Original Research

Validation of a 3-Dimensional Laser Body Scanner for Assessment of Waist and Hip Circumference

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Key words: waist circumference, hip circumference, waist:hip ratio, 3-dimensional photonic scan, body image

Objectives: To evaluate the reliability and validity of a 3-dimensional laser body scanner for estimation of waist and hip circumferences and waist:hip ratio.

Methods: Seventy women were evaluated for waist and hip circumference and waist:hip ratio via laser scanner and tape measure. In a subset of 34 participants, 8 repeated measures of laser scanning were performed for reproducibility analysis. Validity of the instrument was assessed by regression and Bland-Altman comparison of measures of waist and hip circumferences and waist:hip ratio to tape measure.

Results: Reproducibility analysis showed little difference between within-subjects measurements of circumferences (intraclass correlation coefficient ≥0.992, $p < 0.01$). Evaluation of waist and hip circumferences measured by body scanning did not differ significantly from tape measure ($p > 0.05$). Bland-Altman analysis showed no bias between laser scanning and tape measure.

Conclusion: These findings indicate that the 3-dimensional laser body scanner is a reliable and valid technique for the estimation of waist and hip circumferences as compared with tape measure. This instrument is promising as a quick and simple method of body circumference analysis.

INTRODUCTION

The high incidence of overweight and obesity in the United States is a public health concern, as these conditions are associated with type 2 diabetes, hypertension, and dyslipidemia [1]. Body mass index (BMI) is the most frequently used indicator of overweight status, although waist and hip circumferences are indicators of abdominal fat and may be more strongly related to obesity-related diseases [2,3]. For example, a meta-regression analysis recently found that a 1-cm increase in waist circumference increased the relative risk of cardiovascular disease by 2% [4]. In addition, larger waist girth was associated with increased likelihood of diabetes mellitus in a worldwide, cross-sectional study [5]. Furthermore, waist circumference >102 cm in men or >88 cm in women was associated with a >20% increased risk of all-cause mortality in healthy weight subjects (BMI 18.5 to 24.99 kg/m^2) [6].

Greater body circumference at the hip also has been linked to a reduced likelihood of myocardial infarction in a study by Yusuf et al. [7]. After controlling for BMI, larger hip circumference had a protective effect against diabetes, independent of waist girth. The hazards ratio for the highest quintile of hip circumference was 0.41 as compared with the lowest quintile [8]. In addition, the Atherosclerosis Risk in Community (ARIC) study found that waist:hip ratio was related to elevated risk of cardiac incidents [8].

Although waist and hip circumferences are well-established methods to evaluate disease risks, current manual methods have limitations [9]. The required closeness to the body makes it uncomfortable for both the rater and subject, and this method may exhibit low interrater reliability [10]. A newer technique is to measure circumferences by computerized body imaging. To date, 2 body scanners have been evaluated for assessment of waist and hip circumference. Both have reported significant

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differences from tape measure [11–14], so further investigation is warranted. The VITUS XXL laser body scanner produces highly repeatable measures of thigh circumference [15]; other body girths and comparison with tape measure in human subjects have not been reported. Several structured light body scanners focusing on clothing sizing, including SYMCAD [16], BodySCAN3D [17], bodySCAN [18], and the BodyFit3D [19] represent promising devices in this field, although validity has not been well established.

The purpose of this article is to determine the validity of the Xu scanning device for the assessment of body circumferences. This portable system is composed of 2 units, each consisting of a laser depth-sensing device that rotates via motor to scan the body in less than 3 seconds. This 3-dimensional (3D) body scanner has the potential for clinical settings, as it is fast and portable.

MATERIALS AND METHODS

Participants were 70 Caucasian and Hispanic women who were recruited by flyers posted on campus, doctors' offices, and health clinics. Other criteria for inclusion included age 18–65 years, BMI 18.5–39.9 kg/m^2, and absence of current illness, pregnancy, or lactation. Informed consent was obtained, and the study was approved by The University of Texas at Austin Institutional Review Board.

Anthropometric measurements and imaging were performed on 1 occasion. All tests were conducted in the same order for all participants. No effect of order was anticipated, as participants completed all tests within 15 minutes and did not eat or drink between tests. Participants fasted for a minimum of 3 hours before participation began and abstained from alcohol, caffeine, and exercise for at least 8 hours prior to testing.

Anthropometric Measurements

Height via stadiometer (Perspective Enterprises, Portage, MI) was measured to the nearest 0.1 cm. Body mass was determined by a calibrated electronic scale (model TBF-300A Body Composition Analyzer/Scale, Tanita Corporation, Arlington Heights, IL) to the nearest 0.1 kg. Circumferences were measured via tape measure to the nearest 0.1 cm at the navel and the widest point between the crotch and umbilicus for waist and hip girths, respectively. The umbilicus was chosen as the waist measurement site due to its ease of location and ability to predict metabolic syndrome [20]. BMI was calculated as weight in kilograms divided by height in meters squared.

Three-Dimensional Laser Body Scanning

In the laser imaging device, the rotary body scanner included two 123-cm-tall components positioned 2 m apart, each containing a laser line projector, a receiver, and a step motor and weighing 2.5 kg. Rotation of the step motor turned the Class II laser units simultaneously, allowing the laser to scan 4000 steps over a 2-m height, as described by Xu and Huang [21]. A diagram of the scanner is shown in Fig. 1a. When the laser swept the body, an optical triangulation permitted computer identification of 256 3D pixels per scan line, for a maximum of 102,400 points in the scan. These 3D coordinates of the surface were detected and registered in less than 3 seconds. The scanner was calibrated weekly, and accuracy of the calibration sample exhibited $<1\%$ error, or the calibration was repeated. As shown by Xu and Huang [21], coefficients of variation for 5 repeated scans of a test box with dimensions 1500 mm $\times$ 405 mm $\times$ 200 mm were 0.63% on average. Scan time was optimized to give adequate detail for body surface modeling while minimizing participant burden and reducing artifacts of insensible body movement. In the event of body motion, participants were rescanned. Multiple scans for each participant were completed sequentially, then surface simplification and fitting techniques [22] were used to reconstruct a compact, smooth surface model of the participant in 30 seconds per scan, followed by a 20-second automatic landmark location and individual measurement adjustment for each scan [23].

