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Clinical anthropometrics and body composition from 3D whole-body surface scans

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Abstract

BACKGROUND/OBJECTIVES—Obesity is a significant worldwide epidemic that necessitates accessible tools for robust body composition analysis. We investigated whether widely available 3D body surface scanners can provide clinically relevant direct anthropometrics (circumferences, areas and volumes) and body composition estimates (regional fat/lean masses).

SUBJECTS/METHODS—Thirty-nine healthy adults stratified by age, sex and body mass index (BMI) underwent whole-body 3D scans, dual energy X-ray absorptiometry (DXA), air displacement plethysmography and tape measurements. Linear regressions were performed to assess agreement between 3D measurements and criterion methods. Linear models were derived to predict DXA body composition from 3D scan measurements. Thirty-seven external fitness center users underwent 3D scans and bioelectrical impedance analysis for model validation.

RESULTS—3D body scan measurements correlated strongly to criterion methods: waist circumference $R^2 = 0.95$, hip circumference $R^2 = 0.92$, surface area $R^2 = 0.97$ and volume $R^2 = 0.99$. However, systematic differences were observed for each measure due to discrepancies in landmark positioning. Predictive body composition equations showed strong agreement for whole body (fat mass $R^2 = 0.95$, root mean square error (RMSE) = 2.4 kg; fat-free mass $R^2 = 0.96$, RMSE = 2.2 kg) and arms, legs and trunk ($R^2 = 0.79$–0.94, RMSE = 0.5–1.7 kg). Visceral fat prediction showed moderate agreement ($R^2 = 0.75$, RMSE = 0.11 kg).

CONCLUSIONS—3D surface scanners offer precise and stable automated measurements of body shape and composition. Software updates may be needed to resolve measurement biases resulting from landmark positioning discrepancies. Further studies are justified to elucidate relationships between body shape, composition and metabolic health across sex, age, BMI and ethnicity groups, as well as in those with metabolic disorders.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

JAS and BKN designed and conducted the research; BKN, BJH and JAS analyzed data; BKN and JAS drafted the manuscript and had primary responsibility for final content. All authors reviewed and approved the final manuscript.

INTRODUCTION

Regional body shape and composition provide stronger indicators of obesity-related metabolic risk than the body mass index (BMI). Goodpaster *et al.*[1] showed that normal weight men with high visceral adipose levels were twice as likely to have metabolic syndrome. Wilson *et al.*[2] showed that the individuals in the highest quintile of trunk-to-leg volume ratio are at 6.8 times greater risk for diabetes. Common methods for body composition assessment include bioelectrical impedance analysis (BIA), air displacement plethysmography (ADP) and dual energy X-ray absorptiometry (DXA). Of these, DXA is the only method that provides regional information, but DXA is not suitable for large populations because of its relatively high cost and use of ionizing radiation. There is an unmet need for accessible tools for accurate regional body composition assessment.

We investigated the use of 3D whole-body surface scanning for clinical anthropometry, as well as total and regional body composition measurement. These systems generate surface renderings and automated circumference and length measurements across the entire body. Several studies have assessed their ability to accurately and precisely quantify clinically relevant measures. Wells *et al.*[3] reported 0.5 cm precision on body circumferences (chest, waist, hips and so on), using a six-camera structured light scanner. Wang *et al.*[4] reported precise (coefficient of variation (%CV) = 0.38) whole-body volume measurements using a four-camera laser-triangulation scanner. Lin *et al.*[5,6] reported correlations between 3D anthropometric measures and metabolic risk factors. Lee *et al.*[7] demonstrated accurate prediction of whole-body and regional fat mass and percent fat from regional volume and length measures from an eight-camera structured illumination scanner. Development of low-cost light-coding technology has enabled more affordable 3D scanners such as the TC^2 KX-16 (Cary, NC, USA)[8] and the Fit3D Proscanner (Redwood City, CA, USA).

In summary, 3D body surface scanning is a compelling tool for metabolic status assessment that offers inexpensive, radiation-free and automated collection of hundreds of measurements that would otherwise require significant time and personnel resources to collect. The objective of this study was to validate direct anthropometric and derived body composition measurements from 3D whole-body surface scans against criterion methods.

