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Original Research Article

Arm circumference as a marker of muscle mass: cutoff values from NHANES 1999–2006

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A B S T R A C T

Background: Although mid-upper arm circumference (MUAC) is a potential marker of skeletal muscle (SM), no study has proposed MUAC cutoff points using a large young reference population. Additionally, growing evidence highlights the impact of excess adiposity on anthropometric markers, which can mask their value in evaluating SM.

Objectives: This study aimed to propose cutoff points for MUAC as a marker of muscle mass, along with BMI-adjustment factors for individuals outside the normal BMI range (18.5–24.9 kg/m^2), using data from the NHANES 1999–2006 sample.

Methods: Anthropometric and appendicular lean soft tissue (ALST; by dual-energy X-ray absorptiometry) data from the adult NHANES sample (aged ≥18 y) were divided into sex, age, ethnicity, and self-reported race subgroups. Adults aged 18–39 y with a BMI of 18.5–24.9 kg/m^2 were used as the reference population, and MUAC cutoff points were derived at 1 and 2 SDs below the mean. Pearson's correlation (r) was used to assess the correlation between MUAC and ALST. Survey-weighted linear regression analysis was used to derive BMI-adjustment factors for MUAC.

Results: A total of 18,195 individuals were included (weighted proportion: 49.4% male; mean age: 43.9 y, 95% confidence interval: 43.4, 44.4 y). MUAC showed a strong positive correlation with ALST index (ALST/height^2) ($r = 0.83$ for males, $r = 0.79$ for females). Rounded cutoff points for low MUAC were 28 cm (male) and 25 cm (female) and for very low MUAC were 26 cm (male) and 23 cm (female). Overall BMI-adjustment factors were: −3 cm (male), −2 cm (female) (BMI: 25–29.9 kg/m^2); −7 cm (male), −6 cm (female) (BMI: 30–39.9 kg/m^2); −10 cm (male), −9 cm (female) (BMI: ≥40 kg/m^2).

Conclusions: This study proposes practical MUAC cutoff points, a potential marker of SM, along with BMI adjustment factors for individuals with excess weight, aiming to reduce errors in using MUAC for this purpose. Our results have the potential to enhance clinical routine assessments.

Keywords: anthropometry, arm circumference, body composition, muscle mass, cutoff

Introduction

Skeletal muscle (SM) is increasingly recognized as an important biomarker for predicting health-related outcomes [1,2]. Low SM is a consequence of various conditions, including the natural aging process and multiple clinical diagnoses [3–5], which may occur individually or in combination. Low SM may also co-occur within nutritional and inflammatory syndromes, including undernutrition, sarcopenia, sarcopenic obesity, and cachexia, collectively impacting human health [1,2,6]. Despite the emerging number of body composition assessment techniques, their use in the clinical setting remains limited [1].

Abbreviations: ALST, appendicular lean soft tissue; ALSTI, appendicular lean soft tissue index; AMA, arm muscle area; BIA, bioelectrical impedance analysis; CC, calf circumference; CDC, Centers for Disease Control and Prevention; CI, confidence interval; DXA, dual-energy X-ray absorptiometry; MAMC, mid-arm muscle circumference; MEC, Mobile Examination Center; MUAC, mid-upper arm circumference; RMSE, root mean squared error; SM, skeletal muscle; TSF, triceps skinfold thickness.

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As such, anthropometric measurements are widely used in clinical practice [1,7], providing practical, low-cost, and easily interpretable bedside markers of body composition, including SM, and hence nutritional status [7]. For example, calf circumference (CC) is widely recognized as a strong marker of SM [1,7–10] in both research and clinical practice [1,7,9,10]. Its use has become even broader given the now available adjustments (BMI-adjusted cutoffs) for people living with larger body weight, theoretically expanding CC's value as an SM marker [9].

Mid-upper arm circumference (MUAC) is also commonly used in clinical practice [1] and endorsed by clinical societies as a potential phenotypic criterion for defining low SM in the context of undernutrition [7,10]. In this article, we will use the term "malnutrition" to align with terminology adopted by clinical nutrition societies and guidelines [7,10]. Although fewer studies have focused on MUAC, some have demonstrated moderate to strong correlations between MUAC and indirect measures of SM [11,12]. Although CC may be a superior anthropometric marker of SM, accurate measurement can be challenging in certain clinical contexts, such as with bedridden patients, individuals with severe gravitational edema (e.g., cirrhosis, critical illness, or kidney disease), and those with lower-limb amputations. These factors may limit the CC's applicability, making MUAC an anthropometric bedside alternative.

MUAC measurements reflect both muscle and fat masses [13]. It can additionally be corrected for triceps skinfold thickness (TSF) using established equations, serving as a marker of SM, resulting in measures like mid-arm muscle circumference (MAMC, in centimeters) and bone-corrected arm muscle area ($_{\text{corrected}}$AMA, in square centimeters) [13]. This approach, however, requires sufficient expertise in skinfold measurements and the availability of skinfold calipers, which may limit its practicality and use. The challenge may be even greater for individuals with excess weight, as this can lead to inaccuracies in their measurements, negatively impacting nutritional diagnosis.

MUAC is often classified as a percentage of adequacy relative to the 50th percentiles derived from the NHANES sample (1971–1974) of individuals aged 1–74 y [14]. This underscores the need for updated and more suitable cutoffs based on a reference population of young individuals with normal nutrition status (*T*-scores approach), as previously recommended [9].

Given the widespread use of MUAC and the challenges associated with other techniques, this study aims to address this gap by proposing sex- and population-specific MUAC cutoff values. Additionally, we introduce MUAC adjustments for BMI to enhance its clinical utility and overcome the limitations discussed, also using NHANES data. Finally, we propose a practical equation to estimate appendicular lean soft tissue (ALST) using MUAC and other simple anthropometric measurements.

Methods

Study design

This was a population-based observational study, with cross-sectional data collection, utilizing data from the NHANES survey conducted between 1999 and 2006. Participants underwent anthropometric and body composition assessments. The study protocol was approved by the Institutional Review Board of the National Center for Health Statistics (NCHS) and the Centers for Disease Control and Prevention (CDC), and all participants provided written informed consent. All datasets used in this analysis are publicly available on the CDC website: https://wwwn.cdc.gov/nchs/nhanes/ContinuousNhanes/Default.aspx.

This NHANES timeframe (i.e., 1999–2006) was selected to ensure methodological and data management consistency. Although a few later cycles (e.g., 2011–2014) include MUAC and dual-energy X-ray absorptiometry (DXA) data, they lack TSF and differ in data processing, including DXA imputation methods, which were standardized in the 1999–2006 cycles.