Participants underwent 2 scans wearing tight-fitting, white undergarments; eyes protected by a blindfold; and legs and arms slightly abducted to minimize occlusion [21]. Participants were instructed to breathe normally during the scan to minimize changes in size of breath hold. Front and side views of the 360° model produced by the laser body scanner are illustrated in Fig. 1b. Lines indicate circumferences, including measurements at the umbilicus and hip [24]. Resolution for the device is not adjustable and is set sufficiently high for circumference calculations but low enough to prevent identification of facial features.

A total of 8 scans were performed on a subset of 30 participants and compared to test reproducibility. Body girths were located at the widest point of the chest and smallest point of the abdomen, and the waist was located at the umbilicus. Additional circumferences were positioned as follows: hip, at the widest point before crotch; knee, bottom of knee; calf, widest point on lower leg; ankle, smallest point before foot; and thigh circumference was located just above the knee. In the body measurement procedure, a presorted circle was used to find the intersection point sets that form the circumference contours and the guidance for landmark acquisition.

Statistical Analysis

Reproducibility of the body scanner was assessed by intraclass correlation coefficients (ICCs) and coefficients of variation (CVs) for circumference over 8 repeated scans. Mean waist and hip circumferences by measuring tape were

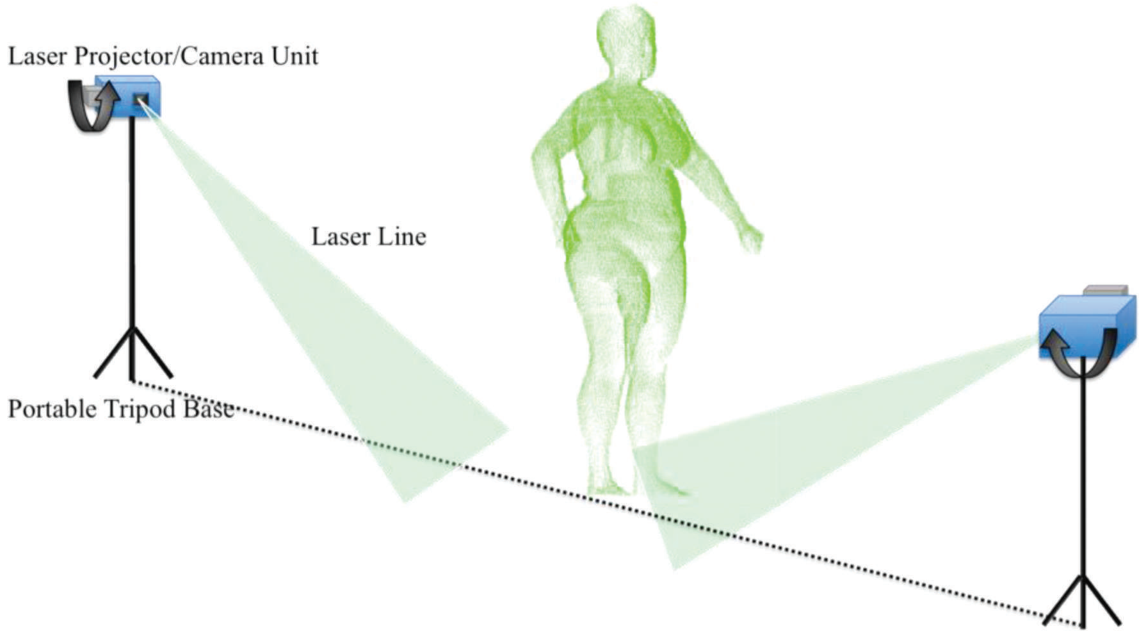

Fig. 1. (a) Diagram of the laser scanner with raw data points displayed. Rotation of the laser device indicated by arrows. (b) Three-dimensional body model from laser scanner with locations of circumference measurements indicated by blue lines.

compared with laser scanning using paired *t* tests, and Pearson's correlation coefficients showed the strength of the relationship between methods. Regression analysis was used to evaluate the ability of laser scanning to predict tape measurement of waist and hip circumference or waist:hip ratio. The regression line was compared with the line of identity (b = 1.0) using the uncorrected slope and standard error of the slope to determine the *t* statistic. Bland-Altman limits of agreement analysis [25] was used to graph the mean circumference of laser scanning and tape measure versus the difference between the 2 methods for each participant, with lines indicating mean differences and 95% confidence intervals (CIs) for the bias between measurement methods. Standard error of the estimate (SEE) was used to show accuracy of laser scanning to predict tape measure circumference. Univariate regression analysis further evaluated the effect of age, BMI, or criterion measurement on bias between the laser scanner and tape measure. Values are given as mean ± standard error (SEM), and the α level adopted for statistical significance was $p < 0.05$. All analyses were performed using SPSS Statistics version 17.0 (SPSS Inc., Chicago, IL).

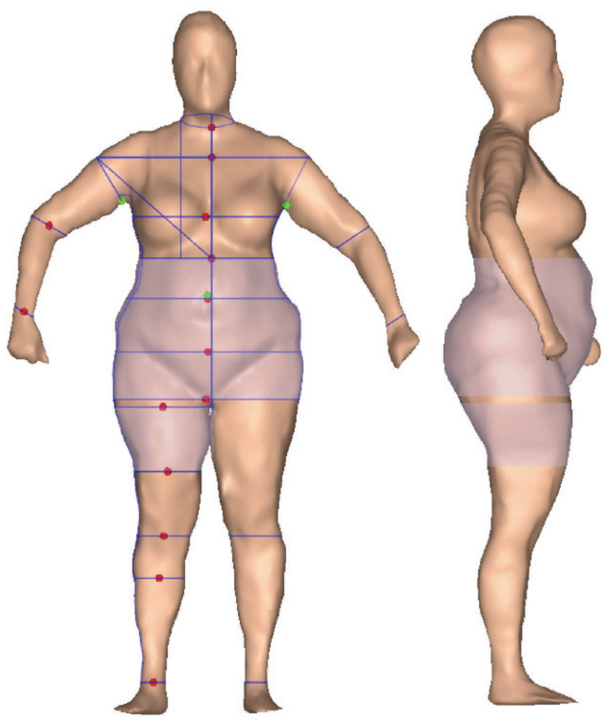

Fig. 1. (b) Continued.

