.

The thoracic gas volume (TGV) of each of the participants was predicted using the age, sex and height factors based on healthy adults' reference values as recorded by Crapo *et al*. (1982). In contrast to UWW, which requires maximal exhalation to residual volume, Bod pod lung volume is typically the average lung volume at normal tidal breathing. Considering this, it was necessary to adjust the raw BV from 3D scanners for the average amount of air in the lung (TGV) during normal tidal breathing (mid-tidal exhalation). Thus, BV derived from 3D scanners was corrected to include TGV which was adjusted to incorporate 50% of the tidal volume.

Participants were from various ethnic origins and for the fact that ethnicity affects the density of different tissues; different equations were used to derive the body density of members of specific ethnic groups. The Siri densitometry equation (Siri, 1956) was used for the general population (comprising Caucasians, Hispanics, Asians and Indians). The Schutte *et al*. (1984) equation was used for Black Americans/African males, while the Ortiz *et al*. (1992) equation was used for Black American/African females.

Fig 1. Bod pod system showing its components (image of the facility used by the researcher at Laboratory)

Procedure for body scanning using the Hamamatsu Photonic Body Line Scanner

121 participants (78 males and 43 females) took part in this session. The 3D scans were acquired using a Hamamatsu BLS 9036 fixed scanner (Hamamatsu Photonics, UK). The participants were scanned in 'scanner' position, which involved looking forwards and the feet were shoulder width apart and legs and arms were abducted from the midline. The hands were extended, while the palms were oriented in an anterio-posterior axis. Following the instructions from the operator, the scan was acquired at the mid-tidal stage of breathing. The time for each measurement lasted for approximately 10 seconds (acquisition mode was set to high resolution).

The scanner output involves a horizontal laser line array projected onto the body surface from four synchronized scan heads and merging the points acquired by different cameras as a point cloud. For the system's software (Body Line Manager Version 1.3) to segment the body appropriately, five primary landmarks were identified at the vertex, C7 (nape), L and R axillae and crotch. All scans were processed and subsequently analysed using its proprietary software to produce a digital solid image that data can be extracted from using system software BLS version 1.3.

Procedure for body scanning using the portable Artec L 3D Scanner

36 participants were involved in this session. The body scans of the participants were acquired in the same scanner position, and end tidal breathing, using an Artec L portable 3D scanner (Artec, Luxembourg). The time for a full body scan acquisition was up to 45 seconds. As a result, the participant's arms were stabilized with a pair of orthopedic working poles which eliminated any movement artefact. In order to reduce the breathing artefact which could result to blurring anatomical surface as it moved, the participants were also asked to maintain breathing that minimized tidal volume (i.e., very shallow breaths). With practice, scan acquisition time reduced to about 30 s.

The Artec L Portable 3D scanner produces and projects a structured light onto the body surface. The irregular body surface distorts the structured light, and the cameras record the distorted structured light on the body contour. The dedicated software merges adjacent scan fragments into the viewed image in real-time as the scan progresses.

The scans were processed through the techniques of global registration (aligning scan fragments with one another), fusion (accurately merging fragments into a single surface), hole filling and smoothing. Analysis and subsequent measurement extraction were performed using Artec Studio 9 software.

Body mass measurement

Each participant's body mass was obtained using Bod pod system electronic scale (Tanita Corp., Tokyo, Japan), which was calibrated with a 20 kg weight to measure the body mass to the nearest 0.01 kg. The participant stood motionless while the reading on the scale was recorded.

Stature and sitting height measurements

Participants' stature and the sitting height (which involved the participants sitting on the anthropometric box) were measured with a Seca 217 portable stadiometer (Seca, Hamburg, Germany). The height was later subtracted to get the real value for the sitting height.

For the stature, the participant stood with the heels together. The heel, buttocks and upper part of the back made contact with the scale. As the head was held in the Frankfort plane, the participant was instructed to take and hold a deep breath. There was a gentle upward traction applied to the mastoid process which was followed by lowering of head board firmly down on the vertex, providing compression of the hair. The measurement was taken before the participant was allowed to exhale.

