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ORIGINAL ARTICLE

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Development and cross-validation of a circumference-based predictive equation to estimate body fat in an active population

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Abstract

Objective: The U.S. Army uses sex-specific circumference-based prediction equations to estimate percent body fat (%BF) to evaluate adherence to body composition standards. The equations are periodically evaluated to ensure that they continue to accurately assess %BF in a diverse population. The objective of this study was to develop and validate alternative field expedient equations that may improve upon the current Army Regulation (AR) body fat (%BF) equations.

Methods: Body size and composition were evaluated in a representatively sampled cohort of 1904 active-duty Soldiers (1261 Males, 643 Females), using dual-energy X-ray absorptiometry (%BF_{DXA}), and circumferences obtained with 3D imaging and manual measurements. Sex stratified linear prediction equations for %BF were constructed using internal cross validation with %BF_{DXA} as the criterion measure. Prediction equations were evaluated for accuracy and precision using root mean squared error, bias, and intraclass correlations. Equations were externally validated in a convenient sample of 1073 Soldiers.

Results: Three new equations were developed using one to three circumference sites. The predictive values of waist, abdomen, hip circumference, weight and height were evaluated. Changing from a 3-site model to a 1-site model had minimal impact on measurements of model accuracy and performance. Male-specific equations demonstrated larger gains in accuracy, whereas female-specific equations resulted in minor improvements in accuracy compared to existing AR equations. Equations performed similarly in the second external validation cohort.

Conclusions: The equations developed improved upon the current AR equation while demonstrating robust and consistent results within an external population. The 1-site waist circumference-based equation utilized the abdominal measurement, which aligns with associated obesity related health outcomes. This could be used to identify individuals at risk for negative health outcomes for earlier intervention.

KEYWORDS
anthropometrics, body composition, circumference equations, U.S. Army

1 | INTRODUCTION

Body composition, including percent body fat (%BF), is associated with physical performance[1] and overall health[2–4] in the general population. This relationship is particularly important when we look at individuals such as athletes and those who need to operate in highly physical demanding settings where increased %BF can result in decreased aerobic and anaerobic capacity and increased injury, illness and absenteeism.[5–7] Researchers and clinicians have looked at various methods for assessing body composition. Modern use of dual-energy X-ray absorptiometry (DXA) to assess body composition has become prevalent, replacing the long-established use of the underwater weighing method for body fat mass assessment. This is due in part to inherent limitations of the latter (e.g., requirement of trained administrator and participant, reliance on estimations for lung air and gastrointestinal gas volumes, etc.)[8] and documented measurement precision of the DXA (i.e., measurement of total body fat mass and fat free mass better than ± 0.5%).[9] However, the devices needed to conduct these measurements are costly, require trained operators for data acquisition and interpretation, need routine maintenance and upkeep and are often not readily available or easily accessible by the communities that could benefit from them.[10,11]

Historically, clinicians and organizations with body composition standards, including the military, have used simplified prediction equations to estimate %BF from body measurements including body mass, height, and/or manually measured circumferences. Prediction equations consider the relationships observed between anthropometric measurements and %BF in large populations and can provide estimates of body fat levels in individuals. Similar to body mass index (BMI) as an assessment of body size, many %BF prediction equations function well at the population level with discrepancies in error within specific groups (i.e., sex, ethnicity, age) or individuals when precision is assessed by measurements using standard technologies (i.e., underwater weighing or DXA).[12] Anthropometric equations for estimating %BF have existed for decades and are continuously being reevaluated and updated. Many of the most accurate equations produced for predicting %BF use skin fold measurements, which have low reproducibility between raters.[13–17] This is concerning because reliance on measurements that are prone to error will increase measurement misclassification, particularly in non-research settings. Thus, having an equation that is capable of accurately predicting %BF, that is simple and can be conducted with easily identifiable anatomical markers, could have tremendous clinical utility.

The U.S. military has used prediction equations to estimate %BF for ≥40 years. Equations are simple, cost-effective, and field-efficient tools utilized to maintain the general health and readiness of the Force. In 2002, all U.S. Services adopted the Hodgdon sex-specific prediction equations,[18,19] standardizing %BF calculation across the military.[19] While the Army has regularly updated the body fat standards (Army Regulation (AR) 600–9[20]), the prediction equations used to assess %BF have not been reevaluated or updated. In January 2021, the U.S. Army Research Institute of Environmental Medicine was tasked to evaluate and provide updates to the %BF equations to ensure accuracy and equality across the modern Army population specific to demographic categories of sex, age and race/ethnicity.

