Nutrition 127 (2024) 112550

Contents lists available at ScienceDirect

Nutrition

journal homepage: www.nutritionjrnl.com

Applied nutritional investigation

Associations of bioelectrical impedance and anthropometric variables among populations and within the full spectrum of malnutrition

Elisabetta Marini Ph.D. [a,*], Silvia Stagi Ph.D. [a], Stefano Cabras Ph.D. [b], Ornella Comandini Ph.D. [a], Jude Thaddeus Ssensamba D.C.M. [c,d], Mary Fewtrell M.D. [e], Laura Busert-Sebela Ph.D. [e], Naomi M. Saville Ph.D. [f], Carrie P. Earthman Ph.D. [g], Analiza M. Silva Ph.D. [h], Jonathan C.K. Wells Ph.D. [e]

[a] *Department of Life and Environmental Sciences, University of Cagliari, Monserrato, Cagliari, Italy*
[b] *Department of Statistics, Universidad Carlos III de Madrid, Gefate, Spain*
[c] *Center for Innovations in Health Africa (CIHA Uganda), Kampala, Uganda*
[d] *Makerere University Walter Reed Project (MUWRP), Kampala, Uganda*
[e] *Population, Policy and Practice Research and Teaching Department, UCL Great Ormond Street Institute of Child Health, London, UK*
[f] *Institute for Global Health, University College London, London, UK*
[g] *Department of Health Behavior and Nutrition Sciences, University of Delaware, Newark, Delaware, US*
[h] *Exercise and Health Laboratory, CIPER, Faculdade de Motricidade Humana, Universidade de Lisboa, Lisbon, Portugal*

A R T I C L E I N F O

Article History:
Received 17 April 2024
Received in revised form 4 July 2024
Accepted 28 July 2024

Keywords:
Malnutrition
Children
Body composition
BIA
BIVA
Interpopulation variability

A B S T R A C T

Objectives: The aim of this study was to evaluate body composition variability assessed by bioimpedance in relation to nutritional status assessed by anthropometry in children and adolescents living in countries characterized by contrasting nutritional conditions.
Methods: The sample was comprised of 8614 children (4245 males; 4369 females), aged 3 to 19 years, from Nepal (477 children), Uganda (488 children and adolescents), UK (297 children and adolescents) and US (7352 children and adolescents). Height-for-age (HAZ) and body mass index-for-age (BAZ) z-scores were calculated according to WHO growth references. *Specific* bioelectrical impedance vector analysis (BIVA) was used to evaluate body composition variability. In each population sample, the relationship of HAZ and BAZ with bioelectrical outcomes was analysed by confidence ellipses and cubic spline regression, controlling for sex and age.
Results: The participants from Uganda and Nepal were more affected by undernutrition, and those from the US and UK by obesity. In all groups, phase angle and specific vector length were weakly associated with HAZ, with null or opposite relationships in the different samples, whereas they were positively associated with BAZ. The stronger association was between vector length, indicative of the relative content of fat mass, and BAZ in the UK and US samples. Confidence ellipses showed that the relationships are more strongly related to phase angle in Nepalese and Ugandan samples.
Conclusions: Bioelectrical values were more strongly associated with BAZ than HAZ values in all population samples. Variability was more related to markers of muscle mass in Ugandan and Nepalese samples and to indicators of fat mass in UK and US samples. Specific BIVA can give information on the variability of body composition in malnourished individuals.

Introduction

Malnutrition affects millions of children and adolescents, with a global increase in the prevalence of overweight and obesity while undernutrition is still widespread in low-income countries [1,2] and is common in pediatric patients [3,4]. Both extremes of malnutrition are associated with an increased risk of diseases, especially of noncommunicable diseases such as cardiovascular diseases, certain cancers, and diabetes, and with higher risk of death [5].

Usually, malnutrition is assessed on the basis of anthropometric measurements of height and weight, and the derived body mass index (BMI: weight/height^2, kg/m^2) [6]. The widespread epidemiological use of anthropometry is due to the method being relatively easy to apply, non-invasive and inexpensive, and reflecting the full

*Corresponding author:
E-mail address: emarini@unica.it (E. Marini).

https://doi.org/10.1016/j.nut.2024.112550

spectrum of nutritional status [6]. By convention, individual measurements of children and adolescents are standardized in relation to sex and age as z-scores, and the resulting indices (height-for-age, HAZ; weight-for-height, WHZ; BMI-for-age, BAZ) allow assessment of chronic or acute undernutrition (categorized as stunting, indicated by low HAZ, or wasting, low WHZ), or overweight and obesity (high BAZ) [6]. Stunting is a complex multifactorial condition that typically commences in utero and worsens in infancy and leads to linear growth failure, which is difficult to recover from. Conversely, wasting is due to a low weight in relation to height and indicates recent and severe weight loss associated with infections and/or insufficient food intake, but treatment is possible [6].