METHODS

We conducted a cross-sectional stratified study of healthy adults. 3D scan measurements (circumferences, surface areas and volumes) were systematically compared with manual anthropometry, DXA and ADP. Predictive equations were derived to estimate DXA body composition using 3D scan measurements.

Participants

There were two participant groups: a calibration group and a field validation group. Calibration participants were recruited using flyers posted around UCSF between January 2014 and May 2015. Calibration group recruitment was stratified by age (20–40, 40–60, 60+ years), sex and BMI (normal<25 kg/m^2, 25 kg/m^2 ⩾ overweight <30 kg/m^2, obese ⩾30 kg/m^2). Eligible participants were identified as ambulatory individuals within the study strata. Exclusion criteria included current pregnancy, missing limbs, non-removable metal in the body (for example, joint replacements), a history of body-altering surgery (for example, liposuction) and significant hair that cannot be contained within a swim cap. Each calibration participant underwent a whole-body DXA scan and two 3D optical scans, with repositioning. Weight, height, and waist and hip circumferences (each in duplicate) were recorded. All measures were acquired at the UCSF Clinical and Translational Science Institute (CTSI) Body Composition, Exercise Physiology and Energy Metabolism Laboratory (San Francisco, CA, USA). Calibration participants gave informed consent, and the study protocol was approved by the UCSF Committee on Human Research.

Participants in the field validation group were scanned at one of the eight fitness centers in the United States and Australia for body shape self-assessment purposes between July and November 2014. Each participant had a BIA percent fat measurement and a 3D body scan on the same day. Validation participants were selected to have height, weight, BMI and age measurements within the minimum-maximum ranges of the calibration data set. It should be noted that BIA measurements were user-reported, and the BIA hardware and acquisition protocols were uncontrolled. All field validation participants signed a waiver of consent authorizing the use of their anonymized scans by the investigators.

3D surface scans

3D surface scans were acquired on a Fit3D Proscanner (Fit3D Inc., Redwood City, CA, USA) according to a standard protocol. The device consists of a rotating platform and a 3D optical light-coding camera mounted in a tower 2 m from the center of the platform. Users grasp adjustable handles mounted on the platform such that their arms are straight and relaxed, abducted from the body. When buttons on the scanner handles are depressed by the user, a 360-degree 3D image is acquired while the platform rotates once around in approximately 40 s. Although only 11 circumferences (chest, waist and hips, as well as left/right biceps, forearm, thigh and calf) are reported to end users, 476 anthropometric measurements from the neck down to the ankles and wrists are automatically derived and stored in a proprietary database. In general, the head, hands and feet are excluded from all circumference, surface area and volume calculations. The Fit3D system was chosen for this study over other models because approximately 100 of these systems are available to the public at fitness centers across the US.

Each calibration participant was scanned twice, with repositioning. Form-fitting boxer briefs and a swim cap were provided for each participant. Male participants were scanned topless, whereas female participants wore a sports bra. Each validation participant was scanned once, in personal form-fitting clothing, with long hair tied above the neck. 3D scan data and measurements were transferred securely from Fit3D to UCSF.

For quality control, we performed 41 scans of a female mannequin (part #DSPEFAMW, Display Warehouse, San Diego, CA, USA) with repositioning over a 2-month period (data not included). Chest, hip, thigh and waist circumference, as well as total body volume, showed high long-term stability with CV between 0.25 and 1.2%.

Dual energy X-ray absorptiometry

Only calibration participants received a DXA scan as the criterion method for body composition. Whole-body scans were acquired on a Hologic Discovery/W or Horizon/A system (Hologic Inc., Malborough, MA, USA). All scans were centrally analyzed at UCSF by a single ISCD-certified technologist using Hologic Apex software (version 13.5.2.1) and NHANES calibration.[9] Participants were scanned in examination gowns, without shoes. Participants were centered on the scanner table with arms out to the side, hands flat on table and feet in planarflex position, in accordance with the manufacturer's standard protocols.[10] The standard DXA output includes percent fat, fat mass, lean mass and total mass for the whole body, as well as the arms, legs, torso and head. In addition, total and regional body volumes were derived for each region on the DXA report (arms, legs, trunk, whole body) using the equations of Wilson *et al.*[10]

