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Anthropometric Measurements from a 3D Photogrammetry-Based Digital Avatar: A Non-Experimental Cross-Sectional Study to Assess Reliability and Agreement

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Abstract: Photogrammetry captures and stitches multiple images together to generate a digital model of the human body, called an avatar, making it potentially useful in healthcare. Its validity for anthropometry remains to be established. We evaluated the reliability and agreement of measurements derived from a three-dimensional digital avatar generated by photogrammetry compared to manual collection. Fifty-three volunteers (34.02 ± 11.94 years of age, 64% female, 22.5 kg·m^{-2} body mass index) were recruited, and twenty-two body regions (neck, armpits, biceps, elbows, wrists, chest, breast, waist, belly, hip, thighs, knees, calves, ankles) were taken by an individual rater with a tape measure. Digital measurements were generated from photogrammetry. Participants' intraclass correlation coefficients indicated strong consistency, with agreement of over 90% for limb regions such as biceps, elbows, wrists, thighs, knees, calves, and ankles, while chest and armpits showed lowest agreement (<60%). Random errors were low in limb regions, while trunk measurements showed highest errors (up to >1 cm) and variation. Bland–Altman analysis revealed wider limits of agreements and higher biases for chest (−2.44 cm), waist and belly (around −1.2 cm), and armpits (around −1.1 cm) compared to limbs. Our findings suggest that photogrammetry-based digital avatars can be a promising tool for anthropometric assessment, particularly for limbs, but may require refinement in trunk-related regions.

Keywords: body measures; anthropometry; physical examination; nutritional status; body composition; humanoid avatar; virtual reality; patient care

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1. Introduction

Anthropometry plays a crucial role in auxology, body composition, and general health. Traditionally, anthropometric assessment of circumferences is a non-invasive and economical evaluation performed by trained professionals with a flexible non-elastic tape measure. However, this method is not free from intra- and inter-rater variability [1,2], with accuracy and consistency strongly depending on the equipment used, how often it is appropriately standardised/calibrated, the number of personnel performing measurements, frequency of their training, and the overall quality of the local standard operating procedure that also takes into account the practicalities, such as the time of day for measurement [3]. Moreover, whole-body manual assessments can be both time-consuming and have limited applicability when performed on subjects with obesity or excess skin [4].

Technological advances positively influenced the development of three-dimensional (3D) surface anthropometry by means of photography, photogrammetry, videography, or surface laser scanning. These have been already used for a range of purposes including the manufacture and fitting of customised artificial limbs [5]. Among emerging digital anthropometric technologies, laser scanning and photogrammetry are the most promising. Three-dimensional laser scanning projects laser beams onto the body surface to obtain a volumetric reconstruction, traditionally outperform other digital technologies [6], and has been studied in various settings, such as the assessment of lower limb oedema or monitoring swelling after orthopaedic surgery [7,8]. The generation of 3D digital avatars from photogrammetry could represent a distinct, but complementary, technology, capable of reconstructing a person's body shape using multiple images from different angles [9]. Unlike laser scanning, photogrammetry relies on algorithms that generate a 3D representation of the person, called an avatar, making it potentially more convenient, accessible, and versatile in the health avatar digital field, enabling users to identify changes in body shapes [10]. However, its validity in terms of anthropometric circumferences compared to traditional manual assessment remains to be established.

Reliability and agreement are data integrity metrics important in method development and quality assurance. Reliability measures include the intraclass correlation coefficient (ICC), which can be used to evaluate inter-method consistency when multiple methods are involved in assessing the same subject, while agreement measures include proportions of specific agreement, random error, coefficient of variation (CV), and Bland–Altman analysis. Previously, these metrics have already been used to evaluate the validity of different digital anthropometric technologies [8]. The aim of this study is to evaluate these integrity metrics derived from the comparison between measurements collected manually with a tape measure and those automatically derived from a 3D digital avatar generated by photogrammetry. This article adhered to the guidelines for reporting reliability and agreement studies (GRRAS) [11].

2. Materials and Methods

2.1. Study Design

This investigation was planned as a non-experimental cross-sectional study involving human participants to assess whether a novel 3D photogrammetry-based digital avatar technology would provide valid body measurements compared to manual assessment. Convenience sampling was conducted among hospital-attending individuals, colleagues in the workplace, and relatives. Informed consent collection from volunteers and manual measurement were conducted at IRCCS Ospedale Galeazzi—Sant'Ambrogio in Milan, Italy, with manual assessment being performed by a trained dietitian. Photogrammetry and the generation of 3D avatars were performed in a dedicated laboratory in the same city.

