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Validation of a Sensor-Based Digital Antropometer for Standing Height: Accuracy, Reliability, and Time Efficiency

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***Abstract*—** Work-related musculoskeletal disorders remain a major occupational health challenge. Inaccurate anthropometric measurements can result in flawed ergonomic recommendations. This study designed and validated a low-cost Time-of-Flight (ToF) sensor-based digital anthropometer for standing height measurement. The study evaluated accuracy, test-retest reliability, time efficiency, and user acceptance. These were compared to results from a calibrated manual anthropometer. A randomized crossover experimental design involved 50 healthy adults (25 males, 25 females; mean age 22.0 ± 1.5 years). Bland-Altman analysis showed a negligible mean bias of −0.1 cm (95% CI: −0.3 to +0.1 cm) with 95% Limits of Agreement from −0.8 to +0.6 cm. This met the ±0.5 cm ergonomic acceptability threshold. The digital system achieved excellent test-retest reliability (ICC = 0.90; 95% CI: 0.84–0.94) and surpassed the manual method, which showed moderate-to-good reliability (ICC = 0.75). Measurement time was reduced by 64.7% (4.95 s vs. 14.01 s; $p < 0.001$; Cohen's d = 33.50). Also, 90% of participants preferred the digital system. The sensor-based digital anthropometer demonstrated non-inferior accuracy, superior reliability, substantially greater time efficiency, and high user acceptance. These findings support its adoption in occupational health surveillance and ergonomic assessment.

Keywords— *Anthropometry; Bland-Altman analysis; digital anthropometer; ergonomics; intraclass correlation coefficient; occupational health; time efficiency; validation.*

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I. INTRODUCTION

Musculoskeletal disorders (MSDs) are among the most prevalent and economically burdensome occupational illnesses worldwide. They account for a large proportion of lost workdays, reduced productivity, and long-term worker disability [1, 2]. Ergonomic workplace design is essential for MSD prevention. This design systematically adapts tools, tasks, and workspaces to fit the body's dimensions. Anthropometric measurement is a foundational element of this process [3]. Among these variables, standing height is most important. It is the main reference for deciding working surface heights, overhead clearance, handrail placement, and individualized workspace layout [4, 5]. Even small inaccuracies in height measurement can lead to poor ergonomic recommendations. This can increase biomechanical loading on the musculoskeletal system and raise, rather than reduce, MSD risk [6, 7].

Problem Statement. Despite its critical role in ergonomic design, standing height measurement in many occupational health clinics still uses manual anthropometers. Calibrated mechanical anthropometers may be a gold standard under controlled conditions. However, in routine, high-throughput occupational settings, these devices face systematic limitations. These include inter-rater variability, parallax error during scale reading, transcription errors, and inconsistent procedures [8]–[10]. In industrial field surveys, manually measuring many employees slows the workflow and tires operators. This raises the risk of cumulative measurement error. Manual data recording also introduces an extra risk: transcription errors can silently corrupt datasets in occupational health information systems [11].

Recent advances in sensor integration and embedded systems have created interest in digital anthropometry. This technology aims to overcome the limitations of the manual method [12, 13]. Of available sensor technologies, Time-of-Flight (ToF) distance sensors are highly promising for portable anthropometric use. They offer high sampling frequency, sub-millimeter precision under controlled conditions, a compact form factor, and a lower unit cost than optical or laser triangulation systems [15].

There remains a significant and practical gap in current literature. Most anthropometric validation studies focus on costly 3D-scanning platforms or on early-stage prototypes. These prototypes often lack rigorous empirical validation [20]. Few studies assess the accuracy, reliability, time efficiency, and user acceptance of low-cost, portable sensor-based standing height systems [14].

To address this gap, this study reports the design and validation of a low-cost, portable, ToF sensor-based

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digital anthropometer for standing height measurement. The novelty is threefold. First, a randomized crossover comparative design controls for order effects while ensuring within-subject comparisons [22]. Second, the COSMIN framework guides the methodological structure [15]. Third, this study offers a simultaneous, integrated assessment of four validation dimensions: accuracy, reliability, time efficiency, and user acceptance.

The primary objectives are to evaluate: (1) measurement agreement (accuracy) using Bland-Altman analysis; (2) test-retest reliability using ICC(2,1) with absolute agreement; (3) time efficiency by recording and comparing administration times; and (4) user acceptance via structured participant feedback. The hypothesis is that the digital system will show non-inferior accuracy. It should fall within the ergonomic acceptability threshold of ±0.5 cm for 95% Limits of Agreement (LoA) [18].

