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Evaluating Alternative Methods for Body Composition Measurement in Field Settings

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Defence Research and Development Canada
Scientific Report
DRDC-RDDC-2018-R142
August 2018

Canada

IMPORTANT INFORMATIVE STATEMENTS

This document was reviewed for Controlled Goods by Defence Research and Development Canada (DRDC) using the Schedule to the *Defence Production Act*.

The data collected as part of this study was approved either by Defence Research and Development Canada's Human Research Ethics Board or by the Director General Military Personnel Research & Analysis' Social Science Research Review Board.

Endorsement statement: This publication has been peer-reviewed and published by the Editorial Office of Defence Research and Development Canada, an agency of the Department of National Defence of Canada. Inquiries can be sent to: Publications.DRDC-RDDC@drdc-rddc.gc.ca.

Abstract

The aim of this study was to determine how several non-invasive body composition measurement techniques compared with hydrostatic underwater weighing (traditional “gold standard”) in order to determine the best options for measuring body composition in military human performance experimental field settings. Sub-cutaneous ultrasound, manual skinfolds, air-displacement plethysmography, bio-impedance, and body circumference techniques were compared. Statistical tests of agreement as well as test/re-test reliability were analyzed. Fixed and proportional biases were examined using Bland-Altman graphical analyses. Skinfolds and ultrasound were found to be the most similar to hydrostatic weighing and would be good candidates for use in military field settings. While the performance of these two methods was similar, ultrasound advantages include high preference by participants and ease of use for practitioners.

Significance to Defence and Security

This study’s results will help guide the choice of non-invasive body composition techniques available for researchers when undertaking human performance studies in military field settings. The results indicate that portable and acceptable methods of measuring percent body fat in Canadian Armed Forces and Allied Military Forces personnel are available to the researcher. These methods are scientifically valid and as reliable as traditional compared to the more cumbersome and generally less tolerable or practical “gold standard” methods used in the laboratory setting.

Résumé

L’objectif de cette étude était de déterminer comment plusieurs techniques non effractives de mesure peuvent se comparer à la densitométrie hydrostatique (modèle de référence classique) afin d’établir la meilleure façon de mesurer la composition corporelle dans le cadre d’études sur le rendement humain du personnel militaire au cours d’expériences sur le terrain. Au nombre des techniques comparées figuraient la mesure par échographie sous-cutanée, la mesure des plis cutanés effectuée manuellement, la pléthysmographie par déplacement d’air, la bio-impédance et la mesure de la circonférence corporelle. On a analysé des tests de concordance statistique et vérifié la fiabilité test-retest. Puis, on a procédé à un examen de la polarisation variable et invariable par l’analyse de graphiques de Bland-Altman. La mesure des plis cutanés effectuée manuellement et la mesure par échographie se sont révélées être les méthodes ressemblant le plus à la densitométrie hydrostatique, et celles-ci représenteraient une bonne solution pour les militaires sur le terrain. Bien que les deux méthodes offrent un rendement similaire, la mesure par échographie a l’avantage d’être la préférée des participants et d’être facile à utiliser par les professionnels.

Importance pour la défense et la sécurité

Les résultats de la présente étude aideront à orienter les chercheurs dans le choix d’une technique non effractive de mesure de la composition corporelle dans le cadre d’études sur le rendement humain du personnel militaire sur le terrain. D’après ces résultats, les chercheurs ont à leur disposition des méthodes portables et satisfaisantes pour mesurer le pourcentage de masse adipeuse chez les membres des Forces armées canadiennes et des forces militaires alliées. Ces méthodes sont valides sur le plan scientifique et sont aussi fiables que les méthodes classiques, comparativement aux méthodes de référence utilisées en laboratoire jugées plus laborieuses et généralement moins acceptables ou moins pratiques.

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1 Introduction

Assessment of body composition, defined as the measurement of body fat percentage, and lean tissues, bone and body water is a valuable metric of overall health and fitness (Durnin and Womersley, 1974; Wagner, 2013). It is used commonly by both health professionals and athletic trainers to track improvements and assess the efficacy of physical fitness and diet interventions (Clark et al., 2004). The Canadian Armed Forces and other Allied militaries also assess and track body composition for purposes of health and fitness promotion, and also to ensure soldier operational effectiveness (particularly in physically demanding trades and in challenging environmental conditions). Mikkola et al., (2012) found that positive changes in body compositions are associated with improvements in aerobic performance for military personnel.

The accurate measurement of body fat (either as a percentage of body mass or absolute fractionation of the today body mass) can be a challenging task and there are many different measurement methods available that vary in cost, ease, accuracy, and skill requirement (Wagner and Heyward, 1999). Commonly used methods cited in the literature to estimate the Percentage of Body Fat (%BF) and other secondary indices of body composition such as fat-free mass, etc., include Skinfold Methods (SF), subcutaneous Ultrasound (UL), Bioelectrical Impedance (BI), Air-Displacement Plethysmography (AdP), Body Circumferences (BC), and Hydrostatic Weighing (HW). Each of these methods are characterised by drawbacks and advantages.

HW has been historically considered the gold standard (Dempster and Aitkens, 1995; Tai, 2013; Wagner and Heyward, 1999). This method uses Archimedes' principle to determine body composition by weighing an individual both in air and underwater, which can be used to calculate their body density and subsequently their body composition (Behnke et al., 1942). Residual lung Volume (RV) must be accounted for in the calculation and is measured either directly through a Pulmonary Function Test (PFT), or indirectly as estimated from standardized and validated nomograms. The volume of gas in the gastrointestinal tract is small and estimated to be 100 mL within the population (Francis, 1990) While this method is considered most valid, it is difficult to perform and requires training and specialized laboratory equipment. It also requires the participant to be completely submerged underwater, with a complete exhalation to their RV, making it challenging and possibly inaccessible for certain populations; such as the elderly, physically disabled, chronically ill, and young children (Levenhagen et al., 1999). More recently, new assessment techniques have emerged that are even more robust than HW, improving the accuracy of this body composition measurement. However, these are typically expensive and difficult to access. These techniques include Magnetic Resonance Imaging, Dual-Energy X-Ray Absorptiometry, Near Infrared Interactance, Total Body Potassium, Computed Tomography and Total Body Protein (Duz et al., 2009; Wagner and Heyward, 1999).

SF has been popular for decades as it is simple, inexpensive, and can be performed outside the laboratory. Once the subcutaneous fat thicknesses of a variety of sites have been measured, these values are used to determine body density, typically by using one of the equations developed by Jackson and Pollock (1980; 1978) and Durnin and Womersley (1974). However, this assessment method has some major pitfalls, such as variability in measurement techniques between researchers, such as skinfold landmark accuracy, tissue compressibility, anatomic site selection differences between researchers, and factors such as participant ethnicity and athletic orientation, which are unaccounted for in the body density formulas (Duz et al., 2009; McNeill et al., 1991).

Several new body composition techniques have recently emerged that are non-invasive and easier to perform compared to HW and SF. One such technique is AdP, commercially available as the BOD POD^{TM} (Life Measurement Instruments, Concord, CA). By using the inverse relationship between volume and pressure, the BOD POD^{TM} calculates body density, and from that, body fat percentage. The BOD POD^{TM} assessment is fast, non-invasive, comfortable for the participant, and can accommodate most populations. Demerath et al. (2002) found that 92% of participants preferred the BOD POD^{TM} test to HW, as it requires only that they sit quietly in a sealed chamber for about two minutes. Thoracic Gas Volume (TGV) can be measured through an additional test in the BOD POD^{TM}, predicted based on the participant's height, gender and age, or entered directly from a recent PFT result. Some limitations of this method are the high cost, the immobility of the device itself, and test sensitivity to food and water intake (necessitating a two-hour fast prior to measurement) (Levenhagen et al., 1999).

Another recently developed method is the use of UL to measure subcutaneous fat tissue thickness. The BodyMetrix Pro System (IntelaMetrix Inc.®, Livermore, CA) is a portable UL device for non-invasive body fat assessment. Ultrasonic waves emitted from a hand-held probe are reflected at different amplitudes by skin, fat, muscle tissue, and bone, which allows for the measurement of body fat. UL utilizes standardized landmarks, similar to the traditional skinfold sites and an automatic averaging algorithm, contributing to higher inter-measurer reliability for UL than for SF (Wagner, 2013). UL results are reportedly immune to hydration, exercise level, or caffeine intake—factors which greatly impact other methods such as AdP and BI (Wagner, 2013). UL measurement of body fat is accurate for both obese and thin individuals, which differentiates it from SF (Duz et al., 2009). The device is highly portable, making it an attractive option for measurement in the field.