2.2. Eligibility Criteria

Caucasian subjects between 18 and 85 years of age, of male or female sex, and with a height between 1.2 and 2 metres, were eligible to participate. Exclusion criteria were congenital or acquired musculoskeletal deformities, cosmetic surgery implants, neuropsychiatric disorders, photosensitivity, claustrophobia, artificial cardiac pacemaker, incapacity to maintain an upright posture independently, and inability to reach the photogrammetry laboratory during working hours. Volunteers had to undergo all study assessments on the same day.

2.3. Anthropometric Measurements

Twenty-two anthropometric measurements were manually collected and then derived from the digital avatars: neck, right and left armpit, right and left bicep, right and left elbow, right and left wrist, chest, breast, waist, belly, hip, right and left thigh, right and left knee, right and left calf, and right and left ankle (Figure 1). According to the standard operating procedure (ISO 7250-1:2017, [12]), measurements of participants wearing only their underwear were taken one time by a trained rater alone (research dietitian with over five year of experience) with a separate investigator to record the measurements takes in the late morning. Participants were instructed to breathe normally and pause briefly at the end of a relaxed exhalation, at which point the measurements of chest, breast, waist, and belly were taken. Stature was measured using a mechanical mobile stadiometer (model 217, SECA, Hamburg, Germany), body weight was measured with a digital flat scale (model 813, SECA, Germany), and circumferences were taken with an ergonomic non-stretchable tape measure (model 201, SECA, Germany).

