



Published in final edited form as:

Eur J Clin Nutr. 2020 June ; 74(6): 920–929. doi:10.1038/s41430-019-0501-2.

Optical Imaging Technology for Body Size and Shape Analysis: Evaluation of a System Designed for Personal Use

Samantha Kennedy¹, Phoenix Hwaung¹, Nisa Kelly², Yong E. Liu², Sima Sobhiyeh¹, Moonseong Heo³, John A. Shepherd², Steven B. Heymsfield¹

¹Pennington Biomedical Research, Louisiana State University, Baton Rouge, LA, USA

²University of Hawaii Cancer Center, Honolulu, HI, USA

³Department of Public Health Sciences, Clemson University, South Carolina

Abstract

Background/Objectives—Three-dimensional optical (3DO) imaging systems that rapidly and accurately provide body shape and composition information are increasingly available in research and clinical settings. Recently, relatively low cost and space efficient 3DO systems with the ability to report and track individual assessments were introduced to the consumer market for home use. This study critically evaluated the first 3DO imaging device intended for personal operation, the Naked Body Scanner (NBS), against reference methods.

Participants/Methods—Circumferences at six standardized anatomic sites were measured with a flexible tape in 90 participants ranging in age (5–74 years), ethnicity, and adiposity. Regression analysis and Bland-Altman plots compared these direct measurements and dual-energy X-ray absorptiometry (DXA) %fat estimates to corresponding NBS values. Method precision was analyzed from duplicate anthropometric and NBS measurements in a subgroup of 51 participants.

Results—The NBS exhibited greater variation in test-retest reliability (CV, 0.4%–2.7%) between the six measured anatomic locations when compared to manually measured counterparts (0.2%–0.4%). All six device-derived circumferences correlated with flexible tape references (R^2 s, 0.84–0.97; $p < 0.0001$). Measurement bias was apparent for three anatomic sites while mean differences were present for five. The NBS's %fat estimates also correlated with DXA results ($R^2=0.73$, $p < 0.0001$) with no significant bias.

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Address Correspondence to: Steven B. Heymsfield, M.D., Pennington Biomedical Research Center, 6400 Perkins Rd., Baton Rouge, LA 70808, **Tel:** 225-763-2541, **Fax:** 225-763-0935, Steven.Heymsfield@pbr.edu.

AUTHOR CONTRIBUTIONS

SK, PH, JAS, and SBH analyzed the data and drafted the manuscript; SK, PH, JAS, and SBH designed the study; SK, PH, and SBH directed implementation and data collection; SK, PH, YEL, and NK collected the data; JAS and SBH provided necessary logistical support; SK, PH, YEL, NK, SS, JAS, and SBH edited the manuscript for intellectual content and provided critical comments on the manuscript.

CONFLICT of INTEREST

The authors declare no conflict of interest.

Supplementary Material is available at EJCEN's website.

Conclusions—This system opens a new era of digital home-based assessments that can be incorporated into weight loss or exercise interventions accessible to clinical investigators as well as individual users.

INTRODUCTION

Anthropometry is the systematic measurement of the physical human form (1–3). While the science dates back centuries, original rudimentary instruments engineered for quantifying size and shape are relevant today with minimal design modifications. For example, measuring rods, tapes, calipers, and weight scales were fixtures of ancient civilizations and remain necessary tools for acquiring linear, circumferential, and mass estimates for a 21st century health assessment (4–6). These pragmatic methods offer a safe and consistent means of collecting repeated measurements to gauge changes in phenotype; and consequently, remain the standard practice for monitoring growth and development in pediatric (7, 8) and pregnant (9, 10) populations.

Today, practical uses for anthropometry extend beyond a conventional health assessment. Businesses, particularly within clothing and fitness industries, now personalize their services based on dimensions of the customer's figure. Their demand for a low cost and efficient means of measuring body shape has resulted in innovative solutions using optical depth technology originally engineered for gaming systems (11–14). Where evaluating body shape, size, and composition traditionally employs a well-trained specialist to collect comparatively few somatic measurements (15, 16), three-dimensional (3D) imaging devices make it possible to capture hundreds of body dimensions, estimate composition, and display user-friendly results within minutes. Furthermore, results from these devices compare favorably with traditional reference methods such as manual anthropometry as well as more modern standards like dual-energy x-ray absorptiometry (DXA) without requiring considerable skill or additional instruction (12, 17). Currently available 3D optical systems designed for research or clinical use range in cost from about \$10,000 to \$20,000 USD.

By the end of 2018, optical imaging technology evolved into such an economical and compact design that 3D optical devices became available for private use within the home setting. Personal systems such as the Naked Body Scanner allow for frequently obtainable and relatively inexpensive (<\$1,500) digital anthropometric assessments, empowering users with the ability to evaluate, track, and monitor their own health information without direction from a trained professional. It is therefore imperative that results from these relatively low-cost home systems undergo critical evaluation to ensure users receive valid circumference and body composition estimates. The specific aim of the current study was to explore the technical features, reproducibility, and accuracy of the Naked Body Scanner results against conventional reference method estimates.