Although informative, anthropometry does not differentiate body composition variability associated with height or weight variability. Both fat and fat-free mass (FM and FFM) are causally and independently related to health status, particularly to the efficiency of immune function [7], and with mortality risk [4,8,9]. Hence, body composition analysis can be insightful for the understanding of malnutrition, and for planning more targeted clinical and public health interventions to prevent or treat it.

The relationship between anthropometric indices of malnutrition and body composition has not yet been extensively studied, although research in the field has intensified during recent decades [10−22]. Such studies may contribute to define the physiological correlates of growth deviations and are potentially helpful to delineate the risk of non-communicable diseases. Indeed, different expressions of malnutrition can be differently associated with body composition changes and different populations may have evolved different biological responses to the same expression of malnutrition. According to a focused review [10] and more recent research [11], severe wasting is associated with major deficits in both FFM and FM. The association of stunting with body composition is less evident and heterogeneous across samples, showing both lower and higher FM levels [10].

Among the existing methods for the assessment of body composition, bioelectrical impedance analysis (BIA) is the most appropriate for epidemiological purposes given its non-invasiveness, low cost and feasibility, which as with anthropometry allows measurements to be obtained even in remote and difficult settings. The use of the conventional approach, predicting fat-free mass using calibrated regression equations, has limitations as samples of children can vary in terms of age and health condition compared to those used to derive the models. This is particularly relevant to the analysis of nutritional status, as undernourished children can be characterized by edema, thus violating the assumption of constancy in FFM hydration and hindering the conversion of raw bioelectrical data into body composition values [23]. The use of alternative approaches, directly analyzing bioelectrical values without prior assumptions on bioelectrical relationships or physical status, is more advisable.

Among such procedures, phase angle (PhA) and *specific* bioelectrical impedance vector analysis (*specific*BIVA; [24]), that analyses phase angle along with impedance vector length, represent suitable options. Phase angle is a recognized indicator of body cell mass, muscle mass in particular, and the quality of cell membranes [25,26], that has shown a good association with dilution techniques in the evaluation of intracellular/extracellular water (ICW/ECW) [27]. In adult and pediatric populations, there is evidence of its association with nutritional status [12]. *Specific* BIVA applies a correction factor based on anthropometry to bioelectrical measurements, in order to reduce the effect of body size and thus disentangling variability in size from that of body composition. It has been validated in US adults [24], showing accuracy in evaluating FM%, and being associated with skeletal muscle index. It has also demonstrated good agreement with reference methods (DXA, 4-component model) in different populations, in both sexes and various age groups, including children and adolescents [28,29].

The aim of this study is to analyze the relationship of body composition assessed by bioimpedance with nutritional status assessed by anthropometry in children and adolescents. In order to increase the variability of the panorama analyzed, the within-sample relationships were studied in groups living in countries characterized by contrasting environmental, cultural, general welfare, and nutritional status, over the full spectrum of malnutrition.

Methods

Samples and variables

The whole sample examined in this study is part of the BIA International Dataset project [30] and is composed of 8614 children (4245 males; 4369 females) aged 3-19 years, from four countries characterised by different environmental and socio-economic conditions: Nepal, Uganda, United Kingdom, United States (Supplementary Table 1).

Nepal is a federal parliamentary republic in South Asia. According to Central Intelligence Agency [31], it is a low-income country with an estimated real GDP per capita of $4,000 in 2022. Population density is relatively low, with most people living in rural areas; only 21.9% of the population is urbanised. The median age in Nepal is 27.6 years, and life expectancy at birth is 73 years. The Nepalese (NEP) sample is composed of 477 children (245 males; 232 females) aged 5-6 years, participants in a longitudinal birth cohort from the rural lowland Terai area (Province 2) started in 2012 and followed up in 2018, where the original cohort was selected on the basis of the following inclusion criteria: 1) the mother planned to live in the region under study for the next 12 months, 2) the child was a singleton baby, and 3) the baby was measured within 72 hours of birth. The study was approved by the Nepal Health Research Council (N. 13/2018), and written informed consent was provided by parents.

