ACCURACY AND AGREEMENT OF MOBILE LIDAR-BASED DIGITAL ANTHROPOMETRY: VALIDATION AGAINST MANUAL ANTHROPOMETRY AND A PROFESSIONAL 3D BODY SCANNER

Bibiána Ondrejová, Ilia Budnik, Lucia Bednarčíková, Norbert Ferenčík, Jozef Živčák

Department of Biomedical Engineering and Measurement, Faculty of Mechanical Engineering, Technical University of Košice, Košice, Slovakia

Abstract

Digital anthropometry has become an increasingly important tool for obtaining body dimensions in clinical, ergonomic, and engineering applications. However, the validity of low-cost mobile LiDAR-based anthropometric systems remains insufficiently documented. The aim of this study was to evaluate the agreement of a mobile LiDAR-based anthropometric application and a professional three-dimensional body scanner with reference manual anthropometry. A total of 41 healthy volunteers underwent standardized manual anthropometric measurements, whole-body scanning using the TC² NX-16 scanner, and mobile scanning using the 3D Measure Up application. Agreement was evaluated using mean paired differences, intraclass correlation coefficients, and Bland–Altman analysis. Both digital systems showed good to excellent ICC values for most evaluated dimensions, but the magnitude and variability of the differences depended on the anthropometric parameter. Mean biases were generally smaller for linear dimensions, whereas the largest differences occurred among circumferential measurements. Representative Bland–Altman analyses showed wider limits of agreement for chest circumference than for body height. These findings suggest that mobile LiDAR-based anthropometry may complement professional scanning for selected linear dimensions under standardized conditions. However, circumferential measurements and measurements used for patient-specific decisions require additional verification.

Keywords

digital anthropometry, 3D body scanning, LiDAR, TC² NX-16, measurement accuracy, ICC, Bland–Altman analysis

Introduction

Anthropometry provides quantitative information about human body dimensions and plays an important role in medicine, ergonomics, biomechanics, orthotics, prosthetics, apparel design, and product development. Accurate anthropometric data are essential for the design of personalized solutions, assessment of body morphology, and optimization of human–product interactions [1, 2]. For decades, anthropometric measurements have been obtained using manual techniques based on standardized anatomical landmarks and dedicated measuring instruments. Due to their long-standing standardization and widespread acceptance, manual anthropometric measurements remain the reference method for evaluating emerging anthropometric technologies [3–6].

Recent advances in three-dimensional (3D) imaging technologies have led to the rapid development of digital anthropometry. Unlike traditional approaches, digital systems allow the acquisition of complete 3D representations of the human body, from which numerous anthropometric dimensions can be extracted automatically [3, 7, 8]. This approach offers several advantages, including reduced measurement time, non-contact data acquisition, digital archiving of body models, and the possibility of repeated analyses without requiring additional participant measurements [9]. Consequently, 3D body scanning technologies have become increasingly utilized in healthcare, ergonomic assessment, apparel design, and biomedical engineering applications [2].

A wide range of technologies is currently used for digital anthropometry, including structured-light scanners, laser-based systems, infrared depth sensors, LiDAR technologies, and photogrammetric approaches [2, 9, 10]. Among these, professional whole-body scanners represent the most established solution for obtaining high-resolution digital body models under controlled measurement conditions. Previous studies have demonstrated high levels of

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agreement between professional scanning systems and manual anthropometric measurements, particularly for linear body dimensions such as stature and segment lengths [4, 5]. As a result, professional 3D scanners are increasingly considered reliable tools for anthropometric data acquisition in both research and applied settings [11].

Despite these advances, several factors continue to influence the accuracy of digital anthropometry. Measurement performance may be affected by sensor characteristics, reconstruction algorithms, environmental conditions, participant posture, and the automated identification of anatomical landmarks [12]. Previous validation studies have shown that digital systems generally achieve high accuracy for large linear body dimensions, whereas circumferential measurements often exhibit larger deviations from manual measurements [4, 5, 13, 14]. These discrepancies are frequently attributed to differences in landmark localization, cross-sectional plane definition, and the reconstruction of soft-tissue geometry within 3D models [9, 13, 15].

