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External validation of a digital anthropometry application for estimating girths and body composition in physically active individuals: The Cybermetron Project – Phase 1

Validación externa de una aplicación de antropometría digital para la estimación de perímetros y composición corporal en individuos físicamente activos: Proyecto CyberMetron – Fase 1

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ABSTRACT

Introduction: Body composition assessment is essential for evaluating nutritional status, which influences physical performance and overall health. In recent years, digital anthropometry (DA) has emerged as a user-friendly tool that provides rapid and non-invasive estimates of anthropometric variables and body composition without the need for expensive equipment. However, external validation is still needed.

Methods: This cross-sectional study, conducted as part of phase 1 of the CyberMetron Project, aimed to externally validate a DA smartphone application by comparing its girth estimates against ISAK-standardized manual techniques and its body composition estimates against dual-energy X-ray absorptiometry (DXA) in physically active individuals. Robust statistics, correlation and agreement analyses were performed.

Results: A total of 141 adults (69F, 72M; 28.1 [5.9] years; 67.3 [11.4] kg; 166 [8.7] cm) participated in this study. The DA application showed low-to-moderate correlation (r <0.5) and low concordance (Linn's coefficient, CCC<0.3) against girths measured under ISAK standards as well as low concordance and significant biases in body composition assessed by DXA. In women, the application consistently overestimated central girths but underestimated thigh girths and body fat percentage (26.4% vs. DXA: 31.1%). In men, it underestimated arm and thorax girths while showing low bias for waist and thighs, with body fat overestimation (27.1% vs. DXA: 22.8%).

Conclusions: Based on our findings, the methodological rigor of ISAK-standardized manual anthropometry is particularly relevant for initial diagnostics and precise adjustments in sports nutrition, while future research could explore a hybrid human-machine approach, leveraging the accessibility and reliability of DA for longitudinal monitoring of nutritional status.

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Keywords: supervised machine learning; mobile applications; computer-assisted image analysis; 3D imaging; body composition; kinanthropometry.

RESUMEN

Introducción: La adopción de buenas prácticas y estrategias nutricionales puede atribuirse a una mejor comprensión de los conocimientos y hábitos alimenticios, lo que favorece un buen rendimiento deportivo. El objetivo de este estudio fue evaluar los conocimientos nutricionales, los hábitos alimenticios y el cumplimiento de la dieta mediterránea entre los deportistas.

Metodología: Encuesta transversal a 70 deportistas adultos. Los datos se recopilaron mediante un cuestionario que evaluaba sus hábitos alimenticios, sus conocimientos nutricionales (Cuestionario abreviado de conocimientos sobre nutrición deportiva, A-NSKQ) y su adherencia a la dieta mediterránea (puntuación Medi-Lite). Los análisis estadísticos se realizaron con el software R (versión 3.0.3), con un nivel de significación establecido en $p < 0,05$.

Resultados: Los deportistas eran adultos jóvenes (18,9-27,8 años) con una media de 7,5 ± 2,8 años de práctica deportiva. La mayoría de los participantes (77,1 %) declararon consumir cuatro o más comidas al día. No se observaron diferencias entre sexos en el consumo de leche y derivados, cereales, legumbres o alimentos ricos en almidón, mientras que los hombres consumían en general otros grupos de alimentos con mayor frecuencia, excepto los productos dulces, que eran consumidos con mayor frecuencia por las mujeres ($p < 0,001$). El conocimiento nutricional general era bajo (46,5 %), con puntuaciones significativamente más altas en nutrición general que en nutrición deportiva (67,3 % frente a 36,9 %; $p < 0,001$). La adherencia a la dieta mediterránea fue moderada (puntuación media: 7,95), con puntuaciones más altas en los hombres que en las mujeres y un gran tamaño del efecto. No se observaron correlaciones significativas entre el tiempo dedicado al deporte y los conocimientos generales sobre nutrición ($r = 0,04$) o los conocimientos sobre nutrición deportiva ($r = 0,03$). Del mismo modo, la adherencia a la dieta mediterránea no se correlacionó significativamente con los conocimientos generales sobre nutrición ($r = 0,0001$), los conocimientos sobre nutrición deportiva ($r = 0,0013$) o los conocimientos totales sobre nutrición ($r = 0,0011$).

Conclusión: El presente estudio no encontró una correlación significativa entre los conocimientos nutricionales y la adherencia a la dieta mediterránea, ya que los atletas mostraron niveles bajos en ambos aspectos. Estos hallazgos subrayan la necesidad de intervenciones específicas de educación nutricional para mejorar los conocimientos y las prácticas alimentarias.

Palabras clave: Atletas; Alfabetización alimentaria; Conocimientos sobre nutrición deportiva; Dieta mediterránea; Hábitos alimenticios.

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KEY MESSAGES

- A smartphone-based digital anthropometry application demonstrated low-to-moderate agreement with ISAK-standardized manual girth measurements in physically active adults.
- Compared to DXA, the application underestimated body fat percentage in women but overestimated it in men, indicating algorithmic limitations in addressing sex-specific anatomical differences.
- Thus, the methodological rigor of ISAK-standardized manual anthropometry is particularly relevant for accurate diagnostic and initial/adjustment assessments.
- Further research is necessary to assess a potential human-machine approach that takes advantage of the accessibility and high reliability of digital anthropometry methods for follow-up reported in previous research.