Participants

NHANES applies a complex, multistage sampling strategy to represent the entire United States population, including noninstitutionalized subgroups. Participants were excluded if aged <18 y, pregnant, or missing data on primary variables of interest: BMI, MUAC, and DXA. The sample was stratified by sex and age. Race and ethnicity were self-reported by participants using NHANES-defined categories: non-Hispanic White, non-Hispanic Black, Mexican American, and "other," which included other Hispanic individuals, multiracial participants, and those who did not identify with the listed categories. Aligning with current recommendations, race was considered a social construct and used descriptively to contextualize subgroup differences. Age categories were divided into 7 groups: 18–19 y and ≥20 y in 10-y intervals, with a final group for those aged ≥70 y.

DXA

Body composition assessments were conducted at the Mobile Examination Center (MEC) using a Hologic QDR 4500A fan-beam X-ray bone densitometer (Hologic Inc), with Hologic Discovery software version 12.1. Whole-body scans were performed according to standardized procedures, detailed in the NHANES manual [15]. Individuals were excluded from DXA scans if they weighed over 136 kg (300 lb), were taller than 1.96 m (6 ft 5 in), or had undergone any contrast-based radiologic examinations in the previous 72 h. ALST was calculated by summing the lean soft tissue (in kilograms) of the legs and arms and adjusting for height squared to derive the appendicular lean soft tissue index (ALSTI, in kilograms per square meter). Fat mass (percentage) was also estimated from DXA scans.

Anthropometry

Body weight (kilograms), height (meters), MUAC (centimeter), and TSF (millimeters) were measured at the MEC using the standard methodology described in detail in the NHANES procedures manual [15]. BMI was computed as kilogram per square meter and classified according to WHO criteria [16].

For MUAC measurements, participants stood upright with their shoulders relaxed and right arm hanging loosely at their side. The evaluator, positioned on the participant's right, placed the measuring tape around the upper arm at the midpoint between the acromion process of the scapula and the olecranon process of the ulna, perpendicular to the arm's long axis. The tape was held gently against the skin without compressing the underlying tissue. The ends of the tape were brought together so that the zero end was positioned below the measurement mark, and the measurement was read on the lateral side of the arm [15]. The TSF measurement was conducted on the right upper arm at a previously marked midpoint (i.e., for MUAC measurements). Participants stood upright, and the technician grasped a fold of skin above the mark, aligning it parallel to the arm. The caliper was placed perpendicular to the fold, and thickness was recorded to the nearest 0.1 mm before releasing [15]. For comparisons, MAMC

(centimeters) was estimated using the equation: MUAC− $\left(\pi * \frac{TSF}{10}\right)$ [14], whereas $_{corrected}$AMA was computed as the equation: $\frac{MAMC^2}{4\pi}$− 10 for males, and $\frac{MAMC^2}{4\pi}$ − 6.5 for females [13].

Data analysis

Data were analyzed using R version 4.3.2 (within R Studio environment) and Stata version 15 (StataCorp LLC). To increase the representativeness of the sample at the individual participant level, probability sampling weights were applied considering survey nonresponse, oversampling, poststratification, and sampling errors. Unweighted analyses were used solely for variables requiring ± SDs from mean values and percentile distribution and simple correlation plots, due to specific analysis constraints. For all other analyses, including those based on unweighted data, weighted analyses were applied. Sample characteristics were described as absolute and relative frequencies (categorical variables) or mean ± SD (unweighted)/95% confidence intervals (CIs) (weighted continuous variables). Outliers for MUAC measurements were identified and removed from the dataset based on the IQR method with a threshold of 3. This conservative IQR threshold (i.e., 3) was chosen to ensure that only extreme outliers were excluded, minimizing the risk of removing valid data points, as done previously [9]. Given the complexity and imputed nature of DXA data in our NHANES cycles (with 5 imputed sets), we combined these sets to produce a single statistical summary. All analyses were performed separately within each imputed dataset, and the results were then combined using Rubin's rules to account for between- and within-imputation variability. This approach incorporates uncertainty from missing data into the SEs, significance levels, and other estimates. A survey-weighted linear regression with the Taylor series variance estimation method on multiple imputed data was applied, as recommended by NHANES guidelines [15]. Variables included in the imputation model were already prespecified by NHANES guidelines without additional modifications.

Descriptive statistics, including MUAC mean ± SD, median, 5th, 50th, and 95th percentiles, were calculated for established sex, ethnicity, race, age, and BMI groups. Not all participants had TSF data, but missing data were not imputed or excluded. The relation between ALSTI, MUAC, MAMC, and $_{corrected}$AMA were tested by the Pearson correlation coefficient, and its strength was classified according to r values as very high (r = 0.90–1.00), high (r = 0.70–0.90), moderate (r = 0.50–0.70), low (r = 0.30–0.50), or negligible (r = 0.00–0.30) [17].

To explore the distribution of MUAC in relation to the age spectrum, we initially applied locally weighted scatterplot smoothing to visualize trends stratified by sex, BMI, race, and ethnicity categories. Subsequently, to confirm nonlinearity, we used weighted polynomial regression models including both linear and quadratic terms for age (i.e., age and age squared). Additional weighted pairwise comparisons applying the Lincom command were used to evaluate the complex weighted sex-specific differences for MUAC across racial and ethnic groups.

Data from the individual age group (18–39 y) were explored to determine MUAC cutoff values in young adults with a normal BMI of 18.5–24.9 kg/m^2 as the reference population, named *T*-scores method. This age group (18–39 y) was chosen to be consistent with the period of peak muscle health (similar to bone), as previously endorsed [9,18]. This method potentially identifies deviations relative to a standard reference population, rather than age-matched comparisons, which may underestimate muscle deficits due to age-related changes in both muscular and nonmuscular components [9]. Although this approach is not without limitations, it may provide a more proactive framework to identify individuals "at risk" of muscle decline.

To derive BMI-specific adjustment factors for MUAC in predicting ALST, we used overall, sex- and race and ethnicity-stratified, weighted linear regression models. We included age, BMI, and fat mass (percentage) as predictors/confounders. No multicollinearity was observed (variance inflation factor for all predictors <2). Using this regression model, we estimated ALST values across different BMI levels. The differences in predicted ALST relative to normal mean BMI values were then translated into MUAC correction factors. These adjustments were applied to participants with BMI values outside the normal range (18.5–24.9 kg/m^2). No interaction terms were included, and model diagnostics confirmed a good model fit. Additional weighted linear regression models were conducted to develop a practical equation for estimating ALST using MUAC, tailored for clinical application. This equation incorporated coefficients derived from age (years), sex, and BMI (kilograms per square meter). The models' performance was evaluated using R^2 and weighted root mean squared error (RMSE) to assess accuracy and error. Statistical significance was defined as $P < 0.05$ for all tests.