RESULTS

Characteristics of the participants are shown in Table 1. All were adults free of known diseases, and 47% were overweight or obese (BMI ≥25 kg/m^2).

Table 2 presents the reproducibility of laser scanning circumference and length measurements, as assessed by 8 repeated scans of a subset of 30 participants. All ICCs were ≥0.99, with chest circumference being the most variable. The CVs exhibited little difference between within-subject measurements, showing high concordance between repeated measures (CV 0.53%–1.68%).

Table 1. Profile of Women Participants (n = 70)

Characteristic	Mean	SEM[1]	Median	Minimum	Maximum
Age (y)	29.64	1.41	25.00	18.00	64.00
Weight (kg)	69.19	1.63	65.97	49.17	101.51
Height (cm)	164.46	0.84	163.83	149.86	181.00
Body mass index (kg/m^2)	25.57	0.57	24.39	18.87	36.79

[1] Standard error of the mean.

Determination of body size at the umbilicus and hip via circumference by imaging was compared with manually derived tape measurement in the full sample of 70 participants. Mean circumference measurements were similar between the 2 methods for waist and hip circumferences and waist:hip ratio ($\bar{x}$: waist, 87.87 ± 1.83 and 87.73 ± 1.83 cm; hip, 104.15 ± 1.23 cm and 104.39 ± 1.25 cm; and waist:hip ratio, 0.84 ± 0.01 and 0.84 ± 0.01 for laser scanner and tape measure, respectively). Paired-samples *t* tests showed no significant differences between methods for waist, hip, or waist:hip ratio ($\bar{x}$ differences ± SEM: 0.13 ± 0.13, −0.24 ± 0.19, and 0.00 ± 0.00, respectively, $p > 0.05$). Measurements were highly correlated by Pearson's *r* ($r = 0.998$, 0.989, and 0.984 for waist, hip, and waist:hip ratio respectively, $p < 0.01$), indicating strong relationships between methods.

Table 2. Reproducibility of Laser Body Scanning Circumference Measurements over 8 Repeated Scans according to Intraclass Correlation Coefficient and Coefficient of Variation (n = 30)

Circumference (cm)	Mean ± SEM[1]	Intraclass Correlation Coefficient	Coefficient of Variation (%)
Chest	104.24 ± 2.61	0.992	1.34
Abdomen	82.87 ± 2.49	1.000	0.83
Waist	96.93 ± 3.25	1.000	0.83
Hip	107.74 ± 2.63	1.000	0.53
Knee	35.46 ± 0.90	0.998	1.59
Calf	36.41 ± 0.77	0.999	1.03
Ankle	21.60 ± 0.37	0.996	1.68
Crotch	86.52 ± 1.57	0.996	1.57
Thigh	43.18 ± 1.39	0.999	1.10

[1] Standard error of the mean.

The relationships between estimates of circumference were assessed further by regression and Bland-Altman analyses.

