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Digital Anthropometric Evaluation of Young Children: Comparison to Results Acquired with Conventional Anthropometry

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Abstract

Objective: Three-dimensional optical (3DO) imaging devices for acquiring anthropometric measurements are proliferating in health-care facilities, although applicability in young children has not been evaluated; small body size and movement may limit device accuracy. The current study aim was to critically test three commercial 3DO devices in young children.

Methods: The number of successful scans and circumference measurements at six anatomic sites were quantified with the 3DO devices in 64 children, ages 5-8 years. Of the scans available for processing, 3DO and flexible tape-measure measurements made by a trained anthropometrist were compared.

Results: 60 of 181 scans (33.1%) could not be processed for technical reasons. Of processed scans, mean 3DO-tape circumference differences tended to be small (~1-9%) and varied across systems; correlations and bias estimates also varied in strength across anatomic sites and systems (e.g., regression R^2s, 0.54-0.97, all p<0.01). Overall findings differed across devices; best results were for a multi-camera stationary system and less so for two rotating single- or dual-camera systems.

Conclusions: Available 3DO devices for quantifying anthropometric dimensions in adults vary in applicability in young children according to instrument design. These findings suggest the need for 3DO devices designed specifically for small and/or young children.

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AUTHOR CONTRIBUTIONS
Authors' contributions to manuscript: SK, MW, JS, and SBH designed research; SK, BS, SS, MED, NK, and MW conducted research; JS and SBH provided essential materials; SK, BS, MW, JS, and SBH analyzed data; SK, BS, SS, MED, MW, JS, NK, and SBH wrote paper; SK, BS, SS, MED, MW, JS, NK, and SBH had primary responsibility for final content.

CONFLICT of INTEREST
The authors and their close relatives and their professional associates have no financial interests in the study outcome, nor do they serve as an officer, director, member, owner, trustee, or employee of an organization with a financial interest in the outcome or as an expert witness, advisor, consultant, or public advocate on behalf of an organization with a financial interest in the study outcome.

Keywords

Optical Imaging; Growth; Nutritional Assessment; Obesity; Body Composition; Dechenaud; Heymsfield; Kennedy; Shepherd; Smith; Sobhiyeh; Wong

INTRODUCTION

The mounting rates of obesity and consequently obesity related diseases including diabetes, cardiovascular complications, metabolic disease, and specific types of cancer present a multifaceted health problem attributed primarily to health practices initiated during youth and adolescence [1, 2]. According to reports from the 1999 to 2016 Nutritional Health and Examination Survey (NHANES), approximately one fourth of children in the United States between the ages of 2 and 19 years were classified as obese. Findings also show that since the year 2000, prevalence of obesity is escalating in both young males and females by 5.3% and 6.4%, respectively [3]. Additional studies show that between 70% and 80% of adolescents with obesity will either maintain this classification or become morbidly obese in adulthood [4], suggesting that screenings and intervention during early childhood development are critical for lifelong prevention of chronic obesity related health complications.

Evaluating childhood nutritional and metabolic status involves acquisition of body size, shape, and composition estimates. Clinical methods of deriving these values implement rudimentary tools such as measuring tape, calipers, and weight scales that have been used for centuries with minimal modification [5–7]. While safe for high frequency application, these time-consuming methods require trained and skilled professionals for delivering accurate, precise, and therefore repeatable results [8, 9]. Research settings typically incorporate advanced technologies such as dual-energy x-ray absorptiometry (DXA) [10–13] and laser scanning into method protocols for acquiring detailed body composition and somatic measurements in younger populations. These methods, however, are accompanied by safety and financial constraints that limit the scope of their application.

Digital anthropometry using relatively low cost three-dimensional optical (3DO) imaging systems has emerged in a growing number of recently published studies as a promising technique for acquiring surface linear and circumferential measurements as well as whole body composition estimates in healthy populations ranging from 5 to 80 years of age [14–16]. An important concern, however, is whether these systems are practical tools for acquiring accurate and reproducible somatic measurements in small children. While previously published population samples incorporate results from individuals as young as 5 years, analyses are largely composed of adults or adolescents with fully developed figures. This kind of mass analysis can possibly skew interpretations of results collected from those with much smaller bodies. Additionally, currently available systems are designed for adults and require a certain degree of subject participation, such as standing still for a defined period of time. Our clinical experience led us to conduct 3DO imaging studies in children at or above the age of 5 years; younger ages are excluded from participation. Subjective observations throughout data collection suggested that participating children age 8 or less were often too small or restless for obtaining high quality scan results [14,18,20]. Therefore, the practicality of using optical devices in younger population samples should also be addressed.

The aim of the current study was to apply 3DO whole-body scanning methods to acquire somatic body dimensions in children between the ages of 5 and 8 years. These measurements were compared to those obtained by highly trained technicians using conventional anthropometric methods.

