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Plethysmographic and anthropometric validation of a 3D body image digitizer to determine body dimensions

Arnulfo Ramos-Jiménez[a,*], Rosa P. Hernández-Torres[b], Rafael Villalobos-Molina[c], René Urquidez Romero[a]

[a] Departamento de Ciencias de la Salud, Instituto de Ciencias Biomédicas, Universidad Autónoma de Ciudad Juárez, Chihuahua, Mexico
[b] Facultad de Ciencias de la Cultura Física, Universidad Autónoma de Chihuahua, Chihuahua, Mexico
[c] Unidad de Biomedicina, Facultad de Estudios Superiores Iztacala, Universidad Nacional Autónoma de México, Chihuahua, Mexico

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ABSTRACT

Image digitizing has facilitated body shape evaluation gained entry in ergonomics industry, in fashion and in health. Objective: to validate the 3D image digitizer (TC^2-18) to determine body dimensions in a fast and reliable manner. Methods: 285 adults of both sexes were studied to measure anthropometrics, plethysmography, and digitized body shape. Results: Digitizer obtained measurements highly correlated with those obtained through anthropometrics and plethysmography ($R^2 \geq 0.75$). However, the TC^2-18 gave lower values in total body volume when compared with plethysmography (CI 95%, −3.9 to −3.5 L). In contrast, the TC^2-18 yielded higher values in mesosternal (CI 95%, 8.8–9.6 cm), neck (CI 95%, 2.6–3.0 cm), *gluteus maximus* (CI 95%, 3.1–3.7 cm), relaxed arm (CI 95%, 2.9–3.3 cm), and minimal waist (CI 95%, 3.1–3.7 cm) circumferences; as well as similar data for the upper thigh, calf and forearm circumference. Conclusion: TC^2-18 3D digitizer yielded valid and reliable measures when adult persons are evaluated. Found differences occur due to movement during digitizing and by difference inherent to the used devices.

1. Introduction

There is a direct relationship between physical form (somatotype) and body components (fat mass, lean mass, muscular mass and bone mass) with health status and the physical-athletic performance, several methods to measure them have been proposed. Then in the physical form there are anthropometric measures (Norton and Olds, 1996); while for body components there are methods for image processing, such as computed tomography scan (Borkan et al., 1982), nuclear magnetic resonance (Fuller et al., 1999), and dual-energy x-ray absorptiometry (DEXA) (Bredella et al., 2013). Other methods include densitometry through plethysmography (Abler, 1995), helium dilution (Siri, 1961), underwater weighing (Goldman and Buskirk, 1961), bioimpedance (BE) (Elia et al., 2000), and infrared interactance (Conway et al., 1984).

Those techniques, underwater weighing, helium dilution and plethysmography are based on body weight and volume measures, to calculate body density and fat percentage (Siri, 1961). The first method is the oldest, but less comfortable, the next two are easy to use; however, plethysmography is the most practical and commercially available (Collins et al., 1999).

In order to measure body shape, image and volume, beside those methods, there are digital photogrammetry techniques currently under development, i.e., body shape measurement through exposing an individual to different intensity, frequency and wavelength light which are captured by photographic cameras of different sensitivity, generating images of body surface in two or three dimensions (3D); the first complete reports of digital photogrammetry to measure body dimensions started back in 1957 (Hertzberg et al., 1957). The equipment is calibrated with known dimensions instruments, to provide valid and reliable measurements; that kind of equipment started in the cosmetic, dressing and protection industries (Robinette et al., 1999); however, they are lately used in both health and sports areas (Jaeschke et al., 2015; Wang et al., 2006), without having enough studies that validate using them. The main aspect of digital photogrammetry is its no invasiveness, fast and easy to use and reproducibility (Zancanaro et al., 2015), generating in 2–15 s a number of anthropometrics measures (lengths, diameters, circumferences). Several digital photogrammetry models are currently available, showing moderate to high correlations with standard anthropometrics measurements despite that averages are

* Corresponding author. Anillo Envolvente del Pronaf y Estocolmo, Ciudad Juárez, 32310, Chihuahua, Mexico.
E-mail addresses: aramos@uacj.mx (A. Ramos-Jiménez), rphernant@yahoo.com (R.P. Hernández-Torres), villalobos@campus.iztacala.unam.mx (R. Villalobos-Molina), rurquide@uacj.mx (R. Urquidez Romero).

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statistically different between methods (Koepke et al., 2017; Wang et al., 2006). Moreover, these devices calculate body volume through a set of algorithms (Wang et al., 2006; Wells et al., 2000). These facts prompted us to validate a digital photogrammetry 3D scanner to measure body circumference and total volume.

2. Material and methods

2.1. Subjects

This a no probabilistic study after an open call during 2015; 285 students from Universidad Autónoma de Ciudad Juárez, Chihuahua, México, of 18–35 years (145 male: 22.0 ± 0.3 years-old, 72 ± 1 kg body weight, and 1.72 ± 0.01 m height; 140 female: 21.4 ± 0.3 years-old, 65 ± 1 kg body weight, and 1.60 ± 0.01 m height) were selected. The inclusion criteria were: to be physically healthy, without heavy exercise 24 h before, no alcohol drinking, neither diuretics nor other drug consumption that affected hydration status. Before any study students signed an informed consent, according to the Helsinki guidelines; after the signature, in a 60 min session anthropometrics, body volume through plethysmography and body shape digitizing measures were conducted in a temperature controlled (22–24 °C) laboratory, and participants wore a tight swimsuit and cap.

