Reliability of Three-dimensional Photonic Scanner Anthropometry Performed by Skilled and Naïve Operators

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Abstract

This work explored the relative and absolute reliability of three-dimensional (3D) anthropometry performed by skilled and naïve operators using a fast, pose tolerant whole-body 3D scanner device. Upon skin landmarking by an experienced operator (skilled anthropometrist, SA), twelve subjects (six males and six females) underwent a thorough 3D anthropometric evaluation by the SA and two naïve operators (NA). Using the same landmarks, the SA also performed traditional anthropometry measurements. All measurements were taken twice. Relative reliability was tested with the Pearson's correlation coefficient r and the intraclass correlation coefficient (ICC); absolute reliability was tested calculating the percentage coefficient of variation (%CV), the standard error of measurement (SEM), the percentage technical error of measurement (%TEM), and paired Student's t test. Results showed that intra-operator relative and absolute reliability was excellent for all and most 3D measurement items, respectively, independently of the operator's skill. Inter-operator (SA vs. individual NA) relative reliability was excellent as well; inter-operator absolute reliability was not acceptable for about only 30% of measurement items. Results of this work show that 3D anthropometry has strong potential in anthropometry due to high intrinsic reliability and less need for operator training vs. traditional anthropometry.

Keywords: Body Dimensions, Measurement Error, Agreement, Intra-operator, Inter-operator.

1. INTRODUCTION

Anthropometric measurements are currently used in the fields of ergonomics and clothing in order to improve the human-product interaction [8,10]; moreover, anthropometric data are useful for nutritional evaluation, and population size and shape surveys [16]. Anthropometric data are usually collected manually by using callipers and measuring tapes (traditional anthropometry), giving information on the static dimensions of the body in a standard position. These measurements are non-invasive, reasonably low-cost and straightforward, but the amount of yielded information is limited to actual measurements thereby making simultaneous acquisition of the multiple variable that determine body shape cumbersome. Moreover, careful training of the observer is required, the results vary in accordance with the observers skill level and measurement protocol, and procedures may be time-consuming; as a result, traditional anthropometry may be impractical in several setting.

Several 3D scanners with a potential for anthropometry have been marketed over the last several years; these devices are usually based on laser or Moiré-fringing-based technologies. In the former a laser stripe is projected onto the body surface and several cameras acquire images: in this way 3D points representing the body shape can be recovered by triangulation. Examples of this kind are the scanners developed by Vitronic (Vitronic Dr. Ing. SteinBildverarbeitungssysteme GmbH, Wiesbaden, Germany) or Human Solutions (Human Solutions GmbH, Kaiserslautern, Germany). Moiré-fringing-based technologies use one or more projectors create light patterns on the body surface and 3D points are estimated by observing the pattern deformations on the body surface with a set of cameras. Examples of this kind are the scanners developed by Textile and Clothing Technology Corporation ([TC]², 5651 Dillard Dr.Cary, NC 27518 USA), Telmat (Telmat Industrie, Soulth-Haut-Rhine, France), InSpeck (InSpeck Inc, Montreal, Canada), and the product used in this work namely, the bodySCAN (Breuckmann GmbH, Meersburg, Germany).

Over the last twenty years a number of 3D anthropometric studies have been performed using fast and contact-free measurements by using 3D whole body scanners. From 1992 to 1994, a nation-wide anthropometric survey was carried out by the Research Institute of Human Engineering for Quality of Life in Japan [21]. From 1998 to 2002 the Civilian American and European Surface Anthropometry Resource (CAESAR) survey was undertaken in the US, the Netherlands and Italy [18]. More recently, 3D body scanners were employed in the Campagne Nationale de Mensuration [2], Size UK [22] and Size Germany [20]. Moreover, 3D scanners are increasingly used in medical research for e.g., health risk assessment [9,25]. The main advantages of 3D scanning in anthropometry are: soft tissues are not compressed during data acquisition, raw data acquisition is rapid (seconds), unlimited repeatability of measurements on the same subjects over time. Limitations of 3D anthropometry are the variable quality of the captured data depending upon the scanning system used and the sensitivity to subject's motion, body position and posing.

Reducing measurement error to a minimum is critically relevant to both traditional and 3D anthropometry. An indication of "relative reliability" (i.e., the degree to which individuals maintain their position in a sample over repeated measurements) is provided by methods based on correlation coefficients and regression; "absolute reliability" assessment (i.e., the degree to which measurements vary because of random errors) includes e.g., the standard error of measurement (SEM) and the coefficient of variation (CV), which are especially suited to compare reliability between different measurement tools [1]. However, data on the reliability of 3D measurements taken by operators with different skill in anthropometry are scarce.

In this work we used a fast 3D scanner tolerant to pose variation, the BodySCAN, to compare the relative and absolute reliability of 3D anthropometric measurements taken by anthropometrists of quite different skill levels.

2. METHODS

2.1 Participants

Six men and six women, students at the University of Verona, were enrolled in this study after signing an informed consent form; the study protocol was in accordance to the Helsinki declaration and approved by the proper local Institutional Review Board. The main physical characteristics of the study group were as follows: mean age 22.7±2.2 years (range: 20.0-27.0); mean stature 168.2±7.4 cm (range: 159.0-184.2); mean body mass 61.5±6.2 kg (range: 53-70).

