BDA The Association of UK Dietitians
THE OFFICIAL JOURNAL OF THE BRITISH DIETETIC ASSOCIATION
Journal of Human Nutrition and Dietetics

ANTHROPOMETRY

Comparison of a 2D iPad application and 3D body scanner to air displacement plethysmography for measurement of body fat percentage

D. R. Wagner F. Castañeda, B. Bohman & W. Sterr

Kinesiology & Health Science Department, Utah State University, Logan, UT, USA

Keywords
Bod Pod, body composition, imaging, reliability, validity.

Correspondence
D. R. Wagner, Utah State University, 7000 Old Main Hill, Logan, UT 84322-7000, USA.
Tel.: (435) 797-8253
Fax: (435) 797-3759
E-mail: dale.wagner@usu.edu

How to cite this article
Wagner D.R., Castañeda F., Bohman B. & Sterr W. (2019) Comparison of a 2D iPad application and 3D body scanner to air displacement plethysmography for measurement of body fat percentage. *J Hum Nutr Diet*. **32**, 781–788 https://doi.org/10.1111/jhn.12687

Abstract

Background: Novel and innovative imaging methods that rapidly estimate body fat percentage (%BF) are publicly available, yet little is known about their accuracy. The present study evaluated the test–retest reliability of a two-dimensional iPad (Apple, Inc., Cupertino, CA, USA) application (2D APP) and a three-dimensional body scanner (3D SCAN) for estimating % BF and compared both imaging methods with air displacement plethysmography (Bod Pod; Cosmed USA, Inc., Concord, CA, USA).
Methods: Seventy-nine adults (37 female, 42 male) varying widely in age [mean (SD), range] [32.9 (12.4), 18–65 years] and body mass index [25.0 (4.9), 18.2–41.8 kg m^{-2}] were measured with the Bod Pod and twice with the 3D SCAN and the 2D APP in a repeated-measures design.
Results: Test–retest reliability was excellent for both the 2D APP (intraclass correlation = 0.993) and the 3D SCAN (intraclass correlation = 0.993) with the SEM <1% BF for both methods. Although the three methods were highly correlated with each other (r = 0.857–0.923), the mean %BF estimations were significantly different (P = 0.001). The 2D APP [19.9 (8.2)%BF] underestimated the Bod Pod value [21.9 (9.4)%BF] and the 3D SCAN [24.0 (6.8)%BF] overestimated. Additionally, the SE of estimate and total error exceeded 4% BF for both 2D APP and 3D SCAN, and both methods tended to overestimate lean participants and underestimate fat participants.
Conclusions: Although highly reliable, neither the 2D APP, nor the 3D SCAN provided valid estimates of $\%BF_{Bod\ Pod}$.

Introduction

According to the American College of Sports Medicine, body composition is an important health-related component of fitness and, as such, a measurement of body fat percentage (%BF) is typically part of health-fitness screenings [1]. Numerous methods exist for estimating %BF. Laboratory-based methods such as hydrodensitometry, air displacement plethysmography and dual-energy X-ray absorptiometry are considered to provide valid estimates of %BF and are regarded as reference measures [2]. However, these methods are often too costly to be used in field settings by clinicians, dietitians, or health-fitness professionals. Field methods, such as bioelectrical impedance and skinfolds, are affordable alternatives for estimating %BF, although these methods come with many assumptions and limitations. For example, an assumption of the bioimpedance method is that the human body is shaped like a perfect cylinder with a uniform length and cross-sectional area [3], and %BF predictions from skinfolds rely on the assumption of a fixed relationship between subcutaneous to internal fat across all individuals [4]. These flawed assumptions reduce the validity of these methods.

New alternatives to these traditional body composition assessment methods have emerged, and they could potentially revolutionise how %BF is estimated in fitness settings. Novel and innovative imaging methods provide a

rapid estimate of %BF by using only photographs without the technician ever touching the client. Three-dimensional body scanners (3D SCAN) produce digital 3D surface models and hundreds of anthropometric measurements in the matter of a few seconds. This technology has been used in the fashion industry for a number of years to provide rapid measurements for clothing sizing [5]. More recently, commercial 3D SCAN manufacturers have converted these anthropometric measurements into %BF estimations with proprietary formulas, providing an easy-to-administer and rapid method for fitness professionals and clinicians to measure body composition.