Results

Initially, 41,474 individuals were screened for eligibility. Figure 1 presents the study flowchart indicating how many individuals were excluded due to age, pregnancy, outliers, or missing relevant data (n = 23,279). After exclusions, a total of 18,195 individuals were included, representing a population of 76,205,182 individuals. A weighted proportion of 49.4% (95% CI: 48.6, 50.1) males and 50.6% (95% CI: 49.8, 51.3) females was observed. Table 1 summarizes sex-specific age, anthropometric, and body composition characteristics of the self-reported race and ethnicity. Weighted race and ethnicity were distributed as follows: Non-Hispanic White: 71.1% (95% CI: 68.1, 73.8); Non-Hispanic Black: 11.1% (95% CI: 9.3, 12.9); Mexican American: 7.4% (95% CI: 6.2, 8.9); and Other: 11.1% (95% CI: 9.3, 12.9).

Sex-stratified MUAC across racial and ethnic groups demonstrated significant differences for most comparisons. For males, individuals self-reported as non-Hispanic Black had higher MUAC than the other groups. Specifically, self-reported Mexican Americans had significantly lower MUAC compared with self-reported non-Hispanic White individuals (mean difference: −0.87 cm; 95% CI: −1.18, −0.55 cm; $P < 0.001$) and self-reported non-Hispanic Black (mean difference: −1.410 cm; 95% CI: −1.79, −1.03 cm; $P < 0.001$). Similarly, self-reported Other males had lower MUAC than both non-Hispanic White (mean difference: −0.97 cm; 95% CI: −1.39, −0.54 cm; $P < 0.001$) and non-Hispanic Black males (mean difference: −1.51 cm; 95% CI: −1.92, −1.10 cm; $P < 0.001$). A nonsignificant difference was observed between self-reported Mexican Americans and Other males (mean difference: 0.10 cm; 95% CI: −0.40, 0.60 cm; $P = 0.69$). Data are not shown in tables or figures.

For females, the results were similar. Self-reported non-Hispanic Black females presented with higher MUAC than all other groups. Self-reported Mexican American females had significantly higher MUAC than Other females (mean difference: 0.88 cm; 95% CI: 0.26, 1.51 cm; $P = 0.006$), but not different from non-Hispanic Whites (mean difference: 0.27 cm; 95% CI: −0.11, 0.64 cm; $P = 0.16$). Self-reported Mexican American females exhibited lower MUAC than non-Hispanic Black females (mean difference: −2.17 cm, 95% CI: −2.61, −1.73 cm; $P < 0.001$). Self-reported Other females had a

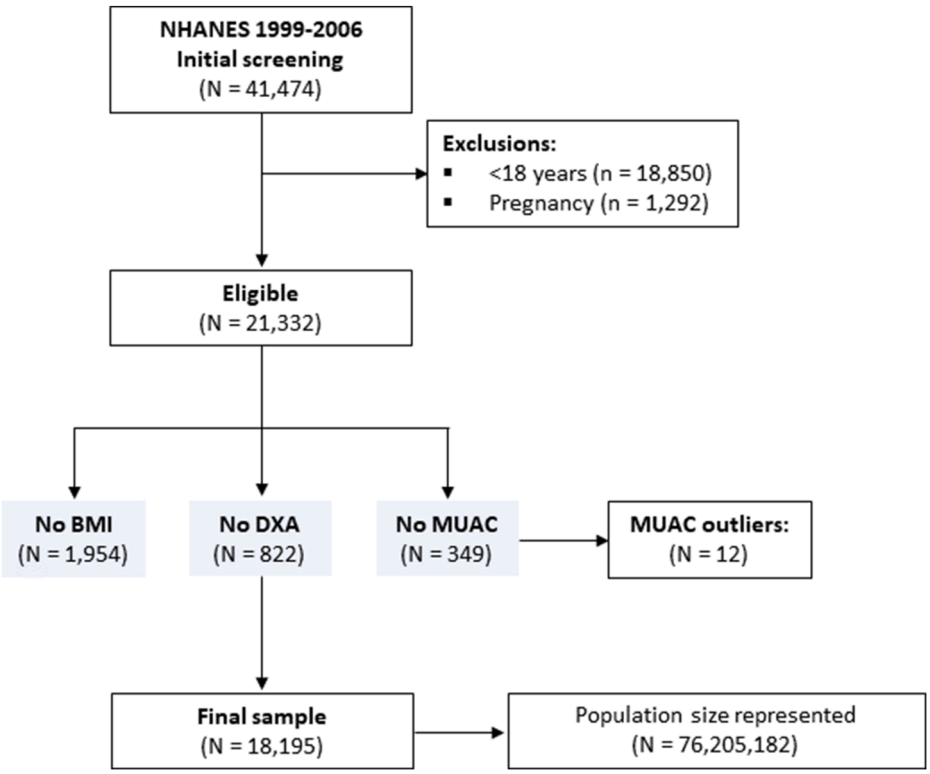

FIGURE 1. Study flowchart. DXA, dual-energy X-ray absorptiometry; MUAC, mid-upper arm circumference.

lower MUAC than those self-reported as non-Hispanic White (mean difference: −0.62 cm; 95% CI: −1.17, −0.07 cm; $P = 0.027$) and non-Hispanic Black (mean difference: −3.05 cm; 95% CI: −3.63, −2.47 cm; $P < 0.001$). Data are not shown in tables or figures.

Table 2 describes sex-specific mean ± SD of MUAC values for the total sample and across racial and ethnic groups. After applying weighted representative analysis, we found that males had a higher MUAC than females (mean difference: 2.07 cm; 95% CI: 1.88, 2.26 cm; $P < 0.001$). Results were consistent across racial and ethnic groups, with males exhibiting higher values, as follows: non-Hispanic Whites (mean difference: 2.41 cm; 95% CI: 2.16, 2.67 cm; $P < 0.001$); non-Hispanic Blacks (mean difference: 0.52 cm; 95% CI: 0.14, 0.91 cm; $P = 0.009$); Mexican Americans (mean difference: 1.29 cm; 95% CI: 0.88, 1.69 cm; $P < 0.001$); and Other (mean difference: 2.07 cm; 95% CI: 1.49, 2.64 cm; $P < 0.001$).