In recent years, mobile devices equipped with integrated depth sensors and LiDAR technology have emerged as a promising alternative to professional scanning systems. Compared with dedicated whole-body scanners, mobile solutions offer lower acquisition costs, greater portability, and improved accessibility, making them attractive for clinical, research, and consumer applications [11, 14, 16]. Advances in mobile depth-sensing technologies have enabled the development of applications capable of generating anthropometric measurements directly from handheld devices, thereby extending the availability of digital anthropometry beyond specialized laboratories [11, 14, 17, 18].

Recent studies have reported encouraging results for LiDAR-based body scanning systems. Callegari et al. [19] demonstrated that handheld LiDAR-equipped scanners are capable of achieving high precision and accuracy under controlled conditions, although measurement performance remained dependent on scanning protocol and operator technique. Similarly, Zamotsin et al. [20] reported the feasibility of obtaining anthropometric measurements using the integrated LiDAR sensor of the iPhone 12 Pro, highlighting the growing potential of consumer-grade devices for body measurement applications. Nevertheless, the authors emphasized that further validation against established anthropometric methods remains necessary before widespread adoption in clinical and technical practice.

A recent systematic review by Mocini et al. [10] highlighted the growing diversity of digital anthropometric technologies while simultaneously emphasizing persistent differences in accuracy, reliability, and validation methodologies among available systems. Furthermore, existing studies often differ substantially in experimental design, measurement protocols, and evaluated anthropometric dimensions, making direct comparison of published findings difficult [10]. While several investigations have validated either professional scanning systems [4, 19] or mobile scanning technologies separately [14, 20], evidence directly comparing professional whole-body scanners and mobile LiDAR-based anthropometric solutions under identical experimental conditions remains limited.

Therefore, this study aimed to quantify the agreement of two digital anthropometric systems—the professional TC² NX-16 whole-body scanner and the mobile LiDAR-based 3D Measure Up application—with reference manual anthropometry for five linear and five circumferential body dimensions.

Materials and Methods

Study Design

The study was designed to evaluate the agreement between manual anthropometric measurements and two digital anthropometric technologies representing different levels of complexity: a professional whole-body scanner (TC² NX-16) and a mobile LiDAR-based application (3D Measure Up). Manual anthropometry served as the reference method for the validation of both digital systems. The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the Technical University of Košice (protocol code 21276/2025, 17 March 2025). An overview of the study workflow is presented in Fig 1.

Participants

A total of 41 healthy volunteers were enrolled in the study. Participants were between 18 and 27 years of age, with a mean age of 19.59 years. The study population consisted of 27 males (65.9%) and 14 females (34.1%). The demographic characteristics of the study population are summarized in Table 1.

The mean body mass index (BMI) was 23.9 ± 4.3 kg/m². Based on BMI classification, the cohort included participants representing all major weight categories, including underweight, normal weight, overweight, and obesity. This variability was considered beneficial for evaluating the performance of digital anthropometric methods across different body proportions and body compositions.

Table 1: Participant Characteristics.

Characteristic	Value
Participants (n)	41
Male (n)	27 (65.9%)
Female (n)	14 (34.1%)
Age (years), mean ± SD	19.6 ± 1.8
BMI (kg/m²), mean ± SD	23.9 ± 4.3