INTRODUCTION

Advances in body composition assessment are of great interest to health researchers and professionals seeking reliable methods that accurately reflect an individual's physiological, nutritional and health status [1]. Among the most established techniques is dual-energy X-ray absorptiometry (DXA), a reliable and relatively fast method (2-5 minutes) for estimating bone mineral content and fat mass [2]. This technique has low measurement errors and subjects are exposed to minimal radiation. DXA limitations include lack of reference values for regions beyond the software developer's database, inability to estimate musculoskeletal mass (only providing fat-free mass), and requiring corrections for lean adipose tissue [3,4]. For assessing musculoskeletal mass, more appropriate methods exist such as magnetic resonance imaging (MRI) or computed tomography (CT), though these require certified professionals and involve higher equipment costs [3].

Anthropometry involves measuring human body parameters including body mass, stature, and arm span, along with girths, lengths, skinfolds, and breadths. While generally considered simple and cost-effective, its main limitations are the time required for measurements (>15 minutes) and dependence on trained professionals to reduce intra- and inter-observer error[5]. Technological advances have increased interest in artificial intelligence and deep learning applications [6]. In fact, the COVID-19 pandemic has spurred research on digital anthropometry worldwide [7,8] as a cost-effective and field-friendly approach that has gained prominence as a potentially valid and rapid methodology [9]. While promising 3D optical systems exist, most remain limited to scientific research due to their high cost (10,000–20,000 USD) [10]. Consequently, smartphone applications using supervised machine learning algorithms to estimate body composition across populations have been developed [11]. Preliminary evidence suggests digital anthropometry requires less time and could be self-administered compared to other methods [12]. Although this technology may become an economical, reliable, and rapid tool [6], current studies indicate the need to standardize technical processes for data collection and analysis [12], validate estimates against conventional anthropometry [11], develop multi-compartment models [13], and establish recommendations for different populations [14].

Additionally, previous studies using anthropometric data have followed the National Center for Health Statistics of United States of America procedures manual [15] which does not fully comply with the standards set by the International Society for the Advancement of

Kinanthropometry (ISAK) [16]. This raises a key question: to what extent is a machine learning-based digital anthropometry application valid for estimating girths and body composition in the physically active populations? Thus, the aim of this study was twofold: i) to validate girth estimates from a digital anthropometry application using ISAK standardized measurements as the reference, and ii) to validate body composition estimates from the same application against DXA as the reference standard.

METHODOLOGY

Study Design

This was a cross-sectional study based on international recommendations for multicentric research to conduct external validation and assess whether a previously developed model performs adequately in a population different from the original[17]. Findings are reported according to the Strengthening the Reporting of Observational Studies in Epidemiology–Nutritional Epidemiology (STROBE–nut) guidelines, an Extension of the STROBE Statement[18].

Setting

This investigation is part of the CyberMetron Project by DBSS (ClinicalTrials.gov ID: NCT07003516), originally formulated by Bonilla (2022)[19], and developed with the support of Universidad CES and Fundación Universitaria del Área Andina. Conventional and digital anthropometry as well as DXA data were collected during the first semester of 2025.

Participants

Men and women from Medellin, Bogotá, and Pereira with moderate-to-high physical activity level were recruited. Inclusion criteria included: i) adults (>18 years old); ii) individuals classified into moderate or high physical activity levels according to the IPAQ questionnaire; iii) individuals who voluntarily sign the informed consent; iv) individuals residing in the abovementioned cities and nearby municipalities in the metropolitan areas. Individuals aged over 60, pregnant women, those with cardiometabolic or respiratory conditions, and anyone suffering from musculoskeletal injuries were excluded.

Variables

Continuous variables of this study include basic measures and girths (cm), assessed following the standards established by the ISAK and a machine learning-based digital anthropometry app. In addition, body fat percentage (%BF), fat free mass (FFM, kg), and lean soft tissue (LST, kg) were estimated via DXA and the digital anthropometry application.

Data sources/measurements

The measurements of eligible participants were conducted at the facilities of the participating Universities (Universidad CES [Medellín] and Fundación Universitaria del Área Andina [Bogotá and Pereira]). To minimize technical errors during the measurements, assessments were performed under controlled environmental conditions in all cities (<24 °C and <60 % humidity).

Physical Activity Level

Participants were categorized into three groups based on their physical activity levels (sedentary, physically active, and amateur athletes) using the validated short-form IPAQ questionnaire [20]. For this stage of the CyberMetron Project, only data from individuals with moderate-to-high physical activity levels were analyzed. The IPAQ instrument demonstrated acceptable internal consistency, with Cronbach's alpha values of 0.619 for moderate activity and 0.823 for vigorous activity. This consideration helps mitigate potential bias from variations in technical procedures and biological factors.

Digital Anthropometry

For this initial phase of the CyberMetron Project, digital anthropometric assessments were performed using a mobile 3D body scanning application (MeThreeSixty Premium, ME360; Size Stream, LLC) installed on three smartphone models (Redmi Note 13 Pro [Android 13], Apple 15 [IOS v18.4.1], and Xiaomi HyperOS [Android 15]). Using a proprietary artificial intelligence model, the application generates a 3D humanoid avatar by analyzing two-dimensional photographs taken from two angles (front and side views) [11]. The interactive features of the generated avatar have been linked to the perceived control, personalization, and responsiveness of consumers [21]. Table 1 presents the measurement protocol recommendations, which integrate both commercial developer guidelines and our research team's prior standardization efforts [19,22]. Following the ISAK philosophy and procedures, recognizing the critical need for methodological consistency and anatomic rigor, strict adherence to these recommendations will improve measurement precision and reproducibility.

Table 1. Procedures of digital anthropometry assessment.