BI for assessment of body composition is an attractive non-invasive method due to its low cost, mobility, and ease of use. By imparting a low level of electrical current through the body, the resistance to flow is evaluated and used to estimate total body water, from which body fat percentage can be determined (Wagner and Heyward, 1999). However, several unrelated factors such as hydration level, previous exercise, and caffeine intake can disrupt the electrical impedance and therefore affect the accuracy of the measurement (Wagner, 2013).

The United States Army has developed a simple body fat estimation using either two (male) or three (female) measurements of BC (Friedle et al., 1992; Hodgdon, et al., 1994a; Hodgdon et al., 1994b; U.S. Army, 2013). These values are applied to two gender-specific formulae to predict body fat percentage. The technique is simple, rapid and useful for multiple subjects in field settings.

Results from previous literature comparing alternative body composition techniques to HW have been varied. McCory et al. (1998) compared body fat percentage from the BOD POD^{TM} with HW and found the results to be comparable. Biaggi et al. (1999) and Demerath et al. (2002) both demonstrated that the BOD POD^{TM} had a high correlation with HW but the mean differences between the methods were significant. Tai (2013) compared SF, UL, and BOD POD^{TM} to HW and found they were all comparable to HW except for the BOD POD^{TM}.

The aim of this study to is to determine which of the alternative and non-invasive methods of body composition compare satisfactorily to HW (the criterion "gold standard"). This information will help inform military human performance and health researchers which body composition methods may be adopted for future laboratory and/or field research. Although many body composition validation studies have been conducted in the past, this study is unique with respect to the number of measurement methods included and its test/re-test assessment of the methods. Additionally, this study aims to compare different options available for BOD POD^{TM} (measuring TGV directly through the BOD POD^{TM}, estimating TGV from standardized nomograms, and obtaining TGV through a separate PFT) and the different options available through the UL (automatic vs manual selection of peak values, and consistent vs personalized body type selection).

2 Methods

This study is divided into three phases. The first phase utilized four assessment methods: HW, SF, UL, and AdP. Halfway through completion of the study, a revision was added to assess two additional techniques and to assess the reliability of all the techniques. The second phase added the BI and BC assessment methods. The third phase re-tested participants to examine the test/re-test reliability of the six different assessment methods. These phases are described in detail below.

The study protocol was approved by the Defense Research and Development Canada (DRDC) Human Research Ethics Committee, following standard Canadian TriCouncil guidelines for human ethics standards in human sciences/health research. Each volunteer signed a voluntary consent form outlining the procedures, risks, time commitments and compensation.

2.1 Phase 1

In this phase of the study, 45 participants (34 males and 11 females) between the ages of 18–60 years old performed HW, SF, UL, and AdP body composition assessments in a random order; but, always with HW being the final test. Three participants were removed because they were unable to perform a PFT. Therefore, there were 42 participants (31 males, 11 females) to complete all the assessments of body composition (male mean age = 36 ±11 years; female mean age = 31 ±5 years).

After refraining from food, drink and exercise for two hours all participants arrived at the DRDC – Toronto Research Centre exercise laboratory, and performed the four body composition assessments within two hours of arriving. The participants also performed the PFT the same day or within a couple days of the four body composition assessments to measure their RV and TGV.

2.1.1 Skinfold Calipers

Seven skinfold measurements (triceps, chest, mid-axillary, subscapular, suprailiac, abdomen, and thigh) were taken on the right side of the participant's body using standard skinfold calipers (John Bull British Indicators, U.K.). The measurements were taken according to Jackson & Pollock's (1978) methods. Each anatomical site was marked prior to obtaining measures and each measure was taken on the participant's right side. The skinfold values were obtained by pinching the skin one centimetre above the site ensuring that no muscle was grasped. The skinfold was held in the calipers for 2–3 seconds to standardize tissue compression, and each measurement was taken to the nearest 0.2 mm. Every site was measured twice, but if the values differed by more than 2 mm then the measurement was repeated a third time and the average of the two closest measurements were used.

The triceps measurement is a vertical fold halfway between the acromion and the olecranon on the posterior surface of the arm. The chest measurement is a diagonal fold halfway between the axillary crease and the nipple; however, for women the chest measurement is a diagonal fold one third of the distance from the axillary crease to the nipple. The mid-axillary measurement is a vertical fold taken at the mid-axillary line that is at the level of the xiphoid process. The subscapular measurement is a diagonal fold taken two centimetres below the inferior angle of the scapula. The suprailiac measurement is a diagonal fold taken two centimetres above the iliac crest in line with the mid-axillary line. The abdomen measurement is a horizontal fold taken two centimetres to the right of the umbilicus. The thigh measurement was taken halfway between the hip crease and the patella on the anterior surface of the thigh.

Sum of seven SF sites data was entered into the equation by Jackson & Pollack (1978, 1980) to derive Body Density (BD). The participant's age is also used in the equation:

Males Sum of Seven:

BD = 1.112 – (0.00043499 x sum of skin folds) + (0.00000055 x square of the sum of skinfolds) – (0.00028826 x age).

Females Sum of Seven:

BD = 1.097 – (0.00046971 x sum of skinfolds) + (0.00000056 x square of the sum of skin folds) – (0.00012828 x age).

To calculate body fat percentage the body density value was entered into the Siri body fat percentage equation (Siri, 1961): % Body Fat = (495/BD) – 450.

2.1.2 Subcutaneous Ultrasound

UL measurements were obtained using the BodyMetrix Pro System (IntelaMetrix Inc.©, Livermore, CA). The portable UL device determines the depth of fat at each location by generating an UL signal that travels through the tissues and measures the boundaries of the reflected signal. The sites and the side of the body used were the same as the SF measurements and the Jackson & Pollack (1978, 1980) equation was used to calculate BD and Siri's (1961) equation to calculate %BF (Bodyview 2D IntelaMetrix Inc.©, Livermore, CA). A small amount of water soluble ultrasound transmission gel (Parker Laboratories Inc., Fairfield, NJ) was applied to the head of the BodyMetrix probe, and rubbed on the desired site. Once there was enough gel to ensure good contact the measurement began where the head of the ultrasound was moved 1–2 centimetres vertically, diagonally, or horizontally along the marked line of the site for 2–3 seconds for averaging, as directed by the manufacturer. The first main peak on the real-time measurement display indicated the fat muscle interface and determined the depth of fat. After each measurement, the graph was checked to ensure proper peak selection. The peak was changed, following the manufacturer's instructions, if it was noted that the software had not chosen the appropriate peak. The measurements were performed in the order given by the Bodyview 2D and each measurement was done two or three times, depending on if there was a discrepancy greater than 10% between the first two measurements. After all seven sites were completed the percent body fat was automatically generated. The "Athletic" descriptor was used for all participants.

2.1.3 Air-displacement Plethysmography

Body fat percentage using AdP was measured using the BOD POD$^{\text{TM}}$ system (COSMED Inc., Life Measurement Instruments, Concord, CA). The BOD POD$^{\text{TM}}$ was first calibrated following manufacturer's instructions, to determine the comparison pressure and volume. The subject's birthdate was recorded, their height was measured to the nearest quarter of an inch, and they were weighed in spandex shorts and spandex swim cap to the nearest gram. The participant's volume was measured while they remained motionless and breathed normally. Two measurements were taken, and if there was a difference of 150 mL or 0.2% between the first two volumes, a third measurement was taken, where an average of the closest two volumes was used. The subject's TGV was also measured. TGV is the total volume of compressible gas in the thorax at any point in the breathing cycle (Collins, 1995). Following the manufacturer's instructions on the visible computer screen outside the pod, the subject was directed to inhale and exhale, following a bar on screen that filled and unfilled, without the filter and tube. As directed, the subject put the tube into their mouth and plugged their nose while following the same breathing pattern as before. The subject was then instructed to "Huff" into the tube 2–3 times at the end of their exhalation. The BOD POD^{TM} then provided a measure of TGV.

