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3D BODY PROCESSING INDUSTRY CONNECTIONS

COMPARATIVE ANALYSIS OF ANTHROPOMETRIC METHODS: PAST, PRESENT, AND FUTURE

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COMPARATIVE ANALYSIS OF ANTHROPOMETRIC METHODS: PAST, PRESENT, AND FUTURE

ABSTRACT

The IEEE 3D Body Processing Industry Connections (3DBP IC) Group develops recommendations that foster interoperability for three-dimensional (3D) body processing, enabling an ecosystem for consumers and creators to use and interchange 3D human body anthropometric information. The 3DBP IC's Quality subgroup focuses on developing preliminary methods, tools, benchmarks, resources, and testing procedures to define and quantify the quality of 3D models as well as the quality of the critical metadata, such as body landmarks and measurements. To further this goal, the 3DBP IC Group completed a comparative analysis of anthropometric methods focused on body measurements and captured 3D body shapes.

The aim of this study is twofold: first, to propose a methodology to assess the compatibility and repeatability of different body measurement extraction methods (e.g., body scanners, smartphone apps, and traditional anthropometry) using consistent criteria, and second, to conduct data collection and the corresponding analyses for the first instance of the application of the proposed methodology.

The experimental study was conducted in two phases. Phase 1 took place in Portland, Oregon (USA) in 2018 and included two booth scanners and four traditional anthropometry measurers. Phase 2 took place in Valencia (Spain) in 2019 and included two booth scanners, four smartphone apps, and two traditional anthropometry measurers. A total of 133 subjects participated in the study. Participants were selected to represent a wide range of body heights and weights. Each subject had 11 body measurements collected twice by each measurer and measuring technology.

The proposed methodology synthesizes: varied, widely used mathematical tools (including statistical models); minimum sample size required for the analyses; and several estimators and plots appropriate for describing the data and quantifying the repeatability and compatibility of the different measurement extraction methods. It provides commonly used criteria to assess most of the statistics. In addition, the methodology includes a procedure to obtain comparable snapshots of the 3D outcomes from digital technologies, facilitating visual assessment by potential data consumers.

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This study has gathered a unique dataset that can be used for future research work. The results of the analyses of this dataset constitute useful benchmarks and references for similar studies. All of the participating technologies exhibited a good repeatability for the 11 body measurements considered; however, despite using similar measurement definitions, the compatibility between technologies was low, even for the experts using traditional anthropometry. These results highlight the need for definitions better adapted to 3D imaging systems as well as new methods to assess compatibility. The visual assessment of the 3D objects also shows a positive performance for all digital methods and reveals the differences between the various body scanning solutions and each of the phone apps.

Data and additional resources can be accessed at the IEEE website (https://standards.ieee.org/industry-connections/3d/bodyprocessing/), specifically measurement data, 3D data, and data from the analyses (i.e., tables, plots, and images).

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1. INTRODUCTION

The IEEE 3D Body Processing Industry Connections (IEEE 3DBP IC) Group is a collection of diverse stakeholders from across technology, retail, research, and standards development working together to streamline three-dimensional (3D) practices for widespread adoption around 3D body processing technology [1].[1]

Despite the rising number of body scanning solutions available to capture the human body shape and extract or estimate body measurements from it, there are no common practices among technology suppliers for assessing and reporting the performance of these systems. Therefore, it is not easy to compare technologies—and the data they produce—or to assess their suitability for a given use case.

The purpose of the work presented in this paper was to study different measurement methods that capture anthropometric data, using consistent populations, data cleaning processes, and analytical methods. Although there have been previous, similar studies that focus on the compatibility and reliability of different anthropometric methods, the unique aspects of this study are the number of anthropometric methods, the number of subjects, and the consistent methodologies to collect and analyze the data.

The high-level objectives of the study were to:

- Help body data "consumers" understand 3D body digitization technologies and make informed decisions when choosing the most suitable technology for their particular business needs,
- Create a common understanding among body scanning "providers" for reporting repeatability and compatibility, and
- Collect datasets enabling the development of new IEEE standards that complement existing ones—for example, International Standards Organisation (ISO) and American Society for the Testing of Material (ASTM) standards—and advancing research into new quality metrics for 3D bodies.