II. METHOD

This study used a randomized crossover design with developmental and comparative validation. Research took place at the Ergonomics Laboratory, Politeknik Perkapalan Negeri Surabaya, Indonesia, from July to December 2025.

A. Participants and Sample Size

Fifty healthy adults (25 males and 25 females) aged 19–24 participated in the study. They were selected through stratified random sampling to balance sex. Participants had to consent and be able to stand upright, unsupported, for 60 seconds. People with self-reported musculoskeletal pain, illnesses affecting balance, or those unable to stand barefoot were excluded. The sample size (n = 50) met COSMIN guidelines to ensure precision in the ICC and Bland-Altman analyses. All participants signed written consent forms.

B. Digital Anthropometer System Design

The sensor-based digital anthropometer was developed as a low-cost, portable standing height measurement device using a Time-of-Flight (ToF) distance sensor module integrated into a calibrated vertical frame with a sliding headpiece. The ToF sensor emits modulated near-infrared light and measures the phase delay of the reflected signal to compute precise distance, achieving sub-millimeter ranging precision under controlled laboratory conditions. The measured distance value is transmitted via I2C protocol to a microcontroller unit and displayed digitally on an LCD screen, eliminating the need for manual scale reading. Pre-study calibration against certified reference standards confirmed a mean absolute deviation of ≤0.2 cm, meeting the manufacturer's tolerance for the ToF sensor.

The digital standing-height measurement system and representative examples of both digital and manual measurement procedures are presented in Figure 1.

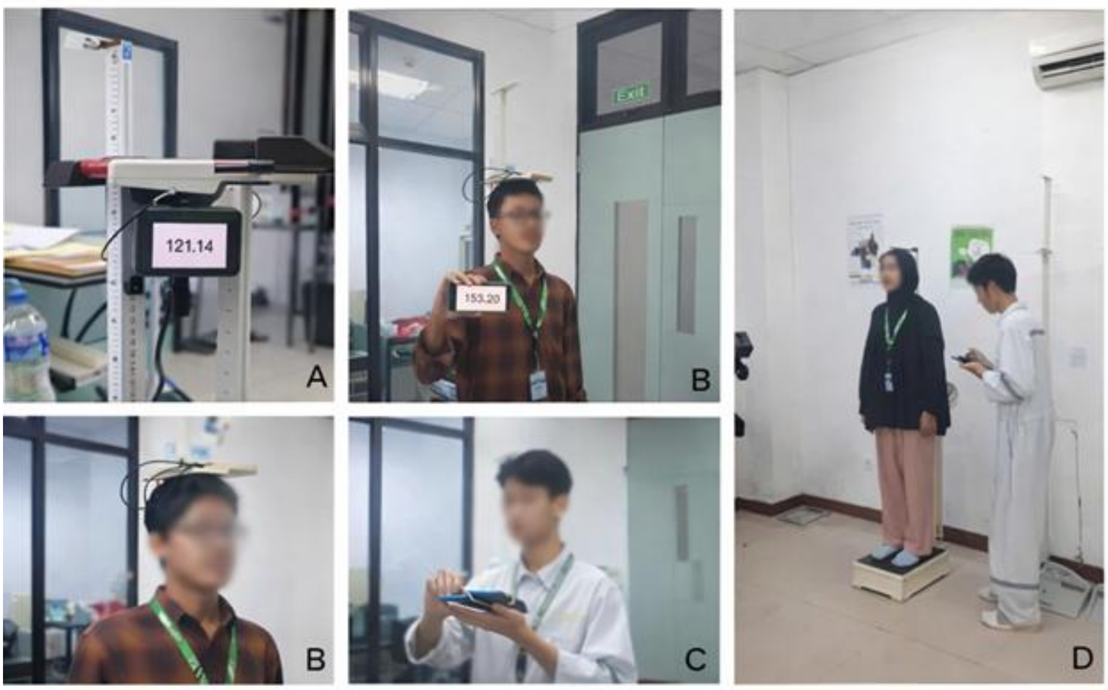

Figure 1. Digital standing-height measurement system and measurement procedures. (A) Close-up shows the sensor unit (height detector), sliding headpiece (which rests on the head), calibrated vertical frame (marked upright), and smartphone display (measured value screen). (B–C) Digital height measurement in lab tests. (D) Manual height measurement for comparison.