As mentioned in the Methods, a subsample of 3,185 individuals aged 18–39 y and with normal BMI range (18.5–24.9 kg/m^2) was used as our reference population. Their mean ± SD MUAC values are described in Table 3. The respective cutoff values to define low and very low were based on the −1 SD and −2 SD, respectively, using rounded values for ease of application, as previously endorsed [9]. The overall cutoff for low MUAC was 28 cm for males and 25 cm for females and for very low MUAC was 26 cm for males and 23 cm for females. Sex-specific cutoff values for different racial and ethnic groups are detailed in Table 3. MUAC distribution varied across sex, racial, and ethnic groups in relation to age (years). Higher MUAC values were observed between ages 20 and 60 y, with values decreasing after this age (Figure 2A, B). This inverse U-shaped trend was confirmed in sex- and race-stratified polynomial models ($P <$ 0.001 in all subgroups), indicating a consistent nonlinear association. When examining MUAC across BMI categories, we found that individuals with excess weight (BMI ≥25 kg/m^2) consistently exhibited higher MUAC values across all age decades, with MUAC increasing proportionally with higher BMI levels (Figure 2C, D). These associations were also nonlinear ($P < 0.001$) in relation to age, except for the subgroup of individuals presenting with underweight by BMI ($P >$ 0.05). Detailed results of these analyses are shown in Supplemental Box 1.

We found a strong positive correlation between MUAC and ALSTI ($r = 0.83$ for males and $r = 0.79$ for females). MUAC alone explained 70% and 65% of ALSTI variability for males and females, respectively (Figure 3A). Supplemental Table 1 shows sex-specific correlation coefficients across age decades, showing a decrease in correlation strength starting from the 50th decade. A strong positive correlation was also observed between MAMC (centimeters) and $_{\text{corrected}}$AMA (square centimeters) with ALSTI for both sexes (Figure 3B, C, respectively). Supplemental Tables 2–9 demonstrate MUAC percentiles, means ± SD across all age, BMI, racial, and ethnic categories.

Considering that MUAC varied among different BMI groups, we propose MUAC adjustment factors for participants with BMI values outside the 18.5–24.9 kg/m^2 range, using age, BMI, and fat mass adjustments in linear regression models to predict ALST. This approach enables the use of the suggested cutoff values in participants with any BMI. The total sample's adjustment factors, stratified by sex, ethnicity, and race, are presented in Tables 4 and 5. An infographic example of the practical application of these cutoff points in healthy and clinical populations is provided in Figure 4.

Applying these adjustment factors, weighted analyses demonstrated that the prevalence of low MUAC across racial and ethnic groups was higher compared with nonadjusted MUAC values. For self-reported non-Hispanic Whites, a higher prevalence of low values was observed with BMI-adjusted MUAC than unadjusted MUAC [unadjusted: 8.3% (95% CI: 7.56, 9.01%); BMI-adjusted: 11.8% (95% CI: 11.01, 12.57%)]. In non-Hispanic Blacks, the difference in

TABLE 1
Characteristics of the participants from NHANES 1999–2006: males and females (n = 18,195).

Males	Total (n = 9201)	NH white (n = 4325)	NH black (n = 1974)	Mexican American (n = 2210)	Other (n = 692)
Age, y	45.0 ± 19.4	49.1 ± 19.7	41.4 ± 18.4	41.3 ± 18.8	41.5 ± 17.8
Weight, kg	84.5 ± 19.1	86.9 ± 18.5	86.4 ± 21.6	79.7 ± 16.8	79.3 ± 17.7
Height, m	1.75 ± 0.07	1.76 ± 0.07	1.76 ± 0.07	1.70 ± 0.06	1.71 ± 0.07
BMI, kg/m^2	27.6 ± 5.5	27.8 ± 5.4	27.5 ± 6.3	27.6 ± 5.0	26.8 ± 5.1
MAMC[1], cm	28.6 ± 3.1	28.6 ± 3.1	29.3 ± 3.4	28.2 ± 2.8	28.1 ± 3.2
$_{Corrected}$ AMA[1], cm^2	56.3 ± 14.5	56.2 ± 14.4	59.5 ± 16.2	54.3 ± 12.9	53.6 ± 14.6
Fat mass, %	27.5 ± 6.5	28.4 ± 6.2	25.0 ± 7.2	28.0 ± 5.8	27.0 ± 6.0
ALST, kg	26.1 ± 5.2	26.1 ± 4.8	28.9 ± 5.8	24.0 ± 4.2	24.7 ± 4.9
ALSTI, kg/m^2	14.9 ± 2.6	14.7 ± 2.4	16.2 ± 2.9	14.1 ± 2.2	14.4 ± 2.4
Females	**Total (n = 8994)**	**NH white (n = 4135)**	**NH black (n = 1994)**	**Mexican American (n = 2116)**	**Other (n = 749)**
Age, y	45.9 ± 19.4	49.9 ± 19.8	42.9 ± 18.3	42.2 ± 18.9	42.9 ± 18.2
Weight, kg	73.9 ± 19.3	73.0 ± 18.5	81.5 ± 21.9	70.7 ± 16.5	68.2 ± 17.9
Height, m	1.60 ± 0.07	1.62 ± 0.06	1.63 ± 0.07	1.57 ± 0.06	1.58 ± 0.06
BMI (kg/m^2)	28.5 ± 7.0	27.6 ± 6.7	30.7 ± 7.9	28.6 ± 6.3	27.2 ± 6.3
MAMC (cm)*	23.5 ± 3.2	23.3 ± 3.1	24.3 ± 3.5	23.5 ± 3.0	22.9 ± 3.0
$_{Corrected}$ AMA (cm^2)	38.4 ± 12.9	37.5 ± 12.3	41.5 ± 14.9	38.3 ± 12.2	35.9 ± 11.9
Fat mass (%)	39.9 ± 6.7	39.6 ± 6.9	39.9 ± 7.1	40.8 ± 5.9	39.0 ± 6.3
ALST (kg)	17.7 ± 4.1	17.2 ± 3.5	20.7 ± 4.5	16.2 ± 3.3	16.5 ± 3.7
ALSTI (kg/m^2)	10.9 ± 2.3	10.5 ± 2.0	12.7 ± 2.5	10.3 ± 1.9	10.4 ± 2.1

Data described in mean ± SD.
Abbreviations: ALST, appendicular lean soft tissue; ALSTI, appendicular lean soft tissue index; NH, non-Hispanic.
[1] MAMC = mid-arm muscle circumference, AMA: corrected arm muscle area; for males n = 8829, for females n = 7866.

prevalence was smaller, but still significant [unadjusted: 5.3% (95% CI: 4.7, 6.0%); BMI-adjusted: 6.1% (95% CI: 5.6, 6.7%)]. Among Mexican Americans, unadjusted MUAC identified a prevalence of low MUAC at 4.2% (95% CI: 3.6, 4.9%), whereas BMI-adjusted MUAC identified 6.7% (95% CI: 5.9, 7.6%). For the Other group, the prevalence of low MUAC was 8.7% (95% CI: 7.3, 10.4%) using unadjusted values, and 12.1% (95% CI: 10.6, 13.9%) with $MUAC_{BMI\text{-}adjusted}$, as shown in Figure 5.