METHODS

Shape Up! Kids is an ongoing, cross-sectional study stratified by age, sex, race, and growth percentile. Data used for this analysis includes assessments from a subset of individuals scanned under this study's protocol. Verbal or written assent was obtained from all participating parties, and written informed consent was signed by their legal guardians. Procedures outlined below were approved by the Pennington Biomedical Research Center Institutional Review Board (IRB# 2017-10-PBRC), the University of Hawaii Office Of Research Compliance (CHS# 2017-24282), and the Human Research Protection Program Institutional Review Board at the University of California, San Francisco (IRB# 16-20197). Shape Up! Kids is publicly listed on ClinicalTrials.gov as ID NCT03706612.

Study Design

The aim of this study was to answer two specific questions: Can each of the evaluated 3DO devices generate usable measurement results from scans of small children? Are the produced results valid relative to the reference tape-measure estimates? To answer these questions, digitally acquired body shape and composition estimates from 3DO devices were evaluated against conventional body measurement methods. Specifically, body shape was defined using circumference dimensions targeting the waist, hips, mid-upper arms, and mid-thighs. Digital anthropometry was evaluated using three optical imaging systems: the Size Stream SS20 (Size Stream, Cary, NC), Fit3D Proscanner version 4.x (Fit3D, San Mateo, CA), and Styku S100 (Syku, Los Angeles, CA). Traditional flexible tape measured anthropometry provided standard reference values for circumferences.

Participants

Data were collected from all children participating in Shape Up! Kids between 5, the youngest individuals recruited, and 8 years of age. Recruitment efforts included web advertisements, locally posted flyers, and word of mouth networking in the local communities. To ensure that subjects were in relatively good health and free of chronic or life-threatening conditions, guardians of all interested candidates completed a pre-evaluation screening questionnaire as part of the recruiting process. Additional screening during the scheduled visit excluded children weighing 440 pounds (~200 kg) or more as well as those unable to hold a standing posture for two minutes. Data included for this analysis were collected from a subset of Shape Up! Kids participants who were racially/ethnically diverse and collectively sampled the full spectrum of body mass index (BMI) classifications. (Table 1)

Procedures

Following the recruitment and clinical screenings, subjects underwent a series of evaluations over the course of a single, 4 to 5-hour visit. Body shape assessments included multiple circumference, height, and weight measurements as well as a series of 3DO scans. Height and weight measurements were completed in minimal clothing and an examination gown. Form-fitting attire comprising a lycra cap, spandex shorts, and a spandex bra (only females) was provided for participants to wear during the anthropometric assessment and 3DO scanning procedures.

Measurements

A Seca 222 wall-mounted stadiometer (Seca GmbH & Co. KG, Hamburg, Germany) and a MC-970 digital scale (Tanita, Tokyo, Japan) were used to accurately determine the height and weight of participants. The magnitude of each dimension was measured twice, height to the nearest 0.1 cm and weight to the nearest 0.1 kg; a third was acquired only when the first two differed > 0.5 cm or > 0.5 kg, respectively. Results were averaged.

A flexible tape was used to estimate body circumferences at six anatomic locations (waist, hip, right/left upper arm, and right/left thigh). The implemented protocols detailing precise placement and orientation of the tape measure, recording methods, and techniques to minimize error are outlined in the US National Health and Nutrition Examination Survey (NHANES) [17]. Triplicate circumferences collected at each location were recorded to the nearest 0.1 cm, and no two measurements corresponding to the same location differed by more than 0.5 cm. Results were averaged. Between-user error was minimized by limiting the number of trained technicians to only three individuals, accommodating simultaneous data collection from multiple centers. Technical training for obtaining accurate circumferences consisted of an initial review of the NHANES protocol followed by a trial period in which multiple observers obtained measurements on the same examinees. Technicians were permitted to collect study data once able to consistently collect accurate measurements compared to an expert observer and repeatable results with 0.5 cm.

Image Acquisition

Images were collected from three independently developed 3DO devices from which each company’s proprietary software was able to process, analyze, and generate a multitude of body shape estimates. While all devices utilize consumer grade optical depth cameras for data capture, each presents with a distinctive hardware design and user interface to create a scan experience unique to each system. The three optical imaging devices implemented in this study have been previously validated in groups of adults (+18 years) [18–20] and children (5 to 17 years) [14, 16]. Image quality was reviewed following each scan and repeated up to five times, and if possible, two scans were collected without error or missing results. For each participant, one valid scan and its associated estimates were used in the analysis.

The Size Stream SS20 Classic Edition is a stationary aluminum framed 3D body scanner. Equipped with 20 infrared depth sensors fixed within four corner towers, this system captures all sides of the body simultaneously. The user, guided by footprint markers and height adjusted handlebars, stands in the center of the frame for six seconds with their feet roughly shoulder-width apart and arms extended downward at a 45-degree angle from each side of the body. During this time, infrared projectors also located within the corner towers emit a structured light pattern onto the area within the frame. The distortions in the light pattern created by the subject's form are captured by cameras and then used to calculate depth.