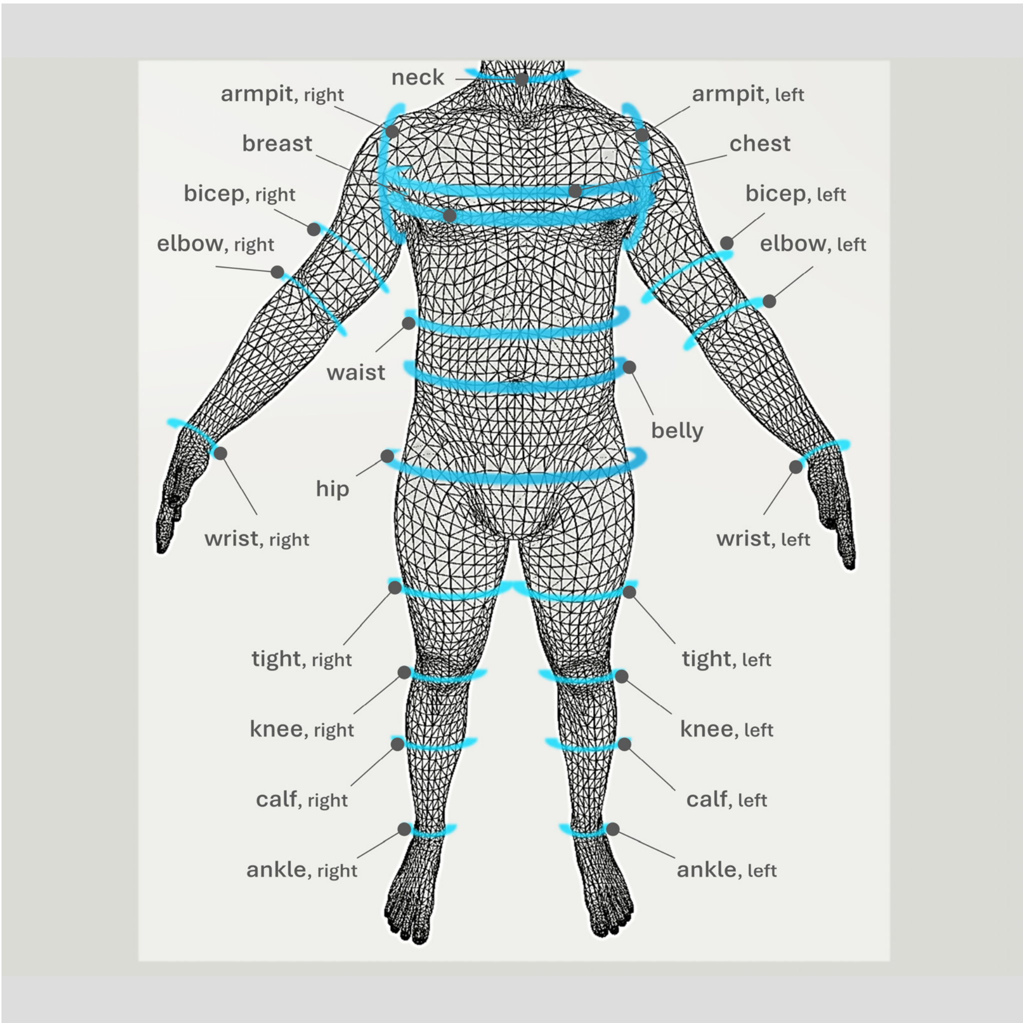

Figure 1. Reference landmarks for automatic anthropometric measurement on the point cloud avatar derived from photogrammetry analysis of a male participant.

Photogrammetry technique and the derived 3D digital avatar were previously described along with its automatic pipeline and smart body concept [9]. Briefly, the scanning cabin used for photogrammetry (commercialised by IGOODI as "the Gate"; patent number 10.924.662, United States Patent and Trademark Office, 2021) was equipped with 128 industrial cameras and sensors to collect anthropometric measurements of the participants in underwear. The automatic pipeline for avatar generation encompasses the photogrammetric reconstruction of a 3D model based on a set of sequential photographs captured one time, retopology and texturing (point cloud avatar), rigging and clothing, and output file.

2.4. Statistics

The primary endpoint for sample size calculation was based on an estimated correlation value between manual and photogrammetry-derived measurements of a conservative R = 0.5, resulting in an estimate of 75 subjects including 20% of drops. Reliability across methods was assessed with the two-way random effects, consistency, and multiple rater ICC [13], with thresholds defined as <0.90 = good, 0.90–0.95 = excellent, >0.95 = optimal. Agreement was assessed with several performance metrics: proportions of values with a deviation within a prespecified limit (difference considered clinically acceptable of ±1 cm), standard error of measurement (SEM) that reflects the random error, CV to compare variability both between the methods and with respect to a reference of 0.1–20.9 [1], and Bland–Altman analysis (mean bias, limits of agreement ±1.96 standard deviations, detection of outliers). Proportional bias was checked to test whether errors systematically increased with increasing measurement size. Analyses were performed using the R programming language (version 2024.04.2 + 764) by means of irr (version 0.84.1), dplyr (version 1.1.4), and ggplt2 (version 3.5.1) packages.

3. Results

Fifty-three participants had complete assessments, with twenty-two subjects being excluded from analysis for incomplete evaluations from study assessments.

Characteristics of the final study sample are reported in Table 1. Most of the automated measurements had mean values higher that those taken manually: +0.59 cm (neck), +1.14 cm (right armpit), +1.16 cm (left armpit), +0.21 cm (right bicep), +0.24 cm (left bicep), +0.05 cm (right elbow), +0.06 cm (left elbow), +0.19 cm (right wrist), +0.21 cm (left wrist), +2.31 cm (chest), +0.70 cm (breast), +1.20 cm (waist), +1.20 cm (belly), +0.13 cm (hip), +0.07 cm (right thigh), +0.02 cm (left thigh), +0.05 cm (right knee), +0.06 cm (left knee), −0.09 cm (right calf), −0.15 cm (left calf), −0.13 cm (right ankle), and −0.21 cm (left ankle). ICC results indicated strong overall consistency between methods. The best-performing measurements with optimal reliability were neck, biceps, elbows, breast, waist, hip, thighs, knees, calves, and ankles. The worst-performing were measurements of armpits and chest, which showed also wider confidence intervals. Based on the clinically acceptable threshold of ±1 cm difference between manual and automatic measurements, agreement of over 90% of values was found for biceps, elbows, wrists, thighs, knees, calves, and ankles. Moderate agreement was found for hip (88.7%), belly (75.5%), breast (77.4%), waist (62.3%), and neck (60.4%) measurements, while low agreement (<60%) was found for chest and armpits. Biceps, elbows, wrists, thighs, knees, calves, and ankles showed low random error (<0.5 cm). Neck, breast, and hip showed moderate variability, and the highest SEMs (>1 cm) were found for armpits, chest, waist, and belly.

Table 1. Characteristics and manual measurements of study participants.