MATERIALS and METHODS

Shape Up! Adults and Shape Up! Kids are, ongoing, cross-sectional studies comprised of samples stratified by age, gender, race, and body mass index (BMI) or growth percentiles for children. Data used for this analysis includes a subset of participants and assessments

completed under these two study protocols within the body composition laboratories at Pennington Biomedical Research Center (PBRC) and the University of Hawaii Cancer Center UHCC. Written informed consent was obtained from each participant or legal guardian and all procedures were approved by the Pennington Biomedical Research Center Institutional Review Board (IRB# 2016–053-PBRC; IRB# 2017–10-PBRC; FWA 00006218), the University of Hawaii Office Of Research Compliance (CHS# 2017–01018; CHS# 2017–24282), and the Human Research Protection Program Institutional Review Board at the University of California, San Francisco (IRB# 15–18066; IRB# 16–20197). These studies are publically listed on [ClinicalTrials.gov](https://clinicaltrials.gov) as ID NCT03637855 and ID NCT03706612.

Participants

Data was collected from 73 adult volunteers over the age of 18 (40 women, 33 men) who participated in the Shape Up! Adults study as well as 17 non-adult volunteers between 5 and 17 years of age (14 females, 3 males) who participated in the Shape Up! Kids study. Recruitment included web advertisements, locally posted flyers, and word of mouth networking from both PBRC and UHCC assessment centers. To ensure that participants were in relatively good health, not pregnant, and free of chronic diseases; all interested candidates completed a pre-evaluation screening questionnaire as part of the recruiting process. Additional exclusionary criteria included inability to stand without aid for two minutes or remain lying flat on a table for ten minutes, metal implantations within the body, as well as any other prior body or shape-altering procedures such as liposuction, amputation, or breast augmentation. While the Shape Up! studies did not include height requirements, the protocols did excluded participants weighing over 200 kg due to limitations of the DXA scanners. User requirements for the Naked Body Scanner prevented acquisition of scans on enrolled Shape Up! participants under 20 kg as well as those over 150 kg in weight or 198 cm in height.

The collective pool of participants from Shape Up! Adults and Shape Up! Kids used for this analysis were ethnically diverse (18 African American, 23 non-Hispanic white, 23 Asian, 6 Hispanic, and 20 NHOPI) and collectively sampled the full spectrum of BMI classifications (9 underweight, 35 normal, 24 overweight, 22 obese).

Procedures

Following initial screening, both ShapeUp! Adults and ShapeUp! Kids participants underwent a series of evaluations over the course of a single, 4 to 5-hour visit. Body shape analysis included an anthropometric assessment, height and weight measurements, whole body DXA scan, and a series of 3D optical scans with repeated assessments performed sequentially. Participants were provided an examination gown and asked to remove all personal items other than undergarments to collect height and weight measurements and complete the DXA scan. Form-fitting attire comprising a Lycra cap, spandex shorts, and a spandex bra was also available for participants to wear during the anthropometric assessment and 3D optical scanning procedures.

Design and Analysis—The accuracy and precision of digitally acquired full body assessment results were compared with measurements collected via conventional methods. Specifically, body shape was defined using circumference dimensions targeting the waist, hips, upper arms and thighs while body composition included whole body percent fat estimates. Digital anthropometry and body composition were evaluated using the Naked Body Scanner (Naked Labs Inc, Redwood City, California, USA), while traditional flexible tape measured anthropometry and DXA provided standard reference values for circumferences and percent fat estimates, respectively.

Measurements

A wall-mounted stadiometer (Seca 222, Seca GmbH & Co. KG, Hamburg, Germany) and digital scale (MC-970; Tanita, Tokyo, Japan) were used to determine height and weight. Each measurement was collected twice, height to the nearest 0.1 cm and weight to the nearest 0.1 kg, with a third reading taken if the first two differed > 0.5 cm or > 0.5 kg, respectively. Results for each were averaged.

Circumferences were measured using flexible tape anthropometry at six anatomic locations (waist, hip, right and left upper arm and thigh) outlined by the US National Health and Nutrition Examination Survey (NHANES) (18). Each measurement was recorded three times to the nearest 0.1 cm where no two measurements corresponding to the same location differed by more than 0.5 cm. Results were averaged. To minimize between-user error, three trained technicians performed all tape circumference measurements. A detailed explanation of the protocol expanding on precise placement and orientation of the tape is outlined in Supplementary Material.

3D Optical Scans

Duplicate 3D optical scans were performed sequentially using the Naked Body Scanner. This system collects an image series of the user from all angles to generate a digital avatar stored as an OBJ file. Using proprietary models, body shape measurements and body composition estimates are calculated on private servers and reported back to the user on a phone application. This data, in addition to multiple measurements not reported to the typical user, were available as comprehensive spreadsheets directly from Naked Labs. These included eleven circumferences taken at the waist, hip, right and left upper arm and thigh for a total of sixty six measurements as well as whole body percent fat estimates.

System Hardware and Design—The Naked Body Scanner has a compact and inexpensive hardware design. The device captures images using three vertically aligned Intel RealSense (Intel Corporation, Santa Clara, California, USA) depth systems built into the standing mirror's aluminum frame coupled with a detached, lightweight scale doubling as the system's turntable. Designed for living spaces, the Naked Body Scanner occupies less than three square feet of space when the scale is docked under the mirror for charging and storage. During a scan, the scale is positioned two feet from the mirror and requires one and a half feet of clearance.

User Interface—The Naked Body Scanner is solely operated by an application, Naked – 3D Home Body Scanner (Naked Labs Inc, Redwood City, California, USA), downloaded directly to the user’s phone. Acting as the only interface for the device, the phone connects to scanner via Bluetooth BLE (Bluetooth SIG, Inc., Kirkland, WA) allowing the application to guide the user through the setup process and provide step-by-step instructions for completing each scan. Once a scan is completed, the user’s measurements, body composition estimates, and avatar are all available for review within the app with the ability to track changes over time. To calculate percent body fat, fat mass, and lean mass; the system factors in additional measures such as age, height, and gender. These attributes are stored within the account created during the setup process or can be entered prior to each scan.