During anthropometry, subjects wore close-fitting underwear. Stature was measured with a Harpenden stadiometer (Holtain Ltd., Crymych, Pembs. UK) with 1mm accuracy; body mass was taken at the nearest 0.1 kg with an electronic scale (Tanita electronic scale BWB-800 MA, Wunder SA.BI. Srl).

2.2 3D Scanning

The BodySCAN typical acquisition consists of about 400.000 points with a precision from 0.2 mm to 1.4 mm. The scanning volume is: 2000 mm height x 1200 mm width x 800 mm depth. High-speed cameras (1392x1040 pixels resolution) and a proprietary algorithm are exploited to detect the actual position of visible light points projected onto the surface of the body through diffraction fringes and reflected to the cameras. Measurement accuracy is affected by factors such as environment, hardware, software, operator, subject, and procedure [3,4,14]. Accordingly, all subjects were scanned in one session by the same operator after scanner calibration; subjects were standing in the center of the scanner over a non-reflective support placed on the floor. They were instructed to stand motionless in the anatomical position and scanned at the end of quite expiration. The acquisition time was 4.5 seconds. The scanner output consists of a triangular mesh obtained by the registration and merging of the points acquired by the different cameras. Meshes are than pre-processed for remove defects like holes, non-manifold edges, bad shaped triangles, and outliers. Meshes nodes include also gray scale information. This allows acquiring added texture (e.g., skin markers) on meshes. Figure 1 shows the acquisition setup, a shot during the acquisition procedure, and an example of mesh processed for 3D anthropometry.

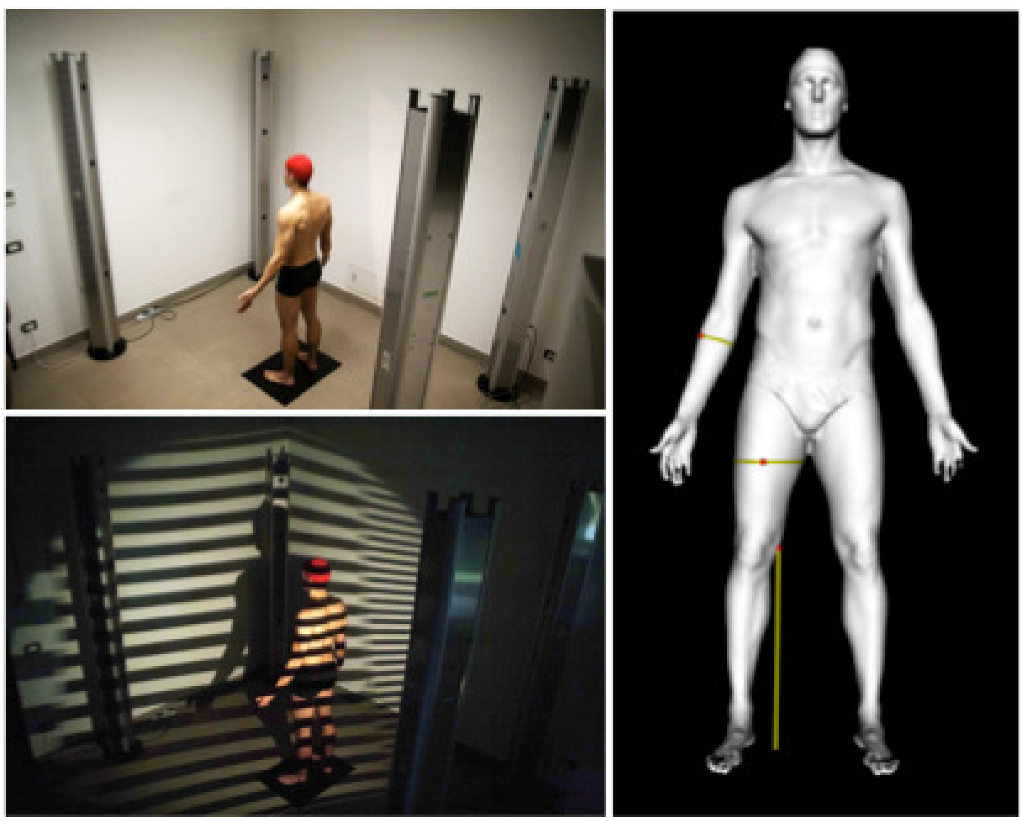

FIGURE 1: Three-dimensional scanning anthropometry. (a), the BodySCAN setup with a subject in the scanning position. (b), during scanning light is projected through diffraction fringes onto the subject, reflected and captured by cameras. (c), the final three-dimensional mesh used for anthropometry is shown.

2.3 3D Anthropometry

Body sites were marked prior to scanning by a skilled anthropometrist (SA) using a dermographic pen; such landmarks were easily visible in 3D scanning images in preliminary experiments and were also used for traditional anthropometry (see below) in order to avoid operator error bias. A set of twenty-three anthropometric measures was chosen (Table 1) to include most of the circumferences, lengths, and widths taken in anthropometric surveys. Measurements were conducted on 3D images of subjects using dedicated software based on the vtk software system [27]. Measurements were independently performed by the SA and two naïve anthropometrists (NA1 and NA2) on two different occasions (Trial1, Trial 2). The mean time required to take the complete set of measurements ranged 15-20min per subject.