In a subgroup analysis including only individuals with BMI ≥25 kg/m^2 (n = 11,858), we compared the correlations between $MUAC_{BMI\text{-}adjusted}$, MAMC, or $_{corrected}$AMA with ALSTI (Supplemental Table 10). Among males, MAMC and $_{corrected}$AMA (i.e., bone corrections) showed slightly stronger correlations with ALSTI (r = 0.66) compared with BMI-adjusted MUAC (r = 0.65) within the BMI range of 25–29.9 kg/m^2. However, among individuals with higher BMIs, $MUAC_{BMI\text{-}adjusted}$ demonstrated a higher correlation with ALST than both MAMC and $_{corrected}$AMA. Specifically, within the BMI range of 30–39.9 kg/m^2, $MUAC_{BMI\text{-}adjusted}$ had a correlation of r = 0.65 (moderate), surpassing MAMC and $_{corrected}$AMA (r = 0.61, also moderate). For BMI ≥40 kg/m^2, $MUAC_{BMI\text{-}adjusted}$ maintained a stronger correlation (r = 0.67) compared with MAMC and $_{corrected}$AMA (r = 0.56). This trend was similarly observed among females, although with slightly lower (weak) correlation coefficients throughout.

Sex-specific equations using MUAC and practical variables to estimate ALST are hereby proposed to estimate ALST. For males, the equation explained 67% of ALST variability (R^2 = 0.67) with an RMSE of 3.03 kg. For females, the equation also explained 67% of ALST variability, with a slightly lower RMSE of 2.43 kg. The equations are described as follows:

ALST (kg) $_{males}$ = −1.32 + (0.81 × MUAC in centimeters) – (0.06 × Age in years) + (0.10 × BMI in kilograms per square meter)

ALST (kg) $_{females}$ = 4.80 + (0.24 × MUAC in centimeters) – (0.06 × Age in years) + (0.26 × BMI in kilograms per square meter)

TABLE 2
Mean ± SD (centimeters) values for mid-upper arm circumference according to sex, ethnicity/race (n = 18,195)[1].

	Males (n = 9201)	Females (n = 8994)
Total	33.4 ± 4.3	31.9 ± 5.4
Non-Hispanic White (n = 8460)	33.5 ± 4.2	31.5 ± 5.2
Non-Hispanic Black (n = 3968)	34.1 ± 5.0	33.7 ± 6.1
Mexican American (n = 4326)	32.7 ± 3.8	31.7 ± 4.8
Other (n = 1441)	32.6 ± 4.1	30.9 ± 5.0

[1] All P values for males and females are significantly different according to ethnicity and race: non-Hispanic White > non-Hispanic Black > Other ethnicity and race > Mexican American for males; non-Hispanic Black > non-Hispanic White > Mexican American > Other ethnicity and race for females (P < 0.005 from pairwise survey weighted Lincom analyses).

Discussion

To our knowledge, this is the first study to propose MUAC cutoff values as markers of ALST/ALSTI using a large NHANES sample of healthy individuals, with analysis by age, sex, BMI categories, and ethnicity/race. Additionally, we introduced sex- and population-specific BMI adjustment factors for MUAC for individuals with BMI outside the normal range (18.5–24.9 kg/m^2). Finally, we developed a practical equation using MUAC and BMI to estimate ALST (in kilograms) from anthropometric measurements.

Only a few studies have proposed MUAC cutoff points [19–21]. One study, including 831 community-dwelling older adults (aged >60 y) from Asia, used receiver operating characteristic curves to establish MUAC cutoffs to better classify low ALST estimated using bioelectrical impedance analysis (BIA). Although they reported a good area under the curve values (0.89 and 0.79 for males and females, respectively), they identified a single cutoff for both sexes: 26 cm for

TABLE 3
Reference[1] and cutoff values[2] for mid-upper arm circumference according to sex, ethnicity/race, from participants with normal BMI[3] ($n = 3185$).

	Males						Females					
	Ref. values[1] (cm)		Cutoff values[2] (cm)				Ref. values[1] (cm)		Cutoff[2] values (cm)			
	n		Low		Very low		n		Low		Very low	
			−1 SD	−1 SD RV	−2 SD	−2 SD RV			−1 SD	−1 SD RV	−2 SD	−2 SD RV
Total	1651	30.0 ± 2.2	27.8	28	25.6	26	1534	27.0 ± 2.0	25	25	23	23
Non-Hispanic White	639	30.3 ± 2.2	28.1	28	25.9	26	681	27.4 ± 1.9	25.5	26	23.6	24
Non-Hispanic Black	431	30.2 ± 2.1	28.1	28	26	26	296	26.8 ± 2.1	24.7	25	22.6	23
Mexican American	431	29.3 ± 2.1	27.2	27	25.1	25	392	26.9 ± 1.9	25	25	23.1	23
Other	150	29.8 ± 2.0	27.8	28	25.8	26	165	26.7 ± 2.0	24.7	25	22.7	23

Abbreviations: RV, rounded value; Ref, reference.
[1] Reference values defined as mean values from participants aged 18–39 y.
[2] Cutoff values defined as 1 or 2 SDs below the mean values.
[3] Normal BMI: 18.5–24.9 kg/m^2; for other BMI groups, use the adjusting factors for correction of arm circumference.

MUAC. However, sex differences in body composition have been extensively discussed [7–10], making the establishment of a single universal cutoff both impractical and potentially misleading. The study also found a moderate to strong correlation between MUAC and estimated ALST [19]. Another study, conducted in South Africa, proposed MUAC cutoffs for low BMI in $n = 266$ adults, defining low MUAC as <23 cm (equivalent to a BMI <16 kg/m^2) and <24 cm (equivalent to a BMI <18.5 kg/m^2) [20]. Similarly, the well-known Malnutrition Universal Screening Tool (MUST) proposed a MUAC cutoff of <23.5 cm as a potential surrogate for BMI <20 kg/m^2 in defining nutritional risk [21].

These previous studies differ meaningfully from ours, in which we defined low MUAC as <28 cm for males and <25 cm for females and very low MUAC as <26 cm for males and <23 cm for females in the total sample. These studies also differed from ours because we assessed ALST directly from the standard reference, DXA, rather than relying on BIA-based predictive equations, making our analyses more robust. Applying the cutoffs from these studies [19–21] would likely identify only cases of very low MUAC, potentially missing individuals who have already experienced substantial muscle mass depletion. This reinforces the need for a cutoff proposal based on healthy, younger individuals, serving as a more appropriate reference population [9].

