Clinically-Applicable Optical Imaging Technology for Body Size and Shape Analysis: Comparison of Systems Differing in Design

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Abbreviations: 3D, three-dimensional; ADP, air-displacement plethysmography; CV, coefficient of variation; DXA, dual-energy x-ray absorptiometry; SD, standard deviation.

Key Words: Body Composition; Anthropometry; Nutritional Assessment; Obesity.

ABSTRACT

Background/Objectives: Recent advances have extended anthropometry beyond flexible tape measurements to automated three-dimensional optical devices that rapidly acquire hundreds of body surface dimensions. Three new devices were recently introduced that share in common inexpensive optical cameras. The design, and thus potential clinical applicability, of these systems differ substantially leading us to critically evaluate their accuracy and precision.

Subjects/Methods: 113 adult subjects completed evaluations by the three optical devices (KX-16 [16 stationary cameras], Proscanner [1 vertically-oscillating camera], and Styku scanner [1 stationary camera]), air displacement plethysmography (ADP), dual-energy x-ray absorptiometry (DXA), and a flexible tape measure. Optical measurements were compared to reference method estimates that included results acquired by flexible tape, DXA, and ADP.

Results: Optical devices provided respective circumference and regional volume estimates that overall were well-correlated with those obtained from flexible tape measurements (e.g., hip circumference: R^2, 0.91, 0.90, 0.96 for the KX-16, Proscanner, and Styku scanner, respectively) and DXA (e.g., trunk volume: R^2, 0.97, 0.97, and 0.98). Total body volumes measured by the optical devices were highly correlated with those from the ADP system (all R^2s, 0.99). Coefficient of variations obtained from duplicate measurements (n, 55) were larger in optical than in reference measurements and significant ($p<0.05$) bias was present for some optical measurements relative to reference method estimates.

Conclusions: Overall, the evaluated optical imaging systems differing in design provided body surface measurements that compared favorably with corresponding reference methods. However,

47 our evaluations uncovered system measurement limitations that with correction have the
48 potential to improve future developed devices.

INTRODUCTION

Anthropometry is an ancient method of quantifying human body size and shape.[1-3] Simple tools such as measuring rods and flexible calibrated tapes, calipers, and weight scales are the traditional approaches whereby linear, circumferential, and mass estimates can be acquired as part of nutritional assessment protocols.[4-6] A relatively small number of somatic measurements are now usually made by observers who ideally are well-trained and who are periodically checked in quality control programs.[7,8] Anthropometric methods, by not requiring ionizing radiation for subject evaluation, are among the safest nutritional assessment approaches and are widely used in pediatric[9, 10] and pregnancy[11,12] evaluations.

Rapid technological developments over the past decade are now revolutionizing anthropometric approaches for assessing nutritional status. Imaging devices, ranging from two-dimensional cellular telephone applications[13,14] to three-dimensional (3D) whole-body laser scanning systems[15-17] can now quickly capture hundreds of body dimensions and with appropriate software can provide numerous estimates of body size, shape, and composition. While early systems, particularly those designed around laser technology,[16] were costly and primarily suitable for use in research settings, a new wave of relatively low-cost approaches is appearing that have potential as clinical tools. One group of these new methods is based largely on inexpensive optical depth cameras that were first introduced as components of gaming systems.[13,16-18]

These newer imaging approaches range in design from a potentially portable single stationary camera coupled to a 360^{o} rotating subject platform to a fixed array of 16 cameras that surround the subject. With the emergence of several imaging methods, an important question

71 arises: do these differing approaches provide accurate and precise anthropometric measurements
72 comparable to those obtained by conventional laboratory-based reference methods? This is a
73 relevant question when applying these newer anthropometric devices to evaluate patients in the
74 clinical setting or subjects in research studies.

75 The aim of the current study was to critically evaluate three of these newer optical
76 devices differing in image acquisition and data processing technology by comparing body size
77 and shape results to those obtained by reference methods. Specifically, we compared device-
78 acquired circumferential and regional/whole body volume estimates to corresponding respective
79 estimates acquired with a flexible tape measure, dual-energy X-ray absorptiometry (DXA), and
80 air-displacement plethysmography (ADP).

MATERIALS and METHODS

Experimental Design

This was a cross-sectional study of an adult convenience sample. The study was approved by the Pennington Biomedical Research Center Institutional Review Board and all subjects signed an informed consent prior to participation.

Following screening and upon enrollment, each subject completed a baseline questionnaire, including demographic information. They were then weighed and had their height measured while clothed in a hospital gown. Anthropometric evaluations were then completed, followed by DXA, ADP, and 3D imaging.

The collected data were used to compare 3D imaging system circumference, regional body volume, and total body volume results between imaging devices and against reference methods. Specifically, body circumferential estimates were obtained from 3D imaging and conventional flexible tape-measure anthropometry; regional body volumes were obtained from the 3D imaging devices and DXA; and total body volume estimates were made by the 3D devices and ADP. The reference estimates for circumferences, regional volumes, and total volumes were thus conventional flexible tape-measure anthropometry, DXA, and ADP, respectively. Corresponding measurements from the imaging devices were compared to those obtained by the reference methods.