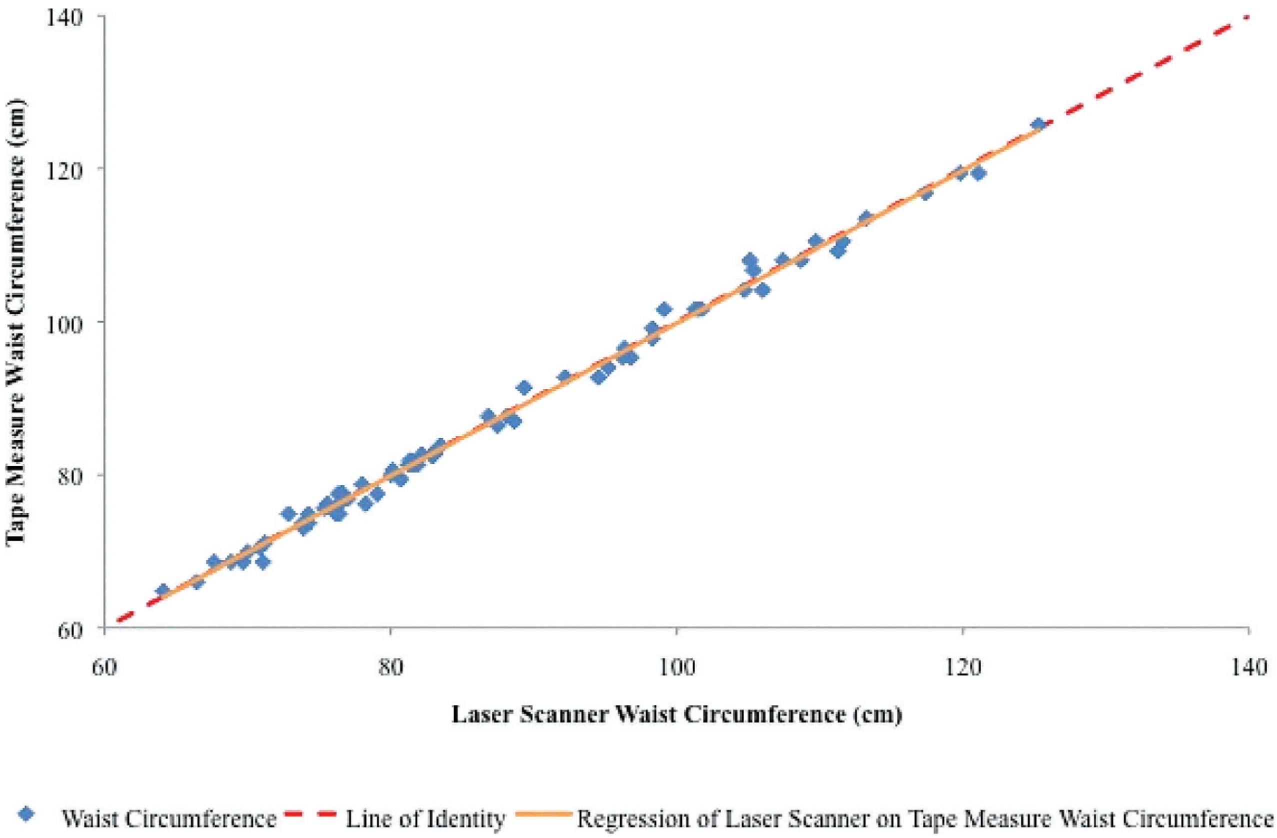

Fig. 2. (a) Regression of measurement of waist circumference by laser scanner versus tape measure. Regression equation y = 1.0x − 0.07, R^2 = 0.995, SEE = 1.08 cm, n = 70. (b) Regression of measurement of hip circumference by laser scanner versus tape measure. Regression equation y = 1.0x − 0.22, R^2 = 0.978, SEE = 1.58 cm, n = 70. (c) Regression of measurement of waist:hip ratio by laser scanner versus tape measure. Regression equation y = 0.95x + 0.04, R^2 = 0.968, SEE = 0.02, n = 70.

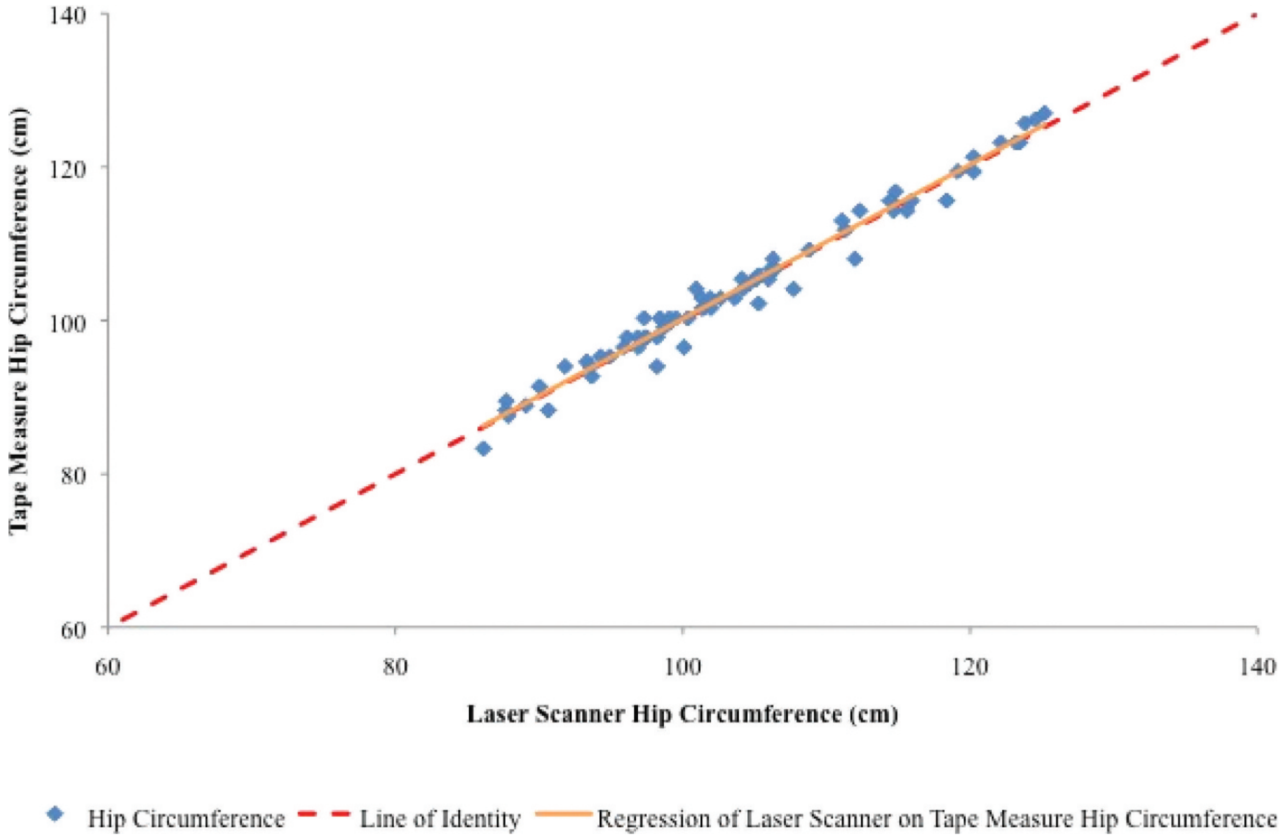

Fig. 2. (b) Continued.

Regression showed that a large portion of the variance in tape measurement was predicted by the laser scanner ($R^2 > 0.97$), with a small SEE for waist, hip, and waist:hip ratio (1.08 cm, 1.58 cm, and 0.02, respectively). The constants for waist and hip circumference or waist:hip ratio did not differ significantly from 0, indicating no general underestimation or overestimation compared with tape measure. A hypothesis test was conducted comparing the slope of the regression equations to the slope of the line of identity, and the relationship between laser scanning and tape measure was not significantly different from 1.0 for waist (b = 0.998; 95% CI, 0.981 to 1.015; Fig. 2a) or hip (b = 1.004; 95% CI, 0.968 to 1.041; Fig. 2b) circumference measurements. However, Fig. 2c illustrates that the regression of the waist:hip ratio was significantly different from the slope of the line of identity (b = 0.955; 95% CI, 0.912 to 0.997).