The low-level objectives of the study were to:

- Propose evaluation techniques (or methods) and consistent criteria to assess reliability and compatibility,
- Quantify and compare the repeatability and compatibility of a representative number of body measurement extraction methods (an example of the application of the proposed methodology is presented and reference values, or benchmarks, are provided), and
- Create and publicly release data resources, specifically, the 3D scans and the measurement data gathered in the study, making them available for other research works.

[1] Numbers in brackets reference the sources listed in Section 6.

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As a result, the 3DBP IC Group expects to demonstrate cross-platform compatibility evaluation techniques sufficient to instill confidence in various use-case scenarios and to propose methodology options for future application.

1.1. BACKGROUND

Anthropometry is widely used and deemed central to research and practice in a variety of industry contexts, such as apparel, ergonomics, and health assessment. Traditionally, anthropometric data collection has followed international guidelines and standards for taking body measurements physically over the body surface using equipment like stadiometers, tapes, calipers, and anthropometers [2]. Standardization bodies such as the International Society for the Advancement of Kinanthropometry (ISAK), ISO [3], [4], and ASTM [5] as well as reference studies like the Anthropometric Survey of U.S. Army (ANSUR) [6] and the National Health and Nutrition Examination Survey (NHANES) have provided direction [7]. Traditional anthropometric methods are widely used in industry, sports, and clinical practice because both the equipment and methods are affordable and accessible. These methods, however, rely on the training and skills of the measurer and are plagued by several shortcomings, including susceptibility to human error, time constraints, reliance on predictive equations to estimate complex anthropometrics, and a lack of standardized procedures for such measurements [8]. The accuracy and repeatability errors of traditional anthropometry are extensively reported in literature with a wide variety of results ranging from error values of a few millimeters to a few centimeters, depending on the body measurement and on the study (see [9]– [17]). Systematic biases between measurers lead to larger interobserver errors in studies involving more than one measurer [11], [13], [18]. Measurements taken by untrained measurers are less reliable and less accurate [19].

Over the past few years, 3D surface imaging has gained popularity as an anthropometric acquisition method due to the fast speed of contactless measuring, the availability of a 3D image, and the ability to acquire measurements that are not attainable through manual means. Also known as *body scanning* or *optical scanning*, 3D surface imaging captures the geometry of the human body surface as data points in a 3D space. The approach is particularly suitable for studies with large sample sizes and atypical populations because the creation of a digital 3D image permits both the immediate and retrospective analysis of data, the collection of vast amounts of data within a short timeframe, and the ability to produce a digital representation of body changes over time. The 3D image also presents an opportunity for the analysis of human size and shape using metrics out of the reach of traditional anthropometry, such as volume, area, and other geometric measurements. Due to these advantages, 3D imaging has experienced rapid market growth, expected to reach a value of at least $5.345 billion by 2025 [20]. A wide variety of 3D body scanners are available now [21]– [23]. They differ from each other in many ways, depending on—among other

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things—the 3D point cloud acquisition technology (e.g., photogrammetry, ultrasound, or projected light such as laser, white, or infrared); the number of sensors; and the type of embodiment (e.g., booths with static sensors, turntables for the body or for the sensors, and handheld scanners). Each body scanner incorporates its own software and computer vision algorithms to filter and clean the point cloud data and to create meshed surfaces out of it. These differences lead to very different specifications in terms of scanning volume, scanning resolution, and scanning time, as well as to variations in the quality of 3D outcomes. Different protocols have been proposed to evaluate the 3D accuracy of these systems using reference objects ([24]– [26]) but not with real subjects.