A detailed explanation on the principles of AdP is outlined in Fields et al. (2002). However, for simplicity, the basic method of AdP uses the difference in chamber air pressure/volume for an empty vs. occupied chamber. This yields a raw volume which is used along with the subject's Surface Area Artifact (SAA) and 40% of TGV to derive their corrected body volume: Vcorr = Vraw + 0.4 (TGV) – SAA (McCory et al, 1998). Corrected body volume was then subsequently used to calculate a value for body density using Volume/Mass, and then body fat percentage was calculated using Siri's (1961) equation.

For the current study we calculated body fat percentage using three different measures of TGV. "Measured" utilized the value provided directly from the BOD POD^{TM}; "Predicted" was estimated by the BOD POD^{TM} software using the participant's height, gender, and weight; "PFT" utilized the value that was determined by a separate PFT.

2.1.4 Hydrostatic Weighing

HW was used to measure the participants' underwater weight which is used to calculate body density and percent body fat. A nude dry weight was taken using a scale (Rice Lake Weighing Systems, Rice Lake, WI) connected to a high resolution counting scale (Setra Systems, Boxborough, MA), prior to entering the water tank. Subjects then entered a tank filled with clean water heated to approximately 28°C, and sat in a suspended harness connected to a Chatillon™ 9 kg x 10 g scale. The participant had the harness around their waist and, when ready, took two deep breaths and on the second exhalation attempted to forcefully expel all air from their lungs to reach their RV. When believed to have reached their RV they would roll forward attempting to submerge their entire body and, if applicable, blow the remaining air from their lungs. Once they were completely submerged and had exhaled their vital capacity, the underwater weight measurement was taken to the nearest 0.05 kg. This measurement was repeated a minimum of three times. The water temperature and harness weight on the scale were taken before the subject entered the tank. Body density was calculated using the following equation (Francis, 1990):

$$BD = WAir/[((WAir - WWater)/DW) - (RV + GV)]$$

Where BD is body density, WAir is weight in air or nude weight (in kilograms), WWater represents the weight of the subject in the water completely submerged (in kilograms), DW is the density of water corrected for the temperature, RV is the participants residual volume (in litres), and GV is the gastrointestinal volume (estimated at 0.1 L; Francis, 1990). Percent body fat was then calculated using Siri's (1961) equation.

2.1.5 Pulmonary Function Test

The RV used in the calculation for HW (Francis, 1990) was obtained during a PFT. A Medical-Grade Pulmonary Function System (MGC Diagnostics Corporation, Saint Paul, MN) along with specialized software (BreezeSuite 6.4.1., MGC Diagnostics Corporation, Saint Paul MN) was used to assess static lung volumes. The PFT involved performing a slow vital capacity, which is performed at the end of a functional residual capacity measurement, to calculate the participants expiratory reserve volume. With expiratory reserve volume and functional residual capacity the participant's RV can then be calculated. TGV was measured by rhythmically compressing and decompressing the thorax, at the end of a normal breath, by "panting" with no resistance and then with resistance when the shutter closed (Clausen, 1982). Boyle's law (P1V1 = P2V2) can then be applied, because the respiratory system is behaving isothermally, to calculate the pressure-volume changes of the volume of air being compressed (Clausen, 1982). For each test the participant was breathing into a mouthpiece and wearing nose clips. The metrics obtained from the PFT are: slow vital capacity, total lung capacity, inspiratory capacity, expiratory reserve volume, TGV and RV. The subject performed 2–4 trials per test, depending on if there was a discrepancy of 3–5% or 500 mL between tests, as instructed by the technician.

2.2 Phase 2

In this section of the study, 35 participants (24 males and 11 females) between the ages of 18–60 performed Bioelectrical Impedance (BI), and Body Circumferences (BC) in addition to the techniques used in Phase 1. The assessment methods were performed in a randomly generated order with HW always occurring last. One participant was unable to perform all the measurements and their results have been removed. Therefore, 34 participants (23 males and 11 females) completed all six assessment methods (male mean age = 35 ±9.3 years, female mean age = 36 ±7.5 years). The preparation before arriving at the laboratory was the same as in Phase 1.

2.2.1 Skinfold Calipers

These measurements were performed as described in Phase 1.

2.2.2 Subcutaneous Ultrasound

These measurements were performed as described in Phase 1; except, when a manual adjustment was made to the measurement both the original and the changes were recorded. Also, when a participant was thought to represent either the "Elite" or "Non-Athletic" athletic descriptors the protocol was performed once using the "Athletic" descriptor and again using the specific descriptor for them. This descriptor was determined following manufacturer guidelines.

2.2.3 Bioelectrical Impedance

BI is measured by sending a small current through the participant and measuring the resistance of the signal across the water compartments, the lean and fat masses of the body, in order to assess the individual's body fat percentage, where with greater fat mass there will be a greater resistance to the signal due to fat being anhydrous (Heyward and Wagner, 1999). The device used to assess BI for fat percentage was the Ozeri ZB 13-W (Ozeri USA, San Diego, California). The measurement involved standing on the scale, in compression garments, for approximately 5–10 seconds. The participant's gender, height, and age were all entered into the scale before taking the measurement, as specified by the manufacturer.

2.2.4 Body Circumference

The BC measurements were taken following the guidelines set by the Army Body Composition Program (2013). The measurements were taken using a standard 60 inch cloth measuring tape. Subjects wore compression garments and the tape was pulled firmly around the body to generate tension, to ensure accuracy for each measurement. For males, neck circumference was measured at the point just below the larynx perpendicular to the long axis of the neck; abdomen circumference at the point of the navel parallel to the floor. For females, neck circumference measurements were taken at the point just below the larynx perpendicular to the long axis of the neck; the abdomen circumference is measured at the natural waist, which is the point of minimal abdomen circumference (approximately halfway between the navel and the end of the sternum); the hip circumference is taken at the point of greatest protrusion of the gluteal muscles parallel to the floor. Each circumference was measured twice to the nearest quarter of an inch and if there was a difference of more than 1 inch between the two measurements it was taken a third time and the average of the two closest measurements was used in the calculation. Height was also taken in inches before the start of the circumference measurements. The subject's height and circumference measurements were then used in the Army Body Composition Program's (2013) circumference calculations:

Males:

$$\%BF = [86.01 * \text{Log10}(\text{abdomen circumference} - \text{neck circumference})] - [70.041 * \text{Log10}(\text{height})] + 36.76$$

Females:

$$\%BF = [163.205 * \text{Log10}(\text{waist circumference} + \text{hip circumference} - \text{neck circumference})] \\ - [97.684 * \text{Log10}(\text{height})] - 78.387$$

2.2.5 Air-displacement Plethysmography

These measurements were obtained as described in Phase 1.

2.2.6 Hydrostatic Weighing

These measurements were obtained as described in Phase 1.

2.2.7 Feedback Form

Participants were asked to rank the assessment methods from one to six based on their personal preference (one being the technique that was most preferred to six being the least preferred).

2.3 Phase 3

Seventeen participants from Phase 2 (13 males and 4 females) returned to complete the measures a second time. This involved returning to the laboratory within the following three days, having maintained their same exercise; diet; and water intake, to repeat all six body composition measurements to assess test/re-test reliability of the measurements. The protocol for the measurements was the same as described in Phase 2.

2.4 Data Analysis

The data was analyzed using IBM SPSS Statistics for Windows Version 22.0. A repeated measure Analyse of Variance (ANOVA) was used to determine if body fat percentages were significantly different across methods (Levenhagen et al., 1999). Post-hoc tests using a Bonferroni-adjusted alpha level were conducted to compare underwater weighing to each alternative method. Two-tailed Pearson product-moment correlation coefficients were used to determine the correlation between an assessment technique and HW (Biaggi et al., 1999). A difference plot was utilized, according to Bland and Altman (1986), to examine the agreement between HW and the alternate assessment methods to help identify the existence of fixed (consistently overestimating or underestimating) or proportional biases (differences in methods more or less pronounced at higher body fat levels). Paired t-tests were performed, for the repeated design participants, between Day 1 and Day 2 for each of the assessment methods. Pearson product-moment correlation coefficients were also performed between Day 1 and Day 2 for each of the assessment methods.