In addition to 3D SCAN technology, two-dimensional iPad applications (2D APP) that give an estimate of %BF from just a few photographs are now available, offering an extremely portable and very low-cost option for the clinician or fitness professional to estimate %BF in almost any setting. Given the large quantity of anthropometric data that can be gathered in a short time with the 3D SCAN and the portability and low-cost of the 2D APP, both of these imaging methods are appealing to professionals seeking alternative methods of body composition assessment. However, research supporting the reliability and validity of these imaging methods for estimating % BF is still very limited. Thus, the present study aimed to evaluate the test–retest reliability of the %BF estimation from a 2D APP and a 3D SCAN and compare both imaging methods to the %BF estimation from air displacement plethysmography.

Materials and methods

Participants

Adults from the general population volunteered to participate. Participants were recruited by word-of-mouth and from advertisements placed at Utah State University and throughout Logan, Utah. Although defined stratified sampling techniques were not used, an effort was made to include a wide range of ages and body types. Participation was limited to individuals 18–65 years, and exclusion criteria included current pregnancy and missing limbs.

Procedures

The study was reviewed and approved by the university's institutional review board (protocol #8759). Participants provided voluntary written consent after being informed of the study procedures, benefits, and risks. All procedures for an individual were completed at the university in a single session of approximately 50 min. Participants were asked to not eat heavy meals or perform strenuous exercise 4 h prior to their appointment and to avoid gas-producing foods 12 h prior to testing.

Upon entering the laboratory, participants were encouraged to void their bladder and bowels. Male participants wore compression shorts, and females wore compression shorts and a sports bra for all measurements. Height was measured to the nearest 0.1 cm with a wall-mounted stadiometer (Seca 216; Seca Corp., Ontario, CA, USA). Weight was measured to the nearest 0.1 kg with a digital scale (Seca 869; Seca Corp.).

Bod Pod (Cosmed USA, Inc., Concord, CA, USA) air displacement plethysmography with measured thoracic gas volume was used to measure body volume. Body density was calculated from the body mass and body volume data provided by the Bod Pod. Subsequently, %BF was estimated from body density with the Siri [6] formula, and this %BF estimation served as the criterion measure in this study. The manufacturer's guidelines were followed for Bod Pod testing procedures as described previously [7].

An iPad (Apple, Inc., Cupertino, CA, USA) with the LeanScreen app (PostureCo, Inc., Trinity, FL, USA) was used to take photographs of the participants in accordance with the manufacturer's guidelines for the 2D APP. The technician stood 2.3 m away from the participant when taking photographs, and the participant's entire body, head to toe, was captured in each photograph. Four photographs were taken: one with the participant facing forward in anatomical position, one from the rear, and one each from both sides. The photographs of the front and right side of the body were used for analysis. The analysis involves using the touch screen of the iPad to mark specific anatomical landmarks on the photographs. The landmarks using the frontal photograph include the left and right borders of the neck, abdomen, waist, and hips. The landmarks using the lateral photograph include the anterior and posterior borders of the same locations: neck, abdomen, waist and hips. The photograph can be zoomed-in, and the landmarks can be adjusted. The LeanScreen app automatically connects the border pairings with horizontal lines. The 2D APP then displays the estimated %BF from a proprietary equation. To evaluate test–retest reliability, the entire LeanScreen procedure was repeated on each participant. For consistency and to eliminate issues of inter-rater reliability, the same technician performed all of the LeanScreen app tests.

Participants were measured on the Fit3D ProScanner (Redwood City, CA, USA) in accordance with the manufacturer's instructions. This involves standing on a turntable and grasping handles at the sides such that the arms will be fully extended and slightly abducted. Once in the correct posture, the participant initiates the test by pressing a button on the handles. The turntable slowly rotates when the scanner moves up and down, rapidly collecting images. The entire scan lasts approximately 40 s. A 3D

digital image is created, and more than 400 measurements including circumferences, heights, lengths, widths, volumes and surface areas are extracted from this digital image [8]. An estimate of %BF from a proprietary formula is generated. The entire Fit3D scanning procedure was done in duplicate to evaluate test–retest reliability.