The objective of this manuscript is to report and discuss the findings of that investigation, which aimed to develop a contemporary prediction equation for accurate %BF estimation in a military population that exhibits a wide range of %BF. This study was the most complete assessment of %BF in the Army to date. The robust sample size and strategic and systematic sampling scheme, which included oversampling of minority populations, allowed us to evaluate the accuracy of the predictive equations within important subgroups of the population.

2 | METHODS

2.1 | Cohorts

The primary study population (Cohort 1) was 1904 (1261 Males, 643 Females) Active-duty Soldiers. The population was sampled using validated methods similar to those utilized in the National Health and Nutrition Examination Survey (NHANES).[21] Demographic data were obtained on all Active-duty Soldiers in the Army on 31 DEC 2020, which was used to calculate the proportion of the study sample required to represent each sex, race/ethnicity (American Indian or Alaskan Native, Asian/Pacific Islander, Black non-Hispanic, Hispanic, White non-Hispanic, and other) and age category (17–20, 21–27, 28–39, >40-years old). Women and demographic groups representing less than 10% of the total Active-duty Army (American Indians or Alaskan Natives, Asian or Pacific Islanders, and those over the age of 51) were oversampled to increase precision and accuracy in estimates within these smaller sub-groups. A separate convenience sample (Cohort 2) of 1073 soldiers (306 Active-duty, 364 National Guard and 403 Reservists) served as a population to externally validate the equations generated in Cohort 1 independently of the population used to derive the equations.

2.2 | Sample size

Sample size was calculated considering feasibility and mathematical (statistical power) considerations in order to select a representative sample of the Army population. To select a representative sample, the entire Army was evaluated using five categorical variables: sex, race/ethnicity, age, rank, and Military Occupational Specialty physical demands category. Every possible combination of these categorical variables was quantified. All combinations were excluded that had less than 10 people with those characteristics. This produced approximately 200 unique combinations of the five categorical variables. A 10-fold increase in the number of individuals that could be selected from these categories for a sample size of the 2000 individuals was assumed in order to collect data on a diverse variety of individuals. With this sample size, the linear regression models would be able to detect a very small global Cohen's F^2 as low as 0.03. This assumes a power of 80% with an alpha = 0.05 for a model that has 100 additional covariates. Although it is unlikely that the models produced would have 100 covariates. For reference, the current models for body circumference measurements currently use 2 and 3 covariates for males and females, respectively.[22,23]

2.3 | Body size and composition assessment

Anthropometric measurements were made in a lightweight shirt, shorts and sports bra with stocking feet. Standing height was measured using a stadiometer (model 217, SECA, Chino, CA) and body mass was measured using a calibrated electronic scale (model DS6150, Doran). Body size was captured via 3D infra-red scanner (SS20 Scanner, Size Stream[24]), which produced automated circumference measurements calculated from preset and defined landmarks for comparison with manually obtained circumference measurements.

Body composition was determined using DXA ($\%BF_{DXA}$, GE Lunar iDXA, GE Healthcare) and by the approved AR circumference-based method ($\%BF_{CIRC}$; AR 600–9[20]). Female participants produced a negative pregnancy test prior to scanning procedures. The in vivo coefficient of variation in an external population for soft tissue and $\%BF_{DXA}$ was 0.4%–1.0%.[25] Manual circumference measurements (MM) for men at the neck and abdomen and women at neck, waist and hips were made in triplicate using a calibrated fiberglass tape measure and recorded to the nearest 0.5 inch to estimate $\%BF_{CIRC}$ using the Hodgdon equations[26] for %BF measurement.[20]

2.4 | Analysis and modeling

Pearson correlations coefficients were used to estimate the correlation between 262 circumferences from the 3D scanners and the $\%BF_{DXA}$. All correlations between $\%BF_{DXA}$ and circumference estimates were ranked to identify those most highly correlated with $\%BF_{DXA}$. From this ranked list, the top measurement sites with easily identifiable anatomical markers for measurement were selected for final equation consideration.

Preliminary variable selection into the equations accounted for statistical associations, field expediency, number of sites, and ease of identification and measurement of anatomical sites. Linear regression models were used to produce $\%BF_{CIRC}$ equations using the 3-D scanner and MM circumferences at the different anatomical sites, with consideration for height and weight. 3-, 2- and 1-site equations were produced for consideration. Final equations were estimated with internal cross-validation using k-fold cross validation with 5 folds to reduce the potential for over-fitting the equation to the study population. Root mean squared error (RMSE) was calculated for all equations. Additionally, for MM equations, intraclass correlation coefficients (ICC) and bias estimates (error from $\%BF_{DXA}$) were calculated to assess the accuracy and precision of the equations in Cohorts 1 and 2. ICCs were calculated using mixed models to calculate the Shrout-Fleiss ICC(2,1) for a two-way random effect with absolute agreement.[27] The AR equation was used as the benchmark equation against which to compare accuracy.