3 Results

3.1 Phase 1

The results below outline differences found between methods of establishing adiposity. 42 participants completed Phase 1 where they were measured by six techniques: HW, SF, UL (ultrasound with “athletic” designation and peak adjustment), and three AdP methods: AdP using measured BOD POD lung volumes (AdPM), predicted lung volumes, (AdPP), and directly measured PFT-lung volumes (AdPPFT).

In Phase 2, an additional 34 participants were added who were measured by the original six techniques plus BI, BC, UL2 (ultrasound with athletic body type setting with no peak adjustment), UL3 (ultrasound with experimenter determined body type setting with peak adjustment), and UL4 (ultrasound with experimenter determined body type setting with no peak adjustment).

3.1.1 Comparison with Hydrostatic Weighing

HW was compared against each alternative method. Descriptive statistics for the original six methods are provided in Table 1, and correlations are provided in Table 2. Descriptive statistics for the additional methods added in Phase 2 are provided in Table 3, and correlations are provided in Table 4. All correlations are significant at the 0.01 level.

Table 1: *Descriptive statistics for the original six methods.*

	Mean	Standard Deviation	N
HW	19.17	6.78	76
SF	19.56	7.34	76
UL	19.99	6.79	76
AdPM	23.14	7.02	76
AdPP	22.49	7.58	76
AdPPFT	21.85	7.23	76

Table 2: *Correlations between Hydrostatic Weighing and the original six methods.*

	HW
SF	.87
UL	.87
AdPM	.93
AdPP	.91
AdPPFT	.92

Table 3: *Descriptive statistics for Phase 2.*

	Mean	Standard Deviation	N
HW	20.32	7.07	34
BI	18.17	8.43	34
BC	22.80	8.32	34
UL2	21.00	6.20	34
UL3	21.05	7.85	34
UL4	20.87	7.41	34

Table 4: *Correlations between Hydrostatic Weighing and additional methods from Phase 2.*

	HW
BI	.87
BC	.83
UL2	.79
UL3	.89
UL4	.89

A repeated measure ANOVA was conducted utilizing the 76 participants who completed the original six methods. Method was the within-subjects variable (HW, SF, UL, AdPM, AdPP, AdPPFT) and percent body fat was the dependent variable. Mauchly's test (chi-square = 196.61, p <.05) indicated that the assumption of sphericity was not met. To correct for this violation, degrees of freedom were adjusted based on the Greenhouse-Geisser estimate (epsilon = .544) (Geisser and Greenhouse, 1958). The results show a main effect of method, F(2.72, 203.84) = 41.16, p = .000. To determine which methods differed, post-hoc tests were conducted. Five post-hoc comparisons were required to compare all methods to HW and so an adjusted significance value of .01 was used (p = .05/5). HW was found not to be significantly different from SF (F(1,75) = 0.84, p = .36), or from UL (F(1,75) = 4.16, p = .045). HW was significantly different from AdPM (F(1,75) = 175.18, p<.000), AdPP (F(1,75) = 86.0, p<.000), and from AdPPFT (F(1,75) = 70.84, p<.000).

A second repeated measure ANOVA was conducted for the 34 participants in Phase 2 who also completed the BI, BC, UL2, UL3, and UL4 methods. Method was the within-subjects variable and percent body fat was the dependent variable. Mauchly's test (chi-square = 69.53, p <.05) indicated that the assumption of sphericity was not met. To correct for this violation, degrees of freedom were adjusted based on the Greenhouse-Geisser estimate (Geisser and Greenhouse, 1958) (epsilon = .623). The results show a main effect of method, F(3.115, 102.78) = 10.71, p = .000. To determine which methods differed, post-hoc tests were conducted. Five post-hoc comparisons were required to compare all methods to HW and so an adjusted significance value of .01 was used (p = .05/5) HW was found to be significantly different from BI (F(1,33) = 8.82, p = .006), and BC (F(1,33) = 9.65, p = .004) but not significantly different from UL2 (F(1,33) = 0.820) = .372), UL3 (F(1,33) = 1.37, p = .251), or UL4, (F(1,33) = 0.914, p = .346).

Bland-Altman plots were constructed to provide a detailed analysis of HW comparisons to each of the alternative methods (Figures 1–10). This technique plots the difference score between two measures against the average of the two measures. To identify the existence of fixed bias one-sample t-tests were computed which determined if the difference score for each set of methods was significantly different from zero. There were a number of fixed biases identified. The body fat estimates given by AdPM (Figure 3) were an average of 3.97 percentage points higher than body fat estimates given by HW, t(75) = 13.24, p<.000. The body fat estimates given by AdPP (Figure 4) were an average of 3.32 percentage points higher than body fat estimates given by HW, t(75) = 9.27, p<.000. The body fat estimates given by AdPPFT (Figure 5) were an average of 2.68 percentage points higher than body fat estimates given by HW, t(75) = 8.42, p<.000. The body fat estimates given by BI (Figure 6) were an average of 2.15 percentage points lower than body fat estimates given by HW, t(33) = -2.97, p = .006. Body fat estimates given by BC (Figure 7) were an average of 2.48 percentage points higher than body fat estimates given by HW, t(33) = 3.11, p = .004. Body fat estimates given by UL (Figure 2) were an average of 0.86 percentage points higher than body fat estimates given by HW, t(75) = 2.04, p = .045.

To identify the existence of proportional bias, a series of linear regressions were performed. The mean body fat percentage given by the pair of assessment methods was the independent variable and the raw difference between the two methods was the dependent variable. The only significant proportional bias was between HW and AdPP such that the difference between the two methods got more pronounced at higher body fat percentages, $\beta = .117$, t(75) = 2.340, p < .05.

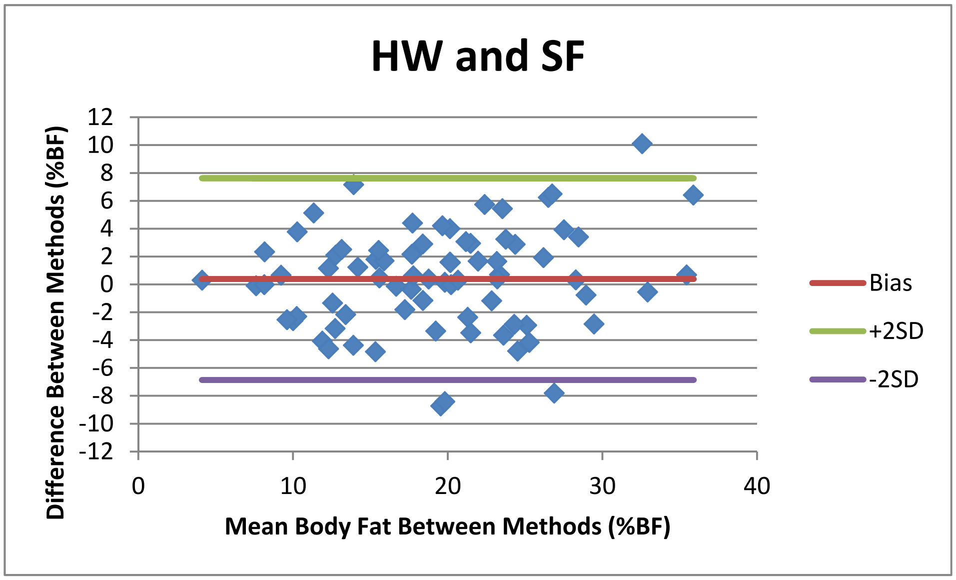

Figure 1: Bland-Altman plot for HW and SF. Differences are shown on the y-axis and averages on the x-axis.