The Fit3D Proscanner uses a rotating platform and a camera tower equipped with three infrared depth sensors to collect 3DO images. Like the Size Stream SS20, this scanner guides the user's pose with footprint markers and handlebars so that feet are separated while arms are fully extended downward and abducted from the body. During one 40-second revolution, a structured pattern of infrared light is projected onto the user from the camera tower. Distortions in the pattern are captured by the cameras and used to calculate depth.

The Styku S100 scanner also uses a rotating platform and camera tower to collect body image data; however, this system uses a single Microsoft Kinect V2 camera and employs "time-of-flight" technology. The user poses on a turntable, aligning their feet with designated footprint markers and arms extended in a downward V position. As the turntable completes a 30 second rotation, an infrared light is projected from the camera tower and reflected to the sensor by the user's body. The phase shifts in the returning light waves are used to measure roundtrip light travel time that allows for direct calculation of depth.

Statistical Methods

Circumference measurements from multiple 3DO scanners were evaluated against tape measure references. Left arm and left thigh reference circumferences were not collected on 14 of the 64 participants. Additionally, Size Stream scans were not collected on 11 participants. Missing measurements correspond to individuals assessed prior to the implementation of an amended protocol that included tape measurements on the left side of the body and a Size Stream 3DO scan.

The percentage of images successfully scanned and processed were first calculated and compared between scanners. Some scans could not be processed as no image was captured or repeated attempts failed to generate a usable scan. Additionally, some scans that could be processed included extreme outliers or no readings at specific measurement sites, and these values were not included in the 3DO-tape circumference comparisons. Extreme outliers were defined as digital results of 0 cm as well as exceptionally large values that more than doubled reference values. These were removed prior to statistical analysis as they resulted from inaccurate landmarking by the software and do not represent estimations of the measurement in question. Figure 1 shows an image produced by the Size Stream SS20 scanner diagraming directly on an avatar what the resulting values measure. This image clearly shows circumferences that do not align with the shape of the individual's body and therefore cannot be directly compared with references. For example, the mid-upper right arm circumference extends not only around the mid-upper arm but the chest as well.

Agreement between 3DO results and reference measurements was assessed by testing for between-method group mean differences, the magnitude of associations between methods, and the degree of between-method bias. Paired, two-sided t-tests were used to compare device-acquired somatic measurements against analogous reference values from flexible tape measure. Simple linear regression models were used to quantify levels of association between digital and reference results and Bland-Altman plots were used to assess method bias. The threshold for declaring statistical significance applied to all analysis was $p<0.05$. All statistical analyses were conducted using Microsoft Excel 2016 (Microsoft Corp., Redmond, Washington, USA).

RESULTS

Subjects

Results from 64 healthy children (29 males and 35 females) ages 5 to 8 years with a wide BMI range (13.1 kg/cm^2 – 39.5 kg/cm^2) and varying race/ethnicity (19 African American, 19 non-Hispanic white, 7 Asian, 6 Hispanic, and 13 Native Hawaiian and Other Pacific Islanders) are included in this analysis (Table 1).

Initial Data Processing

The analysis sample is summarized in the consort diagram presented in Supplementary Materials. Shape Up! Kids had 320 participants across the three centers at the time of this analysis. Sixty-four of these children met the study criteria of age 5 to 8 years. Of these participants, 181 scans were conducted across the three imaging devices; 121 of these scans could be processed and 60 (33.1%) were not evaluable. Processed scans were thus available in 52 of 53 Size Stream scans (98.1%); 43 of 64 Fit3D scans (67.2%); and 26 of 64 Styku scans (40.6%) (Table 2). The percentage of processed scans increased from age 5 to 8 years for the Fit3D and Styku systems; generally, the percentage of processed scans by the Size Stream system approached 100% for all four age groups. Variable numbers of outlier measurements were removed from the analyses that follow as shown in the supplementary consort diagram. Specifically, 6.7%, 2.2%, and 3.4% were removed as nonsensical outliers from the Size Stream SS20, Fit3D Proscanner, and Styku S100 scanner results, respectively.

Analysis of Means

Mean group differences between corresponding manual anthropometric and 3DO measurements are presented in Table 3. Results reveal significant differences between reference value means and device-acquired means for all six circumferences estimated by all three scanners (Δ mean: Fit3D, 1.2 – 4.2 cm; Styku, 1.0 – 5.5 cm; Size Stream, 1.6 – 3.4 cm; $p<0.01$) with the exception of the left thigh measurement generated on the Fit3D Proscanner (Δ mean: 0.3 cm). For measurements collected on the Fit3D Proscanner, Styku S100, and Size Stream SS20; deviations from reference values were respectively largest in the hip (Δ mean, 4.2 cm; $p<0.01$); waist (Δ mean, 5.5 cm; $p<0.01$); and extremities, specifically the right and left thighs (Δ mean right, 3.0 cm; left, 3.4 cm; $p<0.01$). Alternatively, significant differences of digitally acquired right and left upper arm circumferences from tape measurements remained more consistent on all three scanners (Δ mean right, 1.7 – 1.9 cm; left, 1.4 – 2.5 cm; $p<0.01$).