Bland-Altman plots with 95% limits of agreement were used to visually assess systematic or consistent error and identify potential outliers between prediction equations with $\%BF_{DXA}$ as the criterion measure compared to the circumference-based prediction equation measurements. The mean bias and the 95% limits of agreement are presented on each of the presented graphs.

No missing data existed for any of the variables used for Cohort 1 and Cohort 2. Statistical analyses were conducted in R (v4.2.1; R Core Team 2022) and SAS statistical software (Version 9.4, SAS Institute Inc Cary, 2023).

2.5 | Study overview

This study was approved by the US Army Medical Research and Development Command Human Institutional Review Board (Fort Detrick). Investigators adhered to the policies regarding the protection of human subjects as prescribed in AR 70–25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Data collection took place from October 2021 to December 2022 at four Army installations: Fort Liberty, NC, Fort Gregg-Adams, VA, Fort Stewart, GA, and the U.S. Military Academy, West Point, NY (cadets were excluded). All participants provided written informed consent. Exclusion criteria included current pregnancy and large amounts of metal in the body that would impact body scanning procedures.

3 | RESULTS

3.1 | Cohort characteristics

Cohort 1 closely matched the Army population with respect to race/ethnicity, age, and sex, with over sampling for women (+18%), Asians (+3%), Native Americans (+0.5%), and those over 40 (+1%). Average measures were: body weight (kg) 85.9 ± 13.8 and 70.0 ± 11.1 (mean ± SD; M and F); BMI (kg/m^2) 27.6 ± 3.9 and 26.0 ± 3.5; $\%BF_{DXA}$ 24.3 ± 6.3 and 32.9 ± 6.1; % fat free mass 61.7 ± 8.2 and 44.2 ± 6.0 (Table 1). Except for Asian and Pacific Islander men and women and Black Non-Hispanic males, Cohort 1 and 2 had similar distributions within sex for the race/ethnicity categories and across

TABLE 1 Population characteristics stratified by sex.

	Cohort 1		Cohort 2	
	Men $n = 1259$	Women $n = 643$	Men $N = 753$	Women $N = 320$
Race/ethnicity- *n* (%)				
Am. Indian or Alaskan Native	15 (1.2)	9 (1.4)	5 (0.7)	4 (1.3)
Asian or Pacific Islander	147 (11.7)	51 (7.9)	52 (6.9)	19 (5.9)
Black, not Hispanic	235 (18.7)	198 (30.8)	162 (21.5)	100 (31.3)
Hispanic	236 (18.8)	136 (21.2)	147 (19.5)	62 (19.4)
White, not Hispanic	619 (49.2)	239 (37.2)	379 (50.3)	131 (40.9)
Other	7 (0.6)	10 (1.5)	8 (1.1)	4 (1.3)
Age category- *n* (%)				
17–20	126 (10.0)	75 (11.7)	163 (21.7)	68 (21.5)
21–27	538 (42.7)	280 (43.5)	266 (35.3)	96 (30.0)
28–39	468 (37.2)	237 (36.9)	224 (29.7)	102 (31.9)
>40	127 (10.1)	51 (7.9)	100 (13.3)	54 (16.9)
Anthropometrics- mean ± SD				
Height (cm)	176.3 ± 7.1	163.7 ± 6.9	176.1 ± 7.2	163.3 ± 6.2
Body weight (kg)	85.9 ± 13.8	70.0 ± 11.1	84.8 ± 15.4	71.5 ± 11.8
BMI, kg/m^2	27.6 ± 3.9	26.0 ± 3.5	27.3 ± 4.2	26.8 ± 3.9
% Body fat$_{CIRC}$	19.5 ± 6.3	31.2 ± 6.2	18.8 ± 7.1	32.8 ± 7.1
% Body fat$_{DXA}$	24.3 ± 6.3	32.9 ± 6.1	24.4 ± 6.9	34.1 ± 6.6
Fat mass (kg)$_{DXA}$	21.5 ± 8.0	23.7 ± 7.2	20.1 ± 9.6	23.8 ± 9.3
Fat-free mass (kg)$_{DXA}$	61.7 ± 8.2	44.2 ± 6.0	56.4 ± 14.0	42.0 ± 9.4

Abbreviations: BMI, body mass index; CIRC, Army Regulation 600–9 standard equations[11]; DXA, dual-energy x-ray absorptiometry.

anthropometric measurements. Cohort 2 had higher proportions of individuals in the 17–20 and > 40 age categories and lower proportions of individuals 21–39–years old.