Participants

Subjects were adult men and women volunteers at or over the age of 18 years. A pre-evaluation screening questionnaire was used to ensure subjects were in good health and free of chronic diseases. Subjects were recruited through advertisements on the center website. Once

enrolled, subjects were asked to arrive at the laboratory wearing or to change into form-fitting clothing that included Spandex shorts and, for women, a Spandex top for all 3D scans and anthropometric measurements. The same attire applied for ADP with the addition of a Lyrica cap to cover loose hair. The DXA scan attire included only undergarments and an examination gown.

Measurements

Height was measured to the nearest 0.1 cm on each subject using a wall-mounted stadiometer (Seca 222, Seca GmbH & Co. KG, Hamburg, Germany) and screening weight was measured using a digital scale (MC-970; Tanita, Tokyo, Japan) to the nearest 0.1 kg. Each measurement was evaluated twice with a third reading obtained if the first two respective readings were >0.5 cm or >0.5 kg apart; results were averaged.

Anthropometric circumference measurements were taken by a trained staff member at the anatomic locations used in the US National Health and Nutrition Examination Survey.[19] Circumferences of the waist, hip, upper arms, and thighs were measured with a flexible tape and recorded to the nearest 0.1 cm. Each measurement was taken three times and averaged. The specific methods used in measuring these circumferences are presented in **Supplementary Material**.

3D Optical Scans

Image Acquisition. Three imaging systems were used to obtain circumferences, regional volumes, and total body volume. All three systems share in common the use of inexpensive, consumer-grade optical depth cameras. With this feature in common, each device uses unique mechanisms for capturing, assembling, and measuring the 3D subject images (**Figure 1** and **Table S1**).

The KX-16 system (TC^2 Labs, Apex, NC) has four columns, each of which has four evenly spaced Microsoft Kinect V1 cameras. The Kinect V1 sensor uses PrimeSense (Apple, Inc., Cupertino, CA) technology. The columns are positioned in a rectangle and the subject stands with their hands held in a downward V-shaped position, or "A-pose", centered between the columns during the 7-second scan. Each camera includes an infrared emitter that projects a known pattern of points onto the scene. The infrared pattern is distorted by the subject and imaged using an infrared sensor. The deformation of points is used to calculate depth.

The Proscanner (Fit3D, Redwood City, CA) uses a PrimeSense Carmine 1.08 depth sensor that operates in the same way as the KX-16's Kinect V1 sensors, although the configuration of the system is different. The Proscanner uses one camera that oscillates vertically on a tower while the subject rotates counterclockwise on a platform for about 40 seconds. The subject tightly grips handlebars during the scan while their arms are held firmly in the A-pose.

The Styku scanner (Styku, Los Angeles, CA) also uses a single camera built into a tower and a rotating platform to capture body image data. However, the Styku scanner uses a stationary depth camera at a fixed height. The subject stands on the platform with their arms positioned in the A-pose. The subject is then rotated clockwise for about 30 seconds. The Styku scanner uses a Microsoft Kinect V2 camera that employs "time-of-flight" technology that is different from the other systems. Infrared light is projected and reflected back to the sensor. The phase shifts in the returning light waves are used to measure roundtrip light travel time that allows for a direct calculation of depth.

Image Processing. The three systems use various iterative closest point[20] reconstruction algorithms to create a 3D image. Over 250 measurement estimates of lengths, circumferences,

147 and volumes are calculated from the scan. Each system uses its own proprietary software for
148 landmark detection and measurement.

149 The Styku scanner displays a real-time depth video stream from the Kinect V2 sensor on
150 a computer screen while the subject rotates on the platform. As the subject rotates, the camera
151 captures new body views and uses Kinect Fusion software (Microsoft, Redmond, WA) to fuse
152 the depth data into a combined surface in real-time[21] to produce a triangle mesh image. The
153 system then uses Poisson surface reconstruction methods to smooth and fill any surface holes.[22]
154 Once the scan is complete, the Styku scanner's software is designed to recognize features found
155 on the mesh that are easily recognized body landmarks. From these features, a custom script
156 defines how the landmarks are used to calculate and visualize various body measurements. The
157 Styku scanner employs Graham's convex-hull algorithm[23] for refining circumference
158 measurements.

159 The TC^2 KX-16 and Fit3D Proscanner systems use image construction and measurement
160 techniques similar to those used by the Styku scanner. However, the Proscanner system software
161 does not fill in holes in the 3D mesh image while the KX-16 system fills in gaps at a few specific
162 regions such as under the arm. Neither scanner uses the surface smoothing algorithms
163 implemented by the Styku scanner.

164 **Dual-Energy X-Ray Absorptiometry**

165 Whole-body DXA scans were conducted using a Hologic Discovery A system with
166 Hologic Apex software version 40.2 (Hologic, Inc., Marlborough, MA). The completed scans
167 were evaluated for total body mass, regional mass (head, trunk, arms, legs), and body
168 composition (total and regional body fat, fat-free mass, lean soft tissue mass, and bone mineral

content). The regional mass cut-points were described earlier by Schuna et al.[24] Regional volumes were estimated from their corresponding body composition estimates.[25]

Air Displacement Plethysmography

Total body volume was measured with the Bod Pod ADP system (Cosmed USA, Concord, CA). The volume of thoracic gas as quantified by the ADP system was not subtracted from ADP total body volume estimates so as to be comparable to total volumes measured by the three imaging systems.