Girths measurements

All girths were measured with a Lufkin WP606 flexible steel tape (Rosscraft Innovations, Vancouver, Canada). Most girth measurements were acquired in a standing position although subsets of participants' abdominal girth were made in a lying posture.

For waist girth, the tape was adjusted and measurement taken at minimum girth point of waist area (between the 10^{th} rib and iliac crest) at a right angle to the vertical axis of the trunk. Each subject was in standing position with the arms folded across the thorax. Standing by the side of the participant, the tape was passed round the waist of the participant. Holding stub and the case in the right palm, the left hand was used to adjust the level of the tape and spooled to achieve the minimum value without compressing the skin. Each measurement was taken at end of normal expiration. Those without an obvious narrowest point had their waist taken at the mid-point between lower border of the 10th rib and iliac crest.

For the hip girth, the measurement was taken over form-fitting clothing at the level of maximum posterior protuberance at a right angle to the vertical axis of the trunk. In a standing position with the arms folded across the chest, the participant adducted the legs to the midline. On instruction the participant relaxed the gluteal muscles. By the side of the participant, the stub was passed round the gluteal region. Holding both stub and the case in the right hand, the tape was adjusted to the level of maximum posterior protuberance with the left hand. At the target level the measurement was taken with the tape in the horizontal plane.

Statistical analysis

Before statistical analysis, the normality of the data was tested via a Kolmogorov-Smirnov test. Technical error of measurement (TEM) was used to evaluate measurement reproducibility. Correlation between techniques was evaluated using scattered plot. Paired t-test was also used to compare two volumes from two different techniques. One-way ANOVA was used to compare three measured volumes. Agreement for volume measures and % fat estimation between each measurement system was established using Bland and Altman analysis. Statistical analysis was performed using SPSS version 21(SPSS Inc. Chicago, IL).

RESULTS

The reproducibility of techniques was analyzed using absolute Technical Error of Measurement (TEM) and relative Technical Error of Measurement. The absolute TEM and the %TEM were presented on table 1 while the physical characteristics of the participants were presented on table 2.

Table 1: Absolute and % TEM for the volume measurements

	Bod pod	Hamamtsu 3DS	Artec 3DS
TEM (l)	0.02	0.05	0.02
% TEM (%)	0.004	0.01	0.003

Table 2: Physical characteristics of participants

	Males (n =78) Mean±SD	Females(n =43) Mean±SD	P-value
Age (year)	27.8±7.5	23.6±4.2	P>0.05
Stature (cm)	177.5±6.8	165.5±6.7	P<0.05
Weight (cm)	77.9±13.0	60.4±9.4	P<0.008
BMI (kg/m^2)	24.8±3.6	22.1±3.0	P<0.005
Waist girth (cm)	83.4±9.6	72.3±7.2	P<0.0001
Hip girth (cm)	97.7±8.4	94.9±6.7	P<0.003
% Fat	21.9±8.0	23.0±8.7	P<0.0001

Table 3. Paired t-test analysis of differences for volume measures

	N	Mean±SD	Paired mean difference	P-Value
Artec 3DS β vol (l) vs Hamamatsu 3DS β vol (l)	36	67.22±11.41 65.00±11.30	2.20	P < 0.0001
Artec 3DS β vol(l) vs Bod pod (l)	36	67.21±11.41 67.45±12.17	-0.06	P>0.05
Hamamatsu 3DS β vol (l) vs Bod pod (l)	121	66.64±13.04 68.32±14.32	1.68	P < 0.0001

β = measured volume adjusted by subtracting (thoracic gas vol minus 0.25)

* = correlation is significant

Validation of Artec L portable Scanner volume measurement against the Hamamatsu volume and Bod pod volume

The volume measurement of each of the techniques showed significant strong positive correlations between each other (Artec 3DS vs Hamamatsu 3DS volumes, R = 0.994; Artec 3DS vs Bod pod volumes, R = 0.988; and Bod pod vs Hamamatsu 3DS volumes, R = 0.990, P<0.00R01) as depicted by table 3. The paired mean difference was 2.20 (l) (P<0.0001) between Artec 3DS volume and Hamamatsu 3DS volume, 1.68 (P<0.0001) between Hamamatsu 3DS and Bod pod volumes, and -0.06 (P>0.05) between Artec 3DS and Bod pod.