Most body scanners also incorporate software for the extraction or estimation of body measurements from the 3D content captured; in most cases, this software is fully automatic and does not require the interaction of a human. There is also standalone software for this purpose. The body measurements extracted from 3D scans can be as reliable as those obtained by trained measurers using traditional anthropometry ([16], [17], [27], [28]) and can be more reliable than those obtained by untrained users [29]. There is additional literature reporting accuracy and reliability errors for different 3D systems with human subjects ([30]– [39]) and with reference manikins [40]). The main sources of error for body measurements obtained by body scanning are: the resolution and 3D accuracy of the body surface obtained from scanning; body sway during scanning; slight posture changes between repeated scans; and the measurement extraction software [14].

The addition of high-quality cameras to smartphones and the increase in their computing power made it possible to create 3D body content with these ubiquitous and widely available devices [41]. There are two types of smartphone-based applications for body scanning. The first type uses photogrammetry principles for 3D surface reconstruction. Similar to a classic 3D imaging system, while the subject stands still in the scanning pose, the phone is used like a hand-held 3D scanner to capture a sequence of images from around the subject to obtain a large number of points of view [42]. The second type of phone-based technology uses sparse information—such as features extracted from one or two photographs (e.g., silhouettes or key points) along with other information that can be reported easily by a subject (e.g., gender, age, weight, or body height)—to estimate a 3D body avatar within a body shape model ([43]– [47]), typically developed from a dataset of thousands of 3D body scans ([48], [49]). Recently, these technologies have been improved by the development of deep learning techniques that facilitate the efficient and robust extraction of features from images [29]. There are other phone-based solutions that directly estimate body measurements from image features without producing any 3D body representation.

There are two fundamental differences between the model-based technologies and actual 3D imaging systems: first, the actual information captured from the real world is much lower (e.g., a 2D outline versus millions of 3D point coordinates), and second, the 3D bodies they can produce are constrained by the body model used. These

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differences provide several advantages and limitations. Model-based solutions are very robust and always provide a complete, watertight body representation within the parameters of the model. However, the accuracy of the 3D representation is dependent on the representativeness of the model and on the method used to compute the parameters of the model. As with any model, the ability to produce different outputs depends on the number of parameters and on the richness of the input. In theory, for the same underlying data model, model-based solutions that use richer inputs (e.g., an actual outline versus a distance between key points) potentially could cope better with diversity in body shape, provided that the input information is not redundant. For example, a solution that uses only body height and weight to create a 3D body human shape will be extremely robust but will not produce different bodies for two subjects of similar weight and height but with different torso shapes or limb lengths.

As previously mentioned, each body scanner or phone-based technology uses proprietary algorithms for the computation of body measurements from the 3D objects, which often leads to different locations for anatomical references and measurement values. Therefore, it is critical to establish standards to ensure cross-platform compatibility and suitability of use for the appropriate interpretation of the extracted data [50]– [54].

The compatibility between measurements obtained by different body scanners and measuring software is still an open issue being addressed by different standardization bodies such as ISO and the IEEE Standards Association (SA), as noted in references [55] and [56]. Most prior studies that compare the performance between anthropometric methods include just one body scanner and traditional anthropometry measurements. There is a lack of comparable datasets obtained by more than one scanner and more than one traditional anthropometry measurer. The different sample sizes, methods, and indicators used in these studies make it difficult to use them as reference data in new studies. Moreover, criteria for assessing the performance and compatibility of body measurements within and between different methods are limited. As a result of the ANSUR study, Gordon et al. [6] proposed criteria to accept or reject an expert measurer based on its reliability when taking repeated measurements. These criteria were more or less severe depending on the higher or lower repeatability error observed in the experimental study. These ANSUR thresholds are widely used to assess the repeatability of any anthropometric method. ISO 20685-1:2018 [64] sets the criteria to determine the valid compatibility between body measurements obtained from 3D body scanning technologies and those obtained by an expert using traditional anthropometry methods. These ISO thresholds are intended to be generalized to assess compatibility between two anthropometric methods. Both criteria are used and discussed in this study.

Analyses in this study will focus on the repeatability of each individual method and on the pairwise compatibility between technologies. This study does not focus on assessing the accuracy of body measurements acquired, and none of the technologies used is being considered as a ground truth.