Parameter	Cohort (n = 53)	Females (n = 34)	Males (n = 19)
Age (years)	34.02 (11.94) [18; 67]	34.3 (10.83) [21; 64]	33.53 (14) [18; 67]
Body mass index (kg·m^{-2})	22.49 (4.04) [17; 38]	21.73 (3.82) [17; 38]	23.86 (4.16) [19; 38]
Neck (cm)	33.83 (3.35) [29; 44]	31.9 (2.03) [29; 39]	37.28 (2.31) [35; 44]
Armpit, right (cm)	41.00 (4.81) [33; 54]	38.94 (4.04) [33; 53]	44.89 (3.64) [40; 54]
Armpit, left (cm)	41.27 (4.93) [33; 56]	39.2 (4.5) [33; 56]	44.97 (3.25) [40; 51]
Bicep, right (cm)	27.18 (3.54) [22; 38]	25.81 (2.93) [22; 35]	29.64 (3.25) [24; 38]
Bicep, left (cm)	27.08 (3.52) [22; 38]	25.77 (2.88) [22; 36]	29.42 (3.4) [24; 38]
Elbow, right (cm)	24.24 (2.5) [20; 33]	23.05 (1.81) [20; 29]	26.36 (2.17) [23; 33]
Elbow, left (cm)	24.20 (2.49) [21; 32]	23.01 (1.88) [21; 30]	26.32 (2.01) [23; 32]
Wrist, right (cm)	15.45 (1.30) [13; 19]	14.81 (0.96) [13; 18]	16.59 (1.03) [15; 19]
Wrist, left (cm)	15.38 (1.28) [13; 19]	14.75 (0.93) [13; 17]	16.51 (1.01) [15; 19]
Chest (cm)	90.60 (8.59) [79; 115]	86.51 (6.44) [79; 107]	97.92 (6.98) [88; 115]
Breast (cm)	91.42 (9.65) [78; 122]	88.99 (9.07) [78; 122]	95.77 (9.34) [85; 121]
Waist (cm)	76.00 (11.63) [62; 117]	72.11 (9.96) [62; 113]	82.95 (11.36) [68; 117]
Belly (cm)	83.11 (13.40) [45; 126]	81.74 (11.52) [68; 126]	85.56 (16.3) [45; 126]
Hip (cm)	95.78 (9.40) [84; 135]	95.48 (10.04) [84; 135]	96.33 (8.37) [87; 117]
Thigh, right (cm)	50.75 (4.26) [42; 64]	49.98 (4.28) [42; 64]	52.13 (3.96) [47; 63]
Thigh, left (cm)	50.61 (4.11) [42; 64]	49.79 (4.09) [42; 64]	52.09 (3.8) [48; 63]
Knee, right (cm)	37.37 (3.13) [31; 49]	36.6 (3.13) [31; 49]	38.75 (2.68) [36; 47]
Knee, left (cm)	37.39 (3.15) [32; 48]	36.68 (3.12) [32; 48]	38.67 (2.85) [35; 48]
Calf, right (cm)	36.04 (2.95) [30; 46]	35.18 (2.63) [30; 44]	37.58 (2.93) [34; 46]
Calf, left (cm)	36.06 (2.76) [31; 44]	35.17 (2.5) [31; 44]	37.67 (2.51) [35; 44]
Ankle, right (cm)	24.59 (1.88) [20; 29]	23.58 (1.34) [20; 27]	26.4 (1.25) [24; 29]
Ankle, left (cm)	24.42 (1.78) [22; 28]	23.48 (1.25) [22; 27]	26.09 (1.28) [24; 28]

Data were collected manually and reported here as mean (SD) [min; max].

Concerning the CV, the highest percentages were of belly (6.22%), armpits (3.97% and 5%), and chest (3.62%). Bland–Altman agreement analysis showed that the average difference between manual and avatar-derived measurements indicated the highest positive biases for chest (−2.44 cm), waist and belly (around −1.2 cm), and armpits (around −1.1 cm). These same regions had also wider limits of agreements, showing greater individual variability. Conversely, limbs (e.g., biceps, thighs, knees), showed narrower limits. The complete results are reported in Table 2. A significant proportional bias was found for right (slope = −0.102, R^2 = 0.136, p = 0.007) and left wrist (slope = −0.097, R^2 = 0.105, p = 0.018), and chest (slope = −0.220, R^2 = 0.425, p < 0.001). Other regions had consistent error across body sizes.

Table 2. Performance metrics of manually versus digitally obtained body measurements.