Uganda is a presidential republic in East Central Africa. It is a low-income country with an estimated real GDP per capita of $2,300 in 2022 [31]. The population density is relatively high compared to other African countries, but only 26.8% of the population is urbanised. The median age is 15.7 years and life expectancy at birth is 69.3 years. The Ugandan (UGA) sample is composed of 488 children and adolescents (224 males; 264 females) aged 3-16 years. It represents a subsample of a survey carried on in different primary schools belonging to rural or poor contexts near or inside Kampala [32]. All children that were present at school during the data collection period were included in the analysis, excepted for those with absent or unreliable information on their age. The data survey was approved by the Uganda AIDS Support Organization (TASO) independent ethics committee (TASOREC/020/18-UGREC-009) and written informed consent for the analysis was provided by the schools, since head teachers are identified as the legal guardians of the children.

The United Kingdom (UK) is a parliamentary constitutional monarchy in Western Europe. It stands as a high-income country with an estimated real GDP per capita of $47,600 in 2022 [31]. The population is predominantly urban (84.6%), concentrated largely in and around London. The median age is 40.8 years, with a life expectancy at birth of 82.2 years. The UK sample is composed of 297 children and adolescents (128 males; 169 females) aged 5 to 18 years. The sample derives from a previously analyzed database, that includes children and adolescents of European ancestry who were either healthy or receiving treatment for obesity but with other pathological conditions excluded [28]. The studies were approved by the Ethical Committee of UCL Institute of Child Health and Great Ormond Street Hospital (N. 11345/001), and written informed consent was obtained from participants aged 18 years, while assent was obtained from those aged <18 years along with written informed consent from their parents.

The United States (US) is a constitutional federal republic in North America. It is a high-income country with an estimated real GDP per capita of $64,600 in 2022 [31]. The majority of the population (83.3%) lives in urban areas. The median age is 38.9 years and life expectancy at birth is 80.9 years. The US sample derives from the National Health and Nutrition Examination Survey (NHANES) years 1999 to 2004, that is the most recent NHANES survey including bioimpedance data and is composed of 7352 children and adolescents (3772 males; 3580 females) aged 8-19 years. Case selection was based on the availability of measurements and of quality of data, as defined by NHANES. The survey was approved by the National Center for Health Statistics (NCHS) Research Ethics Review Board, and written informed consent was obtained for each participant or their tutor.

Height (cm) and weight (kg) were taken by trained technicians following standard international criteria using different anthropometric equipment: Tanita scale (Tanita Corp, Japan); Toledo digital scale (Mettler-Toledo Inc, Columbus, USA); Seca mechanical scale (Seca GMBH, Hamburg, Germany); ShorrBoard stadiometer (MD, USA); Seca mechanical or electronic stadiometer (Seca GMBH, Hamburg, Germany).

Bioelectrical measurements of resistance and reactance were taken at 50 kHz using the following devices (Bodystat 500 Touch, Bodystat Ltd, UK, in the Nepalese sample; Quadscan 4000 instrumentation, Bodystat, UK, in the UK sample; BIA - Vitality Analyzer, IPGDX, LLC, Littleton, US, in the Ugandan sample; HYDRA ECF/ICF Bio-Impedance Spectrum Analyzer, Model 4200; Xitron Technologies, Inc., San Diego, CA, USA, in the US sample).

Body mass index (BMI) was calculated as weight (in kg) divided by the square of height (in m). Anthropometric indices of nutritional status (HAZ: height-for-age Z-scores; BAZ: body mass index-for-age Z-scores) were calculated according to WHO criteria [6] and to WHO Child Growth Standards or references [33,34]. Malnutrition was defined as an index <-2 or >2 SD: stunting (HAZ <-2), wasting (BAZ <-2), and obesity (BAZ>2). *Specific* BIVA was applied for the body composition assessment. This approach is based on the analysis of bioelectrical vectors, defined by resistance and reactance standardized for body size (height and cross-sectional areas) or by their derived measurements: vector length ($Zsp = (Rsp^2 + Xcsp^2)^{0.5}$) and phase angle (PhA= arctan Xc/R 180/π). A detailed description of the whole procedure (standardization of values and interpretation) can be found elsewhere (e.g., [24]; www.specificBIVA.com). The projection of bioelectrical vectors on the Cartesian plane allows the analysis of body composition: vector length is positively related to %FM, and phase angle to ICW/ECW ratio, body cell mass, and skeletal muscle index [24]. This study used confidence ellipses, which graphically represent the distribution of bioelectrical vectors and allow the statistical analysis between groups.