Regression and Between-Method Bias Analysis

Linear regression and Bland-Altman plot analyses were conducted for each of the six corresponding NHANES defined locations to test the strength of association and agreement between 3DO acquired circumferences and those measured manually. For all locations, optical estimates from the Fit3D Proscanner, Styku S100, and Size Stream SS20 significantly predicted reference measurements (R^2s: Fit3D, 0.70 - 0.96; Styku, 0.54 - 0.97; Size Stream, 0.68 - 0.97; $p<0.01$). All three devices appeared to predict midsection measurements, including waist and hip, the best (R^2s: 0.93 – 0.97; $p<0.01$) and those of the upper extremities, including right and left upper arms, the poorest (R^2s: 0.54 - 0.75; $p<0.01$). Overall, the Fit3D Proscanner was the best predictor of body size in small children (R^2s: waist, 0.96; hip, 0.95; right arm, 0.75; left arm, 0.70; right thigh, 0.88; left thigh, 0.82; $p<0.01$).

Digitally collected circumferences plotted against flexible tape measurements are presented in Figures 2–4 along with corresponding Bland-Altman plots. The Fit3D Proscanner generally overestimated waist, right arm, and left arm measurements by approximately 1.5 cm, and hip measurements by about 4.0 cm. Right and left thigh measurements, however, were better estimated by individuals with thigh circumferences under 40 cm. Measurements of individuals with thigh circumferences exceeding 40 cm were generally underestimated by the Fit3D system (Figure 2). The Size Stream SS20 also showed slight positive bias for waist, hip, right arm, and left arm measurements ranging from 1.6 – 2.5 cm. Thigh circumferences from this device, however, were underestimated by approximately 3.0 cm (Figure 3). The Styku S100 prediction bias was less homogenous between measurement locations (Figure 4).

DISCUSSION

The aim of the current study was to critically evaluate the ability of multiple 3DO devices to successfully scan and estimate body size and shape measurements in small children between 5 and 8 years of age. While all three systems have a hardware design that accommodates larger adult bodies and additionally rely on algorithms that derive measurement results based on adult body size and composition predictions, they varied in their potential for similarly assessing body size measurements in young children. Taking into account the accuracy and likelihood of successful scan completion, the Size Stream SS20 proved to be the most consistently accurate device for this purpose. This scanner was not only able to process more scans collected on the smallest participants, but also derived measurements with an accuracy on par with the Fit3D Proscanner and surpassing that of the Styku S100 (see Figures 2–4 for the full range of circumferences along the X-axis). Users should, however, be aware that unlike the Fit3D and Styku scanners, the Size Stream did produce measurement results for individuals without properly processed scans. Therefore, when scanning small children on this device, the pictorial depiction of measurement locations should be carefully evaluated before considering measurement magnitudes.

A comparison between 3DO scan results of small children to those of adults shows that some degree of error associated with digitally acquired measurements is not isolated to body size. Therefore, the following observations related to scanning young populations should be considered a juxtaposition to previously documented technical concerns associated with these devices.

Landmarking

Prior studies suggest that the degree of difference in circumference magnitudes between analogous results from optical devices and traditional tape measurements is primarily an artifact of landmarking methods [14, 18]. This discrepancy is present in adult scans but can be exacerbated when scanning young children. For instance, the palpation of bony landmarks creates consistency in measurement locations among and between adult and juvenile populations. However, the undeveloped features in prepubescent individuals can make distinguishing superficial landmarks via optical technology more challenging. This is especially evident in the number of measurement results that were removed due to magnitudes measured from erroneous locations like the example shown in Figure 1.

Hardware-user interaction

Interactions between 3D optical hardware design and the user also yield predictable fluctuations in the quality of the resulting avatar and thus indirectly impact the accuracy of digitally derived estimations. Children, especially those who are easily excitable or lack impulse control, tend to have more difficulty keeping their head and arms stationary when the turntables of the Fit3D Proscanner and Styku S100 are in motion. Scan images generated under these conditions often have enlarged heads, like those shown in Figure 1, and missing or distorted body parts. Features such as the Size Stream SS20's stationary platform design can aid in the overall stability of young participants during scanning. The Size Stream SS20 and Fit3D Proscanner allow participants to stabilize their arm movement by grasping onto handlebars for the duration of the scan. However, our observations found that especially small participants, specifically our 5-year-old cohort, struggled to comfortably reach the handlebars of the respective devices. This may have led to measurement error related to distortion of the child's pose or position.

On a few occasions, despite correct positioning and cooperation of the participant, the Styku S100 and Fit3D Proscanner were unable to recognize or capture an image of the participant. This error was observed among the smallest participants.