Aspect	Procedures
Clothing	Wear form-fitting, solid-colored clothing that contrasts with the background. Avoid patterns or stripes that may interfere with silhouette detection. Remove bulky accessories and tie back long hair.
Activity Restrictions	Refrain from physical exercise at least two (2) hours prior to assessment.
Environmental Conditions	Maintain a comfortable room temperature (<25°C) and relative humidity below 60%. Use artificial lighting.
Setup Requirements	Ensure a smooth, unobstructed wall background (minimum 1.5 x 2.5 m area). Remove paintings, plants, or furniture that may interfere with the capture.
Subject Positioning	Adopt the ISAK anthropometric position: standing upright with arms relaxed and hands in neutral position. Feet should align with the app's frame markers (approximately biacromial width).
Device Specifications	Use a smartphone with the MeThreeSixty® application (Size Stream, LLC, USA). Minimum 8-megapixel camera.
Device Placement	Mount phone on a tripod at omphalion height (between waist and knee), at a distance of 2 m. Ensure proper tilt.
Reporting & Avatar	Capture frontal and lateral photos correctly. Allow processing time for automated report generation. Export data to participant's file and save the avatar.
Number of Measurements	Aim for one verified measurement. If unachievable, perform two measurements to improve precision.

Anthropometry-based Analysis of Body Composition

All anthropometric assessments were conducted in compliance with the International Standards for Anthropometric Assessment by ISAK [16]. Body mass was measured to the nearest 100 g using a calibrated digital scale (Seca 874, Hamburg, Germany), while stature was determined with a precision stadiometer featuring 1 mm graduations (Seca 213, Hamburg, Germany). Girth measurements were obtained with a rigid, non-stretch metal tape (0.7 mm thickness; Lufkin w606PM, Apex Tool Group, Sparks, MD, USA). Waist girth was measured according to the ISAK protocol at the narrowest point between the lower costal (10^{th} rib) border and the top of the iliac crest. Abdominal measurement was assessed based on the NCHS protocol as midway between the previous landmarks. Certified ISAK anthropometrists performed all measurements, maintaining a technical error within the acceptable 1% threshold as specified by ISAK for L2 anthropometrists.

Dual-energy X-ray absorptiometry

All DXA scans were conducted in strict accordance with current technical standards of the International Society for Clinical Densitometry [23] and established laboratory protocols previously described by our research team [24]. Measurements were obtained using a Lunar Prodigy™ system (General Electric Healthcare, Madison, WI, USA) operated by a certified bone densitometry technician (L.F.B-B. and K.F.-H.). The system's proprietary software was employed for bone and soft tissue differentiation, edge detection, and analysis. The DXA unit demonstrated high reproducibility, with test-retest reliability coefficients of variation between 1.0% and 2.0%.

Study size

Based on prior recommendations [25], a minimum sample size of 130 participants would be required to achieve (at minimum) a determination coefficient (R^2) of 0.5 with excellent predictive power using three independent variables. A total of 149 Colombian participants (male and female) who responded to our recruitment call were identified as potentially eligible for external validation of girths. The validation of body composition estimates against DXA included only Medellín participants (*n* = 70) for convenience.

Statistical methods

Continuous variables are presented as mean and standard deviation (SD) unless specified. Statistical analyses followed current methodological standards from the XXXX Research Division [24]. For group comparisons, we implemented the Yuen-Dixon test with 20% trimmed means (μ_t) and 20% winsorized standard deviations (σ_w) as a robust alternative to conventional t-tests, providing superior Type I error control under heteroscedasticity [26]. Validation of digital anthropometry application outputs included correlation assessments (Pearson's *r*, R^2, adjusted R^2), root mean squared error (RMSE) and Linn's concordance coefficient (CCC), complemented by agreement analyses via Bland-Altman plots with 95% limits of agreement (LoA) [27]. All computations were set significance at $P<0.05$ and executed in R Studio v2025.05.0+496.

RESULTS

Validation of digital anthropometric girth measurements against ISAK standards

From an initial pool of 149 volunteers, eight participants were excluded (seven due to insufficient physical activity levels and one for inconsistent measurements). Consequently, 141 apparently healthy adults fulfilled the inclusion criteria and underwent complete evaluations using both ISAK protocols and digital anthropometry. As expected, clinically significant differences were found ($\xi > 0.7$) in body mass, stature, and the flexed and tensed arm girths when comparing sexes. No significant differences were found between physical activity levels (moderate versus high, see Supplementary Table S1). Table 2 summarizes the demographic and anthropometric characteristics of the final cohort.