3.2 | Anthropometric correlations

Of the 262 correlations evaluated between %BF$_{DXA}$ and anatomical sites measured by the 3D scanner, the top 50 correlations primarily involved waist or abdominal measurements followed by correlations for circumferences around the hips and gluteal region. Other circumferences evaluated included neck, thigh, shoulders, and chest, all of which were ranked greater than 100 for correlation to %BF$_{DXA}$ with correlations of less than 0.51. Based on these preliminary correlations, variables considered for the final equations were: (1) the abdomen at the umbilicus, (2) the narrowest part of the waist, (3) the widest part of the hips, (4) body weight and (5) height. The circumference most strongly correlated with %BF$_{DXA}$ in both males and females was the abdomen at 0.79 and 0.75 correlations, respectively. Comparing between the anthropometric measures, the abdomen, and the waist were most correlated (Males: 0.96, Females: 0.90), followed by weight and hips (Males: 0.91, Females: 0.90), with height having the lowest correlation to BF% and all other measures (Figure 1).

3.3 | Proposed equations

Table 2 shows the estimated coefficients for the best fit 3-, 2- and 1-site equations using 3D scanner output and MM both with and without the addition of height. As variables were removed from consideration, changes in the remaining coefficients (β_1–β_5) were minimal while the intercept (a constant in the equation) was primarily impacted. This may indicate that the equation variable is unnecessary and can be accounted for with an offset built into the intercept. When comparing between the same-site equations for the 3D scanner and the manual measurements, the coefficients for each variable were comparable with the mean difference of 0.07 and 0.14 in the coefficients for men and women, respectively. Given the closeness of the 3D and MM equations, the remaining results will focus on the MM equation comparison to the AR equation.

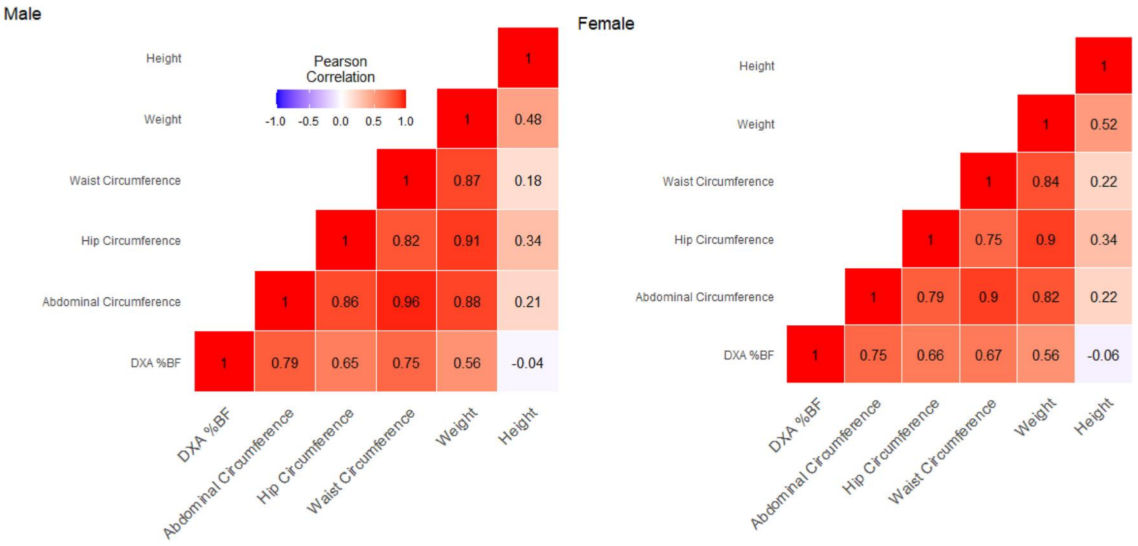

FIGURE 1 Pearson correlations between anthropometric measurements and percent body fat measured by dual-energy X-ray absorptiometry (%BF_{DXA}).