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1.2. TERMINOLOGY

For the purposes of this document, the following terms, and definitions apply. Where possible, these are in concurrence with ISO 20685-1:2018 [64], ISO 13528:2015 [57], and ISO 3534-1:2006 [58].

- *3D imaging system:* Hardware and software system that creates a digital 3D image.
- *3D image:* Digital representation of a human form, or parts thereof, in three dimensions.
- *accuracy:* Extent to which the measured value approximates a true value [63].
- *analysis of variance (ANOVA):* A collection of statistical models and procedures used to analyze the differences among means in a sample.
- *anatomical landmark* or *anatomical reference:* Point clearly defined on the body that can be used for defining anthropometric measurements [4].
- *anthropometric:* As derived from individual body measurements (anthropometric data), for example, waist girth.
- *anthropometric database:* Collection of individual body measurements (anthropometric data) and background information (demographic data) recorded on a group of people (the sample) [65].
- *compatibility*: Extent to which the measured value of a system approximates the measurement value of another system.
- *demographic:* Background or descriptive information (demographic data), for example, age.
- *hardware:* Physical components of a 3D imaging system scanner and any associated computer(s).
- *kernel density estimation (KDE):* A non-parametric method of estimating the probability density function of a random variable.
- *linear mixed model (LMM):* Statistical linear model that allows for both fixed and random effects.
- *measuring station:* A station at which instruments are used for making measurements. For this study, it could be either manual measurements using a tape measure or a 3D imaging system.
- *morphometry:* Study of the size, shape, and relation between size and shape (allometry).

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- *point cloud:* Collection of raw 3D points (to be translated to a human axis system) in space referenced by their coordinate values [64].
- *repeatability:* Extent to which the values of a variable measured several times on the same subject is the same. It can be estimated between methods (interobserver) or with the same measurers (intraobserver).
- *software:* Operating system, user interface, programs, algorithms, and instructions associated with a 3D imaging system.
- *three-dimensional (3D):* Pertaining to the use of three orthogonal scales on which the three coordinates, x, y, and z, can be measured to give the precise position of any relevant anatomical point in the considered space [64].
- *z scores:* A standardized measure of performance calculated using the participant result, assigned value, and the standard deviation for proficiency assessment [58].

2. MATERIALS AND METHODS

2.1. GENERAL RESEARCH DESIGN

The design of the study was observational with repeated measures and was conducted in two phases, during which participants had a series of anthropometric measurements collected using different measurement methods.

According to optimal experiment design methods proposed by Walter et al. [59], a minimum number of 13 subjects is required to conduct reliability analyses for a test reliability hypothesis at 5% significance level with 80% power, a minimum acceptable intraclass correlation coefficient (ICC) of 0.8, an expected ICC of 0.95, and two repetitions. The minimum total number of participants per phase was set at 52 (4×13) so that future analyses could be also conducted with data segmentations by gender, age, body mass index, and any combination thereof, provided that the analyzed dataset included 13 subjects.

The study consisted of two phases: Phase 1 was carried out in December 2018 in Portland, Oregon (USA), and Phase 2 in October 2019 in Valencia (Spain). Participants were selected to represent a wide range of body heights and weights. Each subject had 11 body measurements collected twice by different measuring stations (3D scanning booths, smartphone apps, and traditional anthropometry experts). Phase 1 included two 3D scanners—Vitus bodyscan (Human Solutions GmbH) and SS20 (Size Stream LLC)—and four experts. Phase 2 included two 3D scanners: MOVE4D (Instituto de Biomecánica) and Portal MX (Texel LLC); four smartphone apps: 3D avatar body (Instituto de Biomecánica), SS@Home (Size Stream LLC), 3DLOOK (3DLOOK Inc.), and eM+ (PolyU); and two experts.

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Both phases were compliant with the applicable regulations at the date of the data collection for ethical human participant research and data protection in the United States[2] and Europe.[3] The two phases of the study were approved by the Institutional Review Board (IRB) of Kalypso and by the Comité de Ética en la Investigación of the Universitat Politècnica de València (CEI-UPV), respectively.