An estimate of total body volume was available from DXA in addition to the reference ADP method. DXA total body volume estimates were highly correlated with (**Supplementary Figure S1**; R^2=0.99, p<0.0001) ADP estimates and there was no significant between-method bias.

Statistical Methods

Four circumference measurements, five regional volumes, and total body volume estimates from the 3D devices were compared to the corresponding reference method measurements. At the outset we recognized that in some cases 3D system circumference and regional volume measurements may not exactly match the anatomic sites as defined by the reference methods. However, we did not know in advance to what extent these kinds of differences might be present and their magnitudes. To explore the level of agreement between 3D optical and reference method measurements we examined if between-method group mean differences were present, the magnitude of associations between the methods, and if between-method bias was present.

Specifically, absolute circumference and volume estimates from the 3D optical devices were compared to their reference method counterparts using paired t-tests with a difference of $p<0.05$ considered statistically significant. Associations between 3D optical and reference method measurements were examined using linear regression analysis with statistical significance set at $p<0.05$. Bland-Altman plots were used to determine if significant 3D optical measurement biases were present relative to the reference methods.

A subgroup of participants completed duplicate flexible tape, DXA, and 3D scans and the respective coefficient of variations (CVs) expressed in % are presented in the results section. The ADP CV for total body volume estimation is 0.1%.[26]

Descriptive subject characteristics are presented as the mean±SD. Statistical analyses were conducted using Microsoft Excel 2010 (Microsoft Corp., Redmond, WA) and GraphPad Prism 7 (GraphPad Software Inc., La Jolla, CA).

RESULTS

Subjects

Subject characteristics are presented in **Table 1**. There were a total of 113 subjects (40 men, 73 women) ranging in age from 18 to 77 years and in BMI from 17.9 to 51.8 kg/m^2.

Coefficient of Variations

Fifty-five of the subjects completed duplicate flexible tape, DXA, and 3D optical scans and the respective CVs are presented in **Table 2**. The flexible tape and DXA circumference and volume CVs ranged from <1% to 1.5%. On average the 3D optical system CVs were larger, in particular for the arm volume measurements (5.7, 3.9, 2.0, and 1.5% for KX-16, Proscanner, Styku scanner, and DXA left arm, respectively).

Circumferences

Group averages for the circumferences are summarized in **Table 2**. The mean group difference between the Styku scanner and flexible tape estimates for the representative hip circumference (-0.02 cm) was not significant; significant mean hip circumference differences were, however, present for the KX-16 (4.8 cm, $p<0.0001$) and Proscanner (1.2 cm, $p<0.01$). Root mean square errors for the systems ranged from 2.6 for Styku scanner to 6.0 for the KX-16.

Circumference measurements by the 3D optical devices were all significantly correlated with flexible tape measurements (R^2s, 0.71-0.96, all $p<0.0001$)(**Table 2**). The representative hip circumference measured by each system plotted against flexible tape measurements is shown in **Figure 2** along with Bland-Altman plots. 3D and tape measurements were highly correlated

(R^2s, 0.90-0.96, all p<0.001). Significant hip circumference bias relative to the reference flexible tape measurements was present for the Proscanner 3D system (p<0.01).

Regional Body Volumes

Regional body volume results are summarized in **Table 2**. Representative trunk volumes measured by the 3D systems were larger than DXA trunk volumes with mean differences of 10.4 L, 13.3 L, and 6.0 L for KX-16, Proscanner, and Styku scanner, respectively (all p<0.0001). Of these, the Styku scanner trunk volume estimates were the lowest of the three systems as they were for all of the regional volume measurements. Root mean square errors for the systems ranged from 6.4 for the Styku scanner to 14.0 for the Proscanner.

Regional volume measurements by the 3D optical devices were all significantly correlated with DXA regional volume measurements (R^2s, 0.69-0.98, all p<0.0001)(**Table 2**). Representative trunk volume estimates for the 3D systems are plotted against the DXA trunk volume estimates in **Figure S2**. All of the 3D optical system estimates for trunk volume were highly correlated with DXA trunk volume estimates (R^2s $\geq$0.97, p<0.0001). Significant trunk volume bias relative to the reference DXA measurements was present for all three optical systems (p<0.0001).

Following discussions with the investigators, the Fit3D Proscanner was updated by the manufacturer to provide more significant figures for volume measurements after 80 subjects had completed the study. The results display all 113 subjects for all measurements; however, correlations for small regional volumes improved after the system update. Right arm volume for the Proscanner vs. DXA is plotted from before the update and after the update in **Supplementary Figure S3**.

244 **Total Body Volume**

245 The mean total body volume estimates were significantly different from those by ADP
246 for all three 3D optical systems ($p<0.0001$)(**Table 2**). Root mean square errors for the systems
247 ranged from 2.9 for the Proscanner to 9.7 for the Styku scanner.