Air displacement plethysmography

Only calibration participants received an ADP measurement as the criterion method for total body volume. Measurements were performed using a Bod Pod (COSMED USA, Inc., Chicago, IL, USA). Before each measurement, the instrument was calibrated by placing a hollow cylinder with known volume into the Bod Pod. Participants wore the same outfit for the ADP measure as for the 3D optical scan (swim cap, boxer briefs and a sports bra for females). Body volume is measured by the body's air displacement with corrections for residual lung volume and surface area artifacts. Details of the standard ADP protocol are described elsewhere.[11]

Statistical methods

All analyses were performed using SAS version 9.4 (SAS Institute, Cary, NC, USA). Univariate linear regressions were performed to assess agreement of selected clinically relevant anthropometric measurements acquired on the 3D scanner versus criterion methods: hip and waist circumference tape measurements, body surface area estimated using the Du Bois model[12] and whole/regional body volumes calculated from ADP and DXA, respectively. Student's *t*-tests were performed to detect significant measurement biases between 3D measurements and criterion methods. Measurements were assumed to be normally distributed. A critical *P*-value of 0.05 was considered significant. %CV and root mean square error (RMSE) were calculated for the matched test-retest measurements from the 3D optical scanner. Coefficients of determination (R^2) reported in this study are adjusted for multiple variables where applicable.

Predictive equations were derived for whole-body and regional DXA body composition variables, including percent fat, fat mass and visceral fat mass. Where available, we derived linear regression equations using the parameters described by Lee *et al.*[7,13] The ratio of waist girth to waist width was used as a surrogate for 'central obesity depth' defined by Lee *et al.* Waist girth and width were likewise used as surrogates for 'central obesity width' as defined by Lee *et al.* We further derived predictive equations for fat-free mass in each compartment (whole body, legs and trunk), using the same parameters as the fat mass equations. Equations were derived using linear regression (proc GLM). Additional equations were derived for fat and lean mass in the arms, by using stepwise linear regression (proc

GLMSELECT, selection = STEPWISE) and over 18 length, area and volume measurements of the arms and trunk. Selection was performed subject to minimization of the Schwarz-Bayesian Information Criterion, with fivefold cross validation on the calibration data.

As DXA scans were acquired on two different systems (Horizon/A and Discovery/W), we performed covariate analysis on each equation to determine whether cross-calibration was necessary. Adjusting for age, height and weight, no significant differences were found between the two scanners for all predicted variables, except visceral fat. Consequently, all measurements, except visceral fat, were pooled directly between the two scanners. Visceral fat measurements acquired on the Discovery/W were calibrated to the Horizon/A, using a linear calibration equation derived from a separate study of 13 participants who underwent sequential whole-body scans on the two scanners (unpublished work).

Whole-body prediction equations were applied to the field validation data. Estimated whole-body percent fat, fat mass and fat-free mass were compared with the reported values from bioimpedance analysis using simple linear regression.

RESULTS

Thirty-nine individuals (20 male) completed the calibration study. Thirty-seven individuals (18 male) were included in the validation group. Summary statistics of the calibration and validation populations are provided in Table 1. Example 3D optical and DXA images are shown in Figure 1.

Regression plots are shown in Figure 1 for 3D optical measurements against tape measure circumferences and Du Bois-estimated body surface area. Figure 2 shows 3D measurements against DXA and ADP whole-body volumes, and DXA regional volumes. Strong association was observed for waist and hip circumferences (R^2 = 0.95 and 0.92, respectively). *T*-tests showed significant mean differences of 1.75 cm (95% confidence interval: (0.58, 2.91)) for waist circumference and 3.17 cm (95% confidence interval: (1.93, 4.41)) for hip circumference between the 3D scanner and tape measurements.

Surface area and volume measurements from the 3D scanner showed high test-retest precision (Table 2). Strong association to the Du Bois model was observed for whole-body surface area (R^2 = 0.97), although this 3D system significantly underreports surface area (mean difference −0.38 m^2, 95% confidence interval: (−0.40, −0.36)). Similarly, strong associations to ADP- and DXA-measured whole-body volumes were observed (R^2 = 0.99 and 0.97, respectively), with a significantly smaller 3D scan measured volume relative to ADP (mean difference − 4.15 l, 95% confidence interval: (−5.13, − 3.17)). Regional 3D scan volume estimates were highly correlated to similar measures derived from the DXA scans (R^2 = 0.73–0.97). In general, the 3D scanner includes less volume in the arm and leg compartments than DXA and correspondingly more volume in the trunk compartment (all $P<0.001$).