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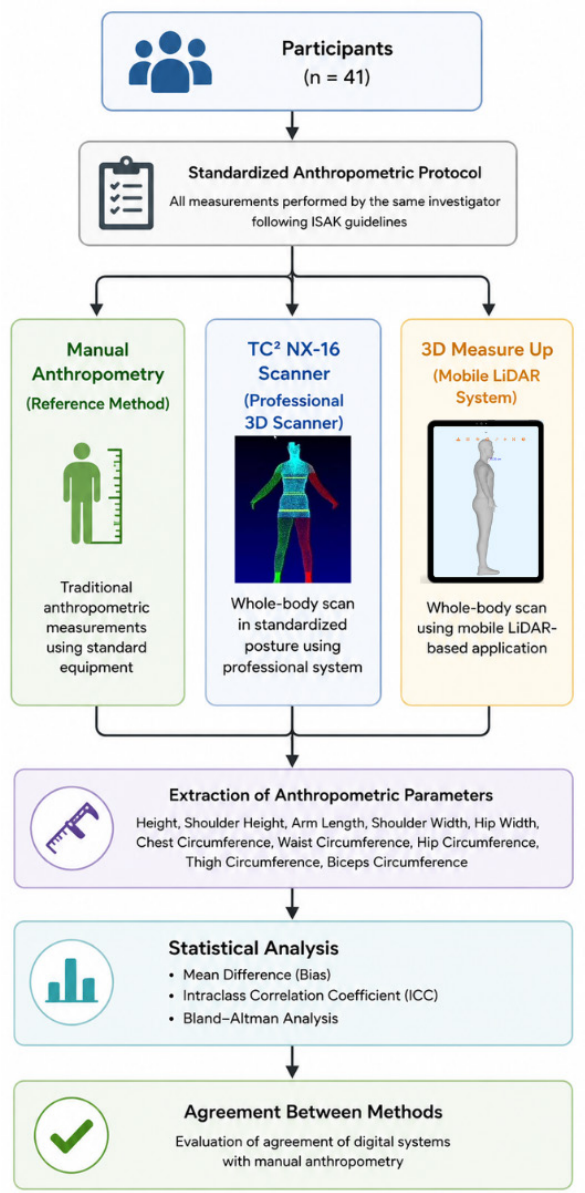


Fig. 1: Workflow of the study.

Only participants capable of maintaining the standardized measurement posture throughout the acquisition process were included in the study. All measurements were performed under identical environmental conditions and according to the predefined measurement protocol.

Measurement Environment

All measurements were performed under controlled laboratory conditions. To minimize the influence of external factors on measurement accuracy, environmental conditions remained constant throughout the study.

Participants were measured barefoot and wore close-fitting clothing to ensure adequate visualization of body contours and anatomical landmarks. Long hair was secured to prevent interference with body surface acquisition. Prior to data collection, participants were instructed about the measurement procedure and required body posture.

During both manual and digital measurements, participants adopted a standardized standing position based on anthropometric measurement guidelines. The same environmental conditions and the predefined system-specific acquisition protocols were maintained for all participants.

Anthropometric Measurements

Anthropometric dimensions were selected according to the definitions provided in ISO 7250-1. Both linear and circumferential body dimensions were included in the analysis to evaluate the performance of digital measurement systems across different types of anthropometric variables. The evaluated parameters included:

- Body height,
- Shoulder height (acromion height),
- Upper limb length,
- Hip breadth,
- Shoulder breadth (biacromial breadth),
- Chest circumference,
- Waist circumference,
- Hip circumference,
- Thigh circumference,
- Biceps circumference.

For manual measurements, anatomical landmarks were identified by the examiner before data acquisition. All measurements were performed using standard anthropometric instruments in accordance with established anthropometric procedures.

Manual Anthropometry

Manual anthropometric measurements served as the reference method for the evaluation of digital measurement systems. The measurement protocol was developed in accordance with ISO 7250-1:2017 and the International Standards for Anthropometric Assessment (ISAK). Anthropometric landmarks, body posture, and measured dimensions were standardized before data collection.

All measurements were performed by the same trained examiner using standard anthropometric instruments, including a flexible anthropometric tape and a sliding caliper. The use of a single examiner minimized inter-observer variability and ensured consistency throughout the study. Each anthropometric dimension was measured three times by the same trained examiner. The arithmetic mean of the three measurements was used as the reference value for subsequent analyses.

The selected anthropometric dimensions included body height, acromion height, upper limb length, hipbreadth, biacromial breadth, chest circumference,

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waist circumference, hip circumference, thigh circumference, and biceps circumference. These dimensions were selected to enable direct comparison between traditional anthropometry and digital 3D body scanning methods while representing both linear and circumferential body measurements.

TC² NX-16 Body Scanner

Digital anthropometric data were acquired using the TC² NX-16 whole-body scanner (TC² Labs, Cary, NC, USA). The system utilizes structured-light technology and multiple synchronized cameras positioned inside a scanning cabin to capture the entire body surface simultaneously.

Participants maintained a standardized standing posture during scanning. Following data acquisition, a three-dimensional body model was automatically generated, and anthropometric dimensions were extracted using the manufacturer's software.

3D Measure Up Mobile Application

The second digital measurement system was the 3D Measure Up application (developed by Protech Solutions), operating on an Apple device equipped with an integrated LiDAR sensor.