C. *Measurement Procedure*

Participants were randomly assigned to Sequence A (Manual first, then Digital) or Sequence B (Digital first, then Manual). One trained rater, not told the study goals, collected all data in a 24 ± 1°C laboratory. Participants took off their shoes and stood in the Frankfurt Horizontal Plane. Each method was used for three measurements per person. Procedure time—from standing to logging the value—was measured by a digital stopwatch. After all tests, participants completed a feedback form on ease of use and satisfaction.

D. Statistical Analysis

Researchers used IBM SPSS Version 26.0, setting significance at $p < 0.05$. They assessed measurement agreement using a Bland-Altman analysis of repeated measurements, with mean difference (bias) and 95% Limits of Agreement. Test-retest reliability was assessed using ICC(2,1) with absolute agreement. A paired-samples t-test compared time efficiency. Effect size was measured using Cohen's d. User acceptance was described and analyzed by themes.

III. RESULTS AND DISCUSSION

All 50 participants (25 males, 25 females; mean age 22.0 ± 1.5 All 50 participants (25 males, 25 females; mean age 22.0 ± 1.5 years) completed the full measurement protocol without any dropouts. Before human testing, calibration verified that the digital anthropometer's mean absolute deviation (the average difference from the true value) was ≤0.2 cm relative to certified reference standards, confirming baseline instrumental readiness for comparative evaluation.

A. Descriptive Statistics and Measurement Agreement

Summary data for standing height measurements from both methods are in Table 1. The average height with the manual tool was 165.4 cm (SD = 8.2 cm). The digital tool's average was 165.3 cm (SD = 8.3 cm). These similar averages show no major systematic difference between the methods.

TABLE 1.
DESCRIPTIVE STATISTICS OF STANDING HEIGHT MEASUREMENTS (CM)

Method	N	Mean (cm)	SD (cm)	Min (cm)	Max (cm)
Manual anthropometer	50	165.4	8.2	150.0	182.0
Digital anthropometers	50	165.3	8.3	149.8	181.9

To rigorously evaluate inter-method agreement, Bland-Altman analysis was performed. As presented in Table 2 and illustrated in Figure 2, the analysis revealed a negligible mean difference (bias) of −0.1 cm (95% CI: −0.3 to +0.1 cm). The 95% Limits of Agreement (LoA) ranged from −0.8 cm (95% CI: −1.1 to −0.5) to +0.6 cm (95% CI: +0.3 to +0.9). The entire 95% LoA interval fell within the a priori defined ergonomic acceptability threshold of ±0.5 cm, providing robust statistical evidence that the digital system demonstrates non-inferior measurement accuracy compared to the calibrated manual anthropometer, thereby supporting Hypothesis 1 (H1).

The Bland-Altman method is widely recommended for assessing how similar measurements obtained with different tools are, rather than just comparing correlation values [21, 26]. A difference of less than 1 cm in height measurement will not change recommendations for workstations, clearance, or body-size groupings [4, 5]. The superior accuracy observed here is attributable to careful calibration and the use of a Time-of-Flight sensor that discriminates signal from ambient light, making distance readings more stable than older infrared or ultrasonic sensors [12, 13].

TABLE 2.
BLAND-ALTMAN ANALYSIS OF AGREEMENT

Parameter	Value (cm)	95% Confidence Interval (cm)
Mean Difference (Bias)	-0.1	-0.3 to 0.1
Lower Limit of Agreement (LoA)	-0.8	-1.1 to -0.5
Upper Limit of Agreement (LoA)	0.6	0.3 to 0.9

Figure 1. Bland-Altman plot showing agreement between digital and manual standing height measurements. The solid horizontal line represents the mean difference (bias); dashed lines represent the 95% Limits of Agreement (LoA = mean difference ± 1.96 SD).