Table 2. Characteristics of the study population

Validation with ISAK		**All (n = 141)** $\bar{X}$ **(SD) [95% CI]**	**Women (n = 69)** $\bar{X}$ **(SD) [95% CI]**	**Men (n = 72)** $\bar{X}$ **(SD) [95% CI]**	**p value**	**ξ**
City	Bogotá	40 (28.37%)	14 (20.29%)	26 (36.11%)		
	Medellín	66 (46.81%)	41 (59.42%)	25 (34.72)		
	Pereira	35 (24.82%)	14 (20.29%)	21 (29.17%)		
PAL	Moderate	31 (21.99%)	17 (24.64%)	14 (19.44%)		
	High	110 (78.01%)	52 (75.36%)	58 (80.56%)		
Age (years)		28.13 (5.98) [27.13, 29.1]	27.55 (5.54) [26.22, 28.8]	28.68 (6.36) [27.18, 30.18]	0.372	0.122
Body mass (kg)		67.35 (11.4) [64.45, 69.25]	60.79 (8.84) [58.67, 62.92]	73.63 (9.98) [71.29, 75.98]	<0.001	0.790
Stature (cm)		165.77 (8.76) [164.31, 167.23]	159.23 (5.58) [157.89, 160.57]	172.03 (6.33) [170.55, 173.52]	<0.001	0.956
Arm flexed and tensed (cm)		31.38 (4.04) [30.71, 32.05]	28.79 (2.99) [28.07, 29.51]	33.87 (3.29) [33.09, 34.64]	<0.001	0.881
Thigh middle (cm)		53.7 (4.68) [52.92, 54.48]	52.81 (4.72) [51.67, 53.94]	54.56 (4.50) [53.50, 55.62]	0.172	0.192
Validation with DXA		**All (n = 66)** $\bar{X}$ **(SD) [95% CI]**	**Women (n = 41)** $\bar{X}$ **(SD) [95% CI]**	**Men (n = 25)** $\bar{X}$ **(SD) [95% CI]**	**p value**	**ξ**
PAL	Moderate	10 (15.15%)	9 (21.95%)	1 (4.00%)		
	High	56 (84.85%)	32 (78.05%)	29 (96.00%)		
Age (years)		28.6 (5.84) [27.1, 30.0]	28.32 (6.21) [26.36, 30.28]	28.96 (5.27) [26.78, 31.14]	0.453	0.166
Body mass (kg)		66.3 (11.75) [64.45, 69.25]	61.30 (9.42) [58.33, 64.28]	74.57 (10.59) [70.20, 78.94]	<0.001	0.810
Stature (cm)		165.1 (8.54) [163.0, 167.2]	160.36 (5.89) [158.50, 162.22]	172.74 (6.34) [170.13, 175.36]	<0.001	0.896
BMC (kg)		2.42 (0.43) [2.31, 2.52]	2.23 (0.34) [2.12, 2.34]	2.72 (0.41) [2.55, 2.89]	<0.001	0.857
Fat mass (kg)		18.34 (5.85) [16.97, 19.72]	19.24 (5.39) [17.54, 20.94]	16.88 (5.69) [14.53, 19.23]	0.039	0.377

Data are presented as mean (standard deviation) unless otherwise is indicated. ξ: Cohen's ξ; PAL: physical activity level. Statistically significance ($p < 0.05$ of the two-tailed p value) for the Yuen-Dixon test would indicate difference between women and men. BMC: bone mineral content.

Although statistically significant, all variables showed low-to-moderate correlation (r<0.5) values when comparing digital anthropometry and the ISAK measures. Digital anthropometry underestimated relaxed arm girths compared to ISAK standards (right: -1.10 cm; left: -0.40 cm). Forearm measurements showed the highest concordance (right CCC = 0.340; left CCC = 0.321), with minimal mean differences (≤0.30 cm) between methods.

In contrast, abdominal, waist, and hip measurements exhibited the largest mean differences and widest limits of agreement (LoA), indicating reduced accuracy for central body segment assessments compared to peripheral measurements. In fact, RMSE values ranged from 2.17 cm (forearms) to 7.54 cm (chest), indicating greater error in torso measurements compared to limbs. Overall, digital measurements systematically overestimated trunk girth measures (abdominal: +4.40 cm; waist: +2.50 cm; hips: +2.00 cm) while underestimating thigh measurements (right: −0.7 cm; left: −1.5 cm) compared to ISAK standards. Figure 1A shows the concordance and Bland-Altman plots of the digital anthropometry application when comparing to ISAK measures.

The correlation analysis accounting for differences by sex revealed similar patterns with no relevant differences when comparing women and men (Supplementary Table S2). However, the sex-specific Bland-Altman analysis showed certain differences. In female participants, digital anthropometry systematically over-estimated all core measurements, with particularly large biases for abdominal (6.46 cm) and waist girths (5.98 cm). The limits of agreement were notably wide for these regions (abdominal: -19.43 to 6.50 cm; waist: -16.78 to 4.82 cm), indicating substantial variability in measurement errors. Similar patterns emerged for thorax measurements (bias: 4.89 cm; 95% LoA: -15.63 to 5.48).

Male participants showed more variable bias patterns. While digital measurements underestimated waist girth (bias: 0.65 cm; 95% LoA: -12.81 to 14.11) and thorax (bias: 4.04 cm; 95% LoA: -9.17 to 17.25), it overestimated hips (bias: 2.71 cm; 95% LoA: -14.39 to 8.98) and abdominal girths (bias: 2.40 cm; 95% LoA: -17.41 to 12.61). Notably, forearm measurements in women demonstrated consistent but smaller-magnitude biases (1.54 to 1.58 cm), while thigh measurements in both sexes showed modest under-estimation (women: 0.87-1.65 cm; men: 0.58-1.21 cm).