Image processing

The 3DO mesh processing also varied between each system and potentially altered the automatically derived circumferences. Reconstructed avatars display differences in resolution, filling, and smoothing. Bourgeois *et al.* [18] suggest that these differences did not appear to give any clear advantage in measurement quality when scanning an adult population. However, for smaller bodies, the over smoothing of Styku S100 scans captured with a single camera can generate impossibly thin or altogether missing features, especially at the ankles and wrists (Figure 1).

Limitations

The design and execution of this work does have limitations that should be recognized and addressed in future studies. Subject body size proved to be a major constraint in acquiring digital somatic measurement information. As stated previously, the hardware design and programming of currently available 3D optical scanning devices are optimized for adult figures and have a difficulty calculating depth data for the smaller bodies of 5- to 8-year-old children. For this reason, we were unable to collect enough duplicate scans to report on the precision of each device. Additionally, due to the temporal and spatial distance between data collection centers, group training and anthropometric cross-calibrations proved infeasible for this measure. Strict adherence to detailed NHANES anthropometry protocols notwithstanding, analysis could not account for variance attributable to between-observer error.

CONCLUSION

As clinical approaches to eradicating obesity related diseases shift from post diagnosis treatment to preventative action, it becomes more imperative that easily acquired, safe, and repeatable methods should be established for assessing body size, shape, and composition in young children. 3DO devices, while optimized for scanning adults, show potential as an approach to measuring and tracking circumference measurements in individuals as young as 5 years of age. Based on the results from this study, hardware designs such as a stationary platform, handlebars, a smaller frame, multiple cameras, and quicker scanning time are useful device features for not only enhancing scanning experience in young participants but also increasing the likelihood of generating complete images and accurate results. Future studies are needed to establish algorithms geared towards small children to derive compositional estimations of body fat, lean mass, and bone from imaging technology.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGEMENTS

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Abbreviation:

3DO three-dimensional optical.

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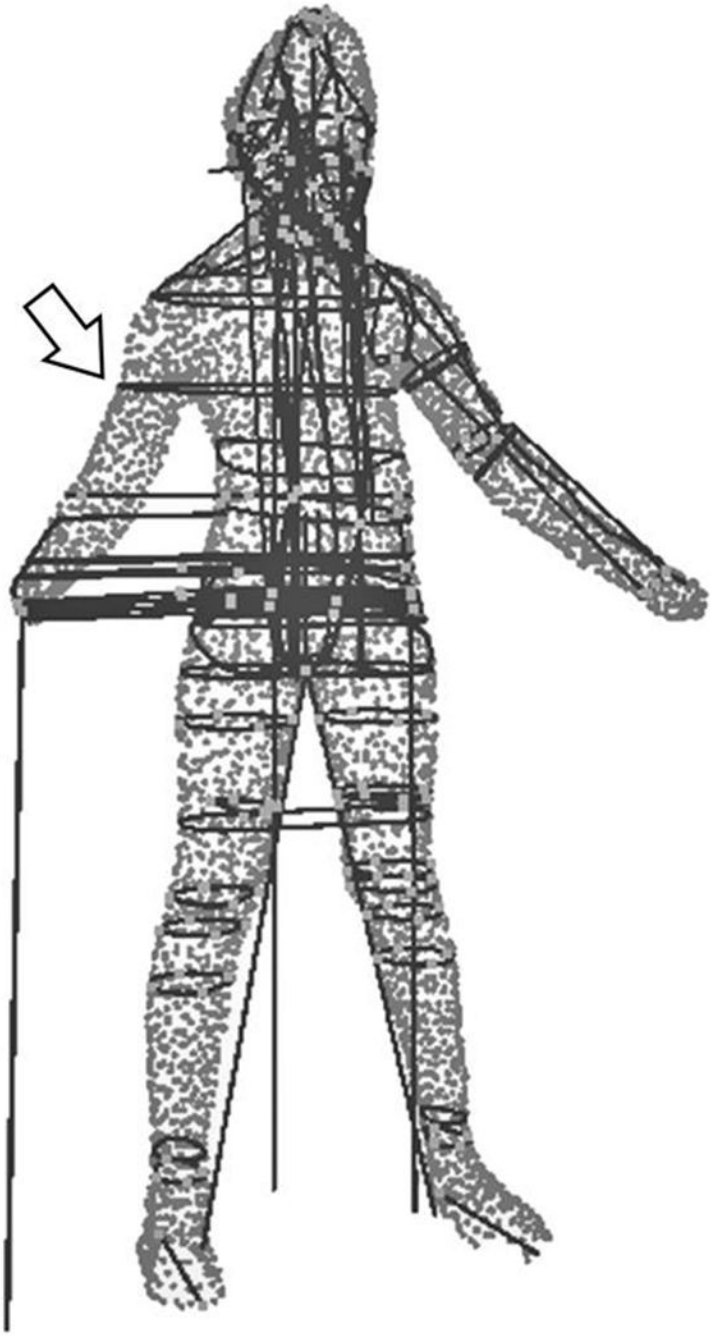

Figure 1.