Bland-Altman analysis is a graphical representation of the mean measurement plotted versus differences between methods (laser scanner – tape measure). This statistical test is designed to show systematic bias. Mean differences greater than zero represent an overestimation, whereas values less than zero indicate underestimation by laser scanning. The mean differences between laser scanner and tape measure were waist circumference, 0.13 cm (95% CI, −2.02 to 2.29 cm; Fig. 3a); hip circumference, −0.24 cm (95% CI, −3.39 to 2.90 cm; Fig. 3b); and waist:hip ratio, 0.00 (95% CI, −0.03 to 0.00; Fig. 3c). No systematic bias was found in waist or hip circumferences or waist:hip ratio assessment, as no significant correlations were observed between mean measurements and the differences between the 2 methods. In addition, regression of differences between the 2 methods on the mean measurement showed no relationships. Slopes and intercepts were not significantly different from 0; this further indicates a lack of bias.

To more specifically evaluate the potential effects of age, BMI, and body size on measurement bias, univariate regression analysis was used (Table 3). Because of issues of collinearity, each predictor was evaluated in an individual regression model. None of these factors significantly predicted the differences in waist, hip, or waist:hip ratio measurements, further indicating a lack of bias. For all analyses, disparities between measurement methods were not significantly correlated with age or BMI by Pearson's r ($p > 0.05$).

DISCUSSION

The 3D laser scanning device produced a 360° computer model of the body, which was used to measure body

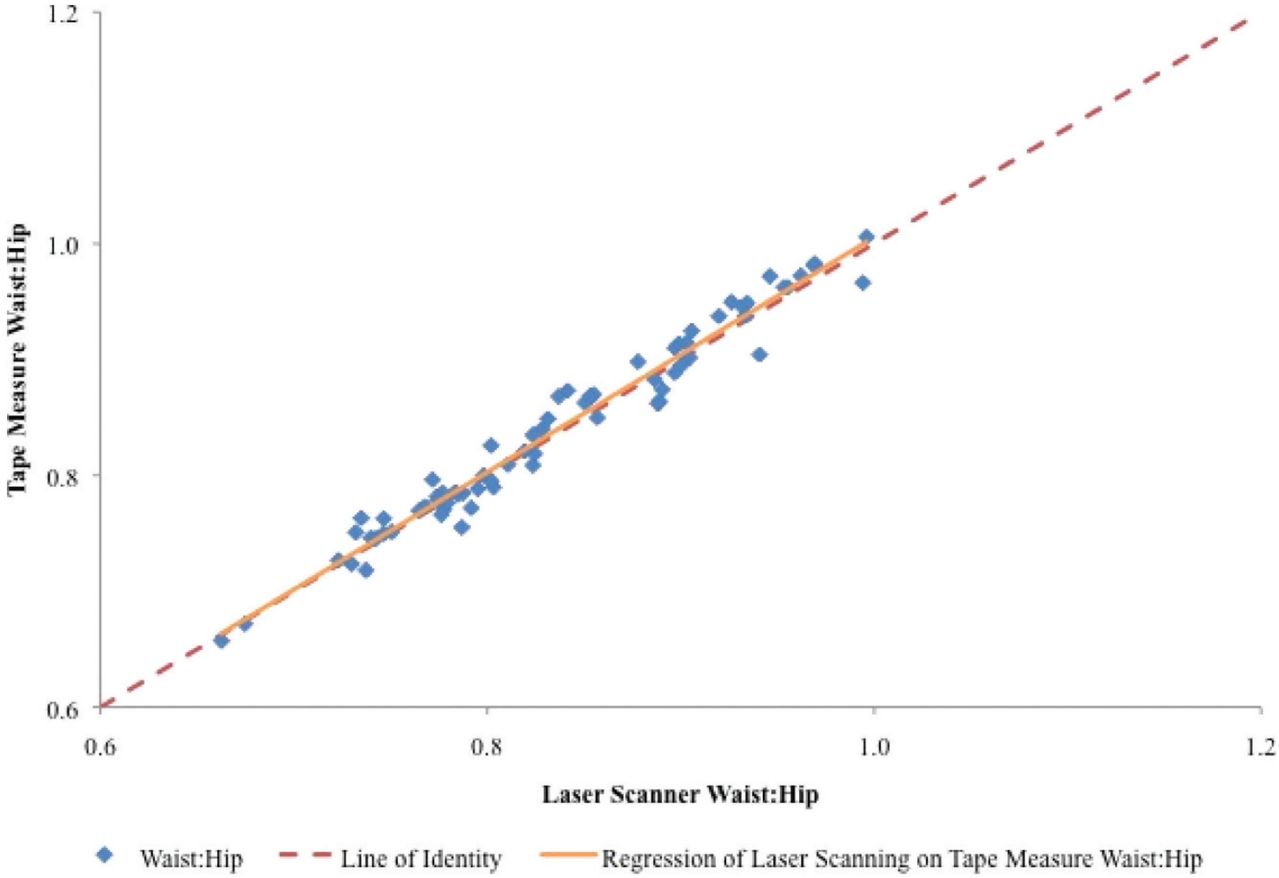

Fig. 2. (c) Continued.

circumferences. This instrument produced highly reproducible measures of waist and hip circumferences and waist:hip ratio measurements that were equivalent to tape measure. According to regression and Bland-Altman analyses, no systematic bias was found for waist or hip circumferences or waist:hip ratio measurements as compared with tape measure.