Figures 2, 3 and 4 depict regression of Hamamatsu 3DS versus Artec 3DS volumes, Hamamatsu 3DS versus Bod pod volumes and Bod pod versus Artec 3DS volumes respectively. Hamamatsu 3DS versus Artec 3DS confirmed that a large portion of variance of Hamamatsu 3DS volume measurement was predicted by Artec portable 3DS (R^2 = 0.989, SEE = 1.37). Bod pod versus Artec 3DS volumes also confirmed that greater portion of the variance of Bod pod was predicted by Artec 3DS (R^2 = 0.977, SEE = 1.90), meanwhile, Hamamatsu 3DS also predicted a large portion of Variance in Bod pod measured volumes (R^2 = 0.979, SEE =2.07).

Bland and Altman analysis of volume measurement agreement between each technique is shown in fig. 5, 6 and 7. The mean difference between Artec versus Hamamatsu 3DS volume measurement was -1.97 l (95% CI -5.66 to 1.73 l; fig. 5); Artec 3DS versus Bod pod volume measurements was -0.093 l (95% CI, -3.97 to 3.79 l; fig.6); and Hamamatsu 3DS versus Bod pod was 0.50 l (95% CI, -3.4 l to 3.9 l; fig.7). There were significant differences in measurements between Artec versus Hamamatsu 3DS volumes and between Hamamatsu 3DS versus Bod pod volumes (P<0.05). However, there was no significant difference in volumes between the portable Artec 3DS (adjusted for thoracic gas volume) and those measured with Bod pod (P>0.05). However, the Bland and Altman analysis of the % BF indicated no significant difference in Bod pod vs Artec 3DS and Bod pod vs Hamamatsu 3DS, but there was significant difference between Hamamatsu 3DS vs Artec 3DS as shown figure 8 A, B C, respectively.

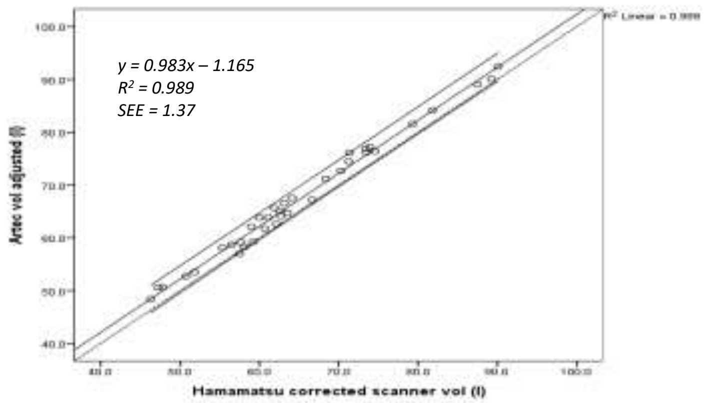

Fig. 2. Scatter plot of Hamamatsu 3DS volume against Artec 3DS volume showing line of identity and 95% CI (n=36). Adjusted volumes were derived by subtracting {thoracic gas volume - 0.25(l)} from the scanner volume. Coefficient of correlation R= +0.994; P<0.0001