Circumferences
Neck
Arm (relaxed)
Forearm
Chest
Waist
Gluteal (Hip)
Mid-thigh
Calf
Ankle
Lengths
Radiale-stylion
Midstylion-dactylion
Foot
Heights
Iliospinale to floor
Trochanterion to floor
Trochanterion-tibialelaterale
Tibiale laterale to floor
Breadths & Depths
Biacromial
Biiliocristal
Transverse chest
Anterior-posterior chest
Biepicondilar (humerus)
Wrist
Bimalleolar

TABLE 1: Set of anthropometric measurements used in this study.

2.4 Traditional Anthropometry

All measurements were taken by the SA on two different occasions (Trial1, Trial 2). Body circumferences were measured with a fiberglass tape; lengths and widths were measured with a Harpenden anthropometer (Holtain) according to standard procedures. All measurements were made directly on the skin, except for chest circumference for females and hip circumferences for both sexes, which were measured over underwear. The time required to take the complete set of measurements was about 20 min per subject.

2.5 Statistical Analysis

Descriptive statistics (mean ± standard deviation) were calculated for each variable, for each measuring mode (traditional and 3D) and for each anthropometrist (SA, NA1 and NA2). Univariate normality of data was tested with the Shapiro-Wilk W test. Relative reliability of measurements was investigated with the Pearson's correlation coefficient r and the intraclass correlation coefficient (ICC) with an exact confidence interval. ICC values were interpreted as follows: ICC≥0.75 indicates excellent reliability, 0.40 < ICC < 0.75 fair to good reliability and ICC≤0.40 poor reliability [6]. To test absolute reliability, the percentage coefficient of variation ($\%CV = \sigma/\mu \times 100$, where σ is the standard deviation of the two trials and μ is the mean), the standard error of measurement ($SEM=s_p \sqrt{(1-ICC)}$, where s_p is the pooled standard deviation of the two trials), and the percentage technical error of measurement (%TEM = 100 x TEM/M, where M is the variable average value, TEM= $s_\Delta/\sqrt{2}$ and s_Δ is the standard deviation of the difference between measurements of the two trials) were calculated. Changes in the mean difference (Δ) between two trials were also estimated (with standard deviation s_Δ) and the null hypothesis that means of body measurements were equal was tested using paired Student's t test. The level of significance for all statistical tests was set at p≤0.05. All statistical analyses were performed using Stata 12 [23]. No simulation was used in data analysis.

3. RESULTS

Mean values (with 95% confidence intervals) and standard deviations of 3D measurements taken by SA, NA1 and NA2 are summarized in Table 2. Duplicate measurements taken by the SA, NA1, and NA2 (Table 3) showed individual correlation coefficients r in the range 0.908-1.000 (p<0.001 for each item) for all variables except for midstylion-dactylion length measured by NA2 (ICC = 0.781); ICCs were in the range 0.915-1.000 (p<0.001 for each item) except for midstylion-dactylion length measured by NA2 (ICC = 0.776).

Measurement item	**SA**		**NA1**		**NA2**	
	Mean(SD)	**95% CI**	**Mean(SD)**	**95% CI**	**Mean(SD)**	**95% CI**
Neck C	344.2(30.2)	325.0-363.4	345.8(31.1)	326.0-365.5	349.6(32.7)	328.9-370.4
Arm (relaxed) C	282.5(24.4)	267.0-298.0	282.3(24.4)	266.8-297.9	282.4(24.1)	267.1-297.6
Forearm C	264.9(22.1)	250.9-278.9	264.8(22.3)	250.6-279.0	264.3(22.9)	249.8-278.8
Chest C	929.8(38.8)	905.1-954.4	927.9(38.4)	903.6-952.3	928.3(38.6)	903.7-952.8
Waist C	740.5(48.6)	709.6-771.4	740.7(48.6)	709.9-771.6	740.8(48.1)	710.2-771.4
Gluteal (hip) C	984.9(56.9)	948.7-021.1	986.1(55.0)	951.2-021.1	987.8(52.5)	954.4-021.1
Mid-thigh C	520.2(30.2)	501.0-539.4	519.8(30.3)	500.6-539.1	519.8(30.8)	500.3-539.4
Calf C	356.4(20.2)	343.5-369.2	356.6(20.2)	343.7-369.4	356.5(20.2)	343.7-369.3
Ankle C	223.3(11.0)	216.4-230.3	223.1(10.9)	216.2-230.0	223.1(10.9)	216.2-230.0
Radiale-stylion L	237.7(18.4)	226.0-249.4	237.9(18.5)	226.1-249.6	241.4(17.7)	230.2-252.6
Midstylion-dactylion L	179.2(10.2)	172.7-185.8	178.4(10.2)	172.0-184.9	176.8(8.1)	171.6-181.9
Iliospinale to floor H	964.2(46.4)	934.7-993.6	963.8(46.4)	934.3-993.3	963.8(46.2)	934.4-993.1
Trochanterion to floor H	808.8(55.7)	773.5-844.2	807.5(54.6)	772.8-842.1	806.0(53.3)	772.1-839.9
Trochanterion-tibialelaterale H	355.6(32.6)	334.9-376.3	354.3(31.6)	334.2-374.4	352.7(31.0)	333.0-372.4
Tibialelaterale to floor H	456.9(25.7)	440.5-473.2	456.6(25.9)	440.2-473.1	456.8(26.0)	440.2-473.3
Foot L	253.3(15.0)	243.8-262.9	253.2(15.1)	243.6-262.8	252.2(15.0)	242.7-261.8
Biacromial B	333.8(34.7)	311.8-355.9	334.3(33.9)	312.8-355.8	334.7(33.5)	313.4-356.0
Biiliocristal B	284.0(10.5)	277.3-290.7	283.9(10.5)	277.3-290.6	284.1(10.6)	277.4-290.8
Transverse chest B	298.9(16.9)	288.2-309.7	299.1(17.1)	288.2-309.9	298.9(16.7)	288.3-309.5
Anterior-post. chest D	194.0(13.8)	185.3-202.8	194.2(13.9)	185.3-203.0	194.1(13.8)	185.3-202.8
Biepicondylar humerus B	64.2(7.6)	59.4-69.1	64.2(7.5)	59.4-69.0	63.9(7.3)	59.2-68.5
Wrist B	54.2(6.9)	49.8-58.6	54.3(7.0)	49.9-58.7	54.6(6.8)	50.3-59.0
Bimalleolar B	71.6(5.3)	68.2-75.0	71.8(5.4)	68.4-75.2	71.8(5.3)	68.5-75.2