2.2. PARTICIPANTS

A total of 133 participants participated in the study (77 females and 56 males). Participants were proactively recruited for comprehensive body height and mass representation (see TABLE 1 and FIGURE 1). The recruitment in Phase 1 was coordinated by Kalypso and was announced via website, email, and flyers distributed in Portland. The recruitment in Phase 2 was coordinated by IBV and was communicated by email and phone using IBV's own database of participants. All participants were volunteers and consented to the use of their data in the study.

TABLE 1 Frequencies, mean ± standard deviation with range in parentheses, basic data for all participants, segmented by gender and phase

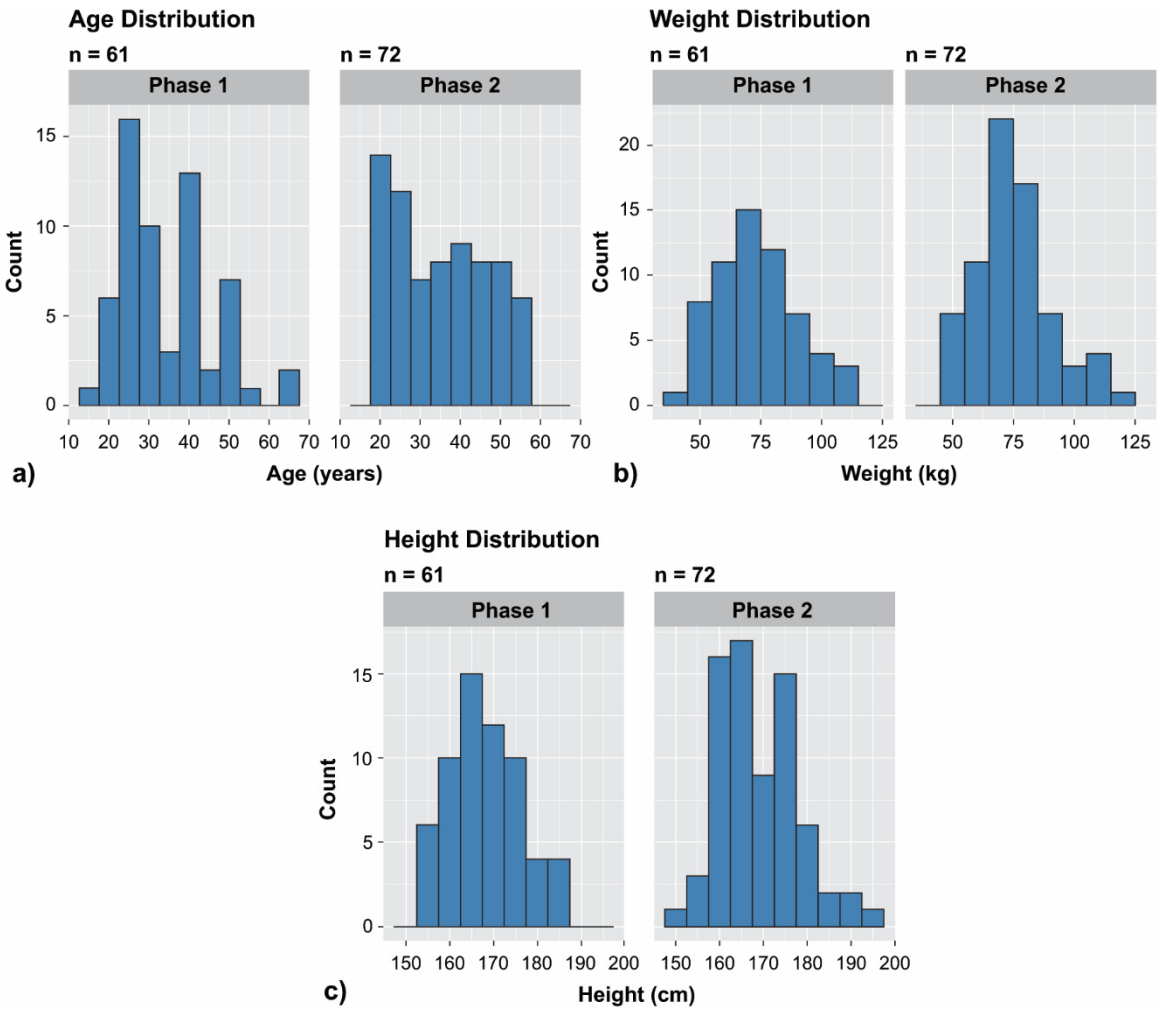
Phase	Demographic	Female	Male	Total
1	*N*	41	20	61
	Age (years)	32 ± 10 (16–57)	39 ± 13 (20–65)	34 ± 12 (16–65)
	Mass (kg)	70 ± 17 (46–114)	82 ± 16 (44–115)	74 ± 17 (44–115)
	Standing height (cm)	165 ± 6 (153–180)	174 ± 8 (156–185)	168 ± 8 (153–185)
2	*N*	36	36	72
	Age (years)	36 ± 13 (18–57)	33 ± 10 (18–55)	35 ± 12 (18–57)
	Mass (kg)	71 ± 16 (50–109)	81 ± 14 (62–122)	75± 16 (50–122)
	Standing height (cm)	163 ± 6 (150–181)	175 ± 8 (160–193)	169 ± 9 (150–193)
Total	*N*	77	56	133
	Age (years)	33.8 ± 11.9 (16–57)	35.5 ±11.3 (18–65)	34.5 ±11.7 (16–65)
	Mass (kg)	70.2 ± 16.2 (46.1–114.2)	80.9 ±14.6 (44.2–122)	74.7 ± 16.4 (44.2–122)
	Standing height (cm)	164.1 ± 6.1 (149.6–181)	174.5 ± 7.8 (156.3–193)	168.5 ± 8.6 (149.6–193)