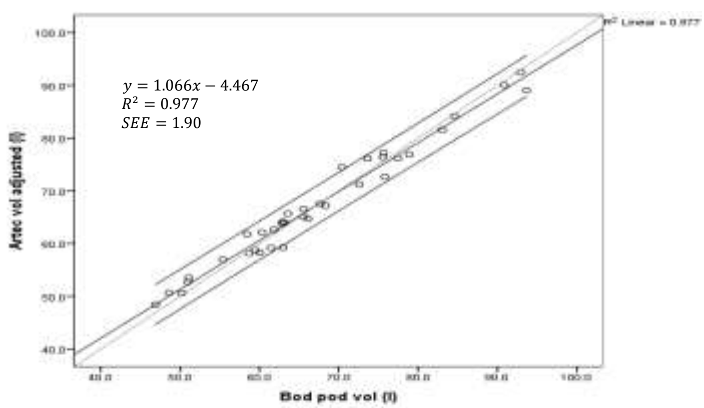

Fig. 3. Scatter plot of Bod pod volume plotted against Artec 3DS volume showing line of identity and 95% CI. (n=36). Adjusted volumes were derived by subtracting {thoracic gas volume - 0.25(l)} from the scanner volume R = +0.988; P>0.05

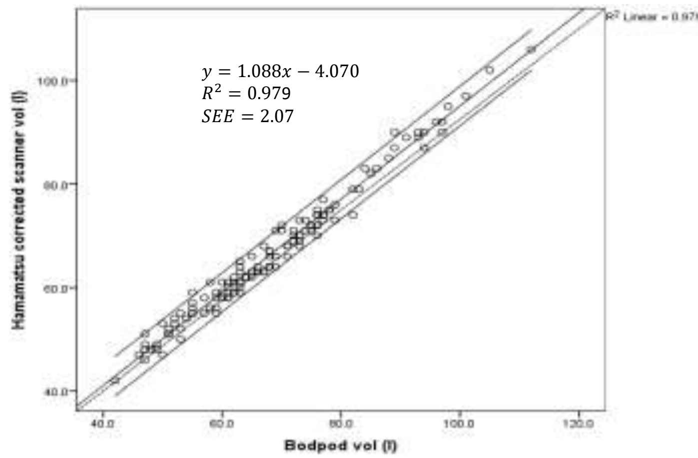

Fig. 4. Scatter plot of Bod pod volume plotted against Hamamatsu 3DS volume showing line of identity and 95% CI. (n=122). Adjusted volumes were derived by subtracting {thoracic gas volume - 0.25(l)} from the scanner volume. R= +0.990; P<0.0001

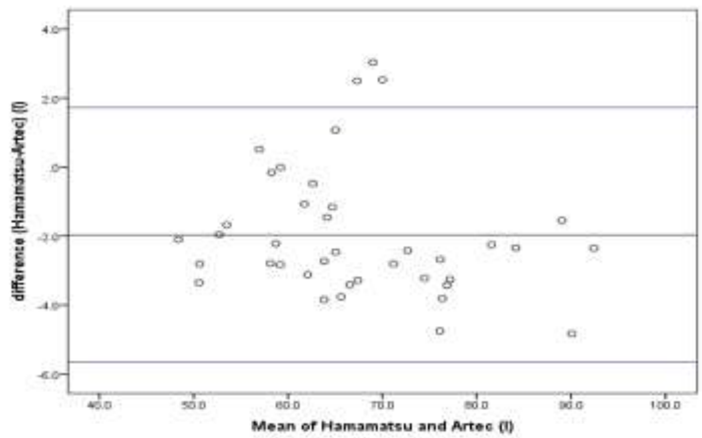

Fig.5. Bland and Altman plot of volumes measured from Hamamatsu 3DS and Artec 3DS. The blue lines represent 95% limit of agreement and the black line represents the mean difference.