B, breadth; C, circumference; D, depth; H, height; L, length

TABLE 2: Means ± standard deviation and 95% confidence intervals (CI) of means of duplicate digital measurements taken by a skilled anthropometrist (SA) and two naïve anthropometrists (NA1, NA2). All measurements are in mm.

The changes in the mean of duplicate 3D measurements taken by any anthropometrists (SA, NA1, NA2) (Table 4) ranged from 0.00 to 1.42 mm and were <1 mm in 23, 23, and 18 out of 23 measurement items for the SA, NA1 and NA2, respectively (<0.5 mm in 22, 23, and 17 out of 23, respectively). Changes were not significantly different except for iliospinale (NA2, 963.6 vs. 964.0 mm, p=0.042) and tibialelaterale (SA, 456.9 vs. 456.8 mm, p=0.022). Mean %CV ranged from 0.02% to 1.55% and was <0.5% in 22, 22, and 18 measurement items for SA, NA1 and NA2, respectively. Percent TEM was in the range 0.03-2.30 (<0.5 in 22, 20, and 16 measurements items for SA, and NA1 and NA2, respectively), and SEM ranged from 0.07 to 5.68 mm (<2 mm in 23, 23, and 17 measurements items for SA, and NA1 and NA2, respectively).

Evaluation of the relative reliability between the SA and each NA (Table 5) showed r values ranging from 0.971 to 1.000 (SA vs. NA1, p<0.001 for each measurement item) and from 0.898 to 1.000 (SA vs. NA2, p<0.001 for each measurement item). ICCs ranged from 0.970 to 1.000 (SA vs. NA1) and from 0.881 to 1.000 (SA vs. NA2). When the absolute reliability between anthropometrists was considered (Table 6), changes in the means were in the range from 0.05 to 1.85mm and from 0.04 to 5.47 mm for SA vs. NA1 and SA vs. NA2, respectively.

Measurement item	SA			NA1			NA2		
	r*	ICC	95% CI	r*	ICC	95% CI	r*	ICC	95% CI
Neck C	0.999	0.999	0.996-1.000	0.998	0.995	0.983-0.998	0.969	0.969	0.900-0.991
Arm (relaxed) C	0.998	0.997	0.990-0.999	0.998	0.998	0.992-0.999	0.993	0.990	0.968-0.997
Forearm C	0.998	0.998	0.992-0.999	0.998	0.998	0.992-0.999	0.988	0.986	0.955-0.996
Chest C	0.999	0.999	0.995-1.000	0.999	0.999	0.997-1.000	0.998	0.998	0.995-1.000
Waist C	1.000	1.000	1.000-1.000	1.000	1.000	1.000-1.000	1.000	1.000	0.999-1.000
Gluteal (hip) C	0.999	0.999	0.997-1.000	1.000	1.000	0.999-1.000	0.999	0.999	0.998-1.000
Mid-thigh C	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000	0.999	0.999	0.996-1.000
Calf C	0.999	0.999	0.998-1.000	1.000	1.000	1.000-1.000	1.000	1.000	1.000-1.000
Ankle C	1.000	1.000	1.000-1.000	0.999	0.999	0.998-1.000	0.999	0.999	0.997-1.000
Radiale-stylion L	0.996	0.996	0.988-0.999	0.998	0.998	0.993-0.998	0.975	0.967	0.895-0.990
Midstylion-dactylion L	0.998	0.985	0.951-0.996	0.998	0.988	0.960-0.996	0.781	0.776	0.409-0.929
Iliospinale to floor H	1.000	1.000	1.000-1.000	1.000	1.000	1.000-1.000	1.000	1.000	1.000-1.000
Trochanterion to floor H	1.000	1.000	1.000-1.000	1.000	1.000	1.000-1.000	0.995	0.995	0.982-0.998
Trochanterion-tibialelaterale H	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000	0.986	0.986	0.953-0.996
Tibialelaterale to floor H	1.000	1.000	1.000-1.000	1.000	1.000	0.999-1.000	0.999	0.999	0.996-1.000
Foot L	1.000	1.000	1.000-1.000	0.999	0.999	0.998-1.000	0.999	0.999	0.995-1.000
Biacromial B	1.000	1.000	1.000-1.000	1.000	1.000	0.999-1.000	0.999	0.999	0.998-1.000
Biiliocristal B	1.000	1.000	0.999-1.000	0.998	0.998	0.992-0.999	0.999	0.999	0.997-1.000
Transverse chest B	1.000	1.000	1.000-1.000	0.999	0.999	0.998-1.000	1.000	1.000	0.999-1.000
Anterior-post. chest D	1.000	1.000	1.000-1.000	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000
Biepicondylar humerus B	0.997	0.997	0.991-0.999	0.993	0.992	0.974-0.998	0.991	0.990	0.968-0.997
Wrist B	0.994	0.994	0.981-0.998	0.992	0.991	0.972-0.998	0.979	0.977	0.925-0.993