Naked – 3D Home Body Scanner is available for download on both the App Store (Apple Inc. Cupertino, California, USA) and Google Play (Google LLC, Mountain View, California, USA) and successfully operates on Apple smartphones running iOS 11 (Apple Inc., Cupertino, California, USA) or better as well as Android smartphones running Android 8.0 or 8.1 (Google Inc. Mountain View, California, USA).

Image Acquisition—Prior to each scan, a class 1 laser is emitted from the mirror’s frame to guide proper alignment of the scale and depth cameras. Once the device is in position, the user poses on the scale with their feet separated and arms extended downward, approximately thumb-length distance from the body. After a brief interval, the scale completes one 360-degree revolution while the depth cameras use rolling shutters to capture overlapping pixels. In total, each scan takes less than one minute to complete. This data is transferred to an Intel x86 processor (Intel Corporation, Santa Clara, CA) installed within the frame where stereo vision is used to triangulate depth. An active infrared projector is coupled with each stereo camera to illuminate objects in the field of view and enhance textural data.

Image Processing—The compiled depth data is transmitted to a private set of servers owned by Naked Labs via wireless internet connectivity. Using iterative closest point (ICP) reconstruction algorithms, 3D images are assembled from the depth calculation. Surface reconstruction methods integrated into processing algorithms then refine the image by smoothing and filling in surface gaps. The company’s proprietary software identifies physiological landmarks on the final image, dictating where various length and circumference measurements are recorded, and calculates body composition estimates. This data is finally uploaded and stored on encrypted cloud servers and made available to the user via the phone application.

Results from the Naked Body Scanner are typically processed and available for review within a few minutes. However, the time required to complete this step is dependent on the available wireless connection speed and new scans cannot be initiated until the prior scan has completed processing.

Dual-Energy X-Ray Absorptiometry

Whole-body DXA scans were performed using either the Hologic Discovery A at UHCC or Horizon A system at PBRC (Hologic Inc., Marlborough, MA, USA) according to the manufacturer's guidelines. Both systems were calibrated according to standard Hologic procedures (19) and DXA cross-calibration phantoms scanned at both sites. All completed scans were evaluated at (UHCC) using Hologic Apex software version 5.6 (Hologic, Inc., Marlborough, MA, USA) with the NHANES Body Composition Analysis (BCA) calibration feature disabled. DXA results comprised a number of body composition estimates including whole body percent fat.

Statistical Methods

Circumferences and percent fat estimates from the Naked Body Scanner were analyzed against corresponding flexible tape and DXA reference measurements. All statistical analyses were conducted using Microsoft Excel 2016 (Microsoft Corp., Redmond, Washington, USA) and all measurements were assumed to be normally distributed.

Comprehensive results received directly from Naked Labs include a circumference measured at the digitally landmarked waist, hip, upper arms and thighs. An additional five parallel circumferences deviating vertically by 1.0 cm in each direction from the landmark are also reported, totalling eleven circumferences for each location. As an example, Figure 1a diagrams where these sixty six circumferences were calculated on a single participant's avatar. To determine which measurements from the Naked Body Scanner most accurately agree with NHANES defined tape measurements, the eleven digital circumferences reported at each location were regressed on the averages of direct measurements collected at corresponding anatomic sites. Digital values correlating the strongest with tape measurements were used for the remaining analyses. Plots comparing the R^2 results are presented in Figure 2.

To explore the level of agreement between the selected 3D optical measurements and reference measurements, we tested if between-method group mean differences were present, the magnitude of associations between the methods, and if between-method bias was present. Paired, two-sided t-tests were used to compare device acquired circumferences and percent body fat estimates to analogous tape measurements and DXA derived percent body fat values. Mean differences at $p < 0.05$ were considered statistically significant. Associations between digital and reference results were examined using simple linear regression analysis and 3D optical measurement bias was quantified with Bland-Altman plots. For both, statistical significance was set at $p < 0.05$. Quality assurance of the Naked Body Scanner was analyzed using a subgroup of fifty-one participants who completed duplicate scans on this device. The coefficient of variation (CV) was calculated for both direct and digital circumferences at all six measurement locations and for whole body percent fat results obtained from the Naked Body scanner(20).

RESULTS

Participants

Results from ninety healthy participants of diverse age, BMI, race, and ethnicity are included in this analysis. For summary characteristics, see Table 1. Of these, one participant was excluded due to a significant offset in the Naked Body Scanner's landmarking of anatomical locations. The error was evident upon reviewing this participant's digitally generated avatar with labeled circumference locations. As Figure 1b shows, thigh measurements generated from this avatar were estimated geographically too low and, consequently, yielded unrealistic measurement magnitudes.

Following initial installation of the Naked Body Scanner, complications with wireless and bluetooth connections frequently prevented the collection of duplicate scans. A total of fifty one participants successfully completed the second scan on this device. Additionally, comprehensive results received from Naked Labs did not include percent fat estimates for eleven scanned participants, most of which were youth volunteers under the age of 18. Therefore, CV analysis of digital circumferences includes fifty one participants and regression analysis comparing percent fat estimates between the Naked Body Scanner and DXA include a subset of data collected from seventy seven participants.