Scan image errors present on a representative avatar produced by the SizeStream SS20 scanner. The image shows circumferences that do not align with the shape of the individual's body and thus cannot be directly compared with reference circumferences. One example is the right mid-upper arm circumference, shown at the arrow, which not only surrounds the mid-upper arm but the chest as well.

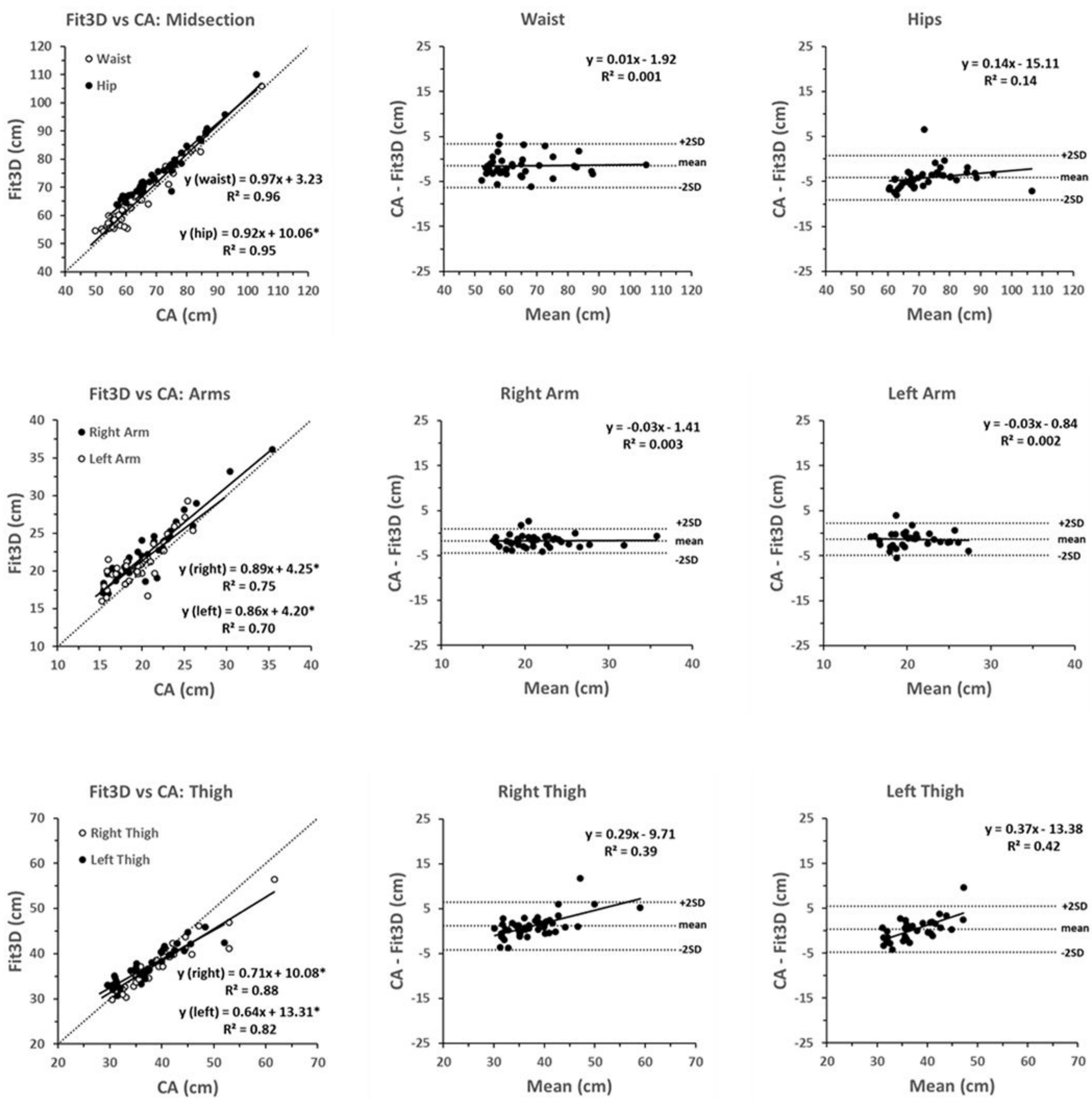

Figure 2.

Circumferences estimated by the Fit3D Proscanner versus circumference tape measurements and associated 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.