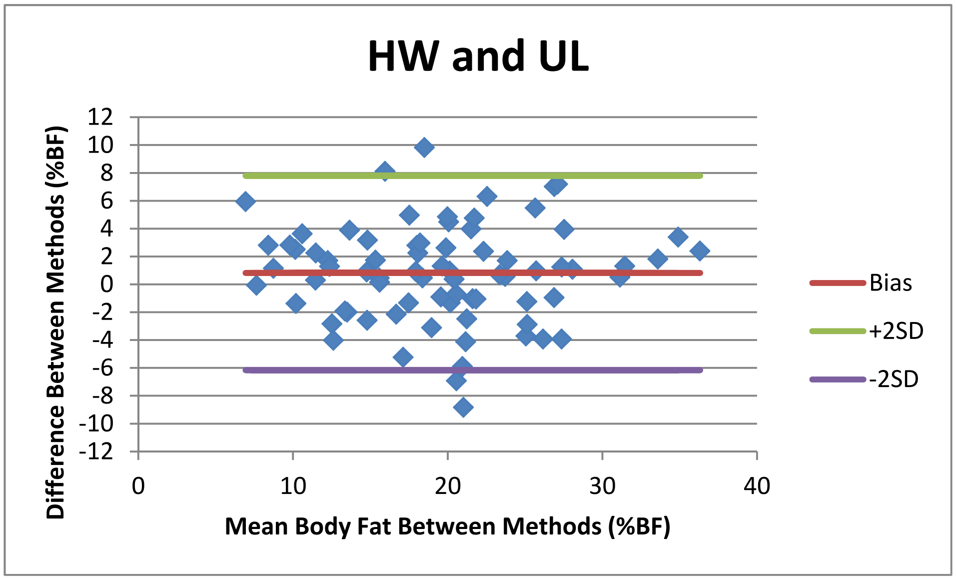

Figure 2: *Bland-Altman plot for HW and UL. Differences are shown on the y-axis and averages on the x-axis.*

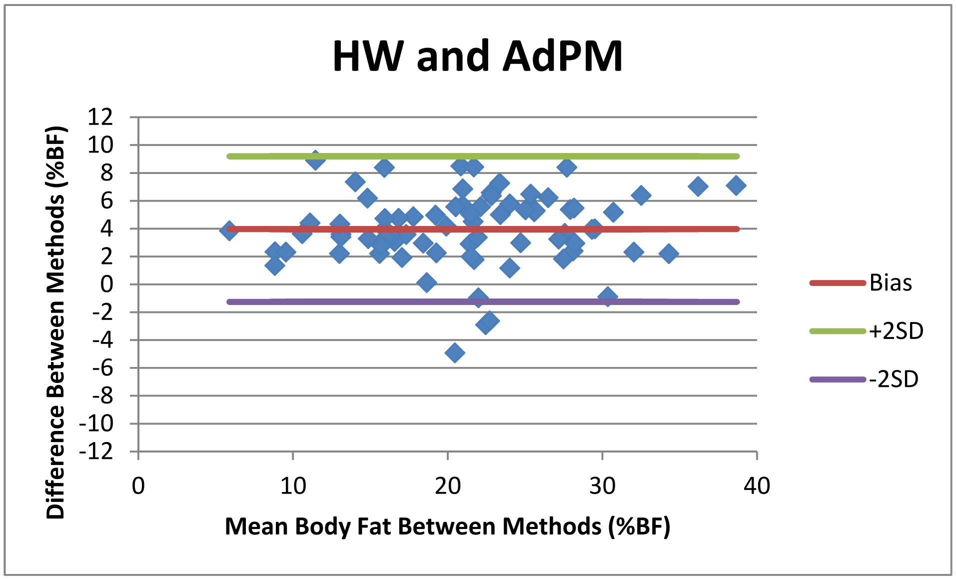

Figure 3: *Bland-Altman plot for HW and AdPM. Differences are shown on the y-axis and averages on the x-axis.*

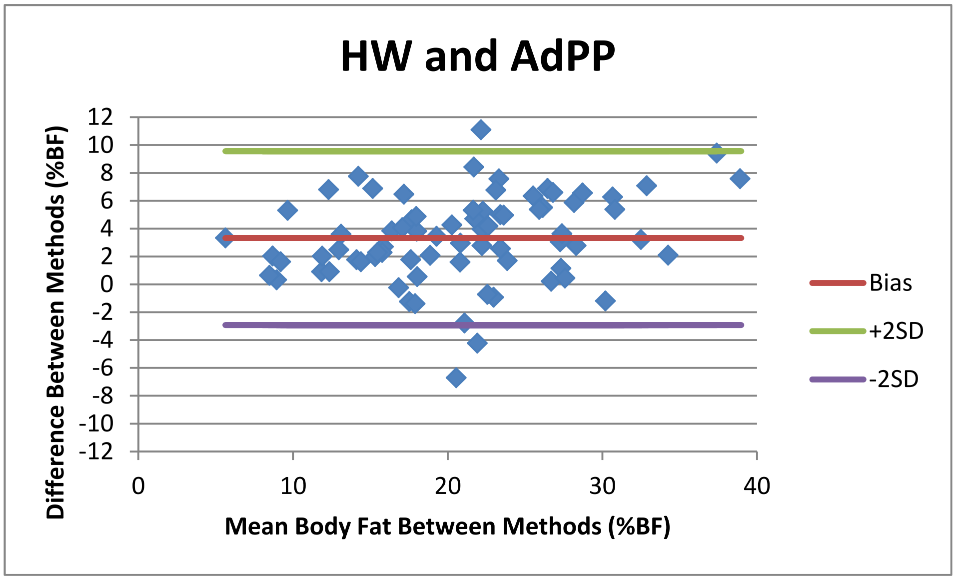

Figure 4: *Bland-Altman plot for HW and AdPP. Differences are shown on the y-axis and averages on the x-axis.*

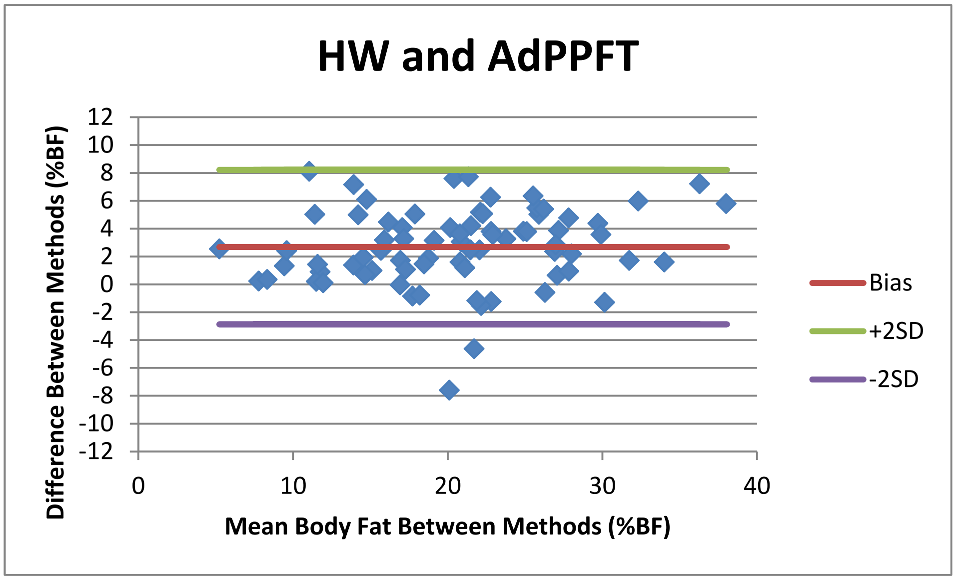

Figure 5: *Bland-Altman plot for Hydrostatic weighing versus AdPPFT. Differences are shown on the y-axis and averages on the x-axis.*

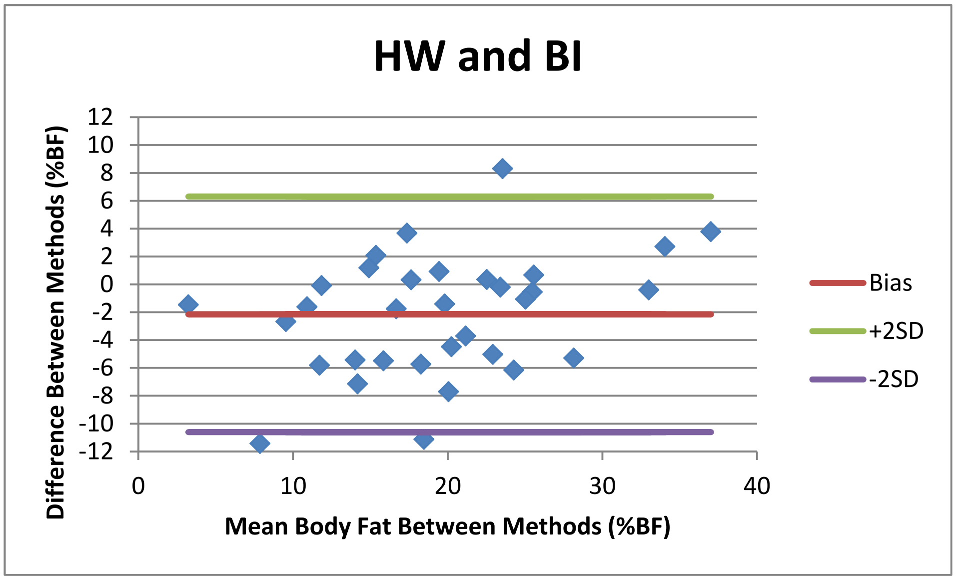

Figure 6: *Bland-Altman plot for HW and BI. Differences are shown on the y-axis and averages on the x-axis.*