B, breadth; C, circumference; D, depth; H, height; L, length
*, p<0.001 for all

TABLE 3: Intra-operator relative reliability for duplicate 3D measurements taken by a skilled anthropometrist (SA) and two naïve anthropometrist (NA1 and NA2); r, Pearson's correlation coefficient; ICC, intraclass correlation coefficient (with 95% confidence interval, CI) for two replicated measurements.

In the former comparison (SA vs. NA1), Student's t test rejected the null hypothesis about equality of means for neck, mid-high and ankle circumference (p=0.006, p=0.022; p=0.002, respectively), iliospinale and tibialelaterale height (p=0.023; p=0.038, respectively), and bimalleolar breadth (p=0.012); in the latter comparison (SA vs. NA2) Student's t test rejected the null hypothesis for chest and ankle circumference (p=0.001, and p=0.007, respectively), iliospinale height and foot length (p=0.022 and p<0.001, respectively), and wrist and bimalleolar breadth (p=0.010 and p<0.001, respectively). Mean %CV ranged from 0.04 to 1.55 (≤0.5 in 23 and 15 measurement items for SA vs. NA1 and NA2, respectively). Percent TEM ranged from 0.04 to 2.55 (<0.5 in 21 measurement items for SA vs. NA1 and 13 measurement items for SA vs. NA2). SEM ranged 0.11 to 6.29 mm. Most measurements (19 out of 23) taken by SA in the traditional and 3D mode (Table 7) showed correlation coefficient r>0.9 (p<0.001 for each measurement item); lower r values were found for radialestylion length (r=0.852, p<0.001), transverse chest breadth (r=0.798, p=0.002), biepicondilar humerus breadth (r=0.611, p=0.035), and wrist breadth (r=0.605, p=0.037). Sixteen measurements items had an ICC above 0.75 (excellent reliability) and seven measurements items had an ICC between 0.40 and 0.75 (fair to good reliability).

4. DISCUSSION

Human body metrics is a relevant source for product innovation to improve consumer-oriented ergonomics and comfort. Three-dimensional shape data may be of use for e.g., the transport, health, footwear, and safety industry. 3D anthropometry is a useful, contact-free tool for measuring human dimensions in several settings. In this work we explored the reliability of anthropometry performed by different skilled anthropometrists with a fast 3D scanner namely, the bodySCAN.