The ability of this device to accurately measure circumferences, coupled with its small size and portability, makes it ideal for determination of obesity-related disease risks in clinical and field settings. For example, this instrument would facilitate accurate measurements of waist and hip circumferences for the identification of elevated risk of cardiovascular disease and/or diabetes. In 2007, a meta-analysis of prospective research confirmed that waist circumference was related to relative risk of cardiovascular disease. Specifically, a 5.04-cm increase in waist circumference corresponded with a 10% augmentation in risk for coronary heart disease or stroke [4]. Elevated waist circumference also was related to increased risk for diabetes mellitus in a cross-sectional, international study [5]. The age- and region-adjusted odds ratios for incidence of diabetes mellitus were 2.65 in men for waist circumferences >102 versus <96 cm and 3.94 in women for waist circumferences >88 versus <80 cm.

In contrast, higher hip circumferences may have a protective effect against obesity-related conditions. The ARIC investigation showed that those in the first quintile of hip circumference had greater levels of low-density lipoproteins and triglycerides, elevated systolic blood pressure, and reduced high-density lipoproteins as compared with the largest quintile, after adjustment for BMI ($p < 0.05$) [8]. A 6-year longitudinal project by Snijder et al. [26] evaluated the relationship between diabetes and hip circumference in older Dutch men and women. A 1–standard deviation increase in hip girth reduced the odds ratio of developing diabetes mellitus to 0.55 in men and 0.63 in women, following adjustment for age, BMI, and waist circumference.

The Xu laser scanner also has the ability to accurately measure wasit:hip ratio. The precision of the instrument is particularly useful in this case, as small changes in waist:hip ratio have the potential to predict risk of cardiovascular disease. For example, a recent meta-analysis by de Koning et al. [4] found that a 0.02-unit increase in waist:hip ratio raised the risk of coronary heart disease by 10%. In addition, the ARIC study found that the same 0.02-unit increase in waist:hip ratio more than doubled the risk of being diagnosed with diabetes mellitus over 12 years [8]. Collectively, these reports

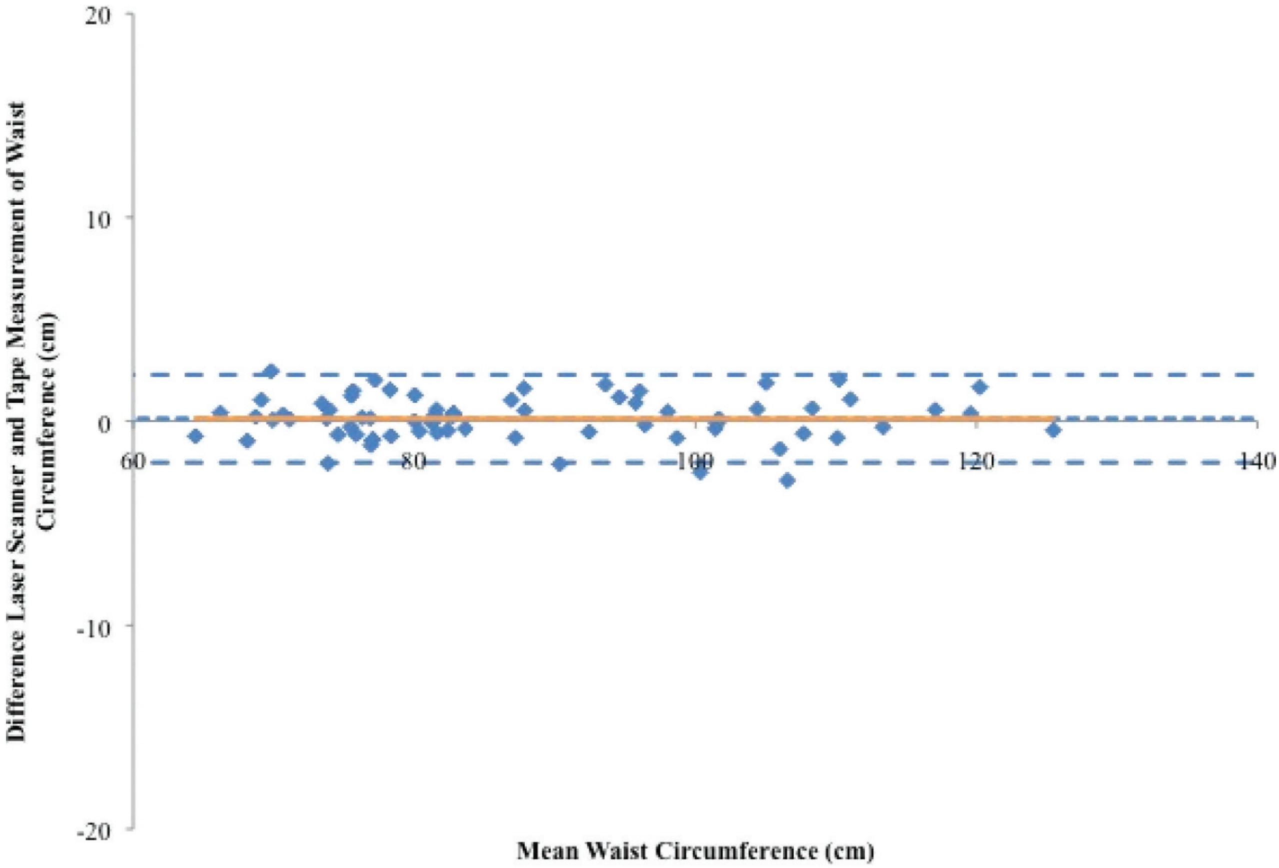

Fig. 3. (a) Bland-Altman plot of the mean waist circumference by laser scanner and tape measure, plotted against the difference between measurements. Dashed lines represent mean difference and 95% confidence intervals, while the solid line represents the regression of the differences on the means. Regression equation $y = -0.00x + 0.15$, $R^2 = 0.000$, SEE = 1.08 cm, n = 70. (b) Bland-Altman plot of the mean hip circumference by laser scanner and tape measure, plotted against the difference between measurements. Dashed lines represent mean difference and 95% confidence intervals, while the solid line represents the regression of the differences on the means. Regression equation $y = -0.11x + 1.41$, $R^2 = 0.011$, SEE = 1.57 cm, n = 70. (c) Bland-Altman plot of the mean waist:hip ratio by laser scanner and tape measure, plotted against the difference between measurements. Dashed lines represent mean difference and 95% confidence intervals, while the solid line represents the regression of the differences on the means. Regression equation $y = -0.11x + 1.41$, $R^2 = 0.03$, SEE = 0.01, n = 70.