Repeatability

The average difference between repeated measurements, CVs, and root-mean square analysis values are reported in Table 2. CVs from the Naked Body Scanner's circumference results exhibit greater variation in test-retest reliability (0.4 – 2.7%) between the six measured anatomic locations when compared to more consistently reliable results across all sites measured manually (0.2 – 0.4%). The magnitude of the average difference between duplicate measurements recorded by the Naked Body Scanner ranged from 0.4 ± 0.4 cm for hip circumferences to 0.7 ± 0.7 cm for waist circumferences. Conversely, the average difference between duplicate tape measurements did not exceed 0.2 ± 0.4 cm for any of the six measured locations. For both methods, repeated hip circumference was the most reliable measurement (NBS CV, 0.4 %; tape CV, 0.2 %).

Circumferences

Mean group differences between corresponding manual anthropometric and 3D optical measurements are presented in Table 3. Results reveal significant, well defined differences between reference value means and device-acquired means from the Naked Body Scanner for waist, arm, and thigh circumference estimates (means, 1.7 cm, 1.5 cm (right), 1.7 cm (left), 3.0 cm (right), and 3.2 cm (left), respectively; $p < 0.0001$). The mean 3D optical hip circumference measurement was the only estimate not significantly different from the tape reference mean (mean, 0.2 cm).

Simple linear regression analyses were conducted for each of the six targeted locations to test agreement between 3D optical acquired circumferences from the Naked Body Scanner and those measured manually. For all locations, 3D optical estimates significantly predicted reference measurements (R^2 s, 0.84–0.97; $p < 0.0001$). Digitally collected circumferences

plotted against flexible tape measurements are presented in Figure 3a along with corresponding Bland-Altman plots. The Naked Body Scanner significantly overestimated waist circumferences by approximately 2.0 cm compared to reference estimates ($p < 0.0001$). Significant bias was also found for left and right thigh measurements ($p < 0.0001$). The scanner showed a mean overestimation of thigh circumferences by approximately 3.0 cm with significantly greater overestimations for relatively smaller thigh circumferences measuring less than ~ 55.0 cm.

Percent Body Fat

Whole body percent fat estimates from the Naked Body Scanner and DXA are summarized in Table 3. Results reveal consistent optical scanner results (CV, 2.4%) that are not significantly different from reference method values. Simple linear regression analysis was used to test agreement between digital and DXA-derived body composition estimates. Results suggest that the Naked Scanner's percent fat estimates significantly predict DXA reference values ($R^2 = 0.73$, $p < 0.0001$). Digital results plotted against DXA reference values and corresponding Bland-Altman plot are presented in Figure 3b. The Naked Body Scanner showed a trending bias to underestimate whole body percent fat values of individuals with less than ~ 30% body fat ($p = 0.09$).

DISCUSSION

The aim of the current study was to critically evaluate the Naked Body Scanner, the first 3D optical system of its kind designed specifically for personal use outside of industry, research, or clinical settings. Despite the considerable minimization of system footprint and cost of the acquisition hardware, the Naked Body Scanner showed consistency in repeated measurements that compared favorably with traditional reference methods. Digital core measurements potentially used to evaluate health risk systematically deviated from direct measurements on the order of several centimeters, a relatively small difference that likely would have minimal effects on health assessment results. Additionally, digitally-derived whole body percent fat estimates significantly predicted DXA results with correlations comparable to other devices (e.g., bioimpedance systems) used in clinical settings.

Overall the system and phone software application are simple to install and operate with minimal steps and interactive instructions; however, beta versions of this device presented with a number of issues. Following initial setup, bluetooth and wireless connection failures between the Naked Body Scanner, cell phone, and the center's secure wireless network often prevented scans from fully processing and consequently precluded the collection of digital measurements altogether. While fully processed scans show promising results, gaps in this analyzed data set due to partially processed scans or missing scans limited further investigation into differences in the accuracy, precision, and possibly bias between gender and race/ethnic groups. Naked Labs was informed of these issues and has since improved the scanner's connection features from the device's early release versions.

While studies examining the capabilities of newly introduced 3D optical devices are limited, our findings for the Naked Body Scanner are consistent with those reported for larger, more expensive optical scanners. In 2017, Bourgeois et. al. published an evaluation of multiple 3D

systems optimized for more traditional applications, namely, garment sizing and physical fitness assessments (17). In a subset of 113 participants from the ShapeUp Adults study, anatomically specific circumferences measured by these optical systems significantly correlated with equivalent measurements collected using a flexible tape (R^2 s, 0.71 – 0.96; $p < 0.0001$); however, peripheral circumferences of the arms and thighs revealed lower correlations than those discovered using the Naked Body Scanner (R^2 s, 0.71 – 0.87, NBS R^2 s, 0.84 – 0.95; $p < 0.0001$). Likewise, reliability of repeated digital measurements by these devices mirrored those found in analysis of the Naked Body Scanner's results. For example, duplicate hip circumferences proved to have the most consistent results for all three previously evaluated scanners (CVs, 0.1% – 0.4%) while more variation was present between repeated waist, upper arm, and thigh circumferences (CVs, 0.3% – 0.8%, 0.8% – 2.6%, 0.3% – 0.9%, respectively).

Device Technical Concerns

A comparison of the Naked Body Scanner's assessment results to those of the larger, more costly 3D optical systems shows that some degree of error associated with digitally acquired measurements is not isolated to this personal-use home system. Therefore, the following technical concerns we encountered with the Naked Body Scanner should be considered juxtaposing previously documented concerns of larger systems (17).