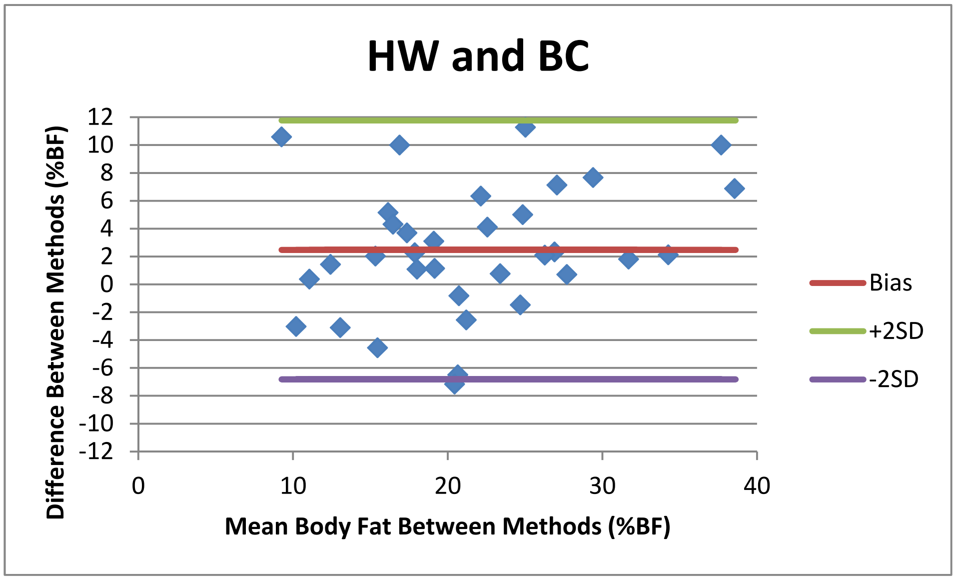

Figure 7: *Bland-Altman plot for HW and BC. Differences are shown on the y-axis and averages on the x-axis.*

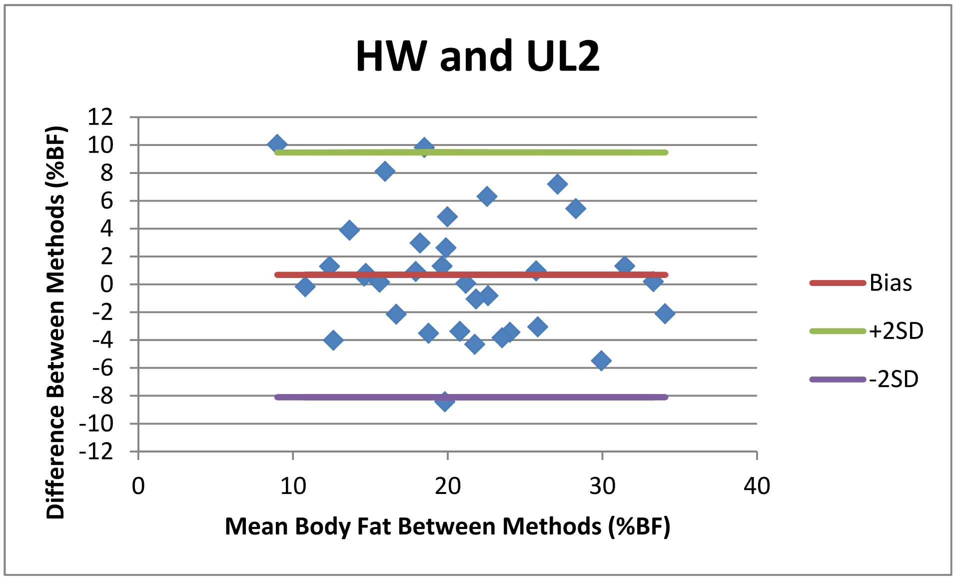

Figure 8: *Bland-Altman plot for HW and UL2. Differences are shown on the y-axis and averages on the x-axis.*

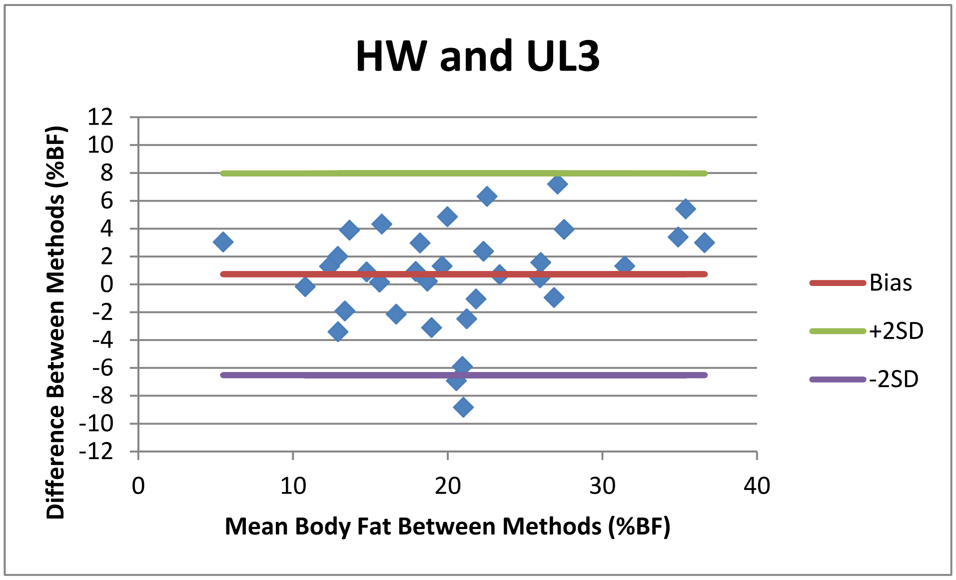

Figure 9: *Bland-Altman plot for HW and UL3. Differences are shown on the y-axis and averages on the x-axis.*

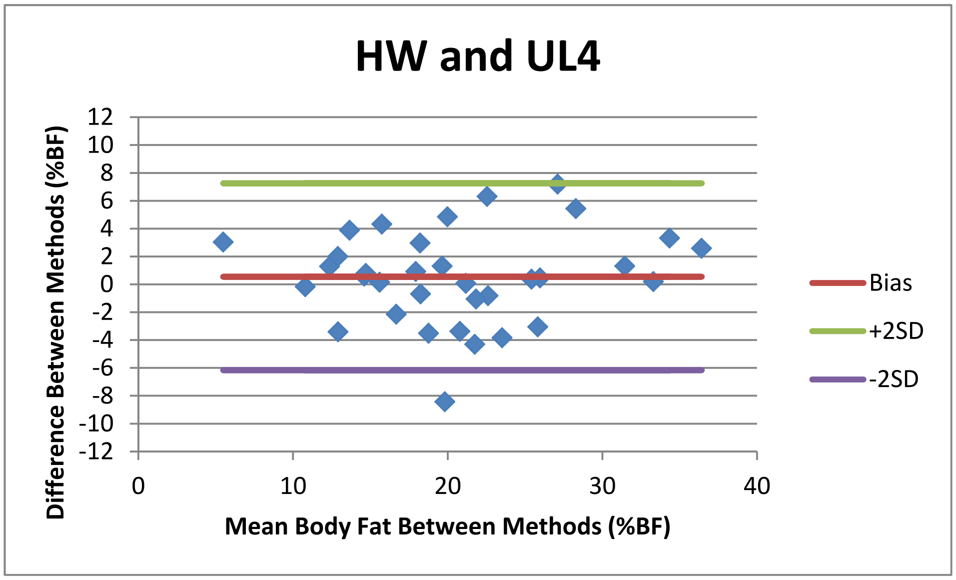

Figure 10: *Bland-Altman plot for HW and UL4. Differences are shown on the y-axis and averages on the x-axis.*

3.1.2 Test/Re-Test Reliability

Sixteen participants were able to return for a second session where they repeated nine of the measurement techniques (SF, HW, UL, UL2, UL3, UL4, AdPM, BC, BI) a second time to allow us to examine test/re-test reliability. Test/re-test correlations are displayed in Table 5. Paired samples t-tests revealed that the only method for which Time 1 and Time 2 measurements were significantly different was UL2, t(15) = -3.83, p = .002.