Statistical analysis

Descriptive statistics of anthropometric and bioelectrical variables were calculated for each sex, population group, and age class separately.

The association between anthropometric indices of nutritional status and body composition was analyzed by multiple nonlinear regression, controlling for the effect of sex and age. The absence of correlation values near 1 among explanatory variables and the large sample of children and adolescents allowed us to exclude the effects of collinearity.

Due to the curvilinear association between variables, regression analysis was performed using cubic splines, that is a kind of mathematical curve usable to interpolate complex relationships in data, with a normally distributed response variable [35]. Because different samples may not show the same relationship, the space of spline coefficients is of infinite dimension; hence, spline coefficients cannot be constrained to estimate the differential effects of specific factors, such as, in our case, different countries. Consequently, splines have been estimated separately for each country, although using the same model for each sample, as follows:

$$Y = \alpha + L(sex, age) + S(Zsp, PhA),$$

where Y is the response (HAZ or BAZ), L is the usual linear term (with the corresponding linear coefficient) which can derive from a categorical variable, such as sex, or a quantitative one, such as age, and S represents the cubic spline term, which is the nonlinear function of the corresponding quantitative variable, Zsp or PhA, composed by spline coefficients. Although splines cannot be conveniently written in an analytical form, they can be interpreted by looking at the overall estimated functions, showing the direction and the strength of the association between the non-linear predictor and the response variable, along with 95% confidence intervals (shadow areas in the graphs). The peculiarities of each sample can be perceived considering the difference in scale, slope and shape of the relative splines.

In this study, the uncertainty around splines and regression coefficients was based on normality assumption of residuals, confirmed by evaluating Quantile-Quantile plots of the theoretical normal quantiles against the empirical quantiles of residuals. The significance of the relationship was assessed using usual F test.

Within each population, in the subsample of children aged 5 to 10 years (in detail: NEP, 5–6 years; UGA, 5–10 years; UK, 5–10; US, 8–10 years) confidence ellipses for groups with different nutritional status (based on HAZ and BAZ) were projected on the RXc plane and groups with divergent nutritional status, specified by HAZ or BAZ limits as described above, were compared by means of Hotelling's T^2 test.

Following consensus on the approach based on Bayesian statistics [36], we used p-values lower than 0.005 for the significance level. Statistical analyses were performed using the free software R with the MASS library (http://www.R-project.org) and specific BIVA software (www.specificbiva.com).

Results

The population samples showed contrasting anthropometric, nutritional and bioelectrical characteristics (Supplementary Table 1, Fig. 1). HAZ and BAZ values were higher in the UK and US samples with respect to the Ugandan and, especially, the Nepalese samples. Undernutrition was frequent among Nepalese children (stunting: 31.4%; wasting: 20.0%) and, to a lower degree, in the Ugandan sample (stunting: 12.2%; wasting: 5.9%) but was almost absent in the US sample (stunting: 1.9%; wasting: 1.2%), and totally absent in the UK sample. Conversely, obesity was frequent in the UK and US children and adolescents (UK: 31.5%; US: 20.7%) but absent in the Ugandan and Nepalese samples. Bioelectrical values varied similarly. In fact, Zsp (indicative of %FM) was lower in the Nepalese and Ugandan samples (both sexes and all age groups) than in UK and US samples (Supplementary Table 1). PhA (indicative of ICW/ECW and a proxy of skeletal muscle mass) was higher