The degree of difference in measurement magnitudes between analogous results from optical devices and traditional methods is primarily an artifact of landmarking techniques. While conventional anthropometric methods rely on palpation for bony landmarks, automated optical imaging techniques orient reported measurements around surface landmarks like midpoints or comparative cross-sectional areas. For larger individuals, specifically users with excess abdominal adipose tissue, we found greater variability when comparing measurements from these two landmarking methods. Visual evidence to support this can be seen in Figures 1c and 1d. Each of the lines encircling the hip region designates one of the eleven circumferences measured by the Naked Body Scanner. It is clear that changes in clothing and measurement location can yield large differences in circumference results and therefore body composition estimates for these figures.

Consistently pinpointing the same somatic locations is essential for optical scanners to accurately track fitness progress over time, a well advertised and valuable feature of these devices. Although not tested directly, the Naked Body Scanner's CV results suggest the potential for this capability. However, like other previously evaluated scanners on the market (17), the landmarks determining these locations do not exactly match sites defined by NHANES. Therefore, while scanners can independently provide the user with valuable information, their results cannot be readily compared to those obtained on other devices nor via tape measure without the institution of universal landmarking definitions.

Interactions between 3D optical hardware design and user's physical characteristics also yield avatar inaccuracies. For example, fusion of the thigh region and distortions in the 3D image are common errors by optical devices typically resulting from limited leg separation and excessive movement during the scanning process. The extent of the imaging error is compounded for users with a relatively high BMI or poor stability who are unable to

separate their thighs or limit their motion on a moving platform. Larger 3D optical systems like those previously reported by Bourgeois et al. (17) mitigate these problems by incorporating features such as handlebars and large turntables into their hardware configuration. Systems like the Naked Body Scanner, however, lack the space necessary for applying similar solutions and consequently generate comparatively lower quality avatars.

The reoccurring errors experienced using the Naked Body Scanner are shown in Figure 1e–g. Following the scanner’s recommended pose, users stand on the turntable with their fists at a thumb-length distance from the body. Without handlebars to stabilize and guide arm placement, any underestimation of the optimal distance resulted in a blending of the avatar structure between the hands and sides (Figure 1e). Additionally, due to the smaller turntable, users stand with their feet approximately shoulder-width apart. This proved to be problematic for large individuals with a broad physique or high BMI who were unable to separate their feet proportional to their body size. For many of their image results, the thighs were fused down to the knees (Figure 1f). Another artifact frequently occurred on the shoulder of Naked Body avatars (Figure 1e and 1f). According to Naked Labs, the error was caused by the scanner picking up on ambient light in the room, a problem which should be resolved with more recent updates. Ultimately, while all of these errors were visually evident in the avatar, circumference measurements and body composition estimates did not appear to be affected.

Study Limitations

The current study sample was relatively small, thus precluding detailed examination of scanner capabilities across age, sex, and race/ethnic groups that are known to vary in body shape and size. Larger and more varied sample studies are needed to address device accuracy within these specific groups with the potential need for future adjusted system software to accommodate for differences in participant anthropometric characteristics. Moreover, the evaluated scanner had limited capabilities for acquiring data on very young and small participants, a technical concern that likely requires an engineering solution.

CONCLUSIONS

The Naked Body Scanner is a more spatially and financially conservative optical system relative to currently available 3D optical devices optimized for business and clinical settings; yet this home system is capable of providing users with accurate and reliable somatic surface measurements and body composition estimates. The device operates using a smartphone application making it practical for personal home use. Scan time is comparable to larger, previously validated 3D scanners, although processing speed is dependent on the wireless internet connection. Results are presented and stored directly on the application making it feasible for monitoring weight loss or fitness program results over time. This system opens a new era of digital home-based assessments available to the individual user that can be applied during weight or exercise interventions.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGEMENTS

The authors thank ShapeUp! Adults and ShapeUp! Kids participants and parents for the time and enthusiasm they contributed to this study. Additionally, this work could not have been completed without the assistance, data, and cooperation from Samantha Winter, Thomas Ward, and Bennett Ng at Naked Labs as well as formatting assistance from Melanie Peterson at Pennington Biomedical Research Center.

FUNDING

This work was partially supported by two National Institutes of Health NORC Center Grants P30DK072476, Pennington/Louisiana; and P30DK040561, Harvard; and R01DK109008, Shape UP! Adults.