248 The results of linear regression and Bland-Altman analyses are displayed in **Table 2** and
249 **Figure S4** for each 3D optical system with ADP total volume as the reference. Total body
250 volumes determined by KX-16, Proscanner, and Styku scanners were highly correlated with
251 ADP volumes (R^2s all 0.99). Bland-Altman plots all showed significant ($p<0.05$) bias with
252 regression line slopes of -3.4 L, -2.4 L, and -9.1 L for the KX-16, Proscanner, and Styku scanner,
253 respectively. All of these slopes are negative indicating that that the 3D systems underestimated
254 body volume for larger subjects. As for regional volumes, the Styku system had the lowest total
255 body volume estimates for the three systems.

256

DISCUSSION

Three-dimensional optical imaging devices can provide hundreds of body surface measurements in less than one minute. The full clinical potential of these many somatic surface measurements has yet to be established. An initial step, the one taken in the current study, is to determine the accuracy and precision of these optical devices relative to their reference method counterparts. The aim of the current study was to evaluate three of these devices that share in common inexpensive optical depth cameras but that differed in how these cameras are configured and in data processing techniques.

Our findings overall indicate that all three of the evaluated systems provide reproducible circumference, regional volume, and total body volume measurements that are well correlated with the reference methods. Thus, even though the surface data acquisition hardware employed by the systems differed, strong associations were observed between the optical device measurements and those acquired with the reference methods. Critically evaluating what technical concerns we did observe is illuminating with respect to these newly introduced technologies.

Measurement Discrepancies

The first concern relates to absolute differences observed between 3D optical and reference method landmarking. We were aware at the outset that optical-device measured anatomic sites might not perfectly match those acquired by the reference methods, although the magnitude of these discrepancies if present was unclear. At the current time there is no standardization guideline adhered to by device manufacturers that states strict landmark definitions. A main concern arising from this measurement inconsistency is that a subject's

279 results cannot be readily compared across systems or to standardized reference values. An
280 important consideration is that conventional anthropometric methods often rely on palpation of
281 boney landmarks for identifying measurement sites. By contrast, automated optical imaging
282 techniques discover measurement sites through identification of surface landmarks. The
283 possibility exists in future comparative studies to closer align measurement sites between
284 systems by application of surface markers prior to optical data acquisition. A similar approach
285 can be used to align 3D optical and DXA regional measurements.

286 Another source of absolute measurement differences is variation in the body regions
287 included in whole body volume estimates. We learned following completion of our analyses that
288 the KX-16 and Proscanner total body volume estimates do not include head, hands, or feet
289 volumes. By contrast, the Styku scanner includes these body parts in the total body volume
290 measurement. The CVs for 3D total body volume estimates were two or more times those by
291 ADP and DXA (**Table 2**) and when considered in light of the absolute measurement concerns it
292 is unlikely that optical devices at present can be used to accurately quantify body density and
293 thus body fat using the two compartment molecular level body composition model.[27]

294 An absolute 3D-reference method difference may also have been caused by Styku
295 system's ToF technology that assumes light reflected from each pixel takes one path. In reality,
296 the geometry of the room or reflective surfaces in the room may cause light to take multiple
297 paths that are unpredictable and can alter the depth measurements.[28] The Styku scanner in our
298 study underestimated the distance between the platform and the sensor causing the measurements
299 to be systematically less than the reference values. While the recommended distance between the
300 platform and sensor still produced favorable correlations with reference methods, adjustments
301 could be made by changing the separation between the camera and platform and comparing

values to standard methods to determine optimal distance in a specific space. The system's ability to track changes would not be affected if the system remains in the same position, but could be if the system is moved.

Another source of measurement error may have resulted from subject characteristics. For example, subjects who have a high BMI, are very tall, or who have poor balance may be challenging to image. Thighs touching, as shown in the avatars created by the devices (**Figure 3**), may lead to errors when system landmarking software attempts to distinguish right from left legs and legs from trunk. For subjects with a large amount of adipose tissue in the arms and trunk, the upper extremities are difficult to distinguish from the trunk with the A-pose implemented by all three systems and an arm may get cut off on KX-16 system avatars (**Figure 3**). These effects may partially explain why subjects who had a BMI within the normal range had optical measurements closer to the reference method than those who were overweight or obese. Additionally, some subjects were too tall for the Styku scanner and KX-16 cameras to capture their full image. By contrast, the Proscanner's tower with mounted moving camera allowed for greater total body imaging of tall subjects. Excluding a tall subject's head from the analysis can lead to measurement bias as the head is a smaller proportion of body volume in people who tall compared to those who are short.[24] The Styku scanner also requires subjects to stand still while rotating with no arm support. Movement during the scan can cause malformed avatars (**Figure 3**) that could affect measurement dimensions and CVs. Our recommendation is to do a quality control check on all acquired 3D images before concluding the subject's evaluation.

System Data Processing Differences

While our focus was mainly on the automatically derived circumference and volume measurements from each system, it should be noted that the 3D mesh processing and image presentation varies between the systems. Reconstructed avatars display differences in resolution, filling, and smoothing as shown in **Figure 3**. The Proscanner and KX-16 show minimal filling of missing data and smoothing whereas the Styku scanner's image appears smooth with no gaps. These differences do not appear to give any clear advantage in measurement quality since the correlations and CVs were similar across the three systems.