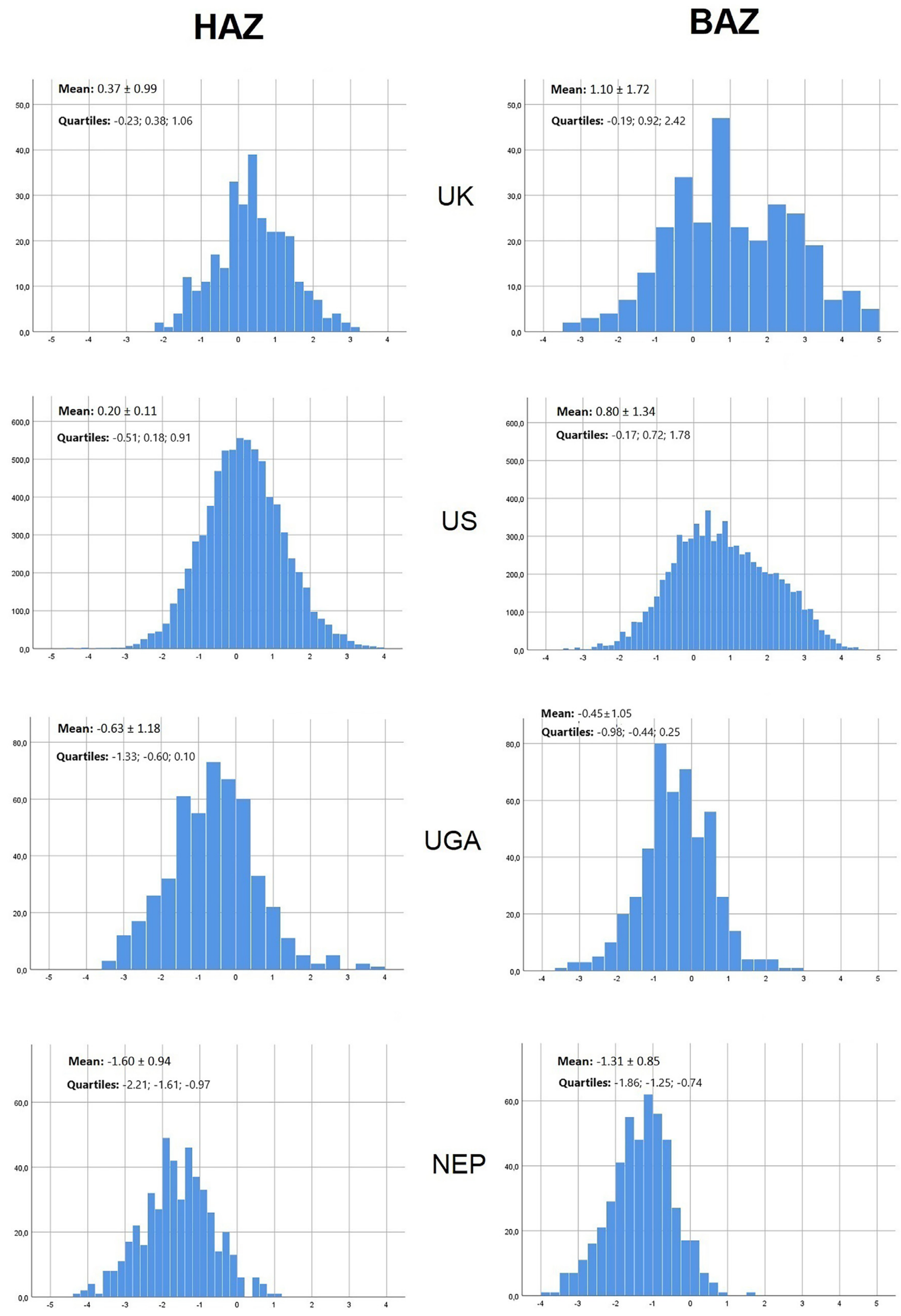


Fig. 1. Histograms showing the distribution of HAZ and BAZ values in the sexes and population groups.
HAZ: height-for-age z scores; BAZ: BMI-for-age z scores. NEP: Nepal; UGA: Uganda; UK: United Kingdom; US: United States.