Table 3. Univariate Regression Analyses for Age, Body Mass Index, Circumference, or Waist:Hip Ratio via Tape Measure to Predict Differences between Laser Scanning and Tape Measure (n = 70)

	Circumference Bias[1]					
	Waist		Hip		Waist:Hip	
Predictor	b[2]	95% CI[3]	b[1]	95% CI	b[1]	95% CI
Age	0.05	−0.02 to 0.03	−0.11	−0.05 to 0.02	0.13	0.00 to 0.00
Body mass index	0.06	−0.04 to 0.07	−0.03	−0.09 to 0.07	0.05	0.00 to 0.00
Tape measure circumference						
Waist	−0.04	−0.02 to 0.01	−0.15	−0.04 to 0.01	0.09	0.00 to 0.00
Hip	−0.08	−0.67 to 0.51	−0.18	−0.06 to 0.01	0.08	0.00 to 0.00
Waist:Hip	0.02	−3.00 to 3.46	−0.08	−6.22 to 3.20	0.07	−0.61 to 0.55

[1] All results were non-significant.
[2] Standardized beta.
[3] Confidence Interval.

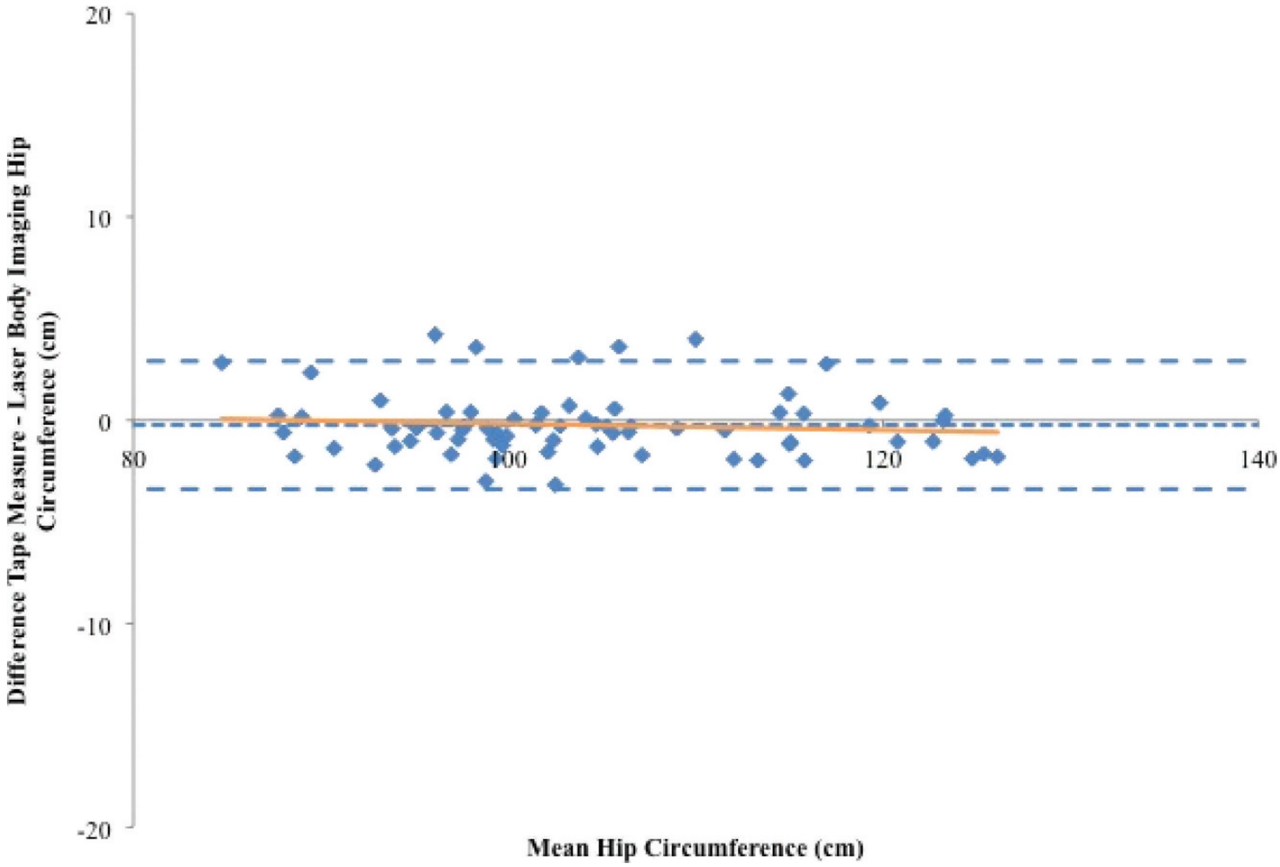

Fig. 3. (b) Continued.

suggest the importance of reliable and valid measurements of waist and hip circumferences.

Two other photonic scanning devices have been developed to date, but these vary in their agreement with tape measure. The Hamamatsu Bodyline Scanner used 4 cameras to obtain a maximum of 2,048,000 data points over the scan area in 10 seconds, providing a model of the body [11]. When waist and hip circumferences were evaluated against manual estimation by Wang et al. [11] in 93 subjects, a small overestimation of <2 cm was reported ($p < 0.01$). This error is slightly larger than the <0.3 cm difference found in the present study. More recently, the NX-16 3D body scanning system used 6 cameras and an 8-second scan that measures up to 1 million data points, providing valuable information about associations between body size and shape [12–14,27]. The mean differences between scanning and tape measure for waist and hip circumferences were 1.3 and 5.7 cm, respectively [14]. This value is somewhat greater than the 0.13-cm difference in waist and 0.24-cm disparity in hip circumference observed in our study. It should be noted that the Xu body scanner uses only 102,400 data points; thus, it exhibits high precision despite fewer number of data points gathered. Presumably, this increased precision was due to the surface-modeling algorithms that predicted the 3D body model [23].