Statistical analysis

All data were analysed using SPSS, version 25 (IBM Inc., Armonk, NY, USA). $P < 0.05$ was considered statistically significant. The means (SD) was calculated for all variables, and normality of sample distribution was assessed with the Shapiro–Wilk test.

Test–retest reliability of the 2D APP and 3D SCAN was assessed with intraclass correlation ($ICC_{3,2}$) with a two-way mixed average measures model and absolute agreement. Additionally, the standard error of measurement [SEM = SD$\sqrt{(1-ICC)}$] was calculated to obtain the minimal difference (MD = SEM × 1.96 × $\sqrt{2}$). The MD is a valuable test–retest variable because it sets the baseline for 'real' change that exceeds the error of measurement when evaluating measurements over time [9].

The validity of the LeanScreen app and Fit3D body scanner to estimate %BF was evaluated against the %BF obtained from the Bod Pod. The evaluation criteria originally described by Lohman [10] and recommended in several body composition assessment texts [11,12] were used, comprising: (i) a substantial relationship between the test method and criterion method as evidenced by a Pearson correlation coefficient (r) >0.80; (ii) no significant mean difference between the three methods (e.g. nonsignificant F from repeated-measures ANOVA with sex as a covariate); (iii) the ordinary least squares regression slope and intercept should not be significantly different from 1.0 and 0.0, respectively; (iv) the standard error of estimate (SEE) and total error (TE) should be small (<3.5%BF); and (v) Bland and Altman [13] plots of residual scores should result in small, nonsignificant correlation coefficients and small 95% limits of agreement.

Results

Seventy-nine adults (37 females, 42 males), varying widely in age (18–65 years) and body type (BMI of 18.2–41.8 kg m^{-2}), completed the study. Descriptive characteristics of the study sample are provided in Table 1. Despite a wide range of participants, the study sample was skewed slightly toward younger ($P < 0.001$) and leaner ($P < 0.001$) people. Nevertheless, with sample sizes exceeding 30–40 participants, as was the case in the present study, violation of the normality assumption should not preclude the use of parametric procedures [14].

The ICCs for test–retest reliability for the LeanScreen app and the Fit3D body scanner were both 0.993 (95% confidence interval of 0.989–0.996 for the app and 0.989–0.995 for the scanner). The 2D APP had an SEM of 0.69%BF and an MD of 1.91%BF. The 3D SCAN had an SEM of 0.57%BF and an MD of 1.58%BF. Given the high test–retest reliability of both methods, the two trials were averaged; consequently, the average 2D APP %BF and average 3D SCAN %BF were compared to the %BF from the Bod Pod.

The %BF estimations from the 2D APP and the 3D SCAN correlated with each other ($r = 0.923$), and both were highly correlated with the %BF estimation from the Bod Pod ($r = 0.857$ and $r = 0.899$, respectively). However, the three methods produced %BF estimations that were significantly different from each other ($F = 8.996$, $P = 0.001$, $\eta^2 = 0.105$) such that the %BF estimation from the LeanScreen app [mean (SD)] [19.9 (8.2)%BF] was significantly ($P = 0.001$) less than the estimation from the Bod Pod [21.9 (9.4)%BF], although the %BF estimation from the Fit3D body scanner [24.0 (6.8)%BF] was significantly ($P < 0.001$) greater than the Bod Pod value. Furthermore, the method × sex interaction was also significant ($F = 3.666$, $P = 0.037$, $\eta^2 = 0.045$). The difference between methods was more pronounced for men than women, with neither the 2D APP ($P = 0.607$), nor the 3D SCAN ($P = 0.091$) being significantly different from the Bod Pod for the women (Fig. 1).

Linear regression for the LeanScreen app with Bod Pod as the dependent variable (Fig. 2) resulted in a slope of 0.981 and y-intercept of 2.4, with $r^2 = 0.735$, SEE = 4.86%BF and TE = 5.22%BF. The regression for the Fit3D body scanner is depicted in Fig. 3. This resulted in a slope of 1.238 with a y-intercept of −7.854, with $r^2 = 0.809$, SEE = 4.13%BF and TE = 4.88%BF.