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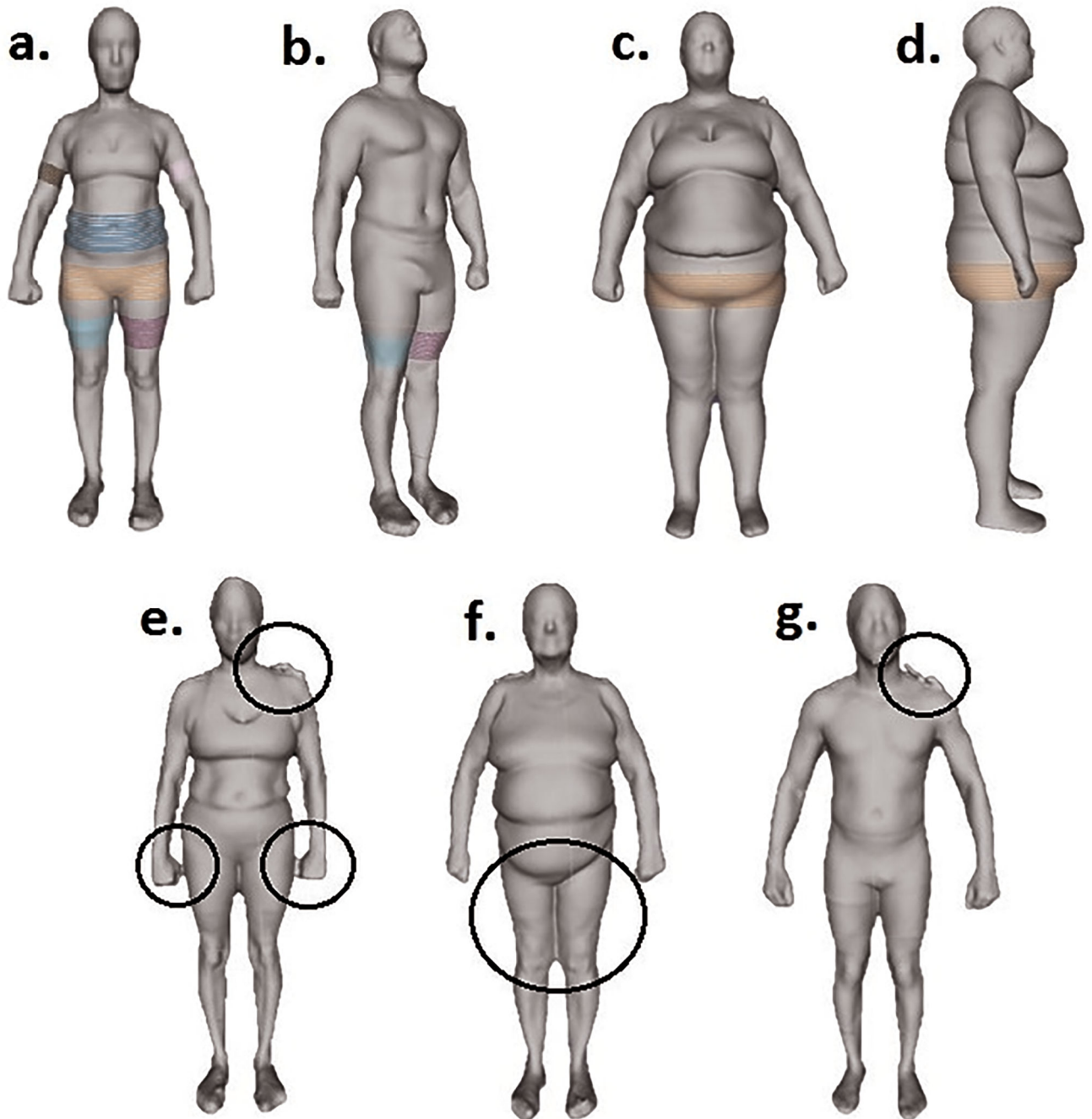


Figure 1.

(a) Example of 3D avatar generated by the Naked Body Scanner. Lines encircling the waist, hips, arms, and thighs indicate locations where circumferences were measured and recorded for each participant. Avatar errors from the Naked Body Scanner including (b) misidentified landmarks, (c, d) variability in results due to landmark placement on overweight and obese users, (e) merging of hands and thighs, (f) fusion of thighs, and (e and g) shoulder artifact.