2.2. Anthropometric measurements

In order to know anthropometric dimensions of participants, we used the described method following recommendations of the International Society for the Advancement of Kinanthropometry (Norton and Olds, 1996). For such actions, a flexible centurion anthropometer (Rosscraft, Vancouver, Canada), a platform digital scale (SECA 656, Hamburg, Germany), and a portable stadimeter (SECA 206) were used, and measurements were conducted by an ISAK certified anthropometrist. Reliable and precise measurements of body girths were: percentage of technical error 1.7, and interclass correlation coefficient 0.99. In this work we used only body circumferences, i.e., obesity related measurements that the 3D image digitizer (TC^2-18) also determines.

2.3. Body volume

For this procedure we used plethysmography through air displacement (McCrory et al., 1995), following manufacturer's recommendations (Bod Pod, Cosmed, Rome Italy), both for equipment calibration and for body weight and volume. The purpose of plethysmography is to calculate body fat percentage using equations (Siri, 1956), calculating density through measuring body weight and volume (Macias et al., 2007) in such a way that the equipment measures lung volume, which is subtracted from the total volume to have a better approach to actual body density. In our study, we added lung volume to obtain a better body volume.

2.4. Digitazing body image

This procedure used the 3D image digitizer (TC^2-18) (Body Measurement, Karnataka India), following that described (Simenko and Cuk, 2016); the scanner gives a digital image (1.5–2.0 million pixels) in a 3D body shape, as well as a series of body dimensions. The TC^2-18 is a dark rectangular box with 16 infrared sensitive cameras distributed in 4 towers, each one in a corner; before digitizing the equipment is calibrated by triangulation with two instruments of known dimensions, as follows: calibration with two 115 mm diameter spheres rows and one 150 cm height and 254 mm diameter cylinder; both instruments were placed in two different occasions in the center of the box (Fig. 1). The test re-test validation has been published (Lee et al., 2001).

2.5. Statistical analysis and equation generation

Equation design: taking plethysmography to measure total body volume, an equation was designed to calculate body volume starting with the 3D digitized body volume, i.e., total sample was randomly divided in two parts: 80% and 20%. With the 80% the equation was created and with the 20% it was checked. To validate the regression equation, variables' linear relationships were plotted, as well as the predicted *vs.* residual values in such a way that the relationships between variables must be linear, and the predicted *vs.* residual values must show a random distribution. The errors (measurement and estimate) were calculated by the standard deviation of differences, either among measured values or those predicted by regression; differences between digitizing and anthropometry are shown with graphs (Bland and Altman, 1986).

To analyze differences between measuring methods a Student's *t*-test of independent measures was determined and plots constructed. The importance in finding differences (magnitude of effects) was analyzed by Cohen's d, i.e., values around 0.20 were considered low, around 0.50 were moderate and ≥0.80 were high (Ledesma et al., 2008). Confidence intervals at 95% of the means (95% CI) are shown, and the strength of associations (R^2) was obtained by linear regression. We used SPSS version 21.0.

3. Results

Eleven subjects were eliminated from data base due to mistakes in data capture in digitizing body shape. The TC^2-18 yielded lower values in total body volume, 95% CI [-3.9 to −3.5 L] *vs.* plethysmography. Regarding anthropometry, TC^2-18 gave higher values in mesosternal, 95% CI [8.8–9.6 cm], neck, 95% CI [2.6–3.0 cm], *gluteus maximus*, 95% CI [3.1–3.7 cm], relaxed arm, 95% CI [2.9–3.3 cm], and minimal waist, 95% CI [3.1–3.7 cm] circumferences; likewise, similar values in the upper thigh, calf and forearm circumferences were obtained (Table 1, Fig. 2). The strength of associations between control measurements (plethysmography and anthropometry) *vs.* the 3D digitizer were high ($R^2 \geq 0.75$); the highest was body volume ($R^2 > 0.99$), followed by minimal waist, *gluteus maximus* and calf ($R^2 = 0.93$) (Table 1). The higher the body volume the higher the difference in calculating total body volume by 3D digitizing (Fig. 3, right).

Regression equation in 80% of the sample:

Densitometry volume = 1.057 x 3D digitizing volumes.

- Standard error of estimate = 0.002.
- Strength of association (R^2) = 0.99.
- An equation was calculated without the constant value (intercept), since when included the value was not significant ($p > 0.05$).

Considering plethysmography as the criteria for body volume measurement, digitizing showed a 6% error (∼ −4.0 L), and regression equation corrects the calculation to a lower one of 1% error (Table 2). Regression showed validity, i.e., linear relationships among variables, data randomly distributed and error lower than 1% (Fig. 3).

4. Discussion

The need for reliable, precise and fast evaluations has guided the invention of complex and expensive instruments, some are not invasive and others show different degrees of invasion. To determine body shape and its components (fat mass, muscle mass, bone mass, among others), image processing has been developed. In this study, we validated a 3D image digitizer, a practical, fast and not invasive method to determine body dimensions. We found that through TC^2-18 scanner measurements are statistically different when compared to standard methods, such as plethysmography to determine body volumes and with anthropometry to determine circumferences. Regarding body volumes TC^2-18 values