The Bland and Altman [13] plots of individual error scores for the app and scanner are depicted in Figs 4 and

Table 1 Mean (SD) (range) of the study sample

	Age (years)	Height (cm)	Weight (kg)	BMI (kg m^{-2})
Female (n = 37)	32.5 (13.1) (18–62)	166.0 (7.6) (149.1–180.1)	66.4 (13.4) (45.8–95.0)	24.1 (4.9) (18.2–40.4)
Male (n = 42)	33.2 (11.9) (18–65)	179.3 (8.0) (162.6–195.2)	82.6 (13.2) (60.3–124.9)	25.7 (4.0) (20.5–41.8)
Total (N = 79)	32.9 (12.4) (18–65)	173.0 (10.2) (149.1–195.2)	75.0 (15.5) (45.8–124.9)	25.0 (4.9) (18.2–41.8)

BMI, body mass index.

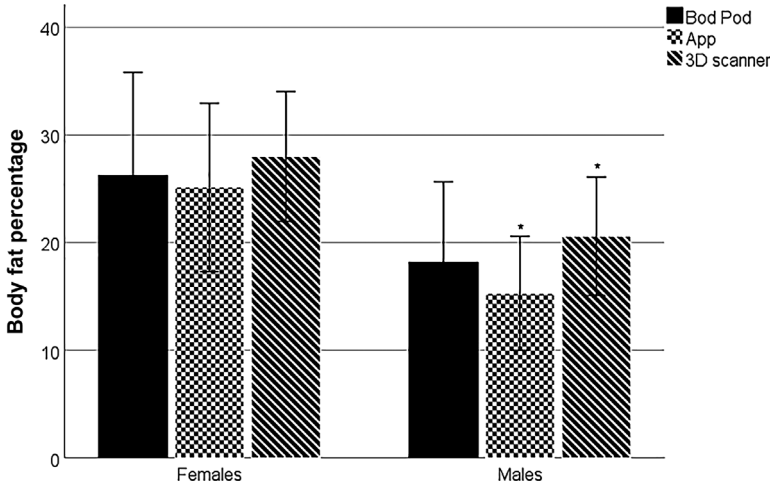

Figure 1 Mean body fat percentages for the three methods separated by sex. Error bars indicate the SD; $*P < 0.05$.

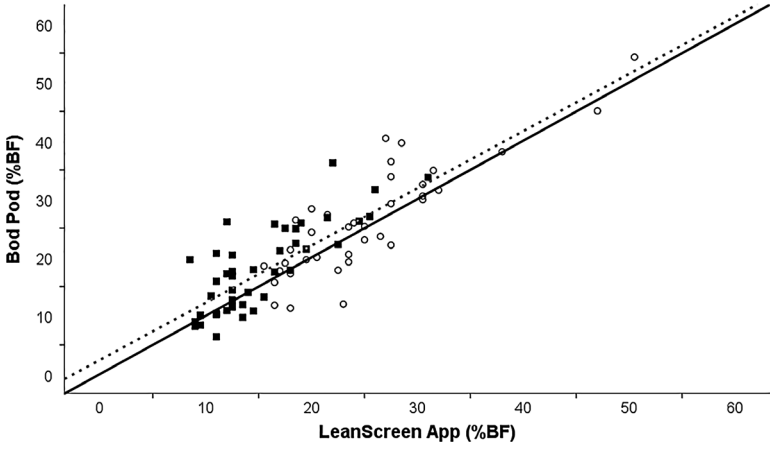

Figure 2 Linear regression of the body fat percentage estimation by the LeanScreen 2D application against the Bod Pod. Solid line, line of identity; dotted line, regression line. Solid squares, males; open circles, females.

5, respectively. The Pearson correlation between the average of the criterion and predicted scores and the residual scores for the LeanScreen app was small but statistically significant ($r = -0.253$, $P = 0.024$), indicating a slight tendency for the 2D APP to overestimate lean individuals and underestimate fatter participants. Furthermore, the 95% limits of agreement were large (−11.7 to 7.6%BF). A statistically significant and more obvious bias was also found for the Fit3D scanner ($r = -0.597$, $P < 0.001$); it overestimated participants at the lean end of the sample and underestimated participants with the most body fat. The 95% limits of agreement for the 3D SCAN ranged from −6.7 to 11.0%BF.