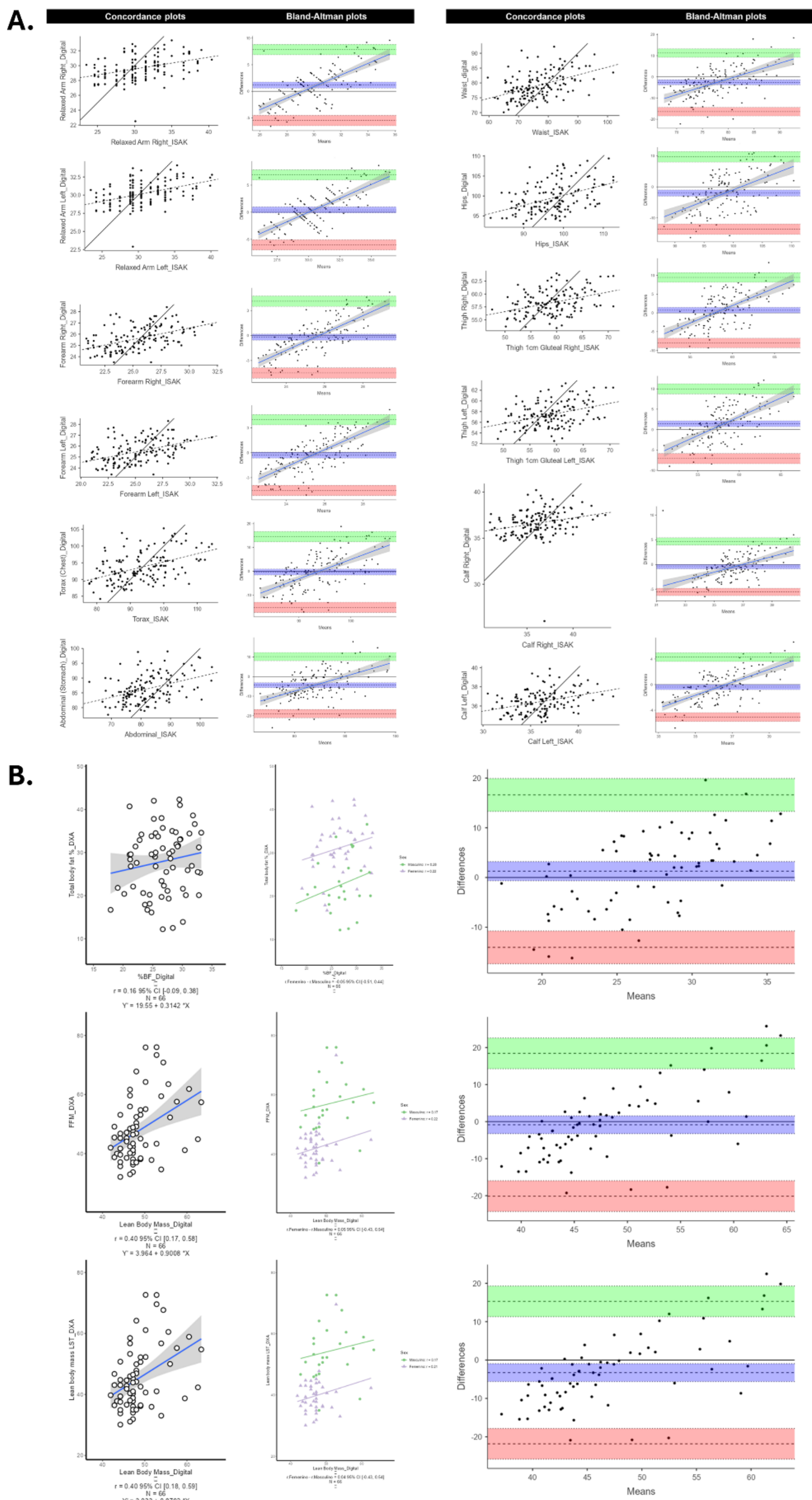

Figure 1. Correlation and agreement analysis of digital anthropometry against ISAK and DXA measurements. **A.** Concordance and Bland-Altman plots of the digital anthropometry against ISAK measures. Left, concordance plot between digital anthropometry (Y-axis) and ISAK protocol measurements (X-axis). The solid line represents perfect agreement while the dotted line corresponds to the best bivariate fit. Right, Bland–Altman plot for differences between measured and estimated values. Bias (blue), upper, and lower limits of agreement with their corresponding confidence intervals as well as the regression fit of the differences on the means (as solid blue line) are shown. **B.** Scatter correlation and Bland-Altman plots of digital anthropometry against DXA measurements. Left, scatter correlation plots for all data. The figure also displays the correlation coefficients (Pearson's *r*) by sex. Right, Bland–Altman plot for differences between measured and estimated values. Bias (blue), upper, and lower limits of agreement with their corresponding confidence intervals as well as the regression fit of the differences on the means (as solid blue line) are shown.

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Validation of digital anthropometric body composition against DXA

Initially, 70 individuals of both sexes were considered for eligibility. However, four women were excluded due to low physical activity level. Therefore, a total of 66 participants were included in the analysis. Table 3 summarizes the demographic and anthropometric characteristics of these participants.

Table 3. Correlation and validation metrics for girths and body composition.