The Hamamatsu photonic scanner also was evaluated for consistency across repeated scans, with high reproducibility of multiple measurements [11]. Reliability of the scanner was high, with ICC >0.99 and CV <0.9% for circumference measurements at the chest, waist, hip, thigh, and knee. These results were similar to the Xu body scanner, which had ICCs >0.992 and CV <1.7% for circumferences including chest, abdomen, waist, hip, knee, calf, ankle, crotch, and thigh.

In this study, the Xu laser body scanner did not exhibit any systematic bias compared with tape measure. Comparisons of Bland-Altman results to other body scanners cannot be conducted at this time, as we were not able to find such data. However, Bland-Altman analyses have been used to validate waist and hip circumference measurements versus self-report. In 2005, a Danish study [28] showed a significant underestimation of self-determined waist circumference as compared with technician measurement (−1.6 cm and −3.0 cm for men and women, respectively). Their Bland-Altman analysis showed systematic bias, and univariate regression analysis indicated that this difference was positively associated with BMI. Larger persons were more likely to underreport waist circumferences than those of lesser body size [28]. On the other hand, a study of overweight men and women found that waist circumference was

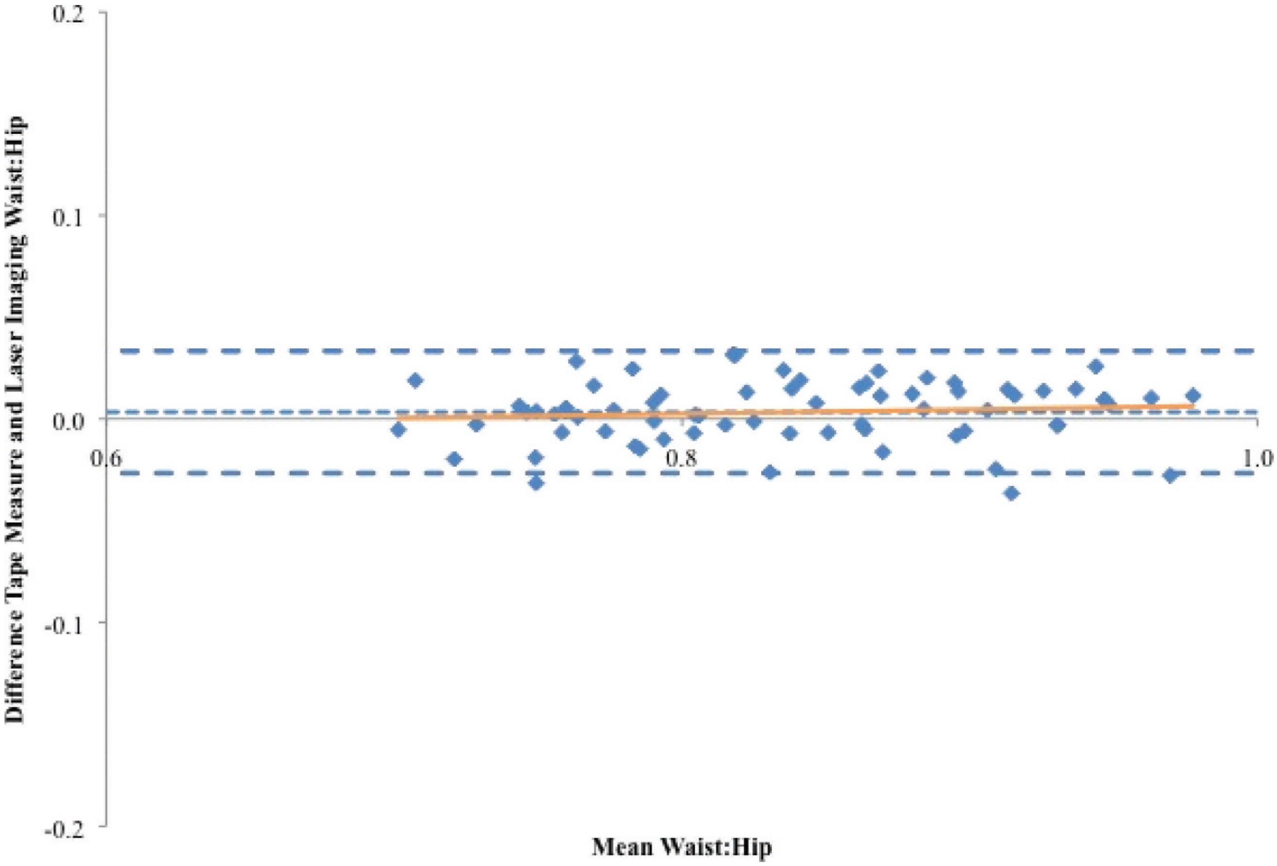

Fig. 3. (c) Continued.

overestimated by participant-reported measurements. The high self-report was related to increased technician-measured values: participants were more likely to overestimate as actual circumference increased [29]. These conflicting reports on the underestimation or overestimation associated with self-report make it difficult to anticipate or correct for error and indicate a need for further work in this area. In the body scanner of the present research, Bland-Altman plots showed no significant relationships between bias and change in body size for waist or hip circumference or waist:hip ratio.

A limitation of the current study was that imaging was examined only in Caucasian and Hispanic women. Also, participants were not asked to hold their breath during laser scanning, which may have affected reproducibility of circumference measurements in the torso. Finally, future studies are needed to validate use of this body scanner in a broader range of BMI, men, and other age groups and ethnicities.

CONCLUSION

In summary, the Xu 3D laser body scanner appears to be a valid technique to analyze body circumferences as compared with tape measure. Thus, it is suitable for both research and clinical applications due to its small size and ease of use.

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