A related data processing observation is that the Proscanner leg and arm volume estimates were not well correlated with the DXA reference measurements at the start of the study. In reviewing these observations we learned that the Proscanner did not provide an adequate number of significant digits to allow for accurate measurement of small body segments. We informed the manufacturer of this limitation and Fit3D developers subsequently added digits to the results. Both the CVs and regional volume estimates improved accordingly (**Figure S3**).

System Attributes

Each system has distinct attributes such as cost, scan speed, and hardware design, but the overall measurements compare similarly to reference methods. The Styku scanner's simple design with a single fixed camera and modular design makes it easy to transport. The system also displays results immediately and allows the user to interactively measure circumferences at any point on the avatar. The Proscanner's moving camera allows capture of a tall subject's head dimensions while the other systems do not include head measurements in tall subjects. The KX-16 has the quickest scan time (7 sec), although this device is large and with 16 cameras is not mobile and the system cost is higher than the other two devices.

Conclusions

The 3D optical systems evaluated in the current study that share in common inexpensive image acquisition cameras provide reproducible circumference and volume measurements that correlate well with reference methods that are often unavailable or too costly to apply in the clinical setting. Our findings exposed important differences and limitations of these systems that are largely correctible when building next generation devices. Future studies are needed to establish the utility of these emerging optical devices in clinical and research settings.

Supplementary Information accompanies the paper on the EJCN website (http://www.nature.com/EJCN)

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AUTHOR CONTRIBUTIONS

BB, CRS, LR, XL, BKN, JAS, and SBH analyzed the data and drafted the manuscript; BB, DL, CRS, LR, JAS, and SBH designed the study; BB, DL, CRS, and SBH directed implementation and data collection; BB, DL, CRS, and LR collected the data; LR, JAS, and SBH provided necessary logistical support; BB, DL, CRS, LR, XL, BKN, JAS, SBH edited the manuscript for intellectual content and provided critical comments on the manuscript.

CONFLICT of INTEREST

The authors declare no conflict of interest.

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FIGURE LEGENDS

Figure 1. Configurations of the three optical imaging devices: KX-16 (left), Proscanner (center), Styku scanner (right). The Proscanner and KX-16 project patterns of infrared light on the subject and use light deformations to determine depth. The Styku scanner uses phase shifts in reflected waves to determine depth. The Styku scanner's camera's field of view is larger than that of the Proscanner and KX-16 (70.6 X 60 as opposed to 58.5 X 46.6).

Figure 2. Hip circumference measured by the 3D optical devices versus hip circumference estimates by a flexible tape measure and associated Bland-Altman plots. The solid line in each upper panel is the regression line and the dashed line is the line of identity.

Figure 3. Avatars from the KX-16 (A), Proscanner (B), and the Styku scanner (C). Images show system limitations such as arm cut off on the KX-16 (A), thighs touching on the Proscanner (B), and movement on the Styku scanner (C). The resolution is 320 X 240, 640 X 480, and 512 X 424 for the KX-16, Proscanner, and Styku scanner, respectively.