3.4 | Equation RMSE

For women, as the number of sites included in the MM equations was reduced, the RMSE error increased but with minimal impact (Max Δ: 0.35%). For men, the 2-site equation performed the best, although RMSE differences were small (Max Δ: 0.13%) (Table 3). Comparing Table 3 where height was not included in the equation to Table S1 where height was included in the equation, removing height resulted in no major impacts on the RMSE (Max Female Δ: 0.27%, Max Male Δ: 0.02%) across sex, race/ethnicity and age. Among women, comparing the AR equation to the 2- and 1-site MM equations, there was a 0.62% improvement in RMSE with the 2-site equation and a 0.28% improvement for the 1-site equation. For men, the improvement in RMSE comparing the 2- and 1-site equations to the AR equation was larger with a 2.66% and 2.54% difference, respectively (Table 3).

The 2- and 1-site MM equations had equivalent ranges of RMSE when evaluating differences in equation performance by race/ethnicity. Using the 1-site equation, the greatest difference in RMSE was 0.37% between Asian women and White women and 0.29% between Asian men and White men. The AR equation had marginally higher RMSE differences by race/ethnicity, with a 0.62% peak difference between Asian women and White women and a 0.49% peak difference between Black men and Hispanic men (Table 3).

For age differences in RMSE, the 1- and 2-site MM equations demonstrated similar RMSE ranges. Using the 1-site, the greatest difference in RMSE by age was 1.02% comparing 28–39-year-old women to >40-year-old women and 0.54% comparing 28–39–year-old men to >40-year old men. In the AR equation, among women, there was a slightly lower RMSE range by age with a 0.89% difference occurring between 28 and 39-year-old women and >40-year-old women. For men, the AR equation had considerable differences in RMSE by age with a 2.89% difference between 17 and 20-year-old men and >40-year-old men (Table 3).

Within Cohort 2, the equations produced similar results for RMSE across age, race/ethnicity and sex (Table S1). The difference in RMSE between Cohort 1 and Cohort 2 was less than 0.1%.

3.5 | Equation ICC

ICC differences between the 3 MM equations were larger in women (Max Δ: 0.06) than in men where ICC differences were approximately equal (Max Δ: 0.004) (Table 4). The AR equation had an ICC that fell between the 2-and 3-site equations ICCs for females and the AR equation was lowest in ICC for males. The trends held across all races/ethnicities and ages with the exception of Hispanic females, where all MM equations had higher ICCs. There were no major differences in the ranges of ICCs between the MM equations when comparing race/ethnicities by sex (women: 0.02–0.05; men: 0.07–0.08). The AR equation had a wider range of ICCs for both men (0.15) and women (0.06) when comparing race/ethnicity by sex. Similarly, in men and women, there were no major differences in the range of ICC between the MM equations when comparing age by sex (women: 0.08–0.11; men: 0.07–0.08). The AR equation had a comparable range of ICCs for women (0.11) and a higher range of ICCs for men (0.17) when comparing age by sex. Within the Cohort 2, the equations produced similar ICC across age, race/ethnicity and sex (Table S2).

3.6 | Equation bias

Between the MM equations, bias was highest for women in the 3-site equation (Table 4). Bias in the 1- and 2-site equations for women

TABLE 2 Coefficients of body fat equations by measurement sites across sex where each table value is the beta (β) coefficient for the column indicated.

FEMALE	**3D MEASUREMENTS WITHOUT HEIGHT**						**3D MEASUREMENTS WITH HEIGHT**						
	Equation	**Intercept (β_0)**	**β_1*Abdomen**	**β_2*Hip**	**β_3*Waist**	**β_4*Weight**	**Equation**	**Intercept (β_0)**	**β_1*Abdomen**	**β_2*Hip**	**β_3*Waist**	**β_4*Weight**	**β_5*Height**
	3 site	−39.71	1.01	1.20	0.39	−0.16	3 site	−2.58	0.98	0.94	0.15	−0.08	−0.48
	2 site	−36.02	1.26	1.11	–	−0.14	2 site	1.21	1.06	0.89	-	−0.06	−0.51
	1 site	−11.96	1.43	–	–	−0.04	1 site	30.69	1.13	-	-	0.04	−0.67
	MANUAL MEASUREMENTS WITHOUT HEIGHT						MANUAL MEASUREMENTS WITH HEIGHT						
	3 site	−34.92	0.87	1.22	0.39	−0.14	3 site	4.87	0.88	0.96	0.06	−0.05	−0.52
	2 site	−31.68	1.09	1.18	-	−0.12	2 site	6.09	0.91	0.95	-	−0.04	−0.53
	1 site	−8.06	1.25	-	-	−0.004	1 site	36.86	0.96	-	-	0.07	−0.72
MALE	**3D MEASUREMENTS WITHOUT HEIGHT**						**3D MEASUREMENTS WITH HEIGHT**						
	Equation	**Intercept (β_0)**	**β_1*Abdomen**	**β_2*Hip**	**β_3*Waist**	**β_4*Weight**	**Equation**	**Intercept (β_0)**	**β_1*Abdomen**	**β_2*Hip**	**β_3*Waist**	**β_4*Weight**	**β_5*Height**
	3 site	−50.12	1.85	0.92	0.08	−0.19	3 site	−49.57	1.85	0.91	0.08	−0.19	−0.01
	2 site	−49.59	1.93	0.90	-	−0.19	2 site	−48.30	1.92	0.89	-	−0.18	−0.02
	1 site	−29.78	2.09	-	-	−0.13	1 site	−23.60	2.03	-	-	−0.12	−0.09
	MANUAL MEASUREMENTS WITHOUT HEIGHT						MANUAL MEASUREMENTS WITH HEIGHT						
	3 site	−38.32	2.23	0.68	−0.43	−0.16	3 site	−26.98	2.23	0.64	−0.53	−0.14	−0.15
	2 site	−41.39	1.89	0.74	-	−0.17	2 site	−34.72	1.84	0.73	-	−0.15	−0.09
	1 site	−27.05	2.06	-	-	−0.12	1 site	−17.70	1.98	-	-	−0.10	−0.13