The scanning procedure consisted of moving the mobile device around the participant while maintaining an approximately constant distance. The acquired depth information was processed by the application to generate a three-dimensional body model. Anthropometric measurements were subsequently extracted automatically using the built-in software algorithms.

Statistical Analysis

Agreement between manual anthropometric measurements and digital measurement systems was evaluated using complementary statistical approaches. The mean difference (bias) was calculated to quantify systematic deviations between measurement methods. Agreement between methods was additionally evaluated using the intraclass correlation coefficient (ICC). ICC values were calculated using a two-way random-effects model with absolute agreement for single measurements (ICC(2,1)) and interpreted according to the recommendations of Koo and Li [21]. Bland–Altman analysis was performed to evaluate the agreement between methods and to identify potential systematic measurement errors across the range of measured values. Statistical analyses were performed separately for comparisons between manual anthropometry and TC² NX-16 and between manual anthropometry and 3D Measure Up.

For each participant, the paired difference was calculated as manual measurement minus digital measurement. Consequently, a negative bias indicates that the digital system overestimated the manual value, whereas a positive bias indicates underestimation. Results are reported as the mean paired difference (bias) and standard deviation (SD) of the paired differences. A two-sided one-sample t-test was used to determine whether the mean paired difference differed significantly from zero. A p value below 0.05 was considered statistically significant. Bland–Altman 95% limits of agreement were calculated as bias ± 1.96 SD. Statistical significance was interpreted as evidence of a systematic difference between methods and not as evidence of clinical importance.

Results

Agreement Between Manual Anthropometry and Digital Methods

Mean paired differences, standard deviations of the paired differences, and p values for all anthropometric parameters are presented in Table 2.

Table 2: Mean paired differences (bias), standard deviations, and statistical comparisons between manual and digital measurements.

Parameter	TC² bias ± SD (mm)	p	3D Measure Up bias ± SD (mm)	p
Body height	−3.29 ± 17.96	0.248	−5.92 ± 20.53	0.072
Shoulder height	3.32 ± 11.34	0.068	−7.71 ± 18.66	0.012
Upper limb length	7.15 ± 10.82	<0.001	−6.81 ± 14.76	0.005
Hip breadth	−8.35 ± 10.83	<0.001	−1.03 ± 9.80	0.505
Shoulder breadth	2.99 ± 9.77	0.057	−8.75 ± 10.13	<0.001
Chest circumference	−52.84 ± 53.57	<0.001	40.03 ± 49.70	<0.001
Waist circumference	−22.64 ± 24.42	<0.001	−21.45 ± 26.42	<0.001
Hip circumference	−16.78 ± 16.64	<0.001	−25.60 ± 38.55	<0.001
Thigh circumference	−3.39 ± 16.50	0.196	−23.45 ± 17.22	<0.001
Biceps circumference	−7.71 ± 9.17	<0.001	−20.15 ± 19.51	<0.001

For the five linear anthropometric dimensions, the absolute mean biases ranged from 2.99 to 8.35 mm

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for the TC² NX-16 scanner and from 1.03 to 8.75 mm for the 3D Measure Up application. For body height, the mean bias was −3.29 ± 17.96 mm for TC² NX-16 ($p = 0.248$) and −5.92 ± 20.53 mm for 3D Measure Up ($p = 0.072$). The largest absolute linear bias for TC² NX-16 was observed for hip breadth (−8.35 ± 10.83 mm, $p < 0.001$), whereas the largest absolute linear bias for 3D Measure Up was observed for shoulder breadth (−8.75 ± 10.13 mm, $p < 0.001$).

Circumferential measurements showed larger systematic differences than linear dimensions. Chest circumference demonstrated the largest absolute bias for both systems: −52.84 ± 53.57 mm for TC² NX-16 and 40.03 ± 49.70 mm for 3D Measure Up (both $p < 0.001$). For the remaining circumferential dimensions, absolute biases ranged from 3.39 to 22.64 mm for TC² NX-16 and from 20.15 to 25.60 mm for 3D Measure Up.

Systematic differences were statistically significant for six of the ten TC² NX-16 comparisons and eight of the ten 3D Measure Up comparisons.

Reliability and Agreement Analysis

The intraclass correlation coefficient (ICC) demonstrated generally high agreement between manual anthropometry and both digital measurement systems. Intraclass correlation coefficients for all evaluated anthropometric parameters are presented in Table 3.