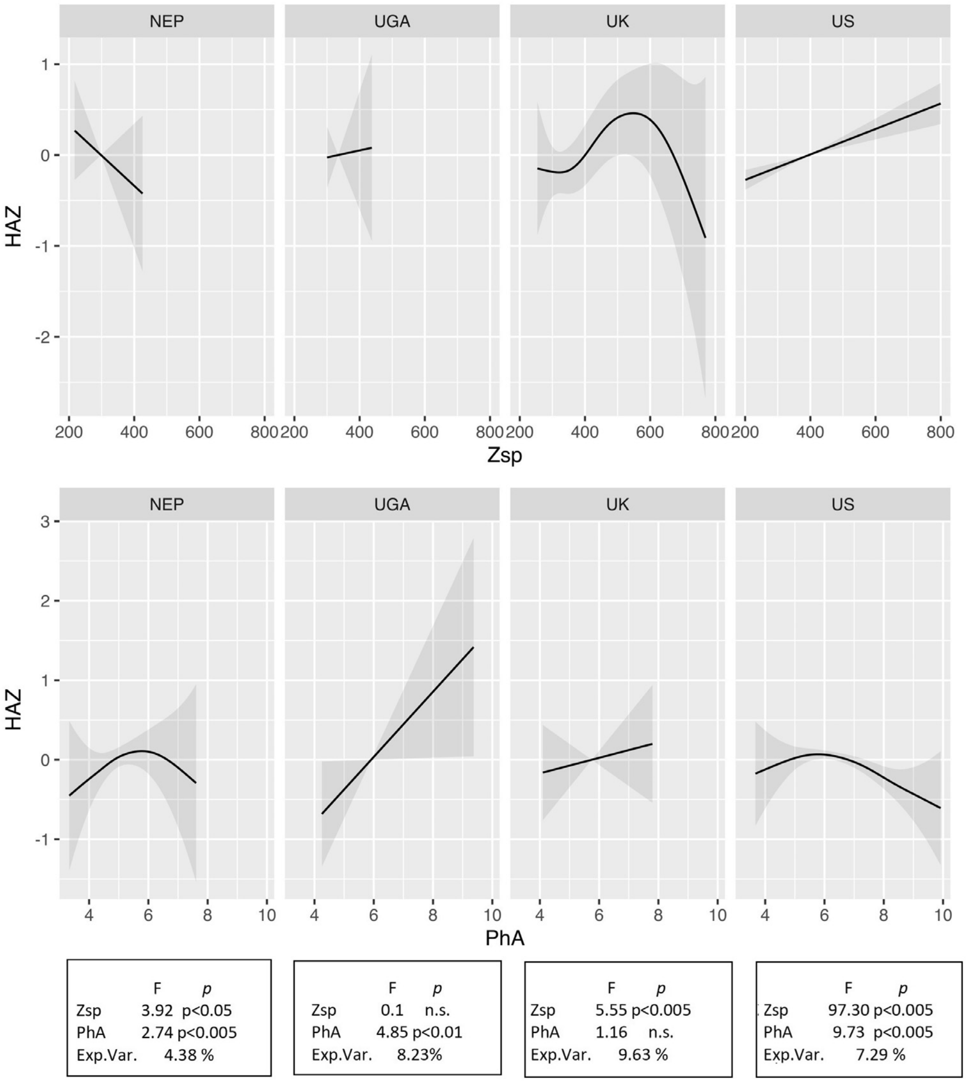


Fig. 2. Results of cubic splines regression results between HAZ values and bioelectrical predictors.
Filled areas show the 95% C.I. about the regression mean estimated with the corresponding spline. HAZ: height-for-age z scores; Zsp: specific vector length; PhA phase angle; NEP: Nepal; UGA: Uganda; UK: United Kingdom; US: United States.

in the Ugandan, especially among females, and US samples, and lower in the Nepalese and UK samples (Supplementary Table 1).

Regression analysis residuals were normally distributed, thus showing the appropriateness of the statistical model.

Bioelectrical values were more strongly associated with BAZ than HAZ values in all population samples, controlling for the effect of sex and age (Figs. 2-5). In particular, HAZ was not clearly associated with bioelectrical variables, with null or weak relationships, or opposite relationships in the different samples, and with a low proportion of variance explained, ranging between 4.4% (Nepal) and 9.6% (UK) (Fig. 2). Zsp was positively related to HAZ in the US and tendentially in the UK samples, unrelated or negatively related in the Ugandan and Nepalese samples (Fig. 2). PhA was positively related to HAZ in the Ugandan and, tendentially, in the Nepalese samples, unrelated or negatively related in the UK and in the US samples (Fig. 2). In the sub-sample of children aged 5-10 years, confidence ellipses (Fig. 3) summarize the above relationships, highlighting a similarity between Nepalese and Ugandan children, where better nutritional status was associated with higher phase angle, and with reduced or steady vector lengths, whereas in the UK and US samples increasing HAZ scores were associated with longer vectors and with lower or unchanged phase angle values.

The relationship between body composition and nutritional status was clearer in the case of BAZ, with a higher proportion of variance explained, particularly in the US and UK samples (82.7% and 70.9%, respectively) with respect to the Nepalese and Ugandan samples (14.6% and 12.4%, respectively) (Fig. 4). Zsp and PhA were always positively associated with BAZ (Fig. 4). Confidence ellipses representing the group of children 5-10 years old showed that the above relationships are more strongly related to phase angle in Nepalese and Ugandan samples, but to vector length in the UK and US samples (Fig. 5).