The derived body composition equations for percent fat, fat mass, lean mass and visceral fat mass are shown in Table 3. Validation results for the whole-body measurements are included. Fat and fat-free mass models exhibited strong fit to the calibration data (R^2 = 0.95

and 0.96) and a reasonable fit to the validation data (R^2 = 0.76 and 0.85). The visceral fat prediction equation showed moderately strong association (R^2 = 0.75). Predictive models for regional fat and lean mass showed generally strong associations on the calibration set (R^2 = 0.79–0.94); however, no validation data were available for these regional models.

DISCUSSION

In this study of automated anthropometric measures from 3D whole-body surface scans, we found strong associations of waist and hip circumference to tape-measured values, body surface area to the Du Bois model and body volumes to DXA volume estimates. 3D measures were used to derive whole-body and regional body composition estimates for both sexes across a wide range of ages and BMI values. The accuracy of these body composition estimates was validated in a separate data set using BIA. Although some biases were found in the anthropometric measures, this study supports the use of 3D surface scanning as an accurate, precise and automated substitute to other methods such as measuring tape, ADP and DXA.

Notably, 3D scanning is a more direct measure of surface area than the criterion method (height/weight equation) available. In practice, there is no established gold standard for body surface area measurement. We found strong correlation between surface area measurements from the present 3D scanner and the clinically prevalent Du Bois model (R^2 = 0.97). Tikuisis *et al.*[14] reported high precision and accuracy of a 3D laser scanner to six different height and weight equations for body surface area, but again no gold standard comparison method was available. This measure is clinically relevant for modeling evaporative water loss, in particular for burn injuries[15] and calculating chemotherapeutic medication dosages.[16]

Whole-body volume measurements from 3D scans exhibited high precision (%CV = 0.74) comparable to ADP (%CV = 0.10).[17] Differences in landmark and partition positioning in the 3D surface scan analysis algorithms led to significant biases in regional volume measurements compared with DXA. For example, the present trunk/leg partition defined by the Proscanner is a horizontal plane at the crotch, whereas on a standard Hologic DXA, the trunk/leg partitions run diagonally from the crotch to the hips, such that the femur is completely in the leg compartment. Calibration to DXA compartments would enable direct assessment of trunk-to-leg volume ratio,[2] a strong independent indicator of metabolic health and disease risk.

Body composition models from 3D features calibrated using DXA data validated well, similar to those reported by Lee *et al.*,[7,18] especially in light of the different body composition measurement methods used (DXA calibration data and BIA validation data in our study and DXA and MRI data in Lee's studies). In particular, our whole-body fat mass prediction model showed strong fit to the calibration data (R^2 = 0.95), matching the equivalent Lee model (R^2 = 0.95).[7] Our visceral fat prediction model showed moderately strong association (R^2 = 0.75), similar to Lee (R^2 = 0.72).[13]

This study had a few limitations. Small sample size (n = 39) limits the statistical power of our models. However, all age/BMI/sex strata defined for this study were represented.

Another issue was that the validation data contained only BIA body composition data rather than DXA data. These BIA data were reported by users rather than trained technicians with a defined protocol. Despite these limitations, the strong validation results suggest good predictive model stability across a range of body shapes in a real consumer environment. Finally, our findings were derived from a healthy population without any known conditions that may alter the relationship between 3D body shape and body composition such as sarcopenia, anorexia or malnutrition.

We conclude that 3D surface scanning presents a compelling modality for clinical anthropometry. This method provides an accessible platform for rapid body measurement, as well as total and regional body composition analysis. Because of low cost, high precision and a lack of ionizing radiation, 3D surface scanning is uniquely suitable for routine clinical use to monitor longitudinal metabolic health. This study shows feasibility of broad clinical use of 3D surface scanning to estimate body composition in a wide range of body shapes. Larger follow-up studies are justified to better understand the relationships of 3D body shape and composition across various sex, BMI, age and ethnicity groups, as well as in special populations with metabolic conditions and potentially abnormal body composition.