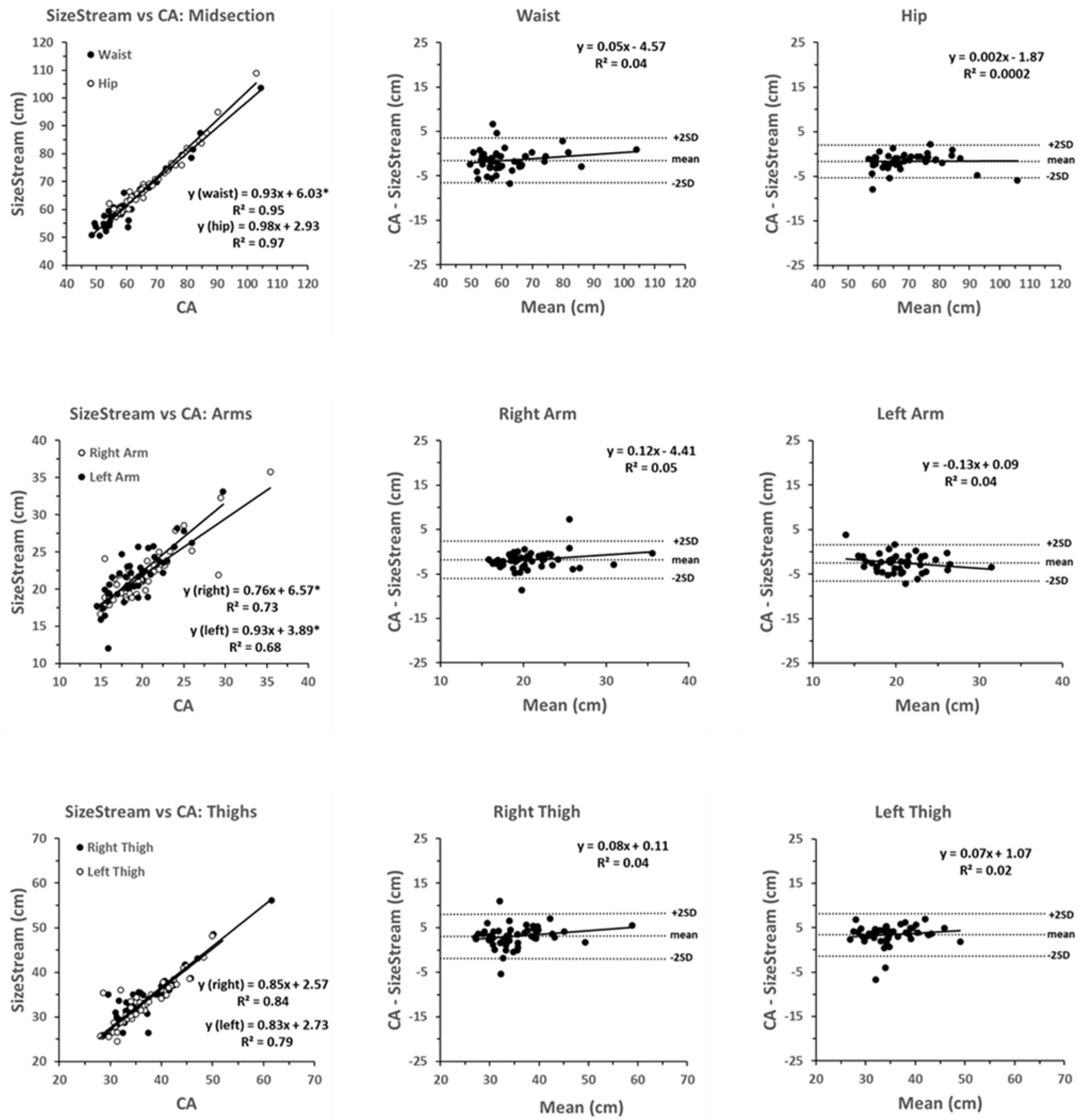

Figure 3.

Circumferences estimated by the Size Stream SS20 versus circumference tape measurements and associated 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.