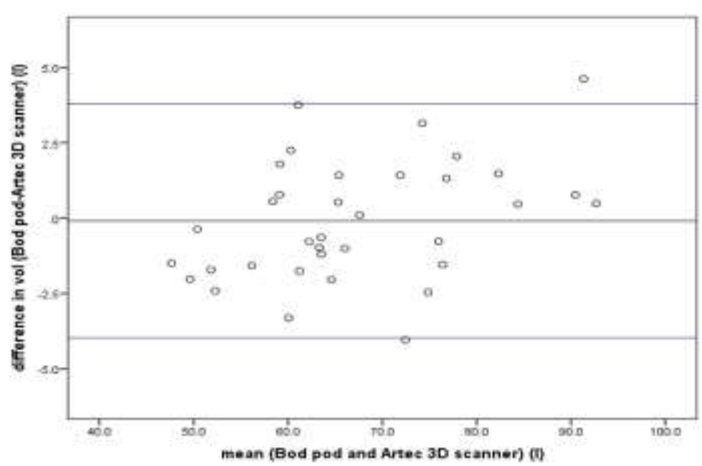

Fig. 6. Bland and Altman plot of volumes measured from Bod pod and Artec 3DS. The blue lines represent 95% limit of agreement and the black line represents the mean difference

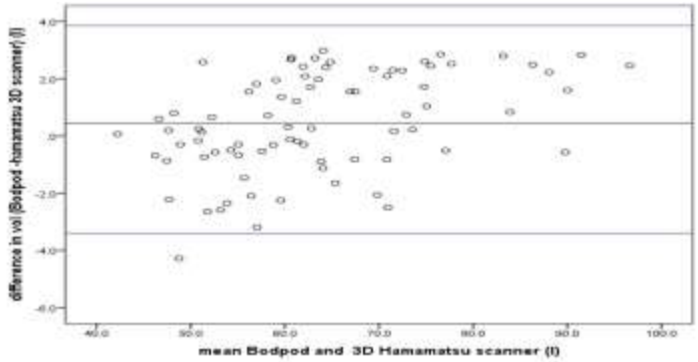

Fig. 7. Bland and Altman plot of volumes measured from Bod pod and Hamamatsu 3DS. The blue lines represent 95% limit of agreement and the black line represents the mean difference.