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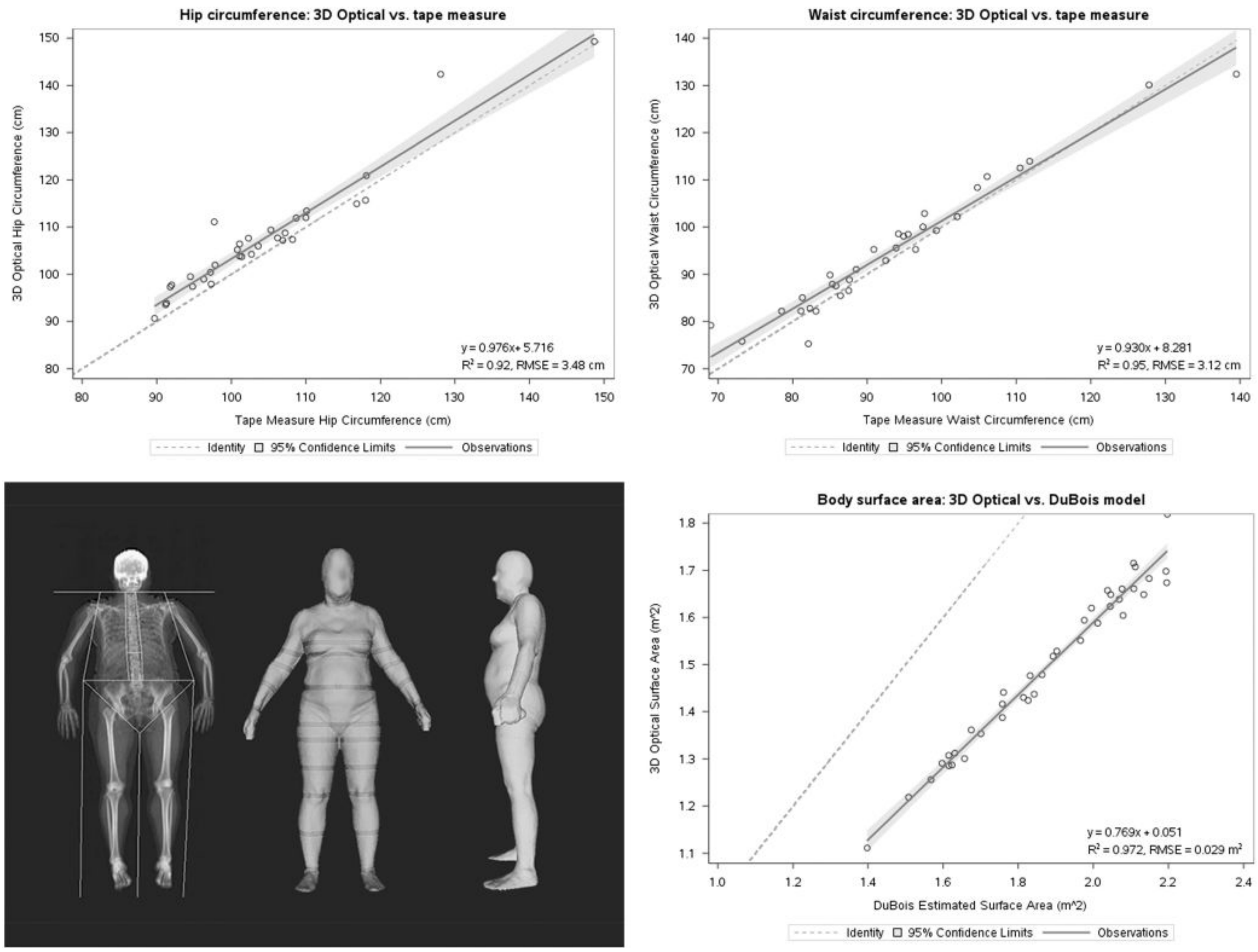

Figure 1.

3D scanner body circumferences and surface area vs criterion methods. Clockwise from top left: hip circumference, waist circumference and body surface area comparisons, then sample matched DXA and 3D optical images with annotated landmarks. 3D circumferences and surface area show high correlation with manual tape measures. Biases may be the result of non-identical landmark positioning between the methods. Of note, body surface area shows significant bias that may be explained by the fact that the 3D scanner software does not report surface area of the head and neck. This omission is not a technical shortcoming but a design decision by the manufacturer to avoid inaccuracies introduced by voluminous hair.