Girth (cm)	Digital $\bar{X}$ (SD)	ISAK $\bar{X}$ (SD)	M_{diff}	Pearson's *r* [95% CI]	R^2	aR^2	RMSE	CCC	Bias [95% LoA]
Arm relaxed (right)	29.7 (1.57)	30.8 (3.67)	−1.10	0.371 * [0.245, 0.486]	0.138	0.132	3.39	0.247	1.17 [−5.51, 7.85]
Arm relaxed (left)	30.2 (1.61)	30.6 (3.65)	−0.40	0.434 * [0.313, 0.540]	0.188	0.182	3.28	0.317	0.42 [−6.01, 6.87]
Forearm (right)	25.6 (1.06)	25.5 (2.50)	0.10	0.477 * [0.362, 0.578]	0.228	0.222	2.19	0.340	−0.18 [−4.49, 4.12]
Forearm (left)	25.5 (1.06)	25.2 (2.43)	0.30	0.443 * [0.324, 0.548]	0.196	0.190	2.17	0.321	−0.28 [−4.54, 3.98]
Chest	93.7 (4.51)	93.3 (8.50)	0.40	0.456 * [0.339, 0.560]	0.208	0.202	7.54	0.377	−0.33 [−15.21, 14.55]
Abdominal	86.3 (4.57)	81.9 (8.01)	4.40	0.409 * [0.286, 0.519]	0.167	0.161	7.29	0.287	−4.39 [−18.94, 10.17]
Waist	79.1 (4.46)	76.6 (7.94)	2.50	0.469 * [0.353, 0.571]	0.220	0.214	6.99	0.370	−2.59 [−16.41, 11.23]
Hips	99.6 (3.75)	97.6 (6.51)	2.00	0.436 * [0.316, 0.542]	0.190	0.184	5.84	0.352	−2.00 [−13.62, 9.63]
Thigh (right)	58.3 (2.37)	59.0 (4.79)	−0.7	0.385 * [0.260, 0.497]	0.148	0.142	4.41	0.300	0.72 [−8.00, 9.45]
Thigh (left)	57.4 (2.33)	58.9 (4.68)	−1.5	0.382 * [0.256, 0.494]	0.146	0.139	4.31	0.283	1.43 [−7.12, 9.98]
Calf (right)	36.6 (1.51)	36.2 (2.54)	0.40	0.251 * [0.116, 0.377]	0.062	0.056	2.45	0.215	−0.44 [−5.55, 4.66]
Calf (left)	36.5 (1.18)	36.1 (2.54)	0.40	0.355 * [0.227, 0.471]	0.126	0.120	2.37	0.267	−0.38 [−5.07, 4.30]
Variable	**Digital $\bar{X}$ (SD)**	**DXA $\bar{X}$ (SD)**	**M_{diff}**	**Pearson's *r* [95% CI]**	**R^2**	**aR^2**	**RMSE**	**CCC**	**Bias [95% LoA]**
Body fat (%)	26.6 (3.73)	27.9 (7.48)	−1.30	0.156 [0.089, 0.384]	0.024	0.009	7.34	0.122	1.27 [−14.06, 16.60]
Fat-free mass (kg)	48.6 (4.75)	47.7 (10.7)	0.90	0.399 * [0.174, 0.585]	0.160	0.146	9.75	0.294	−0.85 [−20.12, 18.41]
Lean soft tissue (kg)	48.6 (4.75)	45.3 (10.3)	3.30	0.401 * [0.176, 0.586]	0.161	0.148	9.38	0.281	−3.27 [−21.83, 15.29]

Data is presented as mean (standard deviation) unless otherwise is indicated. The thigh girths presented in the table correspond to the thigh 1 cm gluteal as the ISAK protocol. Digital anthropometry reports a single variable called "lean body mass" that we compared to both FFM and LST from DXA ξ: Cohen's ξ; aR^2: adjusted coefficient of determination; CCC: Linn's concordance correlation coefficient; CI: confidence interval; M_{diff}: absolute mean difference between digital anthropometry and ISAK/DXA measurements; R^2: coefficient of determination; RMSE: root mean squared error. * Statistically significant Pearson correlation ($p < 0.05$).

Correlations were weak-to-moderate (Pearson's *r* ranging from 0.156 to 0.401), with CCCs <0.30 for all variables. Furthermore, concordance analyses revealed limited agreement between digital anthropometry and body composition measured by DXA. For example, for body fat percentage (%BF), the digital method underestimated DXA by −1.3% (CCC: 0.122; RMSE: 7.34%), with wide LoA (−14.06 to 16.60). However, sex-stratified analyses showed contrasting biases since digital anthropometry underestimated %BF (bias: 4.69%; LoA: −7.91 to 17.29) in women while overestimated this variable (bias: 4.32%; LoA: −17.36 to 8.71) in men. The digital anthropometry application reports a variable called "lean body mass" which we compared in this validation study to FFM and LST by DXA. Indeed, digital anthropometry overestimated both FFM and LST. Notwithstanding, we found sex-based differences since digital data overestimated FFM in women (bias: 5.08 kg; LoA: −18.57 to 8.42) but underestimated in men (bias: 6.07 kg; LoA: −13.76 to 25.90). Similar sex-divergent patterns were found for LST (Women: +7.31 kg; Men: −3.35 kg). See Figure 1B for Bland-Altman plots and check the Supplementary Table S1 for all output of this analysis by sex.

DISCUSSION

Correlations were weak-to-moderate (Pearson's *r* ranging from 0.156 to 0.401), with CCCs <0.30 for all variables. Furthermore, concordance analyses revealed limited agreement between digital anthropometry and body composition measured by DXA. For example, for body fat percentage (%BF), the digital method underestimated DXA by −1.3% (CCC: 0.122; RMSE: 7.34%), with wide LoA (−14.06 to 16.60). However, sex-stratified analyses showed contrasting biases since digital anthropometry underestimated %BF (bias: 4.69%; LoA: −7.91 to 17.29) in women while overestimated this variable (bias: 4.32%; LoA: −17.36 to 8.71) in men. The digital anthropometry application reports a variable called "lean body mass" which we compared in this validation study to FFM and LST by DXA. Indeed, digital anthropometry overestimated both FFM and LST. Notwithstanding, we found sex-based differences since digital data overestimated FFM in women (bias: 5.08 kg; LoA: −18.57 to 8.42) but underestimated in men (bias: 6.07 kg; LoA: −13.76 to 25.90). Similar sex-divergent patterns were found for LST (Women: +7.31 kg; Men: −3.35 kg). See Figure 1B for Bland-Altman plots and check the Supplementary Table S3 for all output of this analysis by sex.