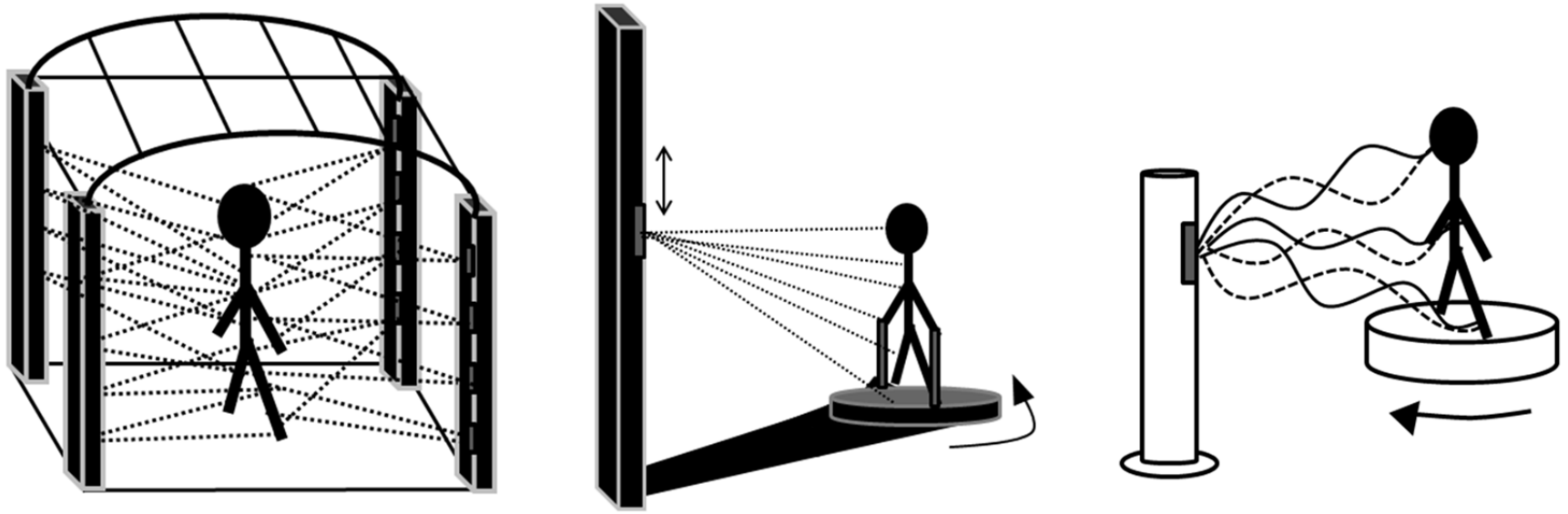

Figure 1

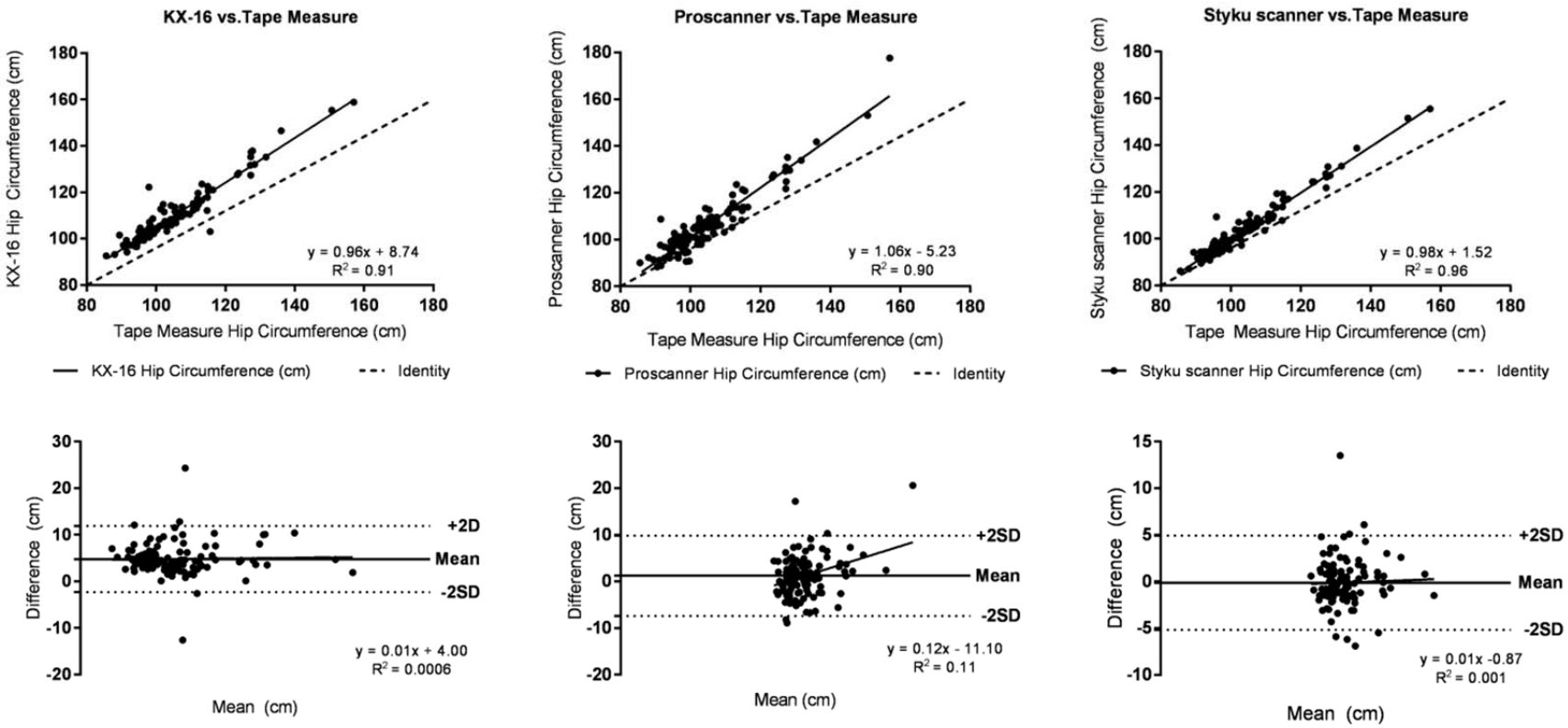
KX-16 vs.Tape Measure
KX-16 Hip Circumference (cm)
Tape Measure Hip Circumference (cm)
y = 0.96x + 8.74
R² = 0.91
KX-16 Hip Circumference (cm)
Identity
Difference (cm)
Mean (cm)
+2D
Mean
-2SD
y = 0.01x + 4.00
R² = 0.0006
Proscanner vs.Tape Measure
Proscanner Hip Circumference (cm)
Tape Measure Hip Circumference (cm)
y = 1.06x - 5.23
R² = 0.90
Proscanner Hip Circumference (cm)
Identity
Difference (cm)
Mean (cm)
+2SD
Mean
-2SD
y = 0.12x - 11.10
R² = 0.11
Styku scanner vs.Tape Measure
Styku scanner Hip Circumference (cm)
Tape Measure Hip Circumference (cm)
y = 0.98x + 1.52
R² = 0.96
Styku scanner Hip Circumference (cm)
Identity
Difference (cm)
Mean (cm)
+2SD
Mean
-2SD
y = 0.01x -0.87
R² = 0.001