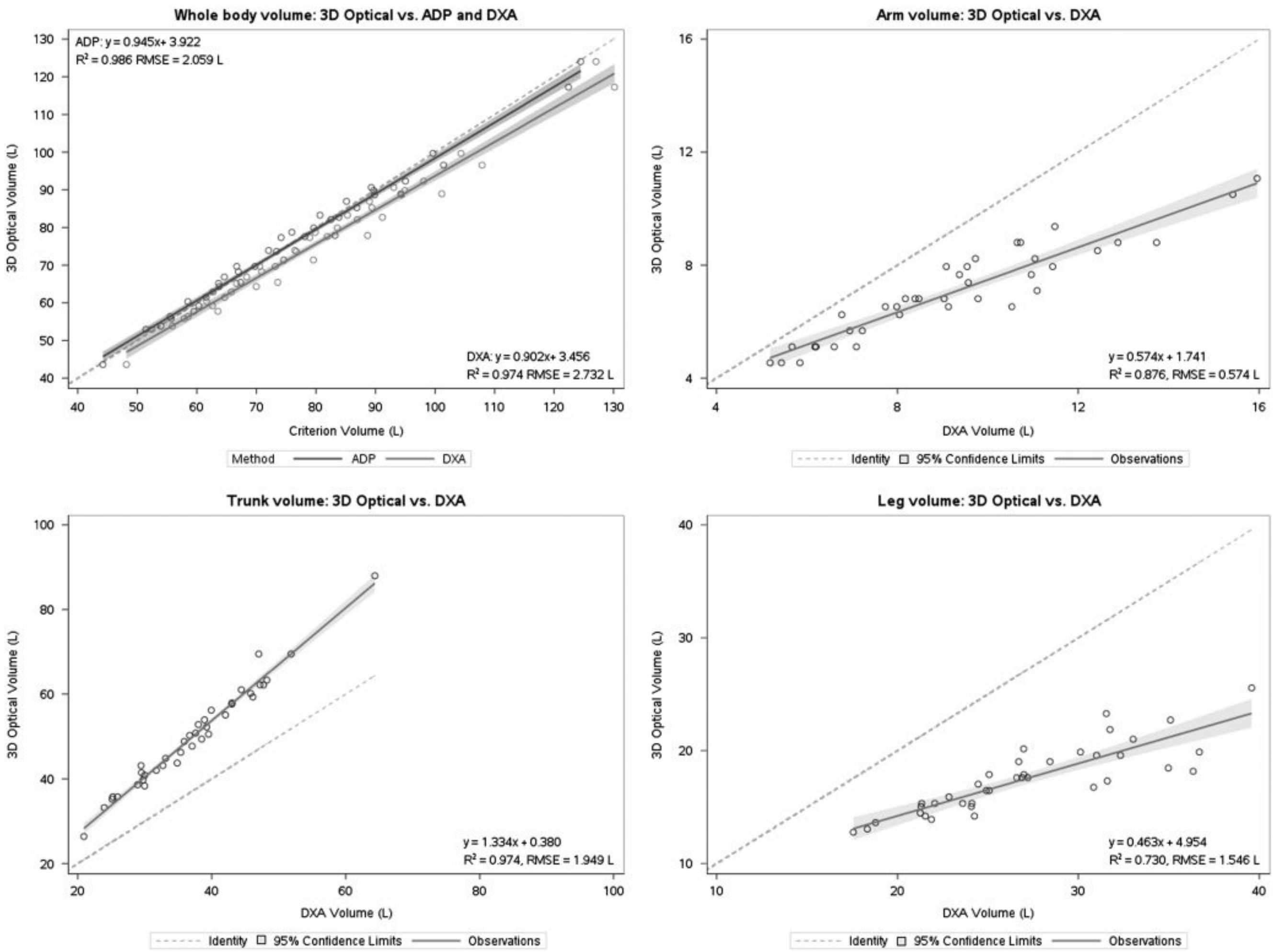

Figure 2.