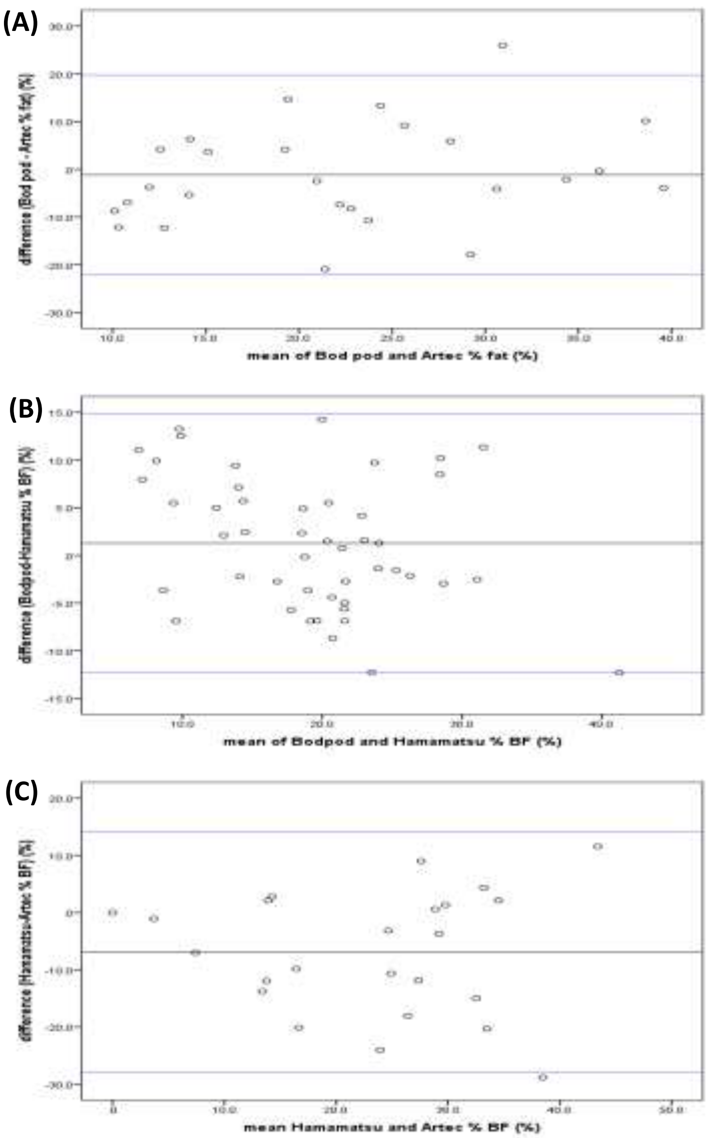

Fig. 8. Bland and Altman plot of % BF from different measurements. (A) Bod pod vs Artec 3DS, P>0.05 (B) Bod pod vs Hamamatsu 3DS, P>0.05, (C) Hamamatsu 3DS vs Artec 3DS, P<0.05. Ethnic-specific formula was used

Discussions

The Bod pod, Hamamatsu 3DS and portable Artec 3DS all produced highly reproducible volume measurements. When each method was compared with the others, the regression analysis indicated that the results of each method explained between 96 and 98% of the variability in the results from the other two methods.

The Results of the Bland-Altman analysis indicated that volume measurement from different techniques may or may not give exact measurements when compared against one another. In using densitometry to convert body volume to fat, a little difference in body volume can result to a profound difference if converted to %fat.

In this context, the Bod pod is considered the 'gold standard' for body volume assessment. Its use enabled the separate estimation of the thoracic gas volume which was subsequently applied to the scanner-derived volumes. The ability of the portable Artec 3DS (which generates data points using structured light from the body surface) to produce highly reproducible BV which is in agreement with the BV produced by Bod pod makes it ideal for clinical and field settings. However, this does not explain why there were observed differences between the Hamamatsu scanner and both the Artec L and the Bodpod-derived volumes, and why some individuals' volume measurements display such scatter between the three methods. Possible explanations for the causes of these differences include the following: acquisition time variability, clothing failing to conform to the body contour, postural differences, pointcloud data density, the mathematical approach adopted to reconstruct volumes from pointcloud data.

Acquisition time variability. Movement artefacts can be reduced via reduction of scanning time: the longer the scanning time, the greater the scope for movement artefacts to affect scanned data, and if the scanning result is to be imperative this should be given due consideration. These include postural sway, breathing and the inability to remain motionless for a longer time especially as muscles work isometrically to maintain a fixed pose. However, few individuals can hold their breath for a complete scan using the portable method, and movement artefacts cause blurring of the surface geometry. This shortcoming was recognised in some early scanner designs – for example Wicks and Wilson 3D scanners were built with grab handles for participants to hold. In the present study, a minimal scanning time (10 s) was used for the Hamamatsu 3D scanner but for the Artec 3D scanner the scanning time was approximately 30 - 45s. A pair of orthopedic working poles was used to stabilise the body which as far as reasonably possible, eliminated movement.

Clothing and hirsutism. While the same clothing assemblage worn for different techniques may theoretically control for itself between scanners, colours and textures, together with pointcloud density differences mean that the same clothing may be differently detected by different scanning systems - both by hardware (i.e. laser v light) and software (hole filling algorithms etc). Hirsutism also affects body surface detection. In their study Voegtle *et al*. (2008) reported an influence of different realistic object materials and object colours on the measurements of terrestrial laser scanners. They reported that grey scaled test plates led to significant dependence between the brightness of the scanned object and the accuracy of the scanned data. They also reported that scanned data acquired during the day was different from those acquired at night. Increase of measurement accuracy was recorded at night-time and based on bright materials. A review by Clark and Robson (2004) shows that materials of varying colours and texture produce point cloud of varying quality; and colours like black and red possessing poor reflectance at 532 nm reflect less of the laser pulse and this causes the scanner to record a great range in detected position as opposed to a single surface of the "true" position. Because clothing worn by men and women is different, it may well be valuable to look at gender and the effect of their differences between the 3 systems. For instance, in many of the females, the sports top may not conform absolutely to the body surface between the breasts, spanning this gap, and this result would lead to a non-trivial (0.5 - 1.0 litre) increase in volume.