Discussion

The population samples analyzed in this research were characterized by contrasting nutritional status, with the UK and US children and adolescents more affected by overweight and obesity, and the Ugandan and Nepalese ones by undernutrition. The relationship between nutritional status and body composition varied

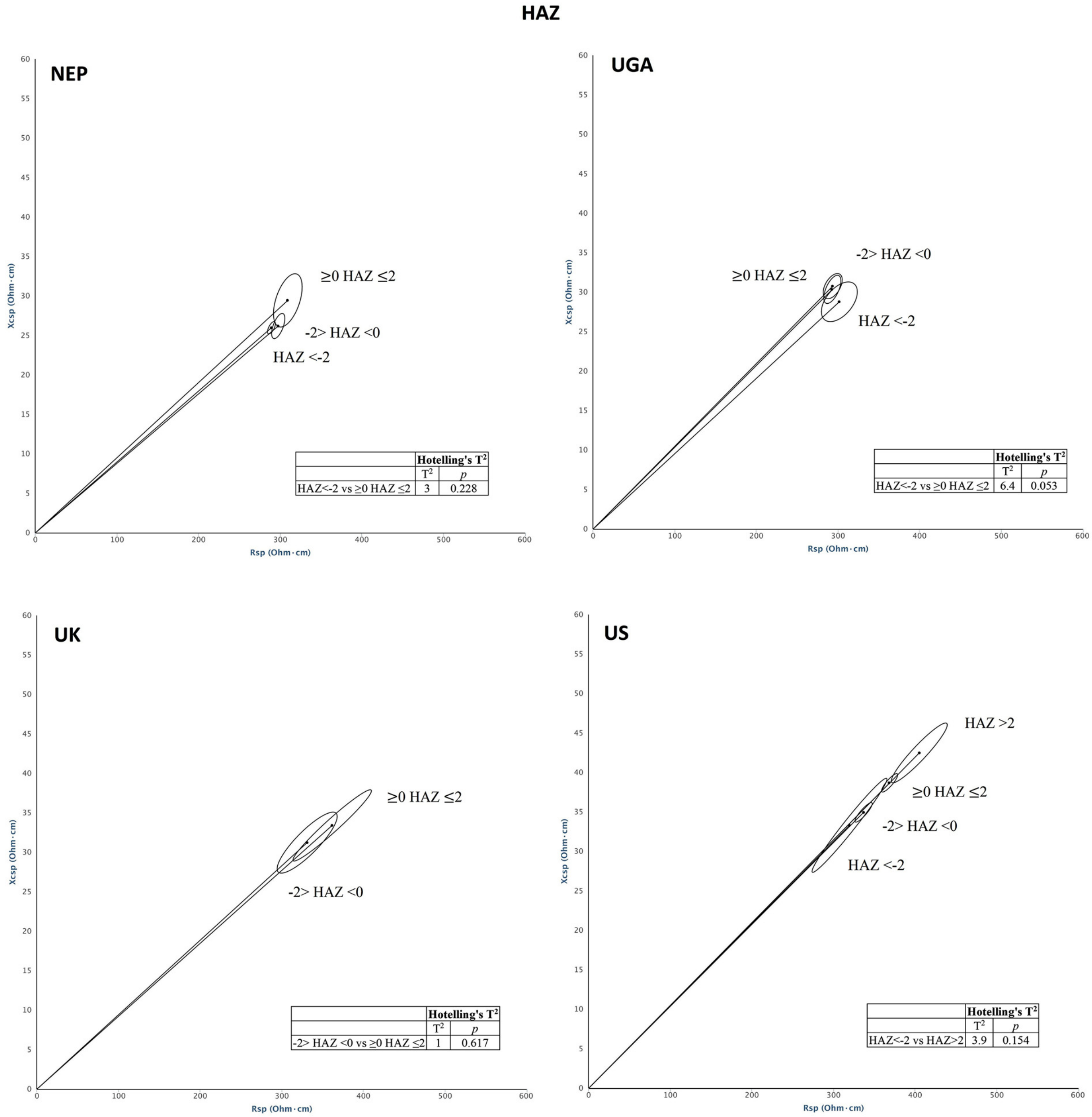