3D scanner body volume vs criterion methods. Clockwise from top left: total volume vs ADP and DXA, arms vs DXA, legs vs DXA and trunk vs DXA. High precision and accuracy is observed for whole-body volume. Because of differences in partition locations, regional measurements are not directly comparable between the 3D scanner and DXA. For instance, the legs are partitioned horizontally at the crotch in the 3D optical system but diagonally from the crotch up to the top of the hip in the DXA system. Consequently, reported leg volumes are lower on the 3D system than the DXA system. Refinement of the regional partitions is necessary before cross-modality comparisons can be performed.

Table 1

Summary statistics of the model calibration population and validation groups

Variable	*Calibration (N = 39, 20 male)*			*Validation (N = 37, 18 male)*			**P-*value***
	Mean (s.d.)	***Min***	***Max***	***Mean (s.d.)***	***Min***	***Max***	
Age (years)	44.3 (15.5)	21.6	72.5	42.6 (11.5)	23.1	62.9	0.60
Height (cm)	169.5 (9.7)	152.4	190.5	174.1 (8.3)	160.0	190.5	0.03[a]
Mass (kg)	78.0 (17.6)	46.8	123.6	80.0 (10.5)	61.0	100.0	0.56
BMI (kg/m^2)	27.5 (6.5)	20.3	51.0	26.4 (3.2)	22.2	34.2	0.36
3D Optical measures							
Circumferences (cm)							
Waist	94.4 (13.6)	66.8	132.4	92.5 (7.2)	80.0	106.8	0.45
Hips	106.2 (11.8)	89.7	149.3	105.3 (7.1)	94.6	122.2	0.70
Biceps	34.3 (4.4)	26.6	45.2	35.0 (3.1)	28.9	41.8	0.44
Forearm	27.9 (2.7)	23.0	34.4	28.3 (2.5)	23.9	36.7	0.49
Thigh	61.8 (6.3)	53.1	80.4	62.4 (5.9)	53.4	80.4	0.67
Calf	39.6 (3.5)	32.0	49.7	39.5 (2.2)	34.3	44.6	0.87
Areas (m^2)							
Torso	0.662 (0.095)	0.453	0.834	0.669 (0.076)	0.513	0.839	0.75
Left arm	0.129 (0.016)	0.102	0.153	0.135 (0.019)	0.068	0.164	0.11
Right arm	0.129 (0.015)	0.100	0.159	0.137 (0.013)	0.116	0.154	0.02[a]
Left leg	0.268 (0.029)	0.217	0.335	0.281 (0.027)	0.235	0.359	0.05[a]
Right leg	0.270 (0.029)	0.212	0.340	0.282 (0.028)	0.233	0.358	0.06
Volumes (l)							
Whole body	75.8 (17.1)	43.7	124.3	76.9 (10.1)	57.6	98.5	0.74
Left arm	3.59 (0.87)	2.27	5.96	3.71 (0.68)	2.27	4.82	0.49
Right arm	3.50 (0.77)	2.27	5.39	3.74 (0.58)	2.55	4.82	0.12
Left leg	8.83 (1.56)	6.53	12.77	9.28 (1.52)	7.10	14.76	0.20
Right leg	8.82 (1.58)	6.24	12.77	9.35 (1.47)	7.10	14.47	0.14
Obesity indices							
Waist–Hip ratio	0.89 (0.07)	0.73	1.00	0.88 (0.05)	0.76	0.99	0.56
Waist–Height ratio	0.56 (0.08)	0.43	0.84	0.53 (0.05)	0.47	0.65	0.11

Variable	*Calibration* (N = *39, 20 male*)			*Validation* (N = *37, 18 male*)			**P-*value***
	Mean (s.d.)	***Min***	***Max***	***Mean (s.d.)***	***Min***	***Max***	
Body composition							
FMI (kg/m^2)	9.0 (4.4)	3.9	25.1	6.4 (3.1)	2.1	13.5	<0.01[a]
FFMI (kg/m^2)	18.4 (3.0)	12.9	26.8	20.0 (2.1)	15.7	24.5	0.01[a]
% Fat	31.7 (7.8)	17.8	50.0	23.7 (9.4)	8.0	39.5	<0.01[a]

Abbreviations: BMI, body mass index; FFMI, fat free mass index; FMI, fat mass index. Reported circumferences, areas and volumes were derived from the 3D optical scans. Unpaired two-tailed *t*-tests were performed to detect significant mean differences in the direct 3D measurements between the two groups (*P*-values shown in the right-most column). Note that body composition was measured using DXA on the calibration group and BIA on the validation group.