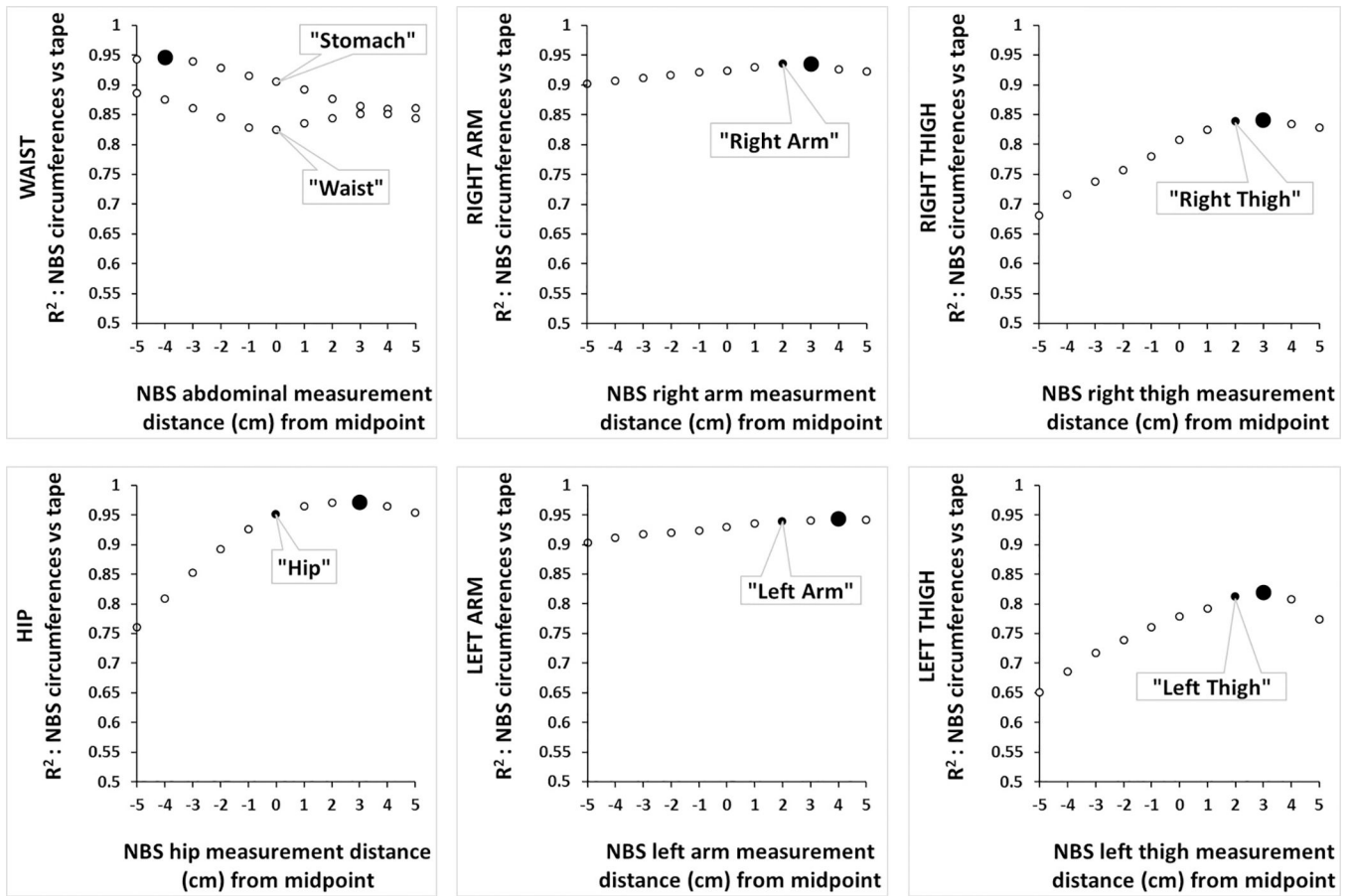


Figure 2.

R^2 plots comparing model results of eleven parallel circumference measurements from the Naked Body Scanner (NBS) regressed onto an analogous tape measurement. Each plot corresponds to one of the six anatomic sites targeted in this study. The X-axis is labeled according to the vertical deviation of the digital measurement in centimeters from a midpoint circumference “0”. Positive and negative deviations are circumferences collected anatomically superior and inferior, respectively, to the midpoint. The points labeled “Stomach,” “Waist,” “Right Arm,” “Left Arm,” “Right Thigh,” and “Left Thigh” are model results derived from circumferences reported by the scanner on the phone application, Naked – 3D Home Body Scanner. The application reports two abdominal circumference measurements, distinguishing between an upper “Waist” and a lower “Stomach”. The first plot labeled WAIST, reports model results of both sets of eleven digital measurements deviating from the reported “Stomach” and “Waist” measurements regressed onto the same NHANES defined waist tape measurement. Digitally acquired circumference measurements that yielded the highest coefficient of determination against tape reference values (in bold) were used in remaining analysis.