Our results showed a strong positive correlation between MUAC and ALSTI across all age decades, further supporting its use as a marker. In contrast, MUAC values were higher among individuals with excess weight (BMI >25 kg/m^2) and even higher in higher BMI

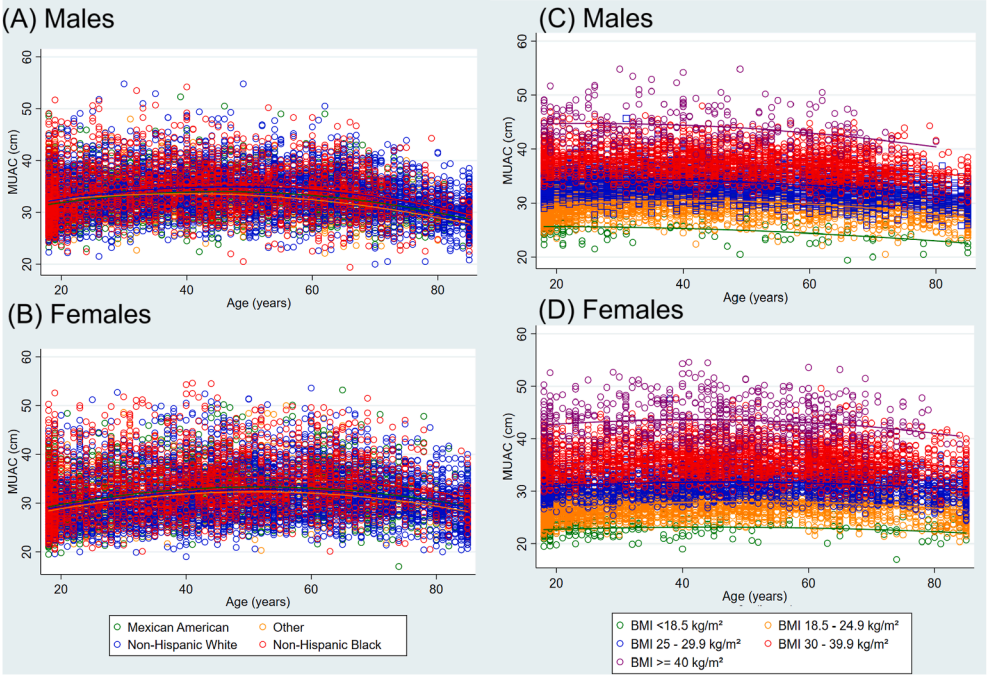

FIGURE 2. Distribution of mid-upper arm circumference (MUAC) in relation to age across ethnicity/race categories in (A) males and (B) females. Distribution of MUAC in relation to age and BMI categories in (C) males and (D) females. Curves represent locally weighted scatterplot smoothing. A significant nonlinear association between MUAC and age ($P < 0.05$) was confirmed by weighted polynomial regression across all race, ethnicity, and BMI categories by sex, except in underweight.

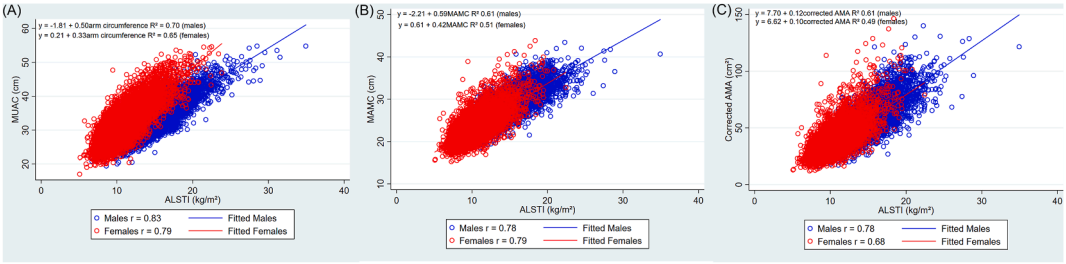

FIGURE 3. (A) Sex-specific correlations between mid-upper arm circumference (MUAC, cm) and appendicular lean soft tissue index (ALSTI, kg/m^2). (B) Sex-specific correlations between mid-arm muscle circumference (MAMC, cm) and ALSTI (kg/m^2). (C) Sex-specific correlations between bone-corrected arm muscle area ($_{corrected}$AMA, cm^2) and ALSTI (kg/m^2).

categories. A previous study focusing solely on individuals with excess weight (BMI >25 kg/m^2) found only a moderate correlation (r = 0.50) between MUAC and DXA-measured arm lean soft tissue [22], suggesting that the correlation between MUAC and ALST may be lower in individuals with excess weight. These findings align with ours and strengthen the rationale for proposing BMI-adjustment factors, as

TABLE 4
BMI adjustment factors for midupper arm circumference for males outside the 18.5–24.9 kg/m^2 BMI range[1].

BMI group (kg/m^2)	Total	
	Adjustment factor	Rounded value (cm)
<18.5	+2.6	+3.0
25–29.9	−2.6	−3.0
30–39.9	−6.7	−7.0
≥40	−10.2	−10.0
	Non-Hispanic White	
<18.5	+2.5	+3.0
25–29.9	−2.5	−3.0
30–39.9	−6.6	−7.0
≥40	−10.1	−10.0
	Non-Hispanic Black	
<18.5	+3.3	+3.0
25–29.9	−3.3	−3.0
30–39.9	−8.6	−9.0
≥40	−13.2	−13.0
	Mexican American	
<18.5	+2.3	+2.0
25–29.9	−2.3	+2.0
30–39.9	−6.1	−6.0
≥40	−9.3	−9.0
	Other	
<18.5	+3.3	+3.0
25–29.9	−3.3	−3.0
30–39.9	−8.4	−8.0
≥40	−12.9	−13.0

Abbreviations: ALST, appendicular lean soft tissue; MUAC, mid-upper arm circumference.

Practical example 1: A male with a BMI of 25.5 kg/m^2 and a MUAC of 30 cm (classified as "normal") would require a 3-cm reduction when using MUAC as a marker of ALST. This results in an "MUAC$_{BMI\text{-}adjusted}$" of 27 cm, classifying the individual as having a low MUAC based on our proposed cutoff (<28 cm).

Practical example 2: For clinical and aging populations, if an individual has a low BMI (<18.5 kg/m^2), adding 3 cm is not necessary, as these individuals are likely to have low muscle mass. Adding extra values could potentially mislead classifications.

[1] Adjustment factor from linear regression for ALST, including arm circumference, adjusted by age and fat mass (%) for BMI outside the 18.5–24.9 kg/m^2 range. All BMI ranges given in units of kg/m^2.