DISCUSSION

This study represents the first rigorous validation of digital anthropometry against ISAK-standardized manual measurements, employing comprehensive statistical analyses across twelve anatomical sites in physically active individuals. We also validated the body composition estimates of digital anthropometry against DXA. Our results demonstrate systematic biases in digital measurements, particularly for trunk girths (e.g., +4.4 cm overestimation in abdominal girth, which is preferred by WHO/NCHS), while establishing limb-specific precision metrics that advance under-standing of this emerging technology's limitations. We found the widest limits of agreement for abdominal, waist and hips measurements, indicating this region may be particularly challenging for digital anthropometry application. Thigh measurements showed moderate agreement (CCC ≈ 0.38) with consistent digital underestimation (left: -1.5 cm; right: -0.7 cm). Calf measurements had the lowest concordance (right CCC = 0.251), despite small mean differences (0.40 cm). Forearm measurements showed the most consistent agreement between methods, though all CCC values fell below the 0.65 threshold for acceptable agreement.

These findings suggest digital anthropometry may have limited utility for clinical diagnoses or athletic evaluation requiring accurate values, such as body recomposition, energy availability or metabolic risk assessment through waist/abdominal girth. This observation aligns with previous studies such as Graybeal et al. (2023) [28], who reported differences of up to -2.5 cm (waist) and +3.7 cm (hip) compared to manual measurements, while Smith et al. (2022) [11] found mean differences ranging from +1.6 to +4.8 cm across various body girths (waist, hips, thigh, and arms). It is worth noting that these studies have followed the NCHS anthropometry procedures manual [15] but not ISAK standards. Sex-specific differences were also detected in our study cohort (Figure 2).

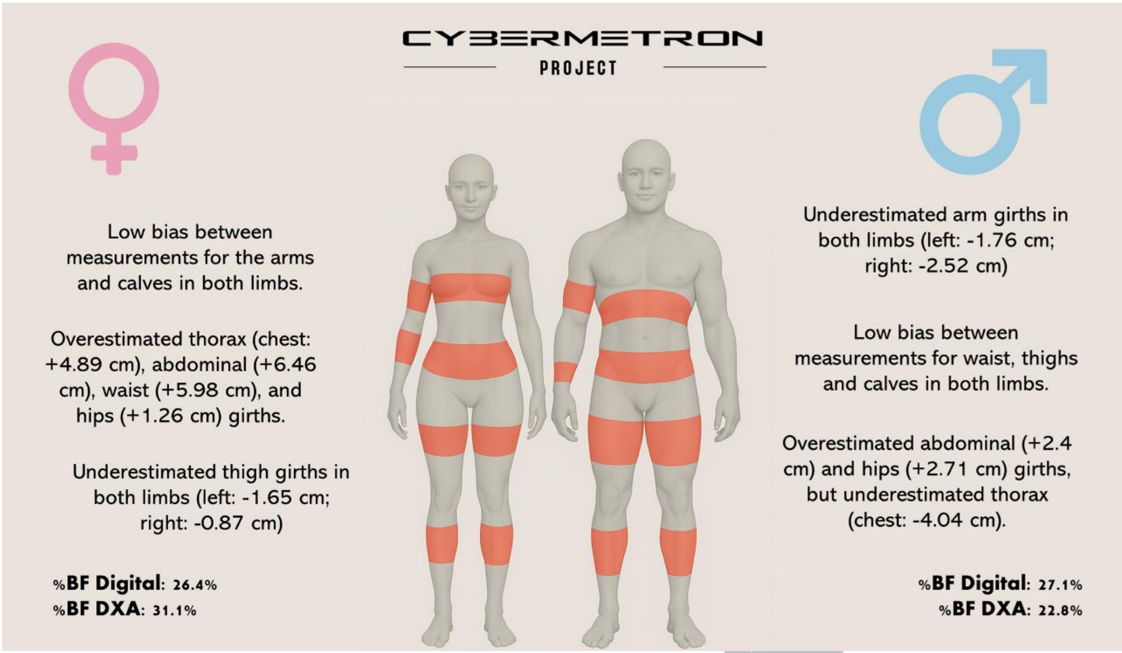

Figure 2. Overall findings of the CyberMetron study (Phase 1). Discrepancies in regional girth measurements (overestimation/underestimation) and body fat percentage (BF%) between digital and ISAK anthropometry or DXA methods are shown. Source: designed by the authors.

Recent research has shown promising results regarding the use of digital anthropometry for estimating body composition. Ferreira et al. [29] found high agreement in body fat percentage estimation when using two-dimensional photographs compared to DXA and other reference methods. Similarly, Farina et al. [30] demonstrated strong concordance for fat mass estimation using supervised machine learning, despite utilizing only a single lateral-image smartphone assessment in healthy adult Caucasian women and men.

Contrary to these findings, our validation of body composition outcomes against DXA revealed substantial bias in BF% and FFM estimates. Although correlations were statistically significant (p<0.05), low concordance (CCC: 0.122–0.294) and predictive power (R^2 values <0.16) were found. Notably, the observed errors (3–7 kg for FFM and >17 kg LoA ranges) exceed clinically acceptable thresholds for individual diagnostics. The sex-dependent biases suggest fundamental algorithmic limitations in accounting for anatomical differences. Among women, we observed systematic underestimation of %BF (4.69%) but overestimation of FFM and LST (5.08 and 7.31 kg, respectively), while men showed opposite in both variables (Figure 2). The overestimation of trunk girths in women suggests that the algorithms might be recalibrated for gynecoid adiposity. This sex-specific bias has direct implications for sports nutrition since the underestimation of %BF in women could lead to misclassification of health risk (e.g., false-negative assessments for Relative Energy Deficiency in Sport, RED-S), while overestimation of FFM may compromise energy availability calculations. Conversely, the opposite pattern in men may overestimate adiposity, potentially leading to unnecessary dietary restrictions [31].