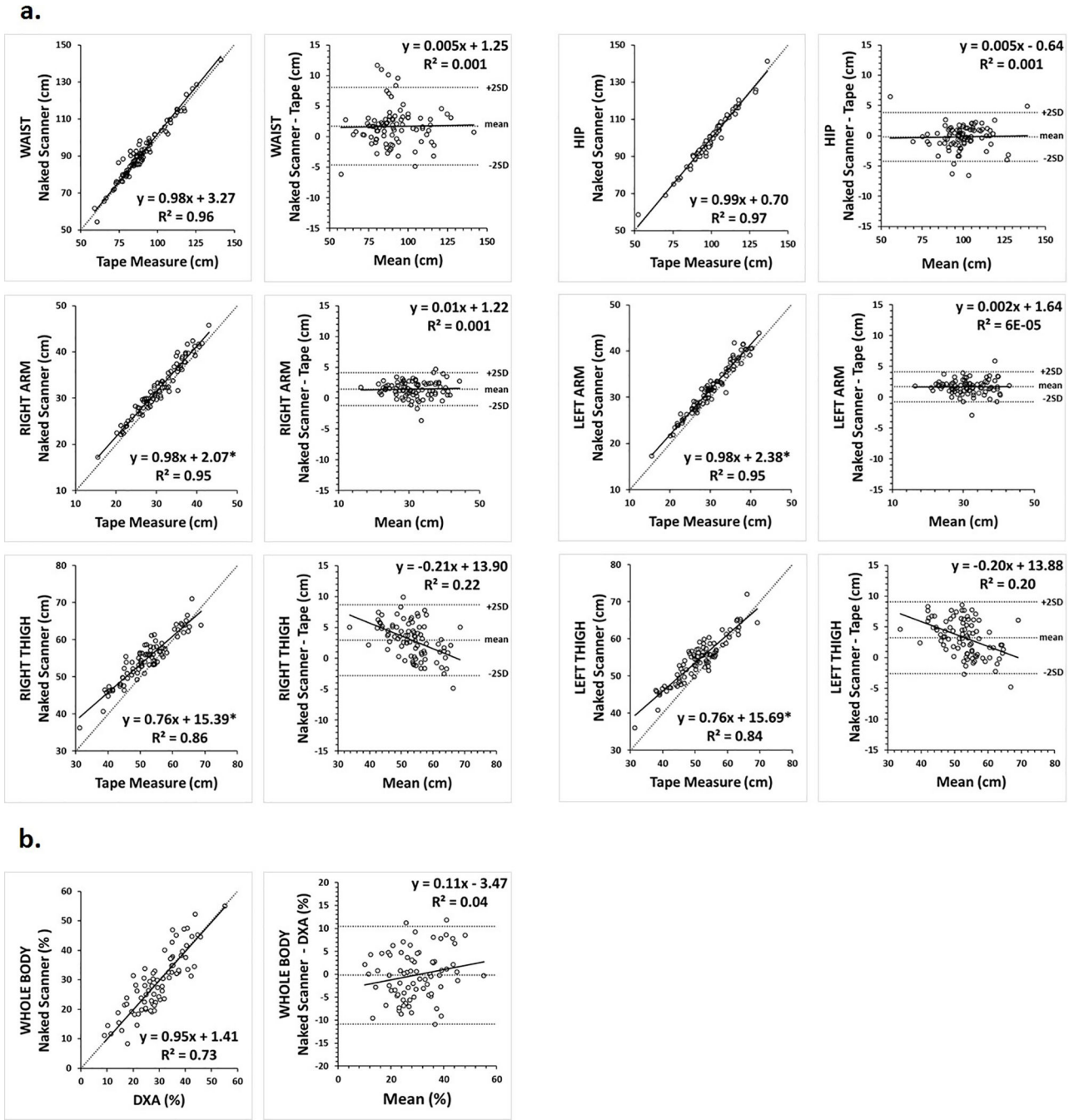


Figure 3. (a) Circumferences and (b) whole body percent fat estimates calculated by the Naked Body Scanner versus reference results from (a) flexible tape measurements and (b) DXA, respectively, along with corresponding Bland-Altman plots. For all regression plots, solid lines denote the line of regression while a dashed line indicates the line of identity. Regression equations with significant intercepts ($p < 0.01$) are marked *; equations with non-significant intercepts are set to the origin.

Table 1.

Subject Characteristics

	Males	Females	Youths †
Total number	33	40	17
African American	10	8	0
White	8	12	3
Asian	11	7	5
Hispanic	2	2	2
NHOPI	2	11	7
Age (yrs)			
Mean	48	46	12
Range	22 – 74	18 – 71	7 – 17
Height (cm)			
Mean	173.6	163.3	151.9
Range	157.6 – 192.1	146.3 – 181.0	124.9 – 173.5
Weight (kg)			
Mean	83.9	68.7	55.1
Range	63.5 – 110.9	43.2 – 125.9	22.5 – 114.7
BMI (kg/m²)			
Mean	27.9	25.7	22.9
Range	20.4 – 37.7	16.9 – 45.5	14.4 – 38.8

† 3 males and 14 females. Abbreviation: BMI, body mass index. NHOPI, Native Hawaiian and Other Pacific Islanders.

Table 2.

Results of Repeated Measurements

	Avg Difference in Repeated Measures (cm)	CV (%)	RMSE
Waist Circumference			
Tape Measure	0.4 ± 0.6	0.3	3.16
Naked Body Scanner	0.7 ± 0.6	0.7	
Hip Circumference			
Tape Measure	0.3 ± 0.2	0.2	2.01
Naked Body Scanner	0.4 ± 0.4	0.4	
Right Arm Circumference			
Tape Measure	0.2 ± 0.2	0.4	1.32
Naked Body Scanner	0.5 ± 0.5	1.4	
Left Arm Circumference			
Tape Measure	0.2 ± 0.2	0.3	1.2
Naked Body Scanner	0.6 ± 1.1	2.7	
Right Thigh Circumference			
Tape Measure	0.2 ± 0.2	0.3	2.26
Naked Body Scanner	0.5 ± 0.8	1.2	
Left Thigh Circumference			
Tape Measure	0.2 ± 0.2	0.3	2.34
Naked Body Scanner	0.5 ± 0.7	1.1	
Whole Body Percent Fat			
Naked Body Scanner	0.6 ± 0.8	2.4	

Abbreviations: Avg, average; CV, coefficient of variation. Results are $X \pm s.d.$ n=51 for coefficient of variations

Table 3.

Summary of means and mean differences between 3DO estimates and reference results

	Mean	Mean	95% CI
Waist Circumference (cm)			
Tape Measure	90.4 ± 15.0		
Naked Body Scanner	92.1 ± 15.1	1.7*	1.2 – 2.2
Hip Circumference (cm)			
Tape Measure	99.5 ± 12.3		
Naked Body Scanner	99.3 ± 12.3	0.2	– 0.5 – 0.1
Right Arm Circumference (cm)			
Tape Measure	30.6 ± 5.7		
Naked Body Scanner	32.1 ± 5.7	1.5*	1.3 – 1.7
Left Arm Circumference (cm)			
Tape Measure	30.4 ± 5.5		
Naked Body Scanner	32.1 ± 5.5	1.7*	1.5 – 1.9
Right Thigh Circumference (cm)			
Tape Measure	51.8 ± 7.4		
Naked Body Scanner	54.8 ± 6.0	3.0*	2.5 – 3.4
Left Thigh Circumference (cm)			
Tape Measure	51.3 ± 7.2		
Naked Body Scanner	54.5 ± 5.9	3.2*	2.8 – 3.7
% Body Fat			
DEXA	33.0 ± 7.3		
Naked Body Scanner	31.0 ± 7.6	2.0	–1.0 – 0.7

* $P < 0.0001$. Results are $X \pm s.d.$ 90 total subject evaluations for circumferences. Confidence Interval (CI) is calculated for the mean difference.