For linear anthropometric dimensions, agreement ranged from good to excellent for TC² NX-16 (ICC = 0.89–0.99) and was excellent for 3D Measure Up (ICC = 0.91–0.97). The highest ICC was observed for shoulder height measured using TC² NX-16 (ICC = 0.99). For circumferential measurements, ICC values remained high for most parameters. TC² NX-16 achieved ICC values between 0.72 and 0.97, whereas 3D Measure Up achieved values between 0.83 and 0.95. The lowest agreement was observed for chest circumference measured using TC² NX-16 (ICC = 0.72), while the lowest ICC for the mobile application was found for biceps circumference (ICC = 0.83).

Across all evaluated dimensions, ICC values ranged from moderate to excellent for TC² NX-16 and from good to excellent for 3D Measure Up. Most parameters demonstrated good or excellent agreement, whereas chest circumference measured using TC² NX-16 showed moderate agreement.

For most parameters, the ICC values indicated that the relative ranking of participants was largely preserved despite the presence of systematic differences between manual and digital measurements. However, this pattern was weaker for chest circumference measured using TC² NX-16, which showed only moderate agreement.

Table 3: Intraclass Correlation Coefficients (ICC) and interpretation of agreement between manual anthropometry and the evaluated digital systems.

Anthropo-metric Parameter	TC² NX-16	Inter-pretation	3D Measure Up	Inter-pretation
Body height	0.98	Excellent	0.97	Excellent
Shoulder height	0.99	Excellent	0.97	Excellent
Upper limb length	0.96	Excellent	0.94	Excellent
Hip breadth	0.89	Good	0.94	Excellent
Shoulder breadth	0.95	Excellent	0.91	Excellent
Chest circumference	0.72	Moderate	0.93	Excellent
Waist circumference	0.95	Excellent	0.95	Excellent
Hip circumference	0.96	Excellent	0.88	Good
Thigh circumference	0.97	Excellent	0.91	Excellent
Biceps circumference	0.96	Excellent	0.83	Good

ICC values were interpreted according to the recommendations of Koo and Li: poor (< 0.50), moderate (0.50–0.75), good (0.75–0.90), and excellent (> 0.90) [21].

Bland-Altman Analysis

Bland-Altman plots for body height and chest circumference are shown in Fig. 2 and Fig. 3. All differences were calculated as manual measurement minus digital measurement, consistently with Table 2.

For body height, TC² NX-16 showed a mean bias of −3.29 mm, with 95% limits of agreement from −38.49 to 31.91 mm. The corresponding mean bias for 3D Measure Up was −5.92 mm, with 95% limits of agreement from −46.16 to 34.32 mm.

For chest circumference, the mean bias was −52.84 mm for TC² NX-16, with 95% limits of agreement from −157.84 to 52.16 mm. For 3D Measure Up, the mean bias was 40.03 mm, with 95% limits of agreement from −57.39 to 137.45 mm. Compared with body height, the substantially wider intervals observed for chest circumference indicate greater individual-level measurement uncertainty.

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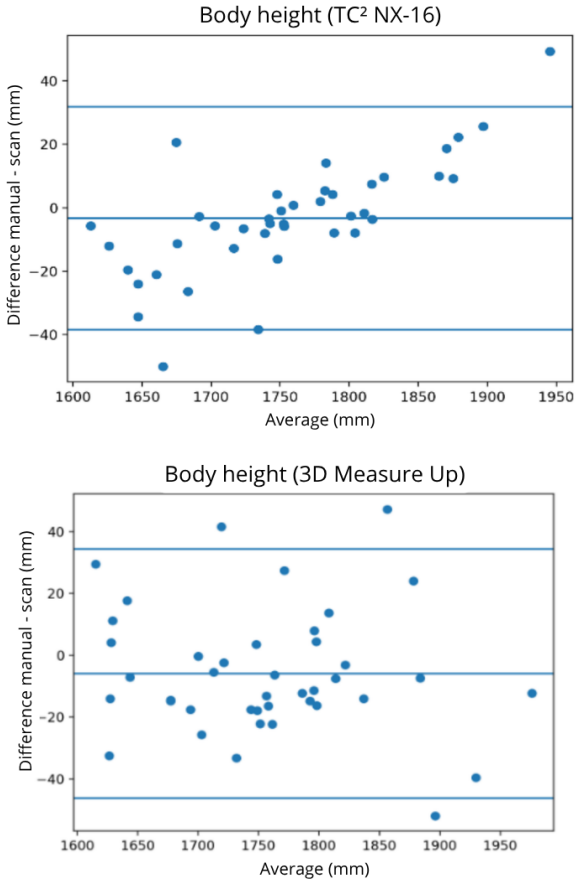