Measurement item	SA				NA1				NA2			
	$\Delta\ (s_\Delta)$ (mm)	% CV	% TEM	SEM (mm)	$\Delta\ (s_\Delta)$ (mm)	% CV	% TEM	SEM (mm)	$\Delta\ (s_\Delta)$ (mm)	% CV	% TEM	SEM (mm)
Neck C	0.33(1.47)	0.19	0.30	1.00	1.28(3.04)	0.38	0.65	2.20	1.11(8.50)	1.29	1.66	5.68
Arm (relaxed) C	0.70(1.80)	0.29	0.47	1.29	0.12(1.73)	0.32	0.42	1.15	1.42(3.18)	0.38	0.84	2.32
Forearm C	0.33(1.53)	0.23	0.40	1.04	0.32(1.59)	0.28	0.42	1.08	1.00(3.84)	0.63	1.02	2.64
Chest C	0.39(2.10)	0.07	0.16	1.42	0.40(1.72)	0.09	0.13	1.17	0.53(2.14)	0.12	0.16	1.47
Waist C	0.11(0.31)	0.02	0.03	0.22	0.23(0.40)	0.02	0.04	0.31	0.59(1.32)	0.10	0.13	0.97
Gluteal (hip) C	0.29(2.70)	0.12	0.19	1.80	0.48(1.42)	0.06	0.10	1.00	0.06(1.90)	0.09	0.13	1.26
Mid-thigh C	0.22(0.52)	0.05	0.07	0.37	0.06(0.67)	0.05	0.09	0.45	0.11(1.58)	0.12	0.21	1.05
Calf C	0.23(0.69)	0.06	0.14	0.48	0.01(0.20)	0.02	0.04	0.13	0.01(0.26)	0.03	0.05	0.18
Ankle C	0.04(0.12)	0.03	0.04	0.09	0.01(0.40)	0.08	0.12	0.27	0.21(0.43)	0.09	0.15	0.32
Radiale-stylion L	0.19(1.61)	0.36	0.46	1.08	0.05(1.22)	0.26	0.35	0.81	0.07(4.76)	0.88	1.33	3.15
Midstylion-dactylion L	0.89(1.62)	0.55	0.71	1.24	0.32(1.62)	0.49	0.63	1.10	0.47(5.99)	1.55	2.30	4.00
Iliospinale to floor H	0.08(0.35)	0.02	0.03	0.24	0.25(0.45)	0.02	0.04	0.35	0.43(0.64)*	0.05	0.05	0.52
Trochanterion to floor H	0.03(0.45)	0.03	0.04	0.30	0.08(0.67)	0.04	0.06	0.45	1.39(5.59)	0.20	0.49	3.83
Trochanterion-tibialelaterale H	0.13(0.58)	0.09	0.11	0.39	0.02(0.83)	0.10	0.16	0.55	1.42(5.30)	0.47	1.06	3.64
Tibialelaterale to floor H	0.16(0.21)*	0.03	0.04	0.18	0.08(0.67)	0.06	0.10	0.45	0.07(1.25)	0.14	0.19	0.83
Foot L	0.05(0.21)	0.05	0.06	0.14	0.03(0.50)	0.10	0.14	0.33	0.16(0.84)	0.16	0.23	0.57
Biacromial B	0.03(0.26)	0.04	0.05	0.18	0.17(0.94)	0.15	0.19	0.63	0.47(1.20)	0.22	0.26	0.86
Biiliocristal B	0.06(0.20)	0.04	0.05	0.14	0.23(0.72)	0.11	0.18	0.50	0.11(0.48)	0.10	0.12	0.33
Transverse chest B	0.03(0.24)	0.04	0.06	0.16	0.01(0.58)	0.08	0.13	0.38	0.11(0.39)	0.08	0.09	0.27
Anterior-post. chest D	0.00(0.11)	0.02	0.04	0.07	0.02(0.28)	0.05	0.10	0.19	0.14(0.39)	0.11	0.15	0.28
Biepicondylar humerus B	0.00(0.57)	0.47	0.60	0.38	0.04(0.99)	0.85	1.04	0.65	0.36(1.00)	0.90	1.13	0.71
Wrist B	0.25(0.73)	0.71	0.97	0.52	0.08(0.95)	0.83	1.19	0.63	0.25(1.51)	1.39	1.90	1.02
Bimalleolar B	0.02(0.11)	0.08	0.11	0.07	0.12(0.39)	0.25	0.38	0.27	0.03(0.42)	0.31	0.40	0.28

B, breadth; C, circumference; D, depth; H, height; L, length. Δ, mean difference; s_Δ, standard deviation of the differences.
*, 0.01<p≤0.05 (Student's t-test).

TABLE 4: Intra-operator absolute reliability for a skilled anthropometrist (SA) and two naïve anthropometrist (NA1 and NA2). Change in the mean Δ (s_Δ), percent coefficient of variation (%CV), percent technical error of measurement (%TEM) and standard error of measurement (SEM) for two replicated 3D measurements.

The study shows that 3D measurements taken on BodySCAN are practical to anthropometry; in fact, the large set of anthropometric measurements taken by the SA in the traditional and 3D mode (Table 7) suggests that 70%digital measurements have excellent (ICC>0.75) and 30% fair to good (ICC between 0.40 and 0.75) relative reliability. These findings are supported by previous data showing higher precision of scan-derived measurements vs. traditional measurements [13]. Therefore, most 3D and traditional anthropometric measurements are strictly correlated. However, it should be taken into account that there are inherent differences in traditional and 3D anthropometry. For example, the skin is slightly compressed during hand-held tape measuring whereas 3D measurement is based on reflected light thereby inducing possible variation in e.g., circumferences [24,26,17]. Similarly, strong compression is to be applied to measure bone breadth in the traditional anthropometric technique, which may be impossible with 3D anthropometry; moreover, difference in posture may be an issue. Accordingly, systematic differences in measurement can occur, which should be considered when using 3D data. We did not explore this issue in the present work as we aimed at assessing the intrinsic reliability of 3D anthropometry using the bodySCAN.

The second result of this work is that intra-operator relative reliability in anthropometric measurement (Table 3, Table 4) is excellent for almost all anthropometric measurement items; this was independent of the antropometrist's skill. In fact, both SA and NAs duplicate measurements had ICCs>0.950 except for one measurement taken by NA2. This figure compares well with previous data obtained with a different scanner [5,24]. Replicated measurements were not significantly different for almost all measurement items for the SA and the NAs, indicating excellent overall reproducibility of measurements. %CV was generally <1, which is fairly acceptable for biological measures and less than that reported in [17] and [19] for several comparable measurements items.