Table 5: *Test/re-test correlations.*

	UW Time 2	SF Time 2	UL1 Time 2	UL2 Time 2	UL3 Time 2	UL4 Time 2	BI Time 2	BC Time 2	AdPM Time 2
UW Time 1	.967**								
SF Time 1		.996**							
UL1 Time 1			.986**						
UL2 Time 1				.953**					
UL3 Time 1					.982**				
UL4 Time 1						.950**			
BI Time 1							.998**		
BC Time 1								.993**	
AdPM Time 1									.980**

** Correlation is significant at the 0.01 level (2-tailed).

3.1.3 Participant Preferences

In Phase 3, a form was distributed to participants immediately following the end of their assessment session to obtain feedback regarding their preference of body composition assessment technique. This was done by rank ordering the assessment methods from 1–6 (one being most preferable). The mean results of these preferences are shown in Table 6.

Table 6: *Participant preferences.*

Method	Average Rank
Bioelectrical Impedance	2.29
Body Circumference	3.14
Ultrasound (All Types)	3.29
BOD POD^{TM} (All Types)	3.63
Skinfold	4.37
Hydrostatic Weighing	4.40

4 Discussion

A wide range of non-invasive body composition methods have emerged with the potential to offer alternatives to HW and SF. They claim to be equally precise as traditional methods, but offer less burden upon the researcher and participant in terms of discomfort, cooperation, duration, and personal obtrusiveness. In this study we compared SF, UL, AdP, BI, and BC against HW, with the aim of determining the most efficient and reliable method for use in military scientific field settings.

4.1 Skinfold Calipers

Similar to findings by Jackson & Pollack (1978), and Tai (2013), the current study found that SF was not significantly different from HW. The two measures were highly correlated and we demonstrated that there were no fixed or proportional biases between SF and HW. The current study also provided evidence for the test/re-test reliability of this measure. A study by Tai (2013), presented similar results with SF having a low average bias with HW and a high correlation value ($r = 0.86$).

The disadvantage of this technique is the requirement for direct manipulation of the individual’s skin, and dealing with body size and fat distribution differences. Skinfold measurements also require training to accurately locate the anatomical landmarks as well as the correct use the calipers. Finally, variances in skinfold thicknesses (factoring in tissue compression factors and caliper tension duration) are additional issues. While these limitations are valid concerns, the current study demonstrated that when using a trained researcher, the skinfold technique can be a reliable and valid assessment tool for measuring body composition. An important advantage of using skinfold calipers is that they are mobile, affording use in both in-lab and in-field settings.

4.2 Subcutaneous Ultrasound

UL relies on the same sites used in the sum of seven skinfold assessment by Jackson & Pollack (1978), but instead of manually measuring skinfold thickness, the depth of subcutaneous fat (corrected for skin and muscle) is obtained at each location (Wagner, 2013). UL is appealing for many reasons. This method is convenient for assessing body composition, both in-field and in-lab settings. UL is non-invasive, as it determines the depth of subcutaneous fat over the standardized site without physical manipulation of the tissue. UL can be learned rapidly, and reduces the human error involved in using skinfold calipers by using an “averaging” function. UL is suggested to have high internal validity (compared to SF) as it has a smaller learning curve (Wagner, 2013). The ultrasound tool is also economical compared to other new assessment tools (i.e., BOD POD^{TM}).

The current study evaluated four different techniques for using the BodyMetrix Pro Ultrasound System. To our knowledge no previous study has explored this. The first setting (UL) utilized an “athletic” body type descriptor and involved manual peak adjustment by the experimenter. The second setting (UL2) also used the “athletic” body type descriptor but the experimenter did not manually adjust the peaks provided by the software. For the third setting (UL3), the experimenter selected the appropriate body type descriptor based on the appearance of the participant and adjusted the peaks manually. The fourth setting (UL4) was the same as setting three but without manual peak adjustment. All of the UL methods were not significantly different from HW and they all demonstrated high correlations. However, UL was found to have a significant fixed bias compared to HW and UL2 was found to have a significant difference between Time 1 and Time 2 measurements. Further research needs to be conducted to compare the various ultrasound methods but there is some evidence to suggest that method of use is important and that manually selecting body type may be advantageous. We have not been able to find any other studies which examined the test/re-test reliability of the subcutaneous ultrasound method.

4.3 Air-displacement Plethysmography

AdP uses a similar concept as HW for assessing whole body density, but instead relies on the changes in pressure in a closed chamber to assess body composition (Fields et al., 2002). This makes it a viable, easy to use alternative “gold standard” method that does not require water immersion. It is a quick assessment and relies on minimal effort from both parties. The disadvantage of AdP is that it cannot be easily transported and, therefore, is best suited for a fixed lab site. The literature comparing AdP vs. HW varies. Results by Demerath et al. (2002), and Tai (2013) showed that the AdP was not comparable to hydrostatic weighing; whereas, McCory et al. (1998) and Levenhagen et al., (1999) found that the AdP was comparable. In the current study, AdP measurement was significantly different from HW even when different lung volumes (BOD POD^{TM} Predicted TGV and BOD POD^{TM} entered TGV) were used to assess the participant’s body composition.

A possible explanation for why utilizing different lung volumes did not make a larger difference is the fact that only 40% of the TGV value is used to assess the individual’s body composition when using the AdP. This means that if there is a difference of 100 mL in the thoracic gas volume measurement, it only results in a change in body fat percentage of 0.3% (McCory et al. 1998). Therefore, even though the TGVs given by AdPM and AdPPFT were considerably different, this did not have a large impact on body fat measurements.

Bland Altman plots indicated that all AdP measures demonstrated a fixed bias and were providing higher estimates of body fat compared to HW. Interestingly, the AdP measurements had the highest correlations with HW compared to the other assessment methods and demonstrated good test/re-test reliability. This suggests that AdP systematically overestimates %BF compared to HW. More research is required, but this raises the possibility that AdP could be the most comparable to HW if a correction factor is utilized.

It was also found that there was a proportional bias between AdPP and HW. The more fat mass an individual had the greater the difference was between the gold standard measurement and the AdPP. This is concerning as most clinical assessments using the AdP device utilize the easy and fast “predicted” measurement of TGV.

4.4 Bioelectric Impedance

BI is a relatively new, convenient, inexpensive, and simple method for near- instantaneous estimation of %BF, and it is gaining popularity in fitness clubs and home use. The advantages of using BI, for assessing body composition include ease of use, and rapid results. Based on participant survey responses, this method was rated as the most preferred assessment technique.

In this study, we aimed to determine if this method can accurately assess body fat percentage in scientific and health settings. Previous studies by Duz et al. (2009) and Sardinha et al. (1998) found low correlations with the accepted gold standard used in their study, where on average the BI measurement consistently underestimated the body fat percentage of the individual. In contrast, Biaggi et al. (1999) found high correlations between HW and BI methods. In the current investigation, the BI measurements were found to be significantly different from HW measurements. Bland Altman plots indicated a fixed bias whereas BI resulted in lower body fat estimates compared to HW.

BI measures body fat percentage by introducing a low voltage current through the body and determining the amount of total resistance in the return signal. This resistance is proportional to the amount of fat present in the body, as white adipocytes act as resistors in the human body to an electrical current due to the anhydrous quality of fat (Duz et al., 2009). BI-derived %BF may however be affected by hydration state, caffeine intake, and exercise level (Wagner, 2013). Hydration may be the most significant of these factors, and the one that can greatly vary for intra- and inter-individual differences. Since hydration level can greatly affect the resistance of the current and, therefore, the measurement of body fat percentage, it can result in a decreased accuracy of the measurement of body fat percentage. In the present study, we report high test/re-test reliability. This does not demonstrate that the hydration state of the individuals was appropriate during the assessments, but instead that it was consistent each time. Considering that every participant was required to refrain from food and drink for two hours prior to arriving to the lab, an artificially stable baseline hydration state was created in this study; we speculate that for operational uses, variabilities in day-to-day hydration state would reduce this precision.