Fig. 2: Bland–Altman plots illustrating the agreement between manual anthropometry and the evaluated digital anthropometric systems for body height measurements: TC² NX-16 whole-body scanner and 3D Measure Up mobile LiDAR-based application.

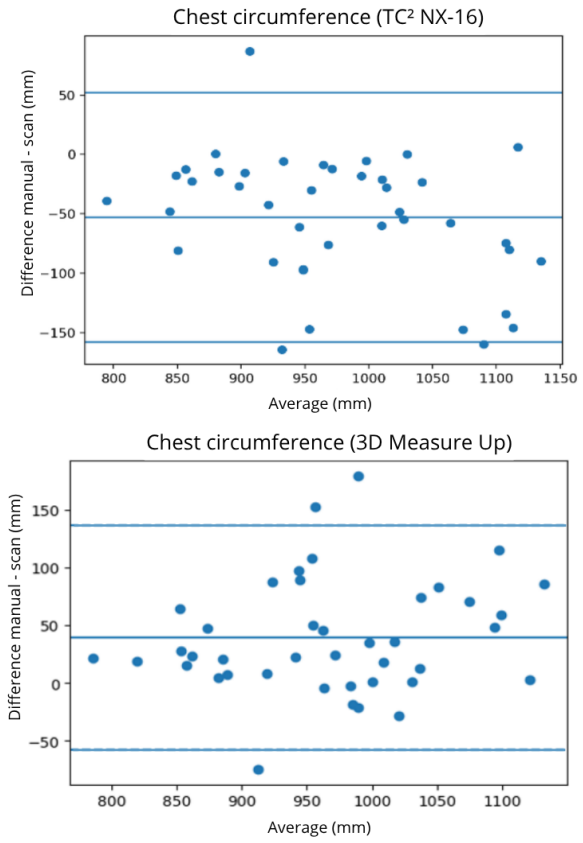


Fig. 3: Bland–Altman plots illustrating the agreement between manual anthropometry and the evaluated digital anthropometric systems for chest circumference measurements: TC² NX-16 whole-body scanner and 3D Measure Up mobile LiDAR-based application.

Discussion

This study yielded three principal findings. First, both digital systems showed good to excellent ICC values for most evaluated dimensions, particularly for linear measurements. Second, the magnitude and variability of paired differences were generally greater for circumferential than for linear dimensions. Third, a high ICC could coexist with a systematic bias and wide limits of agreement, demonstrating that preservation of the relative ranking of participants does not establish interchangeability with manual anthropometry.

Agreement was generally high for linear anthropometric dimensions, although this pattern was not uniform across all parameters. For TC² NX-16, hip breadth showed good rather than excellent agreement (ICC = 0.89), whereas several circumferential dimensions showed excellent ICC values. Similarly, 3D Measure Up achieved excellent agreement for most linear dimensions but also showed high agreement for selected circumferential measurements. These findings indicate that measurement type alone did not fully determine the agreement between manual and digital measurements. Previous studies have nevertheless reported favorable performance for large skeletal dimensions [4, 22].

Circumferential measurements generally showed greater variability than linear dimensions, although this pattern was not uniform across all parameters. For TC² NX-16, the largest systematic differences occurred for chest, waist, and hip circumferences, whereas thigh and biceps circumferences showed smaller mean biases. For 3D Measure Up, all five circumferential dimensions showed absolute mean biases exceeding 20 mm. Similar findings have been reported in previous validation studies of digital anthropometric systems, where circumferential dimensions were identified as the most challenging parameters for automated extraction from three-dimensional body models [4, 15, 23]. The accuracy of circumference measurements depends not only on the quality of the reconstructed surface but also on the correct

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identification of anatomical landmarks and the precise definition of the measurement plane [13, 15].