These results align with Nana et al. [32], who demonstrated clinical equivalence of a digital anthropometry application with DXA only at ±2.5 and ±5.0% thresholds, though with better agreement for fat mass than bioelectrical impedance measures. Our results do not preclude the use of applications entirely, as despite its limited accuracy for single-time-point diagnosis, digital anthropometry exhibits high reliability (ICCs 0.975–0.999) [12], which makes it a suitable tool for longitudinal monitoring of body composition changes. In contrast to its limited diagnostic utility, this technology can reliably track directional changes (e.g., fat loss or lean mass gain) over time, provided the same application and protocol are used.

From a practical perspective, our results open the discussion of implementing a human-machine hybrid approach to anthropometric assessment. For diagnoses requiring high sensitivity (e.g., energy availability assessment based on FFM or cardiovascular risk evaluation via waist girth-based indices), we recommend adhering to ISAK-standardized manual measurements [16] due to the inaccuracy found with the app. However, digital anthropometry could serve as a complementary tool for longitudinal monitoring, particularly in populations where conventional anthropometry faces cultural and technical limitations (e.g., online coaching). For example, ISAK discourages taking skinfold measurements in populations with adiposity excess or very lean athletes (e.g., bodybuilders), making digital anthropometry a potentially valuable tool with low systematic error for tracking body composition changes over time. Beyond online coaching, this hybrid approach could also benefit other nutritional contexts such as remote weight-loss follow-ups, large-scale epidemiological surveillance, and populations with limited access to clinical facilities, where frequent in-person ISAK assessments are impractical. It is important to emphasize that more research is needed to correct the identified biases and to develop novel machine learning-based models using images adapted to specific geographic populations, which could lead to more robust practical applications (e.g., universal software [33]).

Limitations

This study is limited to one smartphone application; therefore, further external validation studies with larger sample sizes across diverse populations and more applications, along with the development of population-specific deep learning models are required. Readers should notice the low generalizability of the presented findings since data is restricted to physically active populations from three Colombian cities (Medellín, Pereira, and Bogotá). Also, the results derive from a cross-sectional observational study which makes necessary future studies on evaluating systematic biases and validating our proposed use of digital anthropometry for longitudinal follow-up and monitoring under a human-machine approach. Finally, the sample size for body composition validation using DXA (n = 66) warrants future external validation adhering to international guidelines for sample size (TRIPOD) [17]. Future studies should also prioritize the development of sex-specific and population-specific algorithms, as well as explore the integration of machine learning with anatomical priors (e.g., gynecoid vs. android adiposity patterns) to correct the systematic biases identified in this study. These represent ongoing research priorities within the next phases of the CyberMetron Project.

CONCLUSIONS

While offering potential to overcome certain technical and sociocultural barriers, digital anthropometry lacks sufficient accuracy for diagnostic purposes of body composition in physically active individuals when compared to ISAK-standardized manual measurements and DXA. The largest errors were observed in central girths (waist, abdominal [WHO and NCHS], and hips), with sex-specific biases as digital measurements consistently overestimated girths in females, while errors in males varied by body region. Regarding body composition, the application underestimated body fat percentage and overestimated FFM relative to DXA, with women being particularly susceptible to false-low adiposity readings and men to underestimation of FFM, both of which may compromise clinical assessments such as energy availability estimations in physically active individuals.

Thus, the methodological rigor of ISAK-standardized manual anthropometry is particularly relevant for accurate diagnostic and initial/adjustment assessments. Nevertheless, given the high reliability reported for digital anthropometry methods [12], future research should explore a human-machine hybrid approach that leverages their accessibility for longitudinal monitoring, provided that systematic biases are properly accounted for.

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AUTHOR CONTRIBUTIONS

Project and study design, D.A.B.; investigation, J.V.O.-L., D.E.A.-S., L.F.G.-V., L.F.B.-B, J.C.G., L.A.C. and L.T.D.-Z.; data curation, K.F.-H., J.C.G., and D.A.B.; software and formal analysis, D.A.B.; visualization, D.A.B.; writing—original draft preparation, D.A.B., J.V.O.-L., D.E.A.-S., L.F.G.-V.; writing—review and editing, L.F.B.-B, J.C.G., L.A.C., C.A.C.-D., K.F-H. and J.L.P.; funding acquisition, C.A.C.-D., K.F-H., and D.A.B. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

D.A.B. and K.F.-H. are certified Level Three Anthropometrists (Instructors) by the International Society for the Advancement of Kinanthropometry (ISAK). D.A.B. is the president of the upcoming ISAK World Conference on Kinanthropometry 2026, has conducted academic-sponsored research on anthropometry, is the leader of the CyberMetron Project, and has received honoraria for selling anthropometric equipment and speaking about anthropometry at international conferences/private courses. The other authors declare no conflicts of interest. All authors are responsible for the content of this article.

DATA AVAILABILITY

Data and statistical analyses are available for non-commercial scientific inquiry and/or educational if request and use does not violate IRB restrictions and/or research agreement terms.

PROTOCOL REGISTRATION

All procedures involving research study participants have been approved by the Research and Innovation Committee at Universidad CES (Acta224_Proy1181, 20th May 2024), and the trial registration was performed in Clinical Trials (CyberMetron_DBSS: NCT07003516).

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