Discussion

Despite excellent test–retest reliability and acceptable correlations with the Bod Pod, the main finding from the present study was that the estimates of %BF from both the 2D APP and 3D SCAN were significantly different from the Bod Pod. On average, the 2D APP underestimated by 2%BF, whereas the 3D SCAN overestimated by about the same amount. Additionally, the errors exceeded the predetermined acceptable standard. A subjective rating of 'good' for evaluating prediction errors of %BF is an SEE and TE <3.5% [10–12]. According to this rating system, the SEE and TE of the scanner and app range between 'fair' and 'poor'. Furthermore, both the 3D SCAN and the 2D APP overestimated the %BF of lean individuals at the same time as underestimating the %BF of the fatter participants, creating large limits of agreement.

According to the Fit3D web site (www.fit3d.com), 'Fit3D has the largest distribution of 3D body scanners and 3D body scans in the world'. Despite this presence, to our knowledge, there has been only one previous peer-reviewed publication specific to this device. Ng *et al.* [8] used dual-energy X-ray absorptiometry (DXA) to develop regression equations for the Fit3D scanner from a sample of 39 adults, and then, they cross-validated their prediction against bioimpedance in a separate sample of 37 adults. They reported a root-mean-square error of 3.75

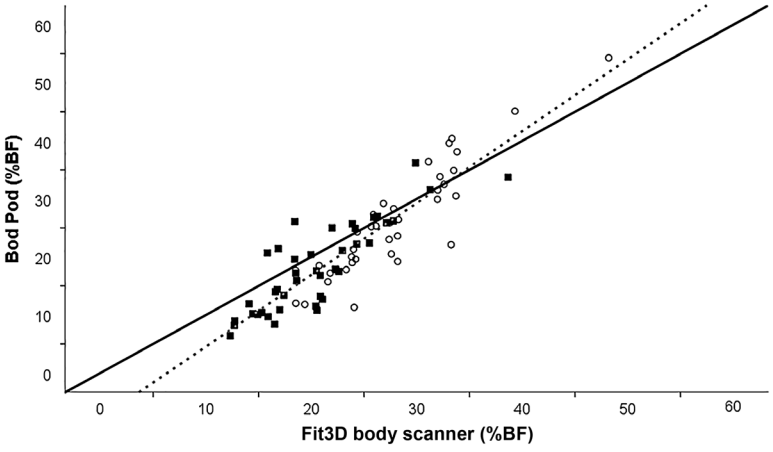

Figure 3 Linear regression of the body fat percentage estimation by the Fit3D scanner against the Bod Pod. Solid line, line of identity; dotted line, regression line. Solid squares, males; open circles, females.

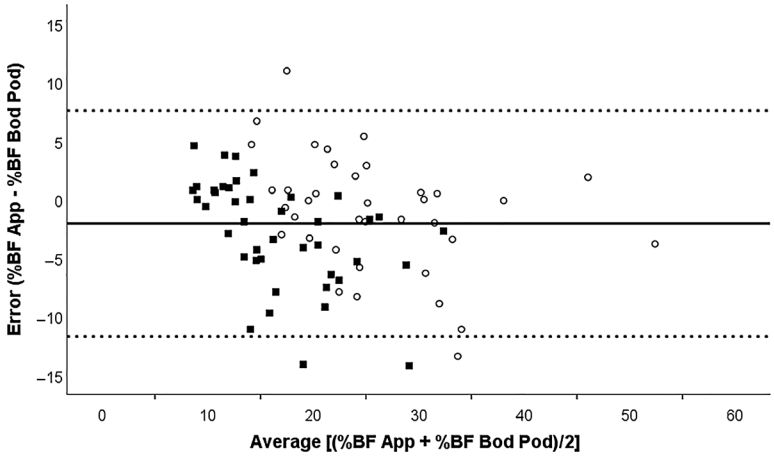

Figure 4 Bland and Altman plots of residual scores of body fat percentage estimated by the LeanScreen 2D application. Solid line, constant error; dotted lines, ±2 SD. Solid squares, males; open circles, females.