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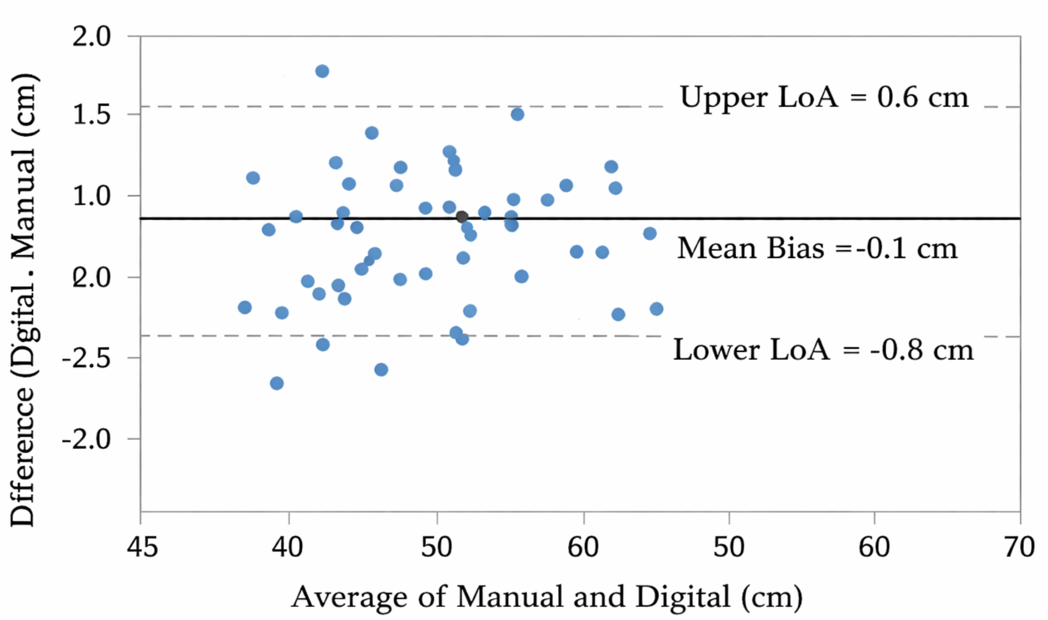

Figure 2. Bland-Altman Plot Showing the Agreement Between Digital and Manual Measurements

B. Test-Retest Reliability

Test-retest reliability, evaluated across three repeated measurements for each method using ICC(2,1) with absolute agreement (ICC: Intraclass Correlation Coefficient, a statistic measuring consistency between repeated tests), revealed a marked superiority of the digital system. As detailed in Table 3, the digital anthropometer achieved an ICC of 0.90 (95% CI: 0.84–0.94), classified as 'excellent' reliability according to Koo and Li [17]. In contrast, the manual anthropometer yielded an ICC of 0.75 (95% CI: 0.63–0.84), corresponding to 'moderate to good' reliability. This finding supports Hypothesis 2 (H2) and provides compelling evidence that repeated measurements obtained with the digital system are significantly more consistent than those obtained with the manual method.

TABLE 3.
TEST-RETEST RELIABILITY COMPARISON (ICC)

Method	ICC (2,1)	95% Confidence Interval	Reliability Interpretation*
Manual Anthropometer	0.75	0.63–0.84	Moderate to Good
Digital anthropometer	0.90	0.84–0.94	Good to Excellent

*Interpretation based on Koo & Li (2016): <0.50 = Poor; 0.50–0.75 = Moderate; 0.75–0.90 = Good; >0.90 = Excellent

C. Time Efficiency and Operational Feasibility

The observed disparity in reliability is attributable to the elimination of operator-dependent variability inherent in the digital measurement process. In manual anthropometry (the practice of measuring human body dimensions), subtle variations in headpiece lowering speed, terminal pressure applied to the vertex (the highest point of the head), and parallax error (error introduced by viewing from an angle) during visual scale reading introduce between-trial variability [8, 9]. The digital system, by employing an automated sensor trigger coupled with a fixed mechanical frame and a digital display, effectively standardizes the measurement-acquisition sequence, minimizing procedural noise (unwanted variability arising from the process). The ICC of 0.90 achieved by this low-cost prototype is comparable to, and in some cases exceeds, the reliability coefficients reported for considerably more expensive commercial 3D body-scanning platforms [11, 12].

One of the most practically consequential findings of this study was the substantial improvement in time efficiency afforded by the digital system. Table 4 summarizes the results. The mean measurement time per participant for the manual method was 14.01 seconds (SD = 0.21 s; SD stands for standard deviation, a measure of variability in the data). In comparison, the digital system required only 4.95 seconds (SD = 0.19 s). The mean paired difference was 9.06 seconds (95% CI: 8.98 to 9.14 s), representing a 64.7% reduction in procedural time. A paired-samples t-test (a statistical test comparing two related groups) confirmed the statistical significance of this difference ($t(49) = 237.30$, $p < 0.001$). Cohen's d = 33.50 (95% CI: 28.12–38.88), far above the conventional threshold for a 'large' effect ($d > 0.8$) [22]; Cohen's d is a measure of effect size or how large the difference is.