Figure 2

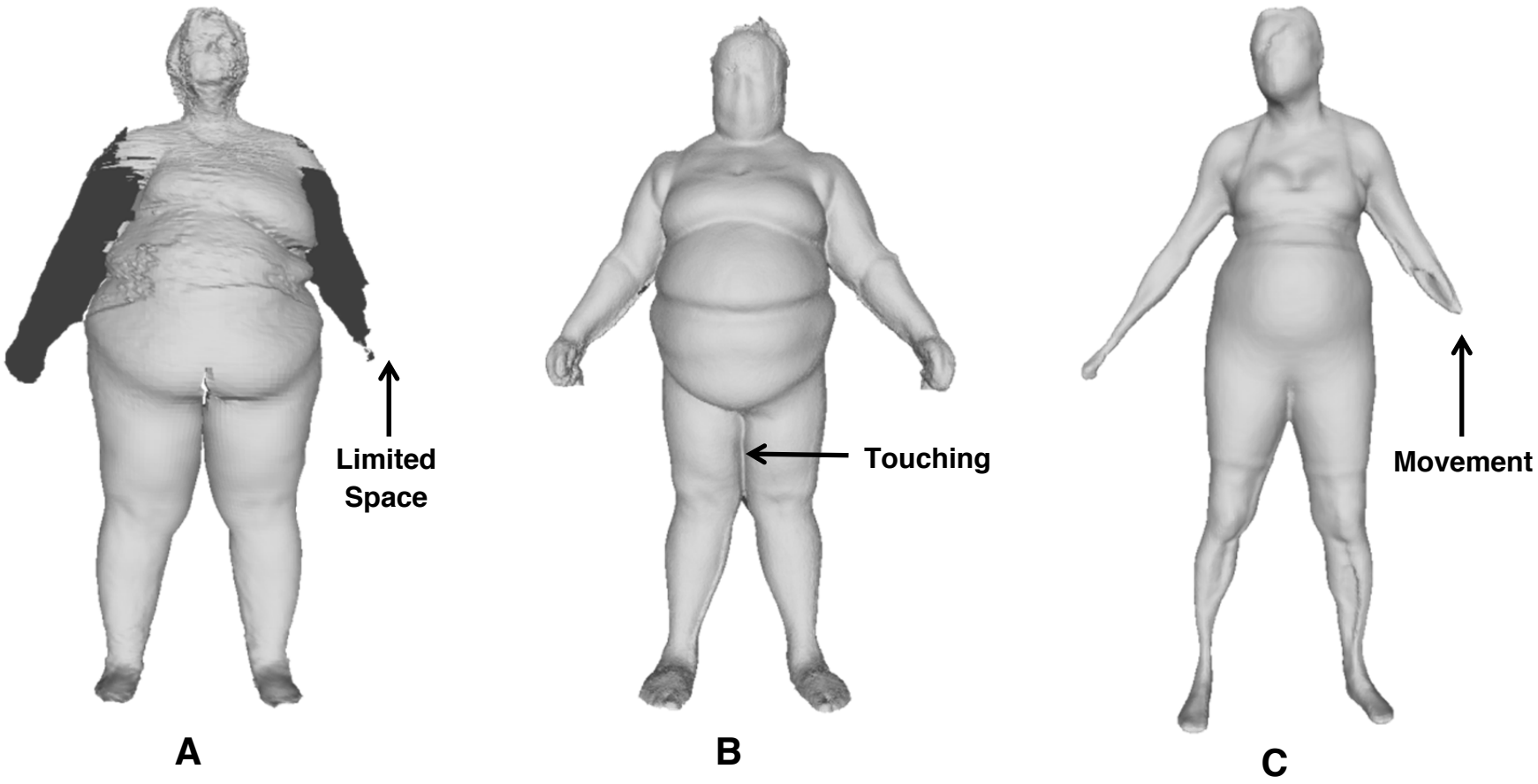

Figure 3

Table 1. Subject Characteristics.

	Men	Women
Number (White/Black/Asian)	40 (30/7/3)	73 (42/28/3)
Age (yrs)	41 ± 17	47 ± 17
Height (cm)	177.7 ± 6.4	163.0 ± 6.7
Weight (kg)	84.8 ± 17.0	73.4 ± 17.0
BMI (kg/cm^2)	26.7 ± 4.3	27.8 ± 7.0
% body fat†	22.3 ± 6.8	37.4 ± 7.8

Results are X±SD. Abbreviations: BMI, body mass index. †Acquired by DXA.

Table 2. Results of Circumference, Volume, and Coefficient of Variation Evaluations.