The greater variability of circumferential measurements cannot be attributed solely to a technical limitation of the mobile LiDAR sensor because the same general pattern was also observed with the professional structured-light system. The present study was not designed to quantify the independent contributions of sensor hardware and measurement methodology. Nevertheless, the findings support a combined explanation involving automated anatomical landmark localization, definition of the cross-sectional measurement plane, reconstruction of local soft-tissue geometry, respiratory phase, posture, and differences between contact tape measurement and non-contact digital measurement [4, 13, 15]. Mobile acquisition may introduce additional uncertainty related to operator trajectory, frame overlap, temporary occlusions, participant movement, sensor resolution, and surface-reconstruction algorithms [19, 20].

An interesting aspect of the results is the relationship between bias and ICC values. Several parameters demonstrated relatively large mean differences while maintaining high ICC values. This finding indicates that although systematic differences existed between manual and digital measurements, the relative ranking of participants remained largely preserved. In practical terms, the systems were able to consistently differentiate between individuals despite producing measurements that differed from the manual reference method. This distinction highlights the importance of evaluating both agreement and reliability when validating digital anthropometric technologies [4, 23].

The representative Bland–Altman analyses showed substantially wider limits of agreement for chest circumference than for body height. Because proportional bias was not formally evaluated using regression analysis, no definitive conclusion was drawn regarding the relationship between measurement error and measurement magnitude [4, 23, 24].

From a practical perspective, both evaluated digital systems may support the rapid acquisition of selected linear anthropometric dimensions under controlled conditions. However, the high ICC values should not be interpreted as evidence that the digital and manual methods are interchangeable. Suitability depends on the magnitude of the acceptable measurement error for the intended application, and digital measurements should be independently verified whenever absolute dimensional accuracy is critical.

The clinical relevance of the observed differences depends on the intended application. Errors of several millimeters may be acceptable for preliminary screening, ergonomic categorization, or applications followed by an individual fitting procedure. In contrast, wider limits of agreement are more concerning for patient-specific orthoses, prosthetic interfaces, compression garments, and longitudinal monitoring, where localized fit or relatively small changes over time may influence clinical decisions. For these applications, circumferential measurements obtained using either digital system should be verified manually or through an independently validated measurement workflow.

Future software development should prioritize anatomically constrained landmark detection, reproducible placement of cross-sectional measurement planes, region-specific surface reconstruction, and automated quality-control or confidence indicators. Allowing trained users to inspect and manually correct automatically detected landmarks and measurement planes could further reduce errors that are not apparent from a single automatically reported value.

The acquisition protocol should also be improved by standardizing clothing, posture, arm position, scanning distance and speed, and respiratory phase. Chest and waist measurements should preferably be acquired at the end of a normal expiration. Repeated scans, predefined rescanning criteria, and operator training should be considered for dimensions showing high variability. Future studies should prospectively evaluate whether these modifications reduce bias and narrow the limits of agreement.

Several limitations of the present study should be acknowledged. The participant sample consisted primarily of young adults, which may limit the generalizability of the findings to other age groups and body types. Furthermore, only one professional scanner and one mobile application were evaluated. Differences in hardware, software algorithms, and anthropometric landmark detection methods may influence the performance of other digital systems. Manual anthropometric measurements were performed by a single examiner; therefore, inter-observer variability was not evaluated. Future studies should include larger and more diverse populations and investigate additional scanning technologies under standardized experimental conditions.

Conclusion

Both TC² NX-16 and 3D Measure Up showed good to excellent ICC values for most evaluated dimensions, but agreement with manual anthropometry was dimension-dependent. Mean biases were generally smaller for linear dimensions, whereas circumferential measurements showed larger systematic differences, and the representative chest-circumference analyses demonstrated substantially wider limits of agreement than body height. Mobile LiDAR-based anthropometry may complement professional scanning for selected linear dimensions under standardized conditions, but circumferential measurements and measurements used for patient-specific decisions should be independently verified.

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Ing. Bibiána Ondrejová, PhD
Department of Biomedical Engineering and Measurement
Faculty of Mechanical Engineering
Technical University of Košice
Letná 1/9, 040 01 Košice

E-mail: bibiana.ondrejova@tuke.sk
Phone: +421 556 022 655