Measurement item	**SA vs. NA1**			**SA vs. NA2**		
	r*	**ICC**	**95% CI**	**r***	**ICC**	**95% CI**
Neck C	0.999	0.997	0.991-0.999	0.991	0.974	0.917-0.992
Arm (relaxed) C	0.999	0.999	0.998-1.000	0.996	0.997	0.989-0.999
Forearm C	1.000	1.000	0.998-1.000	0.997	0.996	0.988-0.999
Chest C	0.997	0.996	0.987-0.999	1.000	0.999	0.996-1.000
Waist C	1.000	1.000	1.000-1.000	1.000	1.000	0.999-1.000
Gluteal (hip) C	0.999	0.998	0.994-0.999	0.995	0.991	0.971-0.997
Mid-thigh C	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000
Calf C	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000
Ankle C	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000
Radiale-stylion L	0.998	0.999	0.995-1.000	0.898	0.886	0.665-0.965
Midstylion-dactylion L	0.971	0.970	0.905-0.991	0.934	0.881	0.654-0.964
Iliospinale to floor H	1.000	1.000	1.000-1.000	1.000	1.000	1.000-1.000
Trochanterion to floor H	0.998	0.998	0.993-0.999	0.988	0.987	0.958-0.996
Trochanterion-tibialelaterale H	0.993	0.992	0.974-0.998	0.961	0.959	0.871-0.988
Tibialelaterale to floor H	1.000	1.000	1.000-1.000	1.000	1.000	0.999-1.000
Foot L	1.000	1.000	0.999-1.000	0.999	0.997	0.989-0.999
Biacromial B	0.999	0.999	0.997-1.000	0.999	0.998	0.993-0.999
Biiliocristal B	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000
Transverse chest B	1.000	1.000	0.999-1.000	1.000	1.000	0.999-1.000
Anterior-post. chest D	1.000	1.000	0.999-1.000	1.000	1.000	1.000-1.000
Biepicondylar humerus B	0.999	0.999	0.998-1.000	0.985	0.985	0.950-0.996
Wrist B	0.998	0.998	0.994-0.999	0.997	0.995	0.985-0.999
Bimalleolar B	0.999	0.998	0.994-1.000	1.000	0.998	0.995-1.000

B, breadth; C, circumference; D, depth; H, height; L, length.
*, p<0.001 for all.

TABLE 5: Inter-operator relative reliability for digital anthropometry. Comparison of 3D measurements taken by a skilled anthropometrist (SA) and two naïve anthropometrists (NA1 and NA2); Pearson's correlation (r) and intraclass correlation coefficient (ICC) with 95% confidence interval.

The third result of this study is that relative inter-operator reliability of 3D anthropometry, explored comparing measurements taken by the SA vs. each NA (Table 5) was excellent (ICC>0.880 for all measurement items). Therefore, 3D measurements taken by operators of different skill were strictly correlated. A limited proportion (about 30%) of measurement items were significantly (or borderline significant) different between SA and any NAs (Table 6) despite comparison of SEMs obtained by the SA and the NAs (Table 4) generally showed worse performance in NAs. The current results compare well with traditional anthropometry where measurement differences of the same subject by different observers may be > 33mm [15]. Actually, technical training is crucial in obtaining reasonably low inter-operator error in traditional anthropometry [11]. Interestingly, only four measurement items taken by both NAs were different from those taken by the SA, indicating that specific instruction would improve NA's performance for a set of measurement items. These findings suggest that naïve operators would be able to perform at an acceptable level of agreement with skilled ones after a limited amount of training.

To summarize, the current findings suggest that 3D scanning has strong potential in anthropometry especially due to high intrinsic reliability and less need for operator training vs. traditional.