Measurement	Mean	Mean Δ	CV (%)	R^2	RMSE	Bland-Altman Analysis	
						R^2	Slope
Waist (cm)							
Tape Measure	89.6 ± 14.2		0.2 ± 0.1				
KX-16	90.2 ± 13.2	0.64	0.8 ± 0.8	0.86*	5.3	0.04‡	-0.08
Proscanner	93.8 ± 14.1	4.21*	0.8 ± 1.2	0.92*	5.8	0.0005	-0.01
Styku scanner	84.5 ± 12.9	-5.08*	0.3 ± 0.4	0.94*	6.3	0.12†	-0.10
Hip (cm)							
Tape Measure	105.0 ± 12.0		0.2 ± 0.3				
KX-16	109.8 ± 12.1	4.8*	0.4 ± 0.4	0.91*	6.0	0.0006	0.01
Proscanner	106.3 ± 13.3	1.2†	0.4 ± 1.2	0.90*	4.6	0.11†	0.12
Styku Scanner	104.9 ± 12.1	-0.02	0.1 ± 0.2	0.96*	2.6	0.001	0.01
Right Arm (cm)							
Tape Measure	33.2 ± 5.4		0.4 ± 0.2				
KX-16	35.9 ± 4.9	2.8*	2.6 ± 2.2	0.75*	3.9	0.05‡	-0.12
Proscanner	33.2 ± 5.1	0.04	1.2 ± 1.0	0.87*	1.9	0.03	-0.07
Styku Scanner	29.1 ± 4.3	-4.1*	0.8 ± 1.3	0.73*	5.0	0.17*	-0.25
Right Thigh (cm)							
Tape Measure	56.8 ± 6.2		0.2 ± 0.1				
KX-16	63.0 ± 8.5	6.2*	0.9 ± 0.9	0.71*	7.7	0.27*	0.34
Proscanner	51.1 ± 5.5	-5.7*	0.7 ± 0.9	0.79*	6.4	0.06‡	-0.12
Styku Scanner	57.3 ± 7.7	-0.2	0.3 ± 0.5	0.83*	3.3	0.24*	0.23
Body Volume (L)							
ADP	76.4 ± 18.3						
DXA	75.6 ± 18.1		0.2 ± 0.1				
KX-16	73.0 ± 16.9	-3.4*	0.8 ± 0.6	0.99*	4.2	0.31*	-0.08
Proscanner	74.0 ± 17.6	-2.4*	0.7 ± 0.6	0.99*	2.9	0.18*	-0.04
Styku scanner	67.4 ± 15.6	-9.1*	0.4 ± 0.4	0.99*	9.7	0.69*	-0.16
Trunk (L)							
DXA	36.4 ± 9.9		0.6 ± 0.5				
KX-16	46.8 ± 11.1	10.4*	1.0 ± 0.8	0.97*	10.7	0.31*	0.12
Proscanner	49.7 ± 13.5	13.3*	0.6 ± 0.9	0.97*	14.0	0.78*	0.31
Styku scanner	42.4 ± 11.0	6.0*	0.3 ± 0.3	0.98*	6.4	0.32*	0.11
Left Arm (L)							
DXA	4.3 ± 1.3		1.5 ± 1.2				
KX-16	3.6 ± 1.1	-0.7*	5.7 ± 4.4	0.82*	0.9	0.25*	-0.25
Proscanner	3.7 ± 1.1	-0.6*	3.9 ± 7.0	0.83*	0.8	0.23*	-0.23
Styku scanner	2.0 ± 0.6	-2.2*	2.0 ± 1.6	0.69*	2.4	0.73*	-0.83
Right Arm (L)							
DXA	4.5 ± 1.3		1.2 ± 1.2				
KX-16	3.7 ± 1.1	-0.7*	4.1 ± 3.0	0.87*	0.9	0.17*	-0.17
Proscanner	3.4 ± 1.1	-1.0*	2.1 ± 4.8	0.89*	1.1	0.21*	-0.17
Styku scanner	2.1 ± 0.6	-2.3*	2.4 ± 2.9	0.80*	2.5	0.79*	-0.76
Left Leg (L)							
DXA	13.0 ± 3.1		1.0 ± 0.8				
KX-16	9.3 ± 2.2	-3.69*	1.6 ± 1.7	0.90*	3.9	0.54*	-0.34
Proscanner	8.7 ± 1.7	-4.34*	2.4 ± 3.1	0.70*	4.8	0.61*	-0.64

Styku scanner	6.3 ± 1.6	-6.73*	0.8 ± 0.9	0.91*	7.0	0.85*	-0.65
Right Leg (L)							
DXA	13.1 ± 3.0		1.1 ± 0.7				
KX-16	9.6 ± 2.3	-3.55*	1.6 ± 1.8	0.90*	3.7	0.46*	-0.29
Proscanner	8.5 ± 1.6	-4.62*	1.5 ± 3.3	0.74*	5.0	0.62*	-0.65
Styku scanner	6.2 ± 1.6	-6.89*	1.4 ± 1.2	0.91*	7.1	0.84*	-0.62

Abbreviations: CV, coefficient of variation. RMSE, root means squared error. *, $p<0.0001$; †, $p<0.01$; ‡, $p<0.05$. Results are X±SD.

113 total subject evaluations for circumferences and volumes, 55 for coefficient of variations.