Postural differences. Maintaining an adequate and consistent posture during whole body 3D scanning is imperative for improving measurement precision. Postural error (the body adopting a minutely different position, when seeking to replicate the same stance) is usually difficult or even impossible to avoid. As a result, different scans capture postures which are not identical in the first place. Again, breathing artefacts, postural sway and muscle contractions may differ between different scan occasions. The arm and leg abduction / tissue overlap between limbs and torso, and potentially the way clothing lies along the body surface affect the precision in measurement extraction in 3D scanning. Tomkinson and Shaw (2013) quantified postural and technical errors in asymptomatic adults using direct 3D whole body scan measurements of standing posture and reported large postural errors (arising from head and neck compared with technical error which indicated high repeatability. Similarly, Brink *et al.* (2013) attributed differences in repeated measures of postural angles in high school students to the trial-to-trial variability in posture rather than operator errors. However, another challenge to measuring body volume lies in gross posture. In the sitting posture (as in Bod pod) the plasticity and potential for compression of soft tissues could have consequences for a range of measurements – for instance the girth and area of abdomen and limb to limb, and torso to torso contact. There is currently no literature to quantify this, and thus it remains unknown whether the impact of tissue compression may be inconsequential (i.e. changes shape but not volume) or whether actual compression does occur, but may be masked by other influences. It is recognised from medical imaging that posture affects the location of organs (Hayers et al. 2013) which exhibit deformation and sliding interactions (Lafon et al. 2010). How these affect body volume and composition measurement may emerge as a future research priority.

Pointcloud data density. Although more datapoints are theoretically likely to generate a more accurate representation of the body, on the effect of other factors (scan technology, hirsutism, skin colour) may lead to an under or overestimate of the true value. What we may see is a compensation of errors whereby the errors associated with a coarse pointcloud are effectively cancelled by other factors which have errors of the opposite polarity. It would be well worth investigating how all potentially confounding factors interact (e.g., across a range of hirsutism, size, etc) but this would require a much larger study.

Mathematical approach to constructing the shape. The Hamamatsu method for volume estimation uses triangulation methods to calculate the location of the point or line which corresponds to its vertical pitch when the array beam is scanning (Wells et al., 2008). However, for the Artec, the manufacturers do not declare what geometric technique they use. While it is possible to speculate that this may involve the use of normals (i.e. perpendicular lines) generated from triangular mesh surfaces, which can be regarded as grid-based approaches, or other complex mathematical approaches which consider angles between every vertex, the evidence for which one is adopted is not in the public domain.

Physics of creating the 3D shape from Artec v Hamamatsu. The Artec L pointcloud density is considerable (20M data points v 700000 points of the Hamamatsu), wavelength and colour visibility. The fixed horizontal array (laser) of Hamamatsu as compared with the upward and downward-looking acquisition of Artec L (which will 'see' into complex shapes and 'corners', means the latter is better at describing intricate shape detail, with less hole-filling necessary. The fact that the Hamamatsu uses a wavelength of 690 nm in the red end of the visible spectrum means that it fails to detect dark brown and black colours, and this may differentially affect those of different skin colour. Since approximately 80% of the participants were recruited froms the black African population (mostly from Nigeria); this could be one of the factors that caused the observed difference between Hamamatsu 3DS and Artec 3DS volume measurements and consequently, derived % fat. Finally, there is implicit evidence of differences in software approaches to creating the model and calculating the volume. This for the Hamamatsu relates to its constant vertical pitch of 2.5 mm making triangular slices from the vertices of the point cloud to a central point on the horizontal plane. Such an approach is impossible for a point cloud whose vertices are not horizontally arranged in slices.