TABLE 3 Root mean squared error for body fat equations without height using measurement technique across sex, race/ethnicity and age.

			Race/Ethnicity										Age							
	MEAN		Asian		Black		Hispanic		White		Other		17–20		21–27		28–39		40+	
Sex	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M
3D MEASUREMENTS																				
3-Site	3.689	3.235	3.625	3.106	3.439	3.255	3.655	3.151	3.916	3.294	3.679	3.086	3.391	3.316	3.656	3.202	3.866	3.102	3.441	3.739
2-Site	3.723	3.236	3.671	3.117	3.445	3.263	3.751	3.142	3.932	3.294	3.756	3.080	3.483	3.325	3.684	3.207	3.899	3.104	3.432	3.719
1-Site	4.001	3.386	3.774	3.227	3.777	3.574	4.024	3.276	4.204	3.396	4.079	3.238	3.883	3.515	3.887	3.442	4.262	3.161	3.504	3.802
MANUAL MEASUREMENTS																				
3-Site	3.760	3.350	3.410	3.290	3.394	3.230	3.640	3.520	3.495	3.360	3.152	1.950	3.502	3.540	3.428	3.280	3.429	3.310	4.960	3.540
2-Site	3.775	3.226	3.642	3.061	3.575	3.072	3.831	3.252	3.882	3.325	4.339	2.695	3.420	3.297	3.698	3.140	4.085	3.204	3.136	3.574
1-Site	4.111	3.351	3.907	3.154	3.934	3.226	4.058	3.398	4.273	3.441	4.712	2.794	3.990	3.385	3.903	3.365	4.498	3.208	3.470	3.750
AR	4.395	5.886	4.766	5.999	4.349	5.682	4.762	6.176	4.148	5.835	4.093	5.432	4.289	7.566	4.476	6.018	4.485	5.494	3.596	4.681

TABLE 4 Intraclass correlations and Bias for body fat MM equations without height across sex, race/ethnicity and age.

	MEAN		Asian		Black		Hispanic		White		Other		17–20		21–27		28–39		40+	
	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M
ICC																				
3-Site	0.761	0.839	0.753	0.805	0.778	0.880	0.743	0.830	0.755	0.830	0.811	0.939	0.774	0.768	0.734	0.844	0.743	0.828	0.813	0.767
2-Site	0.759	0.839	0.767	0.805	0.777	0.878	0.743	0.797	0.747	0.831	0.814	0.922	0.776	0.759	0.734	0.843	0.737	0.830	0.813	0.771
1-Site	0.701	0.835	0.723	0.811	0.709	0.872	0.704	0.790	0.686	0.824	0.688	0.932	0.682	0.758	0.685	0.824	0.662	0.835	0.770	0.762
AR	0.753	0.662	0.738	0.603	0.767	0.739	0.681	0.589	0.762	0.651	0.887	0.941	0.740	0.493	0.711	0.656	0.757	0.654	0.818	0.659
Bias																				
3-Site	−0.150	−0.972	−1.487	−1.301	−0.689	−1.070	−1.141	−1.509	−0.289	−0.637	0.455	0.421	−0.876	−1.691	−0.205	−1.007	0.179	−0.877	−0.311	−0.463
2-Site	0.039	−0.888	−1.927	−1.280	−0.018	−0.928	−0.396	−1.356	0.849	−0.588	0.787	0.623	−0.718	−1.724	−0.005	−0.950	0.358	−0.772	−0.087	−0.222
1-Site	0.080	−0.387	−1.590	−0.625	−0.216	−0.473	−0.544	−0.967	1.067	−0.078	1.734	1.829	−0.975	−1.453	−0.044	−0.639	0.419	−0.198	0.249	1.023
AR	−1.690	−4.791	−2.943	−5.000	−1.177	−4.620	−1.949	−5.170	−1.602	−4.658	−2.016	−2.767	−2.786	−6.750	−1.950	−5.073	−1.077	−4.381	1.499	−3.165

were equivalent with only a 0.04% difference. In men, there was a slight improvement in bias when comparing the 1-site to the 2-site and 3-site MM equations. Bias produced by the AR equation was proportionately larger for men than women. Within the external Cohort 2, the equations produced similar bias across age, race/ethnicity and sex (Table S2).

The Bland Altman plots (Figure 2) visually demonstrate the differences in bias across sex (A-C women; D-F men) between the AR equations and the 1-Site MM equations. Population level bias for the 1-site equation was centered close to zero and approximately equivalent with and without height for both men and women. The AR equation underestimated %BF in the majority of the population with a mean bias of −4.79% and −1.69% in men and women, respectively. The range for the 95% limits of agreement was slightly smaller with the 1-site equation having a 0.69% and 0.20% reduction in range for men and women, respectively.

4 | DISCUSSION

The objective of this study was to develop and validate prediction equations to estimate %BF in a military population while maintaining accuracy across race/ethnicity and age. The resulting equations were more accurate than the existing AR equation, while improving the feasibility of measurement in the field through site reduction. Reducing the number of anthropometric sites in the MM equations to 1-site equations had minimal impact on RMSE and bias. Additionally, the MM equations demonstrated smaller variability in RMSE, bias and ICC compared to the AR equations when results were stratified by race and age, indicating that accuracy is more equitable between these comparison groups with the MM equations. The fact that the equations developed from Cohort 1 produced similar results in Cohort 2 lends validity to the fact that the present findings represent the Army of today. The results from this study are from an active occupational cohort. Whether these results will translate to the general population will need to be further evaluated.

Notably, excluding height from the equations had no impact on accuracy, which is likely because height was not correlated with $\%BF_{DXA}$. The Department of Defense Instruction (DoDI) 1308.3, Department of Defense (DOD) Physical Fitness and Body Fat Programs Procedures, recommended that equations using circumference indexes to determine body fat should consider height in the assessment process.[19] Our findings determined that removing height from the equations did not impact the accuracy of the equations and in the cases of the Bland Altman plots resulted in small improvements in accuracy.

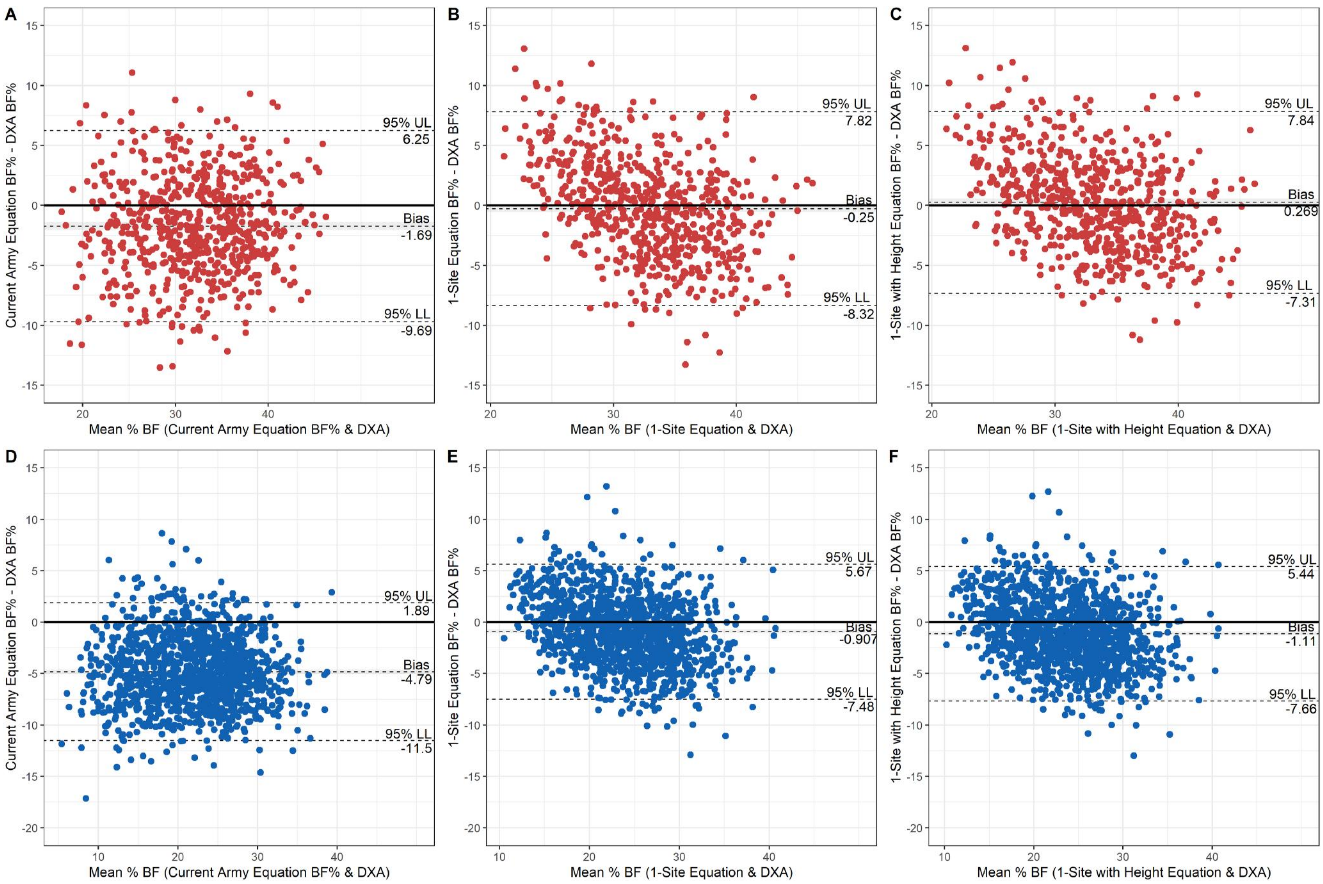

FIGURE 2 Bland Altman plots stratified by sex comparing percent body fat measured by dual-energy X-ray absorptiometry ($\%BF_{DXA}$) to (A, D.) Army Regulation Equation %BF, (B, E.) 1-site Equation %BF, and (C, F.) 2-site Manual circumference measurements equation %BF. The solid black line represents where there is no difference between the equation and $\%BF_{DXA}$. Red dots represent female volunteers and blue dots represent male volunteers. The solid black line is where the plot-specific equation matches the $\%BF_{DXA}$. %BF, percent body fat.

The reproducibility of waist and hip circumference measurements has a higher level of intra- and inter-rater reliability than measurements that incorporate both hips and waist (e.g., hip-to-waist ratio).[28,29] This may be because measurement error for each site may vary by body type and obesity status, thereby magnifying the error when both measurements are used.[30] The present study used the same trained study staff at each data collection site to conduct the circumference measurements. Consistency was apparent in the results between the 1-site and 2-site equations. However, given the potentially higher error in replicating measurements between raters for metrics using both the hips and waist, it could be postulated that error could be higher in the 2-site equation when evaluated with multiple raters, although this should be evaluated further.

Although the present study enrolled only military participants, the wide range of %BF in the study population may suggest that the equations resulting from this work may be useful for other populations. While higher %BF is associated with obesity related health problems,[3] the circumference measurements in the equations developed are also associated with negative health outcomes. In particular, waist circumference is strongly associated with hypertension, type 2 diabetes, cardiovascular disease and metabolic syndrome.[31] This may indicate that the 1-site equation could also be useful in identifying individuals who are at risk of negative health outcomes and should be explored further.

The goal of the Army body composition policy is to ensure that soldiers maintain a level of health and readiness for operational duties. Updates to the current equations may improve upon the Army's ability to identify individuals who have higher %BF, putting them at risk for poor physical performance or adverse long-term health outcomes. One distinct advantage of the equations identified in this study is the use of one site with an anatomical landmark, which likely reduces the variability introduced through the use of multiple measurement sites. Furthermore, the new equations, which are expedient and do not require extensive training, may have utility in populations beyond the military. Future research will focus on evaluating the associations between the 1-site equation and obesity related health outcomes.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DISCLAIMER

The investigators have adhered to the policies for protection of human volunteers as prescribed in AR 70–25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. 2. Citations of commercial organizations and trade names in this paper do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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