TABLE 5
BMI adjustment factors for mid-upper arm circumference for females outside the 18.5–24.9 kg/m^2 BMI range[1].

BMI group (kg/m^2)	Total	
	Adjustment factor	Rounded value (cm)
<18.5	+2.2	+2.0
25–29.9	–2.2	–2.0
30–39.9	–5.9	–6.0
≥40	–9.0	–9.0
	Non-Hispanic White	
<18.5	+2.2	+2.0
25–29.9	+2.2	−2.0
30–39.9	−5.7	−6.0
≥40	−8.9	−9.0
	Non−Hispanic Black	
<18.5	+2.2	+2.0
25–29.9	+2.2	−2.0
30–39.9	−5.9	−6.0
≥40	−9.1	−9.0
	Mexican American	
<18.5	+1.9	+2.0
25–29.9	−1.9	−2.0
30–39.9	−4.9	−5.0
≥40	−7.6	−8.0
	Other	
<18.5	+2.7	+3.0
25–29.9	−2.7	−3.0
30–39.9	−6.9	−7.0
≥40	−10.7	−11.0

Abbreviations: ALST, appendicular lean soft tissue; MUAC, mid-upper arm circumference.

Practical example 1: A female with a BMI of 35 kg/m^2 and a MUAC of 30 cm (classified as "normal") would require a 6-cm reduction when using MUAC as a marker of ALST. This results in an "MUAC$_{BMI\text{-}adjusted}$" of 24 cm, classifying the individual as having a low MUAC based on our proposed cutoff (<25 cm).

Practical example 2: For clinical and aging populations, if an individual has a low BMI (<18.5 kg/m^2), adding 3 cm is not necessary, as these individuals are likely to have low muscle mass. Adding extra values could potentially mislead classifications.

[1] Adjustment factor from linear regression for ALST, including arm circumference, adjusted by age, and fat mass (%) for BMI outside the 18.5–24.9 kg/m^2 range. All BMI ranges given in units of kg/m^2.

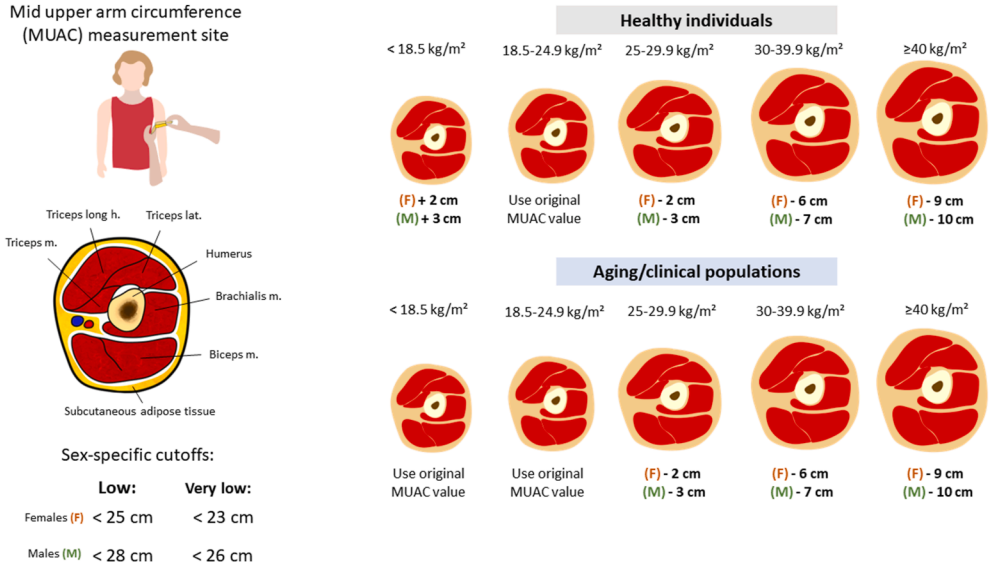

FIGURE 4. Infographic illustrating sex-specific MUAC cutoff values and BMI-adjustment factors across BMI categories. For individuals with normal range BMI (i.e., 18.5–24.9 kg/m^2), the measured MUAC is used directly. When BMI is outside this range, adjustment factors are applied before comparing it with the sex-specific cutoffs. In underweight (BMI <18.5 kg/m^2; only in healthy populations), +2 cm (females) or +3 cm (males) are added to the measured MUAC, because a healthy individual with "low" BMI is less likely to have low muscle mass and this adjustment potentially avoids underestimating "nutritional status." In excess weight (BMI ≥25 kg /m^2; in both healthy and clinical populations), −2 to −10 cm are subtracted according to BMI category and sex, as shown in the figure. These adjustments potentially account for the effect of adiposity on MUAC, enhancing its use as a marker of muscle mass and supporting its application in healthy and clinical populations. F, females; M, males; MUAC, mid-upper arm circumference. ©2025 M.C. Gonzalez. Reproduced with permission.

they could facilitate the widespread and potentially more accurate use of MUAC as a marker of muscle mass in clinical care.

Our additional findings also showed a moderate-to-strong correlation between MAMC, $_{\text{corrected}}$AMA, and ALSTI. Interestingly, when comparing only individuals with excess weight, we observed that correlation coefficients between $_{\text{BMI-adjusted}}$ MUAC and ALSTI increased as BMI categories increased (except for the 25–29.9 kg/m^2 range among males), whereas coefficients for both MAMC and