Intervention	ICC 95% CI	% Within 1 cm	SEM (cm)	CV%	Bland–Altman
Neck	0.958 [0.850; 0.983]	60.4%	0.578	2.42	−0.594 [−2.197; 1.009], 5
Armpit, dx	0.919 [0.794; 0.965]	53.8%	1.152	3.97	−1.137 [−4.329; 2.054], 4
Armpit, sx	0.895 [0.758; 0.948]	52.8%	1.458	5.00	−1.159 [−5.200; 2.883], 4
Bicep, dx	0.992 [0.980; 0.996]	94.3%	0.281	1.46	−0.215 [−0.995; 0.566], 4
Bicep, sx	0.994 [0.975; 0.997]	98.1%	0.228	1.19	−0.237 [−0.869; 0.395], 4
Elbow, dx	0.996 [0.993; 0.998]	100.0%	0.160	0.93	−0.053 [−0.496; 0.391], 3
Elbow, sx	0.995 [0.992; 0.997]	100.0%	0.166	0.97	−0.058 [−0.518; 0.401], 5
Wrist, dx	0.954 [0.895; 0.977]	96.2%	0.266	2.44	−0.195 [−0.933; 0.544], 4
Wrist, sx	0.945 [0.872; 0.973]	94.3%	0.280	2.58	−0.214 [−0.991; 0.562], 3
Chest	0.917 [0.717; 0.966]	25.0%	2.317	3.62	−2.441 [−8.863; 3.982], 3
Breast	0.988 [0.971; 0.994]	77.4%	0.965	1.49	−0.700 [−3.373; 1.974], 3
Waist	0.979 [0.945; 0.990]	62.3%	1.494	2.78	−1.198 [−5.341; 2.944], 1

Table 2. *Cont.*

Intervention	ICC 95% CI	% Within 1 cm	SEM (cm)	CV%	Bland–Altman
Belly	0.918 [0.861; 0.952]	75.5%	3.655	6.22	−1.199 [−11.330; 8.932], 1
Hip	0.997 [0.995; 0.998]	88.7%	0.517	0.76	−0.132 [−1.565; 1.302], 4
Thigh, dx	0.997 [0.995; 0.998]	96.2%	0.218	0.61	−0.069 [−0.673; 0.535], 2
Thigh, sx	0.997 [0.995; 0.998]	98.1%	0.223	0.62	−0.024 [−0.642; 0.594], 2
Knee, dx	0.995 [0.992; 0.997]	98.1%	0.212	0.80	−0.046 [−0.635; 0.542], 3
Knee, sx	0.990 [0.983; 0.994]	92.5%	0.316	1.19	−0.056 [−0.931; 0.819], 6
Calf, dx	0.994 [0.990; 0.997]	98.1%	0.213	0.84	0.087 [−0.503; 0.677], 4
Calf, sx	0.991 [0.981; 0.995]	96.2%	0.235	0.92	0.154 [−0.498; 0.806], 2
Ankle, dx	0.974 [0.953; 0.985]	98.1%	0.291	1.67	0.132 [−0.674; 0.937], 2
Ankle, sx	0.956 [0.913; 0.976]	92.5%	0.341	1.97	0.207 [−0.738; 1.152], 1

ICC = intraclass correlation coefficient, reported as 95% CI [lower limit; upper limit]; SEM = standard error of measurement; CV = coefficient of variation; Bland–Altman analysis reported as mean bias [lower LoA; upper LoA], outliers; LoA = limits of agreement.

4. Discussion

This study assessed the reliability and agreement between anthropometric measurements obtained automatically from a photogrammetric analysis, which generated a 3D digital avatar, and those measured manually using a tape measure. Overall, the new technology demonstrated strong reliability for most of the measurements, particularly in the limbs, effectively distinguishing between subjects with different morphologies. However, measurements from the trunk area, such as chest, breast, waist, and belly, showed notably lower reliability and wider confidence intervals, with higher random error and absolute overestimation compared to the manual method. Bland–Altman analysis confirmed systematic error and proportional bias in these regions, especially the chest, whereas limb measurements showed high agreement and low variability. Compared to the state of the art, these findings align with prior research reporting similar limitations in trunk measurements [6,8,14,15], but also demonstrate that limb measurements using this technology can achieve precision comparable to trained human raters [1,16]. The main advantage of this technology is improved efficiency and automation, while the main disadvantage is lower accuracy in specific anatomical areas, particularly the trunk.