[a] denotes $P \leq 0.05$.

Table 2

Test-retest precision of measurements derived from the 3D optical scanner

Measurement type	*Variable*	*%CV*	*RMSE*
Circumference (cm)	Waist	1.50	1.41
	Hips	0.75	0.79
	Biceps	2.24	0.77
	Forearm	1.93	0.54
	Thigh	0.95	0.59
	Calf	0.92	0.36
Surface area (m^2)	Whole body	1.38	0.0168
	Torso	0.81	0.0057
	Average (L/R) arm	3.45	0.0044
	Average (L/R) leg	2.75	0.0074
Measured volume (l)	Whole body	0.74	0.57
	Average (L/R) arm	4.49	0.16
	Average (L/R) leg	2.61	0.23
	Trunk	0.99	0.51
Derived fat/fat-free mass (kg)	Whole-body fat	1.96	0.50
	Whole-body fat-free	0.94	0.50
	Whole-body percent fat (%)	2.16	0.68
	Visceral fat mass	6.69	0.03
	Trunk fat	2.38	0.30
	Trunk fat-free	0.50	0.13
	Arms fat	11.63	0.34
	Arms fat-free	6.67	0.42
	Legs fat	1.25	0.11
	Legs fat-free	1.99	0.36

Abbreviations: CV, coefficient of variation; RMSE, root mean square error. Each participant in the calibration data set was scanned twice, with repositioning.

Table 3

Derived fat mass, fat-free mass and percent fat prediction equations from 3D optical measurements

Region	*Variable*	*Prediction equation*	*Train R^2adj*	*Train RMSE*	*Valid R^2adj*	*Valid RMSE*
Whole body	Fat mass (kg)	−19.06+4.05 (waist circumference/waist width) −11.78 (average leg volume)	0.95	2.36	0.76	3.72
		−10.48 (is male)+22.29 (torso volume)				
	Fat-free mass (kg)	(measured mass) - (predicted fat mass)	0.96	2.24	0.85	3.14
	Percent Fat	(predicted fat mass)/(measured mass)	0.84	3.06	0.72	3.75
	Fat mass index (kg/m^2)	(predicted fat mass)/(measured height)^2	0.95	0.90	0.83	1.13
	Fat-free mass index (kg/m^2)	(predicted fat-free mass)/(measured height)^2	0.93	0.84	0.64	1.04
	Visceral fat mass (kg)	9.93–0.10 (is male) −3.93 (waist circ/waist width)	0.75	0.11		
		−0.91 (waist width) + 1.31 (waist circumference/hip circumference) + 0.33 (waist circumference)				
Trunk	Fat mass (kg)	−22.49+5.67 (waist circ/waist width) + 11.71 (torso volume) −4.71 (is male)	0.94	1.49		
	Fat-free mass (kg)	11.00–0.65 (waist circ/waist width) + 7.31 (torso volume)+ 5.31 (is male)	0.88	1.72		
Arms	Fat mass (kg)	0.54 – 1.01 (is male) −0.0097 (torso surface area) +6.25 (torso volume) + 47.92 (arm volume/body volume)	0.90	0.53		
	Fat-free mass (kg)	−1.44 +2.93 (is male) + 0.46 (average upper arm circumference)	0.92	0.55		
Legs	Fat mass (kg)	−3.72 + 0.51 (waist circ/waist width) + 8.61* (average leg volume) −3.90 (is male) + 5.82 (torso volume)	0.79	1.69		
	Fat-free mass (kg)	−8.46 + 3.26 (waist circ/waist width) + 44.17 (average leg volume) + 0.55 (is male) + 0.39 (torso volume)	0.84	1.60		

Abbreviation: RMSE, root mean square error. Models were trained using gold-standard measurements from whole-body DXA scans. Whole-body models were validated against an external data set that included scale weight and bioelectrical impedance measurements. Parameters were selected to validate previous work by Lee *et al.*[11,18]