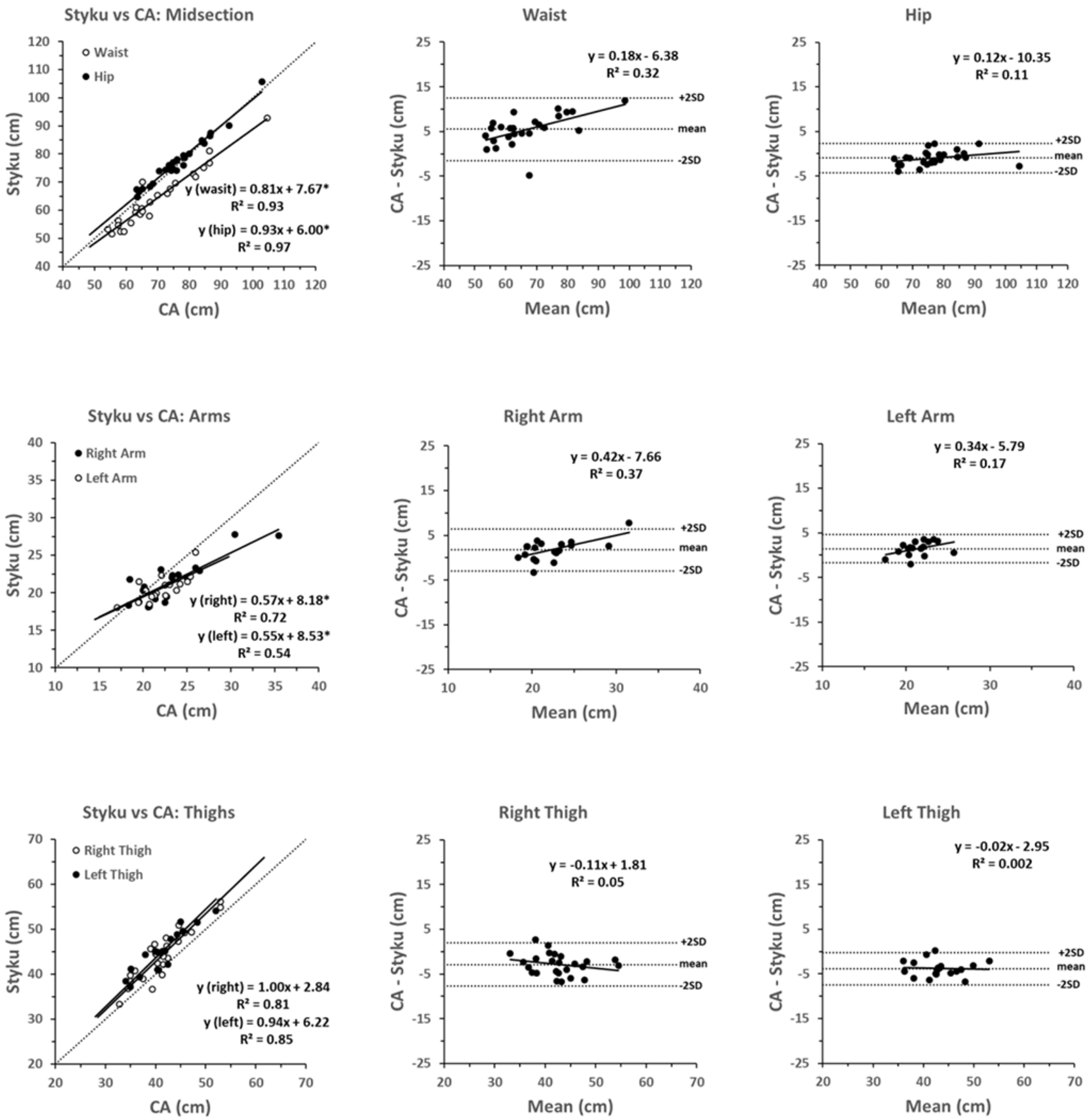

Figure 4.

Circumferences estimated by the Styku S100 versus circumference tape measurements and associated 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*
Total	29	35
African American	10	9
White	10	9
Hispanic	4	2
Asian	1	6
NHOPI	4	9
Age (yrs)		
Mean	6.9 ± 1.1	6.6 ± 1.2
Range	5-8	5-8
Height (cm)		
Mean	126.0	125.2
Range	112.8 - 142.6	106.4 - 146.2
Weight (kg)		
Mean	29.6 ± 10.8	28.7 ± 9.2
Range	19.2 - 66.5	17.4 - 55.0
BMI (kg/m^2)		
Mean	18.4 ± 5.6	17.9 ± 3.1
Range	13.9 - 39.5	13.1 - 25.7

Abbreviations: NHOPI, Native Hawaiian and Other Pacific Islanders; BMI, body mass index. Results are X ± SD

Table 2.

Processed scans by age

N	Fit3D	Size Stream	Styku
Total	64	53	64
Processed	43	52	26
Age	**%**	**%**	**%**
5	38.5	90.0	0.0
6	63.6	100	45.5
7	84.2	100	57.9
8	71.4	100	47.6
Total	67.2	98.1	40.6

Table 3.

Results summary of processed scans

	Mean (cm)	*Δ Mean (cm)*
WAIST		
Fit3D	65.5 ± 11.9	−1.5*
Styku	64.2 ± 10.3	5.5*
Size Stream	62.5 ± 10.2	−1.6*
HIP		
Fit3D	75.4 ± 9.9	−4.2*
Styku	77.5 ± 9.0	−1.0*
Size Stream	70.0 ± 10.4	−1.7*
RIGHT ARM		
Fit3D	22.3 ± 4.1	−1.8*
Styku	22.3 ± 4.2	1.7*
Size Stream	22.3 ± 4.3	−1.9*
LEFT ARM		
Fit3D	21.2 ± 3.2	−1.4*
Styku	20.6 ± 1.8	1.5*
Size Stream	21.8 ± 3.6	−2.5*
RIGHT THIGH		
Fit3D	37.2 ± 5.1	1.2*
Styku	44.0 ± 5.6	−2.9*
Size Stream	33.8 ± 5.7	3.0*
LEFT THIGH		
Fit3D	37.4 ± 3.9	0.3
Styku	45.1 ± 4.7	−3.8*
Size Stream	33.3 ± 4.8	3.4*

Abbreviation: Δ mean = tape measurement mean - device measurement mean. Results are X ± SD

*$P < 0.01$.