These results are consistent with prior research on digital anthropometry [6,8,14–18], which has repeatedly documented the challenges of accurately assessing body measurements using photogrammetric methods. Specifically, the highest random errors of trunk circumferences have already been observed in several reliability and agreement studies [8], confirming chest and waist circumferences, but not that of the hip [6], as having the lowest accuracy and consistency [14,15]. It has also been highlighted that difficulties may arise when measuring circumferences of hidden regions or others that strongly depend on body posture [16,18]. Several factors likely contributed to the inaccuracies observed. First, the scanning cabin required participants to stand with arms slightly raised, making it difficult to capture hidden anatomical areas like the armpits, which is a known challenge even when scanning inanimate objects [19]. Second, trunk measurements are influenced by respiration. While manual measurements were standardised to the end of expiration, photogrammetry lacked control over the respiratory phase, introducing variability. This may have caused (for example, for chest, breast, waist, belly, and hip measurements) a collection of photos at different phases of inspiration and expiration between subjects compared to a manual assessment, which was instead performed at the same respiration phase. Additionally, manual measurements compress soft tissue, while photogrammetry does not, likely explaining why automatic measurements overestimated trunk dimensions on average. Importantly, our findings contribute to the field by identifying specific anatomical areas where photogrammetric measurement remains problematic and offering insights into potential sources of error.

This study has several limitations. Although the sample size of 53 participants was adequate for statistical power (≈0.9 from post hoc power analysis), it limits generalisability, especially since stringent eligibility criteria were used, and individuals with obesity or older adults were not included. Convenience sampling may have overrepresented certain body shapes. Furthermore, the findings are specific to the particular photogrammetric technology and the scanning conditions used (including resolution, lighting, and subject positioning), which may differ from other systems such as high-precision 3D laser scanners. Importantly, the detection of proportional bias in some anatomical regions indicates measurement error that may be body size dependent. Moreover, we did not assess precision in terms of repeatability and reproducibility through replicate observations, nor did we compare our system against other photogrammetric technologies, which limits the clinical applicability of the results.

The findings have important practical implications. Digital anthropometric technologies offer promising alternatives to manual anthropometry for applications in nutritional assessment, ergonomics, and musculoskeletal health monitoring [17]. The reliability demonstrated in limb measurements suggests these systems can improve efficiency in settings where manual measurements are currently standard. However, before clinical or high-stakes applications can adopt this technology broadly, the limitations in trunk measurements must be addressed. Possible improvements include refining photogrammetric reconstruction of hidden regions like the armpits (for example, using images with arms raised to a 90-degree angle), better standardisation of breathing protocols during scans, and improving 3D reconstruction algorithms to account for individual body morphology [4,20]. These developments could extend the use of photogrammetry to healthcare, sports science, and apparel industries, where fast, reliable, and non-contact body measurement is increasingly valuable. Additionally, this research informs ongoing debates about the integration of automated measurement tools into clinical and research workflows, highlighting both their potential and their current limitations.

5. Conclusions

This study demonstrates that a 3D photogrammetry-based digital avatar could prove to be an auxiliary technology in anthropometric assessment, particularly for limb body regions (biceps, elbows, wrists, hip, thighs, knees, calves, ankles), with a variability no higher than that of humans. However, armpits, chest, breast, waist, and belly measurements may need further refinement because of higher variability and error due to difficulty in detection, dependence on respiration, or presence of soft tissue.

Future Directions

Automated digital 3D body scanning technology can be a non-invasive, non-contact, and safe alternative of manual anthropometry. Potential areas of use go beyond traditional applications in medicine (e.g., body composition [21,22]), encompassing the creation of plaster cast of teeth, personalised protheses, surgical planning flow, 3D figures, customised clothing, gaming, and animation for movies. However, future studies should evaluate the reliability and agreement of this technology on a more diverse sample, including stratified analyses by sex, which we could not perform in this study due to sample size constraints. Additionally, reproducibility of the measurements remains to be validated. Developments in predictive algorithms and machine-learning-based shape correction models can help improve accuracy in anatomical regions difficult to scan. Furthermore, for this technology to truly replace manual anthropometry, the system should be portable and available within the individual clinic.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15105738/s1, File S1: Raw data.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the San Raffaele Ethics Committee of Milan, Italy (70/INT/2022; 14 December 2022), to be hosted and conducted at our IRCCS Ospedale Galeazzi—Sant'Ambrogio (protocol name: AVATARGET). The study was registered on Clinical-trials.gov (NCT05864820), with the first patient being recruited on 18 April 2023, and the last on 27 June 2024. The study was declared terminated on 28 November 2024.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the Supplementary Materials. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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