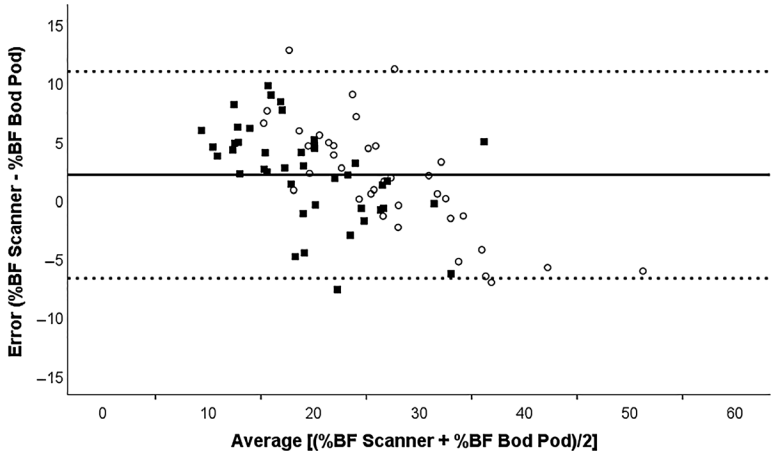

Figure 5 Bland and Altman plots of residual scores of body fat percentage estimated by the Fit3D scanner. Solid line, constant error; dotted lines, ±2 SD. Solid squares, males; open circles, females.

for the %BF formula. Despite some biases in the data, they concluded that the 3D method was an accurate substitute for other methods including the Bod Pod. However, in contrast to their conclusion, Ng *et al.* [8] reported a significant underestimation of body volume (−4.15 L) for the Fit3D scan compared to the Bod Pod. Presently, body volume is not a variable included in the displayed results of a Fit3D scan. Body volume data cannot be accessed from the scan because the Fit3D proprietary algorithm for %BF was based off of anthropometric

measurements that correlate with DXA %BF data and not volumetric measurements [15].

Previous investigators have evaluated the potential of other brands of 3D scanners as a body composition method. In 2000, Wells *et al.* [16] used an early version of a Hamamatsu Photonics scanner (Hamamatsu Photonics, Hamamatsu, Japan) to measure body volume and %BF. They reported body volume differences of 0.3 and 0.5 L compared to the Bod Pod and underwater weighing, respectively, and this scanner underestimated %BF by 2.6% compared to the Bod Pod and 4.1% compared to underwater weighing. A few years later, Wang *et al.* [17] reported a similar body volume overestimation of 0.5 (0.1) L for a newer version of this scanner compared to underwater weighing, although the difference in %BF estimation was not significant [0.7 (1.0)%BF] ($P = 0.48$). Similarly, Garlie *et al.* [18] reported excellent agreement with no statistical difference between %BF estimates from a Cyberware WB4 scanner (Cyberware, Inc., Monterey, CA, USA), DXA and the US Army manual anthropometric formula. Pepper *et al.* [19] found a mean difference of 0.2 L in body volume between hydrodensitometry and a rotary laser scanner developed by their laboratory. Their scanner produced a %BF estimation 1.4% higher than a Bod Pod, although 1.9% lower than DXA. Adler *et al.* [20] compared the Bod Pod with a VitusSmart XXL 3D scanner (Human Solutions GmbH, Kaiserslautern, Germany). Their scanner produced significantly ($P < 0.001$) greater body volume and %BF than the Bod Pod by 1.1 (0.9) L and 7.0 (5.6)%BF, respectively. The conflicting results among these studies can be attributed to different criterion methods (e.g., underwater weighing, Bod Pod, DXA), and different proprietary prediction models among the manufacturers as well as differences in the quality of the scan. For example, Wang *et al.* [17] noted that the scanner used in their study collected over 2 million data points in 10 s, and this was a 20-fold increase over the previous generation of this scanner.

To our knowledge, only two other research teams have published body composition data specific to the LeanScreen app. Shaw *et al.* [21] reported no significant differences when comparing estimates of %BF obtained from the 2D APP to estimates obtained from other field methods. The app-estimated mean (SD) of 21.9 (6.7)%BF was within ±1%BF of the skinfold [22.9 (4.8)%BF] and bioimpedance [22.3 (7.6)%BF] measures in a sample of 15 males and 15 females. By contrast, MacDonald *et al.* [22] reported a significant underestimation of 3.26%BF compared to DXA in a large heterogeneous sample. By comparison, the 2%BF underestimation observed in the present study using the Bod Pod as the criterion method falls between the underestimations reported by these two previous investigations. Similar to the present study, MacDonald *et al.* [22] also noted large limits of agreement (−10.26 to 3.73%BF) for the 2D APP.