In this study, Hamamatsu 3DS indicated slight difference when compared with Bod pod BV, supporting evidence from Wang *et al*. (2006) who concluded that for an accurate total body volume that can be used to estimate percentage fat to be generated, subjects must wear close-fitting minimal clothing and be able to stand motionless for 10 s. However, Wang and his colleagues found a 0.4 l mean difference between the Hamamatsu and UWW. They did a TGV determination using spirometry on these participants, but some opted out of UWW, a procedure which is not feasible for those who are not water confident, and their sample was only 63 participants. In the present study the TGV determination was predicted from Bod pod values based on healthy adults' reference values as in Crapo *et al.* (1982). In theory, UWW theory uses the same 2 compartment methodology as Bod pod but other differences between the methods exist such as isothermal nature of air within the Bod pod chamber. In larger research programme which this study forms a part of, the waist and hip girths extracted digitally with Hamamatsu 3DS had an excellent correlation and indicated no significant difference with manually measured waist and hip girths. This suggests that the slight difference obtained in volume measurement in this study and that of Wang *et al.* (2006) between Hamamatsu and Bod pod probably arose from the concealed parts of the body beyond the field of view of the camera heads and these were presented as missing data (appearing as shadows, but are more accurately holes). After being filled automatically by the software the presence of such holes either increases or decreases the total body volume. Holes which typically occur in the rendered polygon at the axillae and crotch are not likely to be present in the abdomen, and this explains the agreement in waist and hip girths extracted from Hamamatsu 3DS and manually measured waist and hip girths. Errors arising from missing data can be easily overcome with the portable Artec 3DS which acquires many times more data points, and can 'see' above and below the horizontal, and be manipulated easily to ensure that any obscured areas of the body and complex topography are captured. As with the Hamamatsu scanner, the body is scanned 'from the outside in' but the Artec 3DS is able to capture much more complex surface geometry.

Into this developing discipline, 3D scanning has the potential to take an increasingly important role, as it offers the possibility of having digital models using a 3D template. Portable Artec 3DS (Artec, Luxembourg) is affordable and can produce dense meshes of rendered body shape (approx. 20 million data points) and yield data on body image, and measures body volume and surface dimensions. However, no study has yet validated its volume measurement against densitometry or ADP. Since the volume measurement from different techniques has the potential to be used interchangeably, it becomes increasingly important to compare their volumes and suggest possible causes of the differences.

Although there is a significant difference between predicted and measured lung volumes as reported by Blaney (2008), the correction of predicted lung volume which was automatically generated by the Bod pod was applied to both 3DS volume measurements, so if there was under or overestimated the thoracic gas volume of an individual, the same adjustment would be applied to the scan volume. As a result, any estimation error would cancel itself out. As a result, the discrepancies observed here must have an alternative cause.

Conclusion

Aside from the medical imaging techniques which are used for diagnostics, there is no single method of body composition that gives direct *in vivo* quantification of different components of the body. However, as this study has demonstrated that different techniques can be combined to inform a number of useful models of body composition, using tools which are portable and are becoming increasingly affordable.

The validation of 3D scanner volumes against Bod pod indicated that volume measurements could be accurately estimated using 3D scanning technology, with the appropriate thoracic gas correction. However, the source of variations in volume measurements could be attributed to so many factors ranging from acquisition time variability, clothing and hisurtism, postural differences, pointcloud data density, mathematical approach to constructing the shape and physics of creating the 3D shape from Artec v Hamamatsu. With the increasing technological advancement and affordability of the novel techniques included in this body of work, it is likely that they will become increasingly popular for research. In addition, there exists further scope to combine two or more methods to establish new approaches, and possibly the emergence of fully integrated multi-modal digital models of body composition, which may use 3D scanning as a template to be enriched with composition data acquired by other techniques.

Authors' contributions

ADS designed the project. CON carried out the experimentations, extracted data and drafted the research paper. BEE carried out the statistical analysis. ADS also proof-read the manuscript and made some corrections.

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