[2] Social-Behavioral Education Foundations for Human Subjects Research, https://about.citiprogram.org/course/social-behavioral-educational-sbe-foundations/.

[3] General Data Protection Regulation (GDPR) is available from https://eur-lex.europa.eu/legal content/EN/TXT/PDF/?uri=CELEX:32016R0679.

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FIGURE 1 **Histograms showing the distribution of a) age, b) body mass, and c) standing height for each phase**



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2.3. DATA COLLECTION

Eleven body measurements were selected for inclusion in this study (TABLE 2 and FIGURE 2). Measurements were selected for industry relevance (apparel), body segment coverage, and type variety (i.e., lengths, girths, and heights).

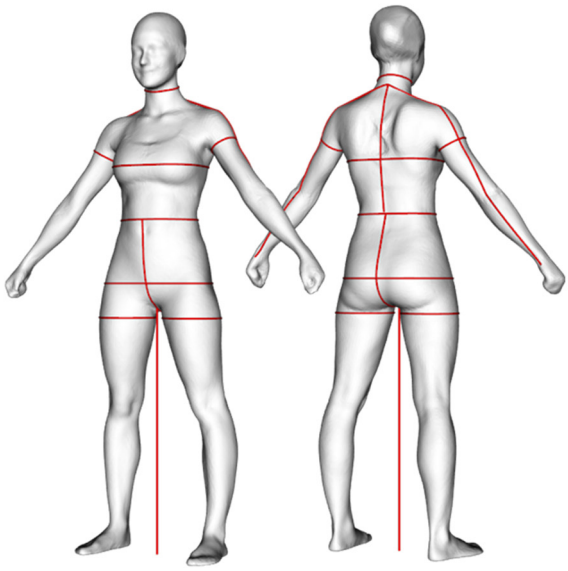
TABLE 2 **List of the designation and reference to ISO definitions of each of the measurements used in the study**

Number	Measurements	ISO Reference [3]
1	Neck girth	ISO 8559-1:2017, 5.3.2
2	Back neck point to waist	ISO 8559-1:2017, 5.4.5
3	Upper arm girth	ISO 8559-1:2017, 5.3.16