An argument could be made that the reliability of field measurements of body composition may have just as much practical importance as the validity of the methods because a reliable device can be used to track changes over time even if it is not deemed valid compared to a laboratory method [23]. Both the 3D SCAN and the 2D APP proved highly reliable. This finding was consistent with previous investigations. Although not specific to the Fit3D brand, other researchers have reported ICC >0.97 for the 3D scanning method [17,19,20]. Additionally, Adler *et al.* [20] found high reliability extended over a 4-week period for this method. Regarding the 2D APP, MacDonald *et al.* [22] reported reliability coefficients that exceeded 0.99 for both intrarater and inter-rater reliability. Similarly, Shaw *et al.* [21] reported high relative test–retest reliability (ICC = 0.974) for the LeanScreen app, although they cautioned that the absolute reliability (coefficient of variation = 6.5%) was not as good as the skinfold and bioimpedance methods. Comparatively, the coefficient of variation for %BF estimations from the Bod Pod is 3.1% [24]. Despite high reliability leading to the potential to track changes in %BF over time, high reliability does not necessarily indicate that either the 3D SCAN or 2D APP will be capable of accurately monitoring longitudinal changes in body composition; such longitudinal studies are still needed.

The present study aimed to evaluate the predictive accuracy and reliability of these photographic imaging devices to estimate total %BF rather than circumferences or other anthropometric measures. Thus, no manual circumference measurements were included in the present study. However, previous investigators have documented that valid circumference measurements can be obtained from photographic scanning [17,18,25,26]. Another potential study limitation is that the Bod Pod was used as the criterion method of %BF; however, the proprietary formulas to estimate %BF from both the Fit3D and the LeanScreen app were derived from DXA data. Hence, DXA might be the preferred reference method for validity studies of these imaging devices. Nevertheless, agreement between the Bod Pod and Fit3D scanner and LeanScreen app in the present study was superior to the agreement between DXA and the Fit3D scanner in the Ng *et al.* study [8] and DXA and the LeanScreen app in the MacDonald *et al.* study [22]. Given that these imaging devices rely on anthropometric measurements (i.e. lengths, breadths and widths) to estimate %BF and these anthropometric measurements directly relate to body volume, a volumetric analysis, such as the Bod Pod, might actually be a more appropriate reference than DXA.

In summary, both the Fit3D body scanner and the LeanScreen iPad app are novel and appealing methods of body composition assessment for the fitness professional.

However, we cannot recommend them as valid methods of %BF estimation because of significant mean differences compared to the criterion method, the Bod Pod. Furthermore, the prediction errors and limits of agreement were large. We echo the statement of MacDonald *et al.* [22] that this technology is still in its infancy, and it is possible that the proprietary algorithms to estimate %BF from 2D and 3D images could be refined, making this a viable body composition method in the future; however, at this time, the errors are too large to be acceptable. Both the scanner and the app were reliable. This suggests that they might be useful for tracking change in %BF over time; however, such longitudinal studies have yet to be conducted, and this is an area of future research.

Transparency declaration

The lead author affirms that this manuscript is an honest, accurate and transparent account of the study being reported. The reporting of this work is compliant with STROBE guidelines. The lead author affirms that no important aspects of the study have been omitted and that any discrepancies from the study as planned have been explained.

ACKNOWLEDGMENTS

This research was completed without external funding. We thank the Aggies Recreation Center for the use of their Fit3D body scanner for this data collection.

Conflict of interests, source of funding and authorship

The authors declare that they have no conflicts of interest.

No funding declared.

DW was responsible for the study conception and design. DW was responsible for IRB submission. FC, BB and WS were responsible for participant recruitment. FC, BB and WS were responsible for data collection. DW, FC, BB and WS were responsible for data entry. DW and FC were responsible for study data interpretation. DW was responsible for drafting of the manuscript. FC, BB and WS were responsible for editing the manuscript. All authors critically reviewed the manuscript and approved the final version submitted for publication.

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