4.5 Body Circumference

BC is a relatively simple method to assess body composition compared to some of the other techniques analyzed in the report, and relies upon the logarithmic Equation of 2 to 3 circumference measurements, depending on gender, to estimate %BF. This method has been utilized by the U.S. Army (Army Body Composition Program, 2013) to characterize and track body composition across very large cohorts of troops as one of the parameters of individual fitness/readiness.

There are only a few studies that have validated the BC method against accepted gold standards measures (Friedle et al., 1992; Hodgdon, et al., 1994a; Hodgdon et al., 1994b). In the present study, of all other assessment methods, the BC technique produced one of the lowest correlations to HW and was found to have a significant fixed bias from the Bland Altman plot analysis, with BC providing higher body fat percentages. That this method consistently overestimates an individual's body composition is notable, as the U.S. Army is currently assessing all their troops using this method (Army Body Composition Program, 2013). If this assessment method consistently overestimates soldiers' %BF, then recommendations for body fat loss targets to meet accepted U.S. Army %BF standards might be proportionally skewed and thus may require adjustments for military personnel body fat loss targeting purposes.

BC measurements are a convenient, quick, and mobile assessment tool that could be utilized in many different environments. This measurement system is also very easy to learn as it involves either 2 or 3 measurements, which are taken at landmarks around the body. However, this measurement system is sensitive to small changes in the assessment (0.5 in) which can result in large changes in %BF.

5 Limitations

Some of the limitations to the current study include the method chosen for assessment for the measurement of body composition. The method for assessing BI is not the typical measure to assess body fat percentage in a laboratory setting. Previous works by Biaggi et al., (1999) and Duz et al., (2009) utilize BI analysis by placing electrodes at standardized locations across the body to assess body composition. The accuracy of this method may be improved if a previously reported standardized method was used instead. Another limitation to this study was the use of hydrostatic weighing as the "gold standard." Though HW has a long history of being the certified "gold standard," recently the use of dual-energy x-ray absorption has gained credibility as the most accurate assessment of body composition (Duz et al., 2009). DEXA improves the accuracy of the assessment due to its ability to differentiate between different components of the body, specifically between fat-free mass, fat mass, and bone mineral content, compared to HW (Duz et al., 2009). HW also has a reduced validity due to its dependence on RV, where Wagner and Heyward (1998) found that the measurement and the participant's ability to reach their RV during the experimental protocol is the biggest limitation to HW's use. Due to the resources available HW was used as the method of comparison in this study; however this could affect the validity of these results as it is no longer considered the "gold standard" for the assessment of body composition.

6 Conclusion

Further investigations with larger sample sizes and more diverse populations should be performed before definitive recommendations for body composition methods in clinical and/or research settings that replace the HW "gold standard" method can be made. There seems to be a systematic over-prediction of %BF when using the AdP methodology found in the BOD POD™ system, despite its greater ease of use and tolerability, and despite inputting directly-measured lung volume correction data into the software. Of the mobile methods, the current study finds the most support for SF and UL (with manual selection of body type). These two techniques are found to be comparable to HW, do not demonstrate fixed or proportional biases, and have good test/re-test reliability. In addition, UL is relatively fast and mobile, allowing for use in remote field research settings, both in athletic and military populations. A significant drawback to the SF technique is that it may involve some discomfort to the participant with physical "pinching" of their skin when obtaining the skin fold. Indeed, this method was among the least preferred by participants in the current study (second only to HW). Given this drawback, the UL method is more tolerable and satisfies many requirements for both laboratory and field research. Despite the ease of use and simplicity, BC technique over-estimates percent fat estimations, and more research is needed to verify accuracy, especially when using BC for weight/fat loss targeting in military populations.

From this investigation, UL is recommended to be used in future experiments that involve the assessment of body composition for military personnel. Due to its comparable results to HW, its test/re-test reliability, its ease-of-use in both a clinical and field setting, and high preference among participants it is the most suitable method for future research conducted by DRDC.

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List of Symbols/Abbreviations/Acronyms/Initialisms

AdP	Air-Displacement Plethysmography
AdPM	Air-Displacement Plethysmography with BOD PODTM Measured TGV
AdPP	Air-Displacement Plethysmography with BOD PODTM Predicted TGV
AdPPFT	Air-Displacement Plethysmography with TGV Measured from PFT
ANOVA	Analysis of Variance
%BF	Percentage of Body Fat
BC	Body Circumferences
BD	Body Density
BI	Bioelectrical Impedance
DRDC	Defence Research and Development Canada
HW	Hydrostatic Weighing
PFT	Pulmonary Function Test
RV	Residual Volume
SAA	Surface Area Artifact
SF	Skinfold Method
TGV	Thoracic Gas Volume
UL	Ultrasound

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3. TITLE (The document title and sub-title as indicated on the title page.)

Evaluating Alternative Methods for Body Composition Measurement in Field Settings

4. AUTHORS (Last name, followed by initials – ranks, titles, etc., not to be used)

DeVries, Z.; Goodman, L.; Blackler, K.; Moes, K.; DuCharme, M. B.; Powelsland, C.; Sullivan-Kwantes, W.

5. DATE OF PUBLICATION (Month and year of publication of document.) August 2018	6a. NO. OF PAGES (Total pages, including Annexes, excluding DCD, covering and verso pages.) 32	6b. NO. OF REFS (Total references cited.) 29

7. DOCUMENT CATEGORY (e.g., Scientific Report, Contract Report, Scientific Letter.)

Scientific Report

8. SPONSORING CENTRE (The name and address of the department project office or laboratory sponsoring the research and development.)

DRDC – Toronto Research Centre
Defence Research and Development Canada
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Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 04K	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a. DRDC PUBLICATION NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC-RDDC-2018-R142	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11a. FUTURE DISTRIBUTION WITHIN CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

Public release

11b. FUTURE DISTRIBUTION OUTSIDE CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.)

Body Composition; measurement technique; gold standard; percent fat; non-invasive; portable; validation

13. ABSTRACT (When available in the document, the French version of the abstract must be included here.)

The aim of this study was to determine how several non-invasive body composition measurement techniques compared with hydrostatic underwater weighing (traditional “gold standard”) in order to determine the best options for measuring body composition in military human performance experimental field settings. Sub-cutaneous ultrasound, manual skinfolds, air-displacement plethysmography, bio-impedance, and body circumference techniques were compared. Statistical tests of agreement as well as test/re-test reliability were analyzed. Fixed and proportional biases were examined using Bland-Altman graphical analyses. Skinfolds and ultrasound were found to be the most similar to hydrostatic weighing and would be good candidates for use in military field settings. While the performance of these two methods was similar, ultrasound advantages include high preference by participants and ease of use for practitioners.

L’objectif de cette étude était de déterminer comment plusieurs techniques non effractives de mesure peuvent se comparer à la densitométrie hydrostatique (modèle de référence classique) afin d’établir la meilleure façon de mesurer la composition corporelle dans le cadre d’études sur le rendement humain du personnel militaire au cours d’expériences sur le terrain. Au nombre des techniques comparées figuraient la mesure par échographie sous-cutanée, la mesure des plis cutanés effectuée manuellement, la pléthysmographie par déplacement d’air, la bio-impédance et la mesure de la circonférence corporelle. On a analysé des tests de concordance statistique et vérifié la fiabilité test-retest. Puis, on a procédé à un examen de la polarisation variable et invariable par l’analyse de graphiques de Bland-Altman. La mesure des plis cutanés effectuée manuellement et la mesure par échographie se sont révélées être les méthodes ressemblant le plus à la densitométrie hydrostatique, et celles-ci représenteraient une bonne solution pour les militaires sur le terrain. Bien que les deux méthodes offrent un rendement similaire, la mesure par échographie a l’avantage d’être la préférée des participants et d’être facile à utiliser par les professionnels.