Measurement item	SA vs. NA1				SA vs. NA2			
	$\Delta\ (s_\Delta)$ (mm)	% CV	% TEM	SEM (mm)	$\Delta (s_\Delta)$ (mm)	% CV	% TEM	SEM (mm)
Neck C	1.58(1.60)**	0.34	0.45	1.52	5.47(4.87)**	1.29	1.46	4.97
Arm (relaxed) C	0.17(0.90)	0.16	0.22	0.61	0.16(2.09)	0.29	0.50	1.39
Forearm C	0.10(0.72)	0.15	0.19	0.48	0.60(1.94)	0.34	0.52	1.35
Chest C	1.85(2.94)	0.15	0.26	2.33	1.50(1.21)***	0.11	0.14	2.09
Waist C	0.25(0.57)	0.05	0.06	0.42	0.30(1.08)	0.08	0.10	1.31
Gluteal (hip) C	1.23(3.34)	0.12	0.25	2.37	2.91(6.98)	0.24	0.52	0.75
Mid-thigh C	0.35(0.46)*	0.07	0.08	0.39	0.37(0.85)	0.09	0.12	5.04
Calf C	0.19(0.37)	0.04	0.08	0.28	0.10(0.41)	0.04	0.08	0.62
Ankle C	0.20(0.18)**	0.06	0.08	0.18	0.18(0.18)**	0.06	0.08	0.28
Radiale-stylion L	0.17(1.03)	0.23	0.30	0.69	3.67(8.18)	1.55	2.55	0.17
Midstylion-dactylion L	0.80(2.46)	0.60	0.98	1.72	2.49(3.95)	1.49	1.80	6.00
Iliospinale to floor H	0.37(0.49)*	0.04	0.04	0.41	0.39(0.51)*	0.04	0.05	3.14
Trochanterion to floor H	1.37(3.36)	0.12	0.31	2.42	2.85(8.65)	0.26	0.77	0.43
Trochanterion-tibialelaterale H	1.27(3.96)	0.28	0.80	2.77	2.89(9.00)	0.61	1.81	6.06
Tibialelaterale to floor H	0.23(0.34)*	0.05	0.06	0.27	0.08(0.62)	0.06	0.09	6.29
Foot L	0.15(0.34)	0.09	0.10	0.25	1.11(0.59)***	0.31	0.35	0.42
Biacromial B	0.44(1.56)	0.18	0.33	1.08	0.85(2.11)	0.25	0.46	0.86
Biiliocristal B	0.05(0.24)	0.05	0.06	0.16	0.08(0.22)	0.05	0.06	1.52
Transverse chest B	0.11(0.50)	0.09	0.12	0.34	0.04(0.37)	0.07	0.08	0.16
Anterior-post. chest D	0.16(0.34)	0.10	0.13	0.25	0.05(0.15)	0.05	0.06	0.25
Biepicondylar humerus B	0.05(0.26)	0.23	0.28	0.17	0.36(1.31)	1.00	1.44	0.11
Wrist B	0.11(0.42)	0.45	0.54	0.29	0.45(0.50)**	0.71	0.85	0.90
Bimalleolar B	0.21(0.24)*	0.27	0.31	0.21	0.28(0.14)***	0.27	0.30	0.45

B, breadth; C, circumference; D, depth; H, height; L, length; Δ, mean difference; s_Δ, standard deviation of the differences
*, 0.01<p≤0.05; **, p≤0.01; ***, p≤0.001 (Student's t-test)

TABLE 6: Inter-operator absolute reliability for 3D anthropometry. Comparison of digital measurements taken by a skilled anthropometrist (SA) and two naïve anthropometrists (NA1 and NA2). Change in the mean [Δ (s_Δ)], percent coefficient of variation %CV, percent technical error of measurement (%TEM), and standard error of measurement (SEM) for two replicated measurements.

A limitation of this work is the low number of measured subjects, which are not representative of the wide spectrum of human shapes. Further, we did not explore the intra- and inter-operator error in 3D anthropometry, which is mainly associated with landmark positioning. This is a crucial issue in traditional anthropometry [12], related to exact anatomical localization of the landmark. While many traditional anthropometric landmarks are identified by palpation, this is obviously impossible in 3D anthropometry. Hence, attempts are being made to automatically extract meaningful anthropometric parameters independent of strictly anatomical localization of landmarks [7].

Measurement item	r	ICC	95% CI
Neck C	0.984***	0.957	0.863 - 0.987
Arm (relaxed) C	0.980***	0.968	0.899 - 0.991
Forearm C	0.968***	0.868	0.619 - 0.960
Chest C	0.934***	0.748	0.353 - 0.919
Waist C	0.934***	0.886	0.665 - 0.965
Gluteal (hip) C	0.957***	0.794	0.447 - 0.935
Mid-thigh C	0.986***	0.936	0.802 - 0.981

Calf C	0.985***	0.978	0.929 - 0.994
Ankle C	0.962***	0.885	0.663 - 0.965
Radiale-stylion L	0.852***	0.401	0.000 - 0.778
Midstylion-dactylion L	0.915***	0.608	0.105 - 0.867
Iliospinale to floor H	0.960***	0.899	0.699 - 0.969
Trochanterion to floor H	0.993***	0.993	0.977 - 0.998
Trochanterion-tibialelaterale H	0.987***	0.983	0.946 - 0.995
Tibialelaterale to floor H	0.957***	0.947	0.833 - 0.984
Foot L	0.991***	0.990	0.967 - 0.997
Biacromial B	0.955***	0.902	0.709 - 0.971
Biiliocristal B	0.967***	0.966	0.891 - 0.990
Transverse chest B	0.798**	0.458	0.000 - 0.804
Anterior-post. chest D	0.911***	0.682	0.228 - 0.895
Biepicondylar humerus B	0.611*	0.505	0.000 - 0.825
Wrist B	0.605*	0.518	0.000 - 0.830
Bimalleolar B	0.940***	0.791	0.441 - 0.934

B, breadth; C, circumference; D, depth; H, height; L, length.
*, $0.01<p\leq0.05$; **, $0.001<p\leq0.01$; ***, $p\leq0.001$.

TABLE 7: 3D anthropometry reliability. Comparison of measurements taken by a skilled anthropometrist in the digital vs. traditional mode. r, Pearson's correlation coefficient; ICC, intraclass correlation coefficient (with 95% confidence interval, CI).

5. ACKNOWLEDGEMENTS

This work was supported in part by a grant from the University of Verona (Joint Projects 2007) and Departmental funding to C.Z. C.L. was in the PhD program in Multimodal Imaging in Biomedicine at the University of Verona. The authors thank F. Piscitelli for help with the 3D mesh shown in Fig. 1.

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