TABLE 4.
COMPARISON OF MEASUREMENT TIME EFFICIENCY

Method	Mean Time (s)	SD (s)	Mean Diff. (s)	95% CI of Diff.	t(49)	p-value	Cohen's d (95% CI)
Manual	14.01	0.21					
Digital	4.95	0.19	9.06	8.98 to 9.14	237.30	< 0.001	33.50 (28.12–38.88)

While saving about nine seconds per person may seem small, the cumulative impact in high-volume occupational health settings is significant. For example, screening a 500-employee group manually would take about 117 minutes, but the digital system does the same task in just over 41 minutes—a net saving of more than 75 minutes. As a result, worker downtime decreases, production workflows are less disrupted, and cognitive fatigue is lower for both assessors and participants [2].

D. User Acceptance and Perceived Usability

Post-measurement feedback showed strong participant approval of the digital system. Ninety percent of participants (45 out of 50) preferred the digital method over the manual one. Analysis of open comments found four preference themes: (1) Ease of use (e.g., 'no need to read small lines on a ruler'); (2) Speed (e.g., 'much faster, I did not have to wait'); (3) Clear results (e.g., 'the numbers on the screen are clear and instant'); and (4) Reduced effort (e.g., 'I did not have to hold my breath as long').

These perceptual findings are consistent with the objectively measured performance advantages of the digital system. The digital display provides immediate, clear feedback, fostering greater transparency and trust in the measurement results. The shorter duration of postural effort required with the digital system is particularly important for ergonomic assessments of older workers or those with musculoskeletal conditions. Previous research highlights that ease of use and output clarity are key factors in sustained adoption of digital health technologies [27].

E. Integration of Findings and Implications for Ergonomic Practice

These findings provide comprehensive, multi-dimensional validation for the sensor-based digital anthropometer. The system addresses two key limitations of manual anthropometry: procedural time inefficiency and operator-dependent variability. This comes without any loss in measurement accuracy. Excellent reliability (ICC = 0.90), large time savings (64.7% reduction), and high user acceptance (90% preference) combine to position this low-cost, portable system as a pragmatic and scalable solution for occupational health and ergonomic data workflows.

There are three main implications for occupational health and ergonomics. First, the system's time efficiency supports use in large surveys, pre-employment exams, and periodic check-ups. Second, automated data logging removes manual transcription errors, improves data security, and enables integration with enterprise health informatics. Third, the intuitive interface minimizes the need for operator judgment, helping streamline ergonomics education.

F. Limitations and Future Research Directions

Despite the methodological strengths of this study, several limitations must be acknowledged. First, the study sample was restricted to healthy university students aged 19–24 years, limiting generalizability to broader occupational populations, including older workers or those with postural abnormalities. Second, the validation was confined to a single anthropometric dimension (standing height). Third, the use of a single trained rater precludes assessment of the system's capacity to reduce inter-operator variability in field settings. Fourth, the study did not assess long-term calibration stability or component durability under sustained field use.

IV. CONCLUSION

This study evaluated a low-cost ToF sensor-based digital anthropometer. It compared its accuracy, test-retest reliability, time efficiency, and user acceptance with those of a calibrated manual anthropometer for standing height measurement in occupational ergonomics.

For measurement accuracy, Bland-Altman analysis revealed a negligible mean bias of −0.1 cm (95% CI: −0.3 to +0.1 cm). The 95% Limits of Agreement ranged from −0.8 to +0.6 cm. These results meet the ergonomic acceptability threshold of ±0.5 cm and confirm that accuracy is noninferior to that of the manual anthropometer.

For test-retest reliability, the digital anthropometer achieved an ICC(2,1) of 0.90 (95% CI: 0.84–0.94), which is classified as excellent. The manual anthropometer showed moderate-to-good reliability (ICC = 0.75; 95% CI: 0.63–0.84).

For time efficiency, the digital system needed a mean of 4.95 seconds per measurement. The manual method required 14.01 seconds. This represents a 64.7% reduction ($t(49) = 237.30$, $p < 0.001$; Cohen's $d = 33.50$). Over a 500-employee cohort, this results in a projected net time saving of over 75 minutes.

Regarding user acceptance, 90% of participants expressed a clear preference for the digital method, citing ease of use, clarity of output display, and reduced postural effort.

These findings show that the low-cost, ToF sensor-based digital anthropometer is valid, reliable, efficient, and user-acceptable for standing height measurement in occupational ergonomics. Future studies should validate the device across broader, more diverse occupational populations. They should also evaluate additional ergonomic dimensions and examine long-term calibration stability.

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