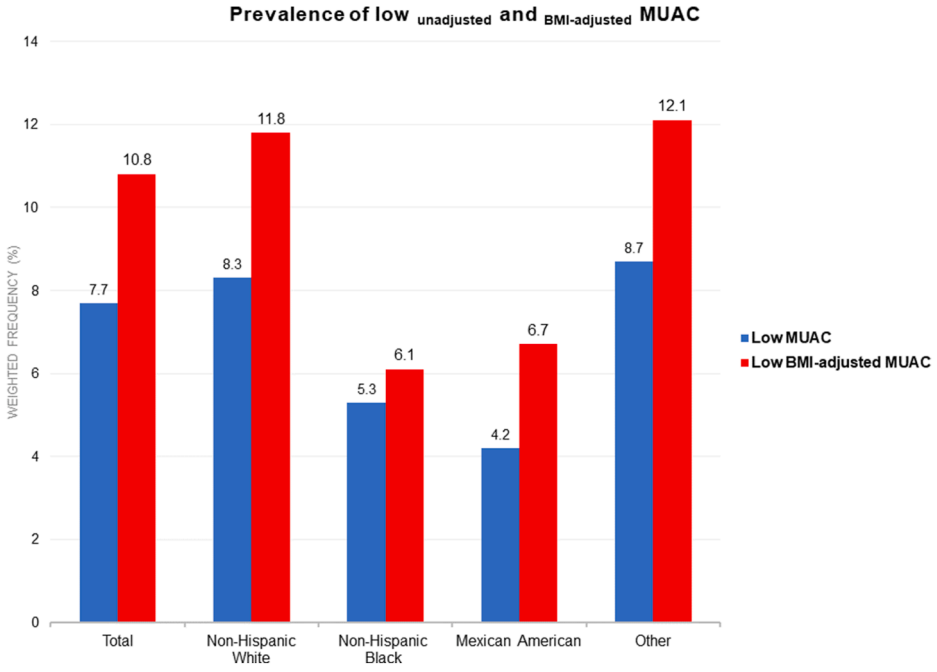

FIGURE 5. Frequency (%) of low unadjusted and BMI-adjusted MUAC in relation to the overall sample and stratified by ethnicity and race (n = 18,195). MUAC, mid-upper arm circumference; Other, other ethnicities/races.

$_{corrected}$AMA with ALSTI decreased, eventually reaching a low threshold level. These findings further reinforce the use of mathematical adjustment, rather than relying on skinfold caliper measurements, which can be challenging in individuals with higher levels of obesity; however, this remains to be tested in healthy and clinical populations [23].

As mentioned earlier, a BMI-adjustment was first proposed using the same NHANES dataset for CC, based on the rationale that higher adiposity can mask anthropometric markers of SM [9]. This BMI adjustment for CC [9] has since been explored in various clinical conditions, demonstrating prognostic value [24–28]. Growing evidence suggests that lower-limb muscle health may deteriorate earlier than upper-limb [29,30], making CC and $_{BMI\text{-}adjusted}$ CC potentially superior markers of SM. Although we acknowledge the importance of CC adjustments, we also propose an alternative, practical anthropometric marker: cutoff points and BMI adjustments for MUAC, which can be used when CC measurements are unfeasible. Although an edema correction for CC has additionally been proposed [31], it was developed for individuals from Asia and may not be universally applicable without further validation.

Additionally, although we identified an adjustment factor for individuals with low BMI <18.5 kg/m^2, this approach is not ideal for clinical populations. In patients with low BMI, low MUAC values likely reflect true muscle depletion. Therefore, increasing MUAC values for these individuals may not be appropriate, as it could lead to misclassification.

We also proposed sex-specific equations using simple anthropometric measurements (BMI and MUAC) and age to estimate ALST. To our knowledge, no previous study has proposed a similar equation (i.e., using MUAC) using a population-based dataset. Our regression models explained $>65\%$ of the ALST variability, with an error of 3.03 kg for males and 2.43 kg for females. Although we acknowledge that this equation is not statistically perfect, especially when compared with other equations using CC [32], incorporating additional variables could further enhance its performance and reduce errors. However, we intentionally selected simple variables to facilitate ALST estimation in clinical practice, potentially enhancing nutritional evaluation. This approach has the potential for real-world application, aiding in the diagnosis of conditions such as sarcopenia, sarcopenic obesity, malnutrition, cachexia, and others. However, external validation and comparison with gold standard methods are necessary, and future studies should confirm its effectiveness.

This study is not without limitations. Because of dataset constraints, no "gold standard" reference was available to assess SM, meaning we relied on DXA scans, which estimate ALST rather than measuring appendicular SM [33]. Not all individuals had skinfold data available, which could potentially skew our findings. The use of BMI as an adjustment factor may not account for all forms of adipose tissue distribution, for example, in individuals with excess visceral adiposity. Although the NHANES dataset is large and representative, its findings may not be fully generalizable to populations outside of the United States. Furthermore, some unweighted descriptive analyses, due to statistical constraints, may further limit data representativeness. Another potential limitation is the use of data from the cycles 1999–2006, considering subsequent changes in the anthropometric profile of the United States population, including shifts in BMI across sex, age, and ethnicities [34]. However, this is potentially minimized in our study, in which our cutoffs were derived from a subsample of individuals with a normal BMI range and aged 18 to 39 y. Additionally, key lifestyle and behavioral variables such as alcohol intake and smoking status were self-reported and had substantial missing data, preventing their inclusion in our analyses. Furthermore, alcohol-related data were only publicly available for individuals aged ≥ 20 y, which was not fully consistent with the age range of our study population. Although physical activity was assessed using a validated scale, it also had considerable missingness (e.g., >7000 missing responses in a single cycle), preventing its use as an adjustment factor. Given the well-established relationship between these variables and (markers of) muscle mass, we recommend that future studies with more complete and objectively measured data explore their potential confounding role, particularly in the associations between MUAC and ALST. Future studies are also welcome to explore the validity of our cutoffs approach in the context of low muscle mass-related syndromes (e.g., sarcopenia and malnutrition) as well as for predicting outcomes. However, we acknowledge that population-specific cutoffs are always recommended.

In conclusion, this study introduces cutoff points for MUAC and provides insights into its potential as a practical and accessible method for estimating/evaluating ALST. By proposing BMI- and sex-specific adjustment factors along with a simple equation incorporating BMI and MUAC, we offer innovative and practical approaches to enhance nutritional assessments in clinical practice. It potentially makes body composition evaluation more feasible and cost effective.

Author contributions

The authors' responsibilities were as follows – JPCP, MCG: contributed to the conception and design of the research; JPCP, LAAMJ: acquired the data; JPCP, LAAMJ, MCG: contributed to the data analysis; JPCP, MCG: wrote the manuscript; APTF, CMP, LAAMJ, MCG, PCC, SBH: critically revised the manuscript; and all authors: critically reviewed, interpreted, and read and approved the final manuscript.

Conflict of interest

JPCP has previously received travel support from Fresenius Kabi as part of the Jumpstart Clinical Nutrition Program, travel costs from Danone Nutricia Brazil for a Speaker engagement, as well as speaking honoraria from Prodiet Medical Nutrition. CMP has previously received honoraria and/or paid consultancy from Abbott Nutrition, Nutricia, Nestlé Health Science, and Novo Nordisk; and investigator-initiated funding from Almased. APTF reports receiving a research grant from Prodiet Medical Nutrition. SBH serves on the medical advisory boards of Tanita Corporation, Novo Nordisk, Abbott, Novartis, Versanis, and Medifast. MCG has received honoraria and/or paid consultancy from Abbott Nutrition, Nutricia, and Nestlé Health Science Brazil. All other authors report no conflict of interest.

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Data availability

Data described in the manuscript and codebook are publicly and freely available without restriction at https://wwwn.cdc.gov/nchs/nhanes/Default.aspx.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ajcnut.2025.09.034.

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