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Number	Measurements	ISO Reference [3]
4	Back neck point to wrist	ISO 8559-1:2017, 5.4.17
5	Across back shoulder width	ISO 8559-1:2017, 5.4.3
6	Bust girth	ISO 8559-1:2017, 5.3.4
7	Waist girth	ISO 8559-1:2017, 5.3.10
8	Hip girth	ISO 8559-1:2017, 5.3.13
9	Thigh girth	ISO 8559-1:2017, 5.3.20
10	Total crotch length	ISO 8559-1:2017, 5.4.18
11	Inside leg height	ISO 8559-1:2017, 5.1.15

FIGURE 2 Illustration of the 11 body measurements selected over the surface of a 3D avatar



Fourteen measuring stations—each using a different measuring method or technique—were set up for the study: six in Phase 1 and eight in Phase 2. They included both digital technologies and traditional methods (TABLE 3). The maximum number of stations at each phase was determined by the space and resources available at each location. IEEE IC 3DBP members were prioritized for participation. For Phase 2, the call for full body scanning booths and phone apps was open to any company complying with the minimum requirements, namely eligible candidates were able to: a) set up and operate the scanning station during the five days of the study; b) deliver a 3D file in standard format of the outer body surface (e.g., mesh or point cloud); and c) deliver the set of 11 body measurements (TABLE 2). The public call was posted on LinkedIn[4] and the IEEE website. Moreover, more than 30 companies and startups identified by the IEEE IC 3DBP Group were contacted directly by email.

[4]The call for participation was posted at https://www.linkedin.com/feed/update/urn:li:activity:6557973921222664192/.

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TABLE 3 Measuring stations participating in each phase by type of technology

Type	Phase 1	Phase 2
Traditional anthropometry experts	▪ Julianne Harris (Independent, apparel industry) ▪ Emma Scott (Fashion Should Empower) ▪ Gina Patterson (Independent, apparel industry) ▪ Ruth Dang (Independent, apparel industry)	▪ Emma Scott (Fashion Should Empower) ▪ Alice Bullas (ISAK Level 2; Sheffield Hallam University, Sports Engineering)
Full body scanner	▪ VITUS bodyscan, Human Solutions GmbH ▪ SS20, Size Stream LLC	▪ MOVE4D, Instituto de Biomecánica ▪ Portal MX, Texel LLC
Smartphone apps		▪ 3D avatar body, Instituto de Biomecánica ▪ Size Stream @Home, Size Stream LLC ▪ 3DLOOK, 3Dlook Inc. ▪ eM+, PolyU

In order to reduce the impact of clothing on the accuracy and compatibility of the measurement method, all participants were provided with the same type of form-fitting attire, which was compatible with all the measuring stations All participants wore close-fitting shorts on top of their own underwear. Female participants also wore tight-fitting tops over their own bras. In Phase 2, one station required a specific tight-fitting two-piece, full-body suit, which was worn on top of the other garments. Participants were allowed to keep the garments provided.

Upon arrival, all participants provided basic demographic data (i.e., age and gender) and were measured with digital scales (Tanita BF-684W and SECA) to acquire mass and stadiometers (SECA) to acquire standing height. In Phase 2, these data were used as input for the phone apps requiring it.

All participants were measured twice at each measuring station (FIGURE 3). In the case of digital stations, the 3D images or photographs were taken with repositioning between the two repetitions (i.e., participants went in and out at each repetition). At each station, the participants adopted the specified pose for that station; therefore, participants' poses were slightly different from one station to another. All digital stations were operated by personnel designated by each company (e.g., trained users took the images). Each measuring station was responsible for providing to the data manager the data gathered and processed (i.e., 3D images plus anthropometrics). For traditional anthropometry stations, to prevent both order and report effects and to ensure the measurers' independence, experts were not able to share methods; the measurers did not take repetition measurements consecutively (two to three other participants were measured between a participant's repetitions); stickers were allowed to mark body features but were refreshed at each repetition; and the measurement values were annotated on paper by an independent recorder. An independent annotator digitized both the traditional measurements and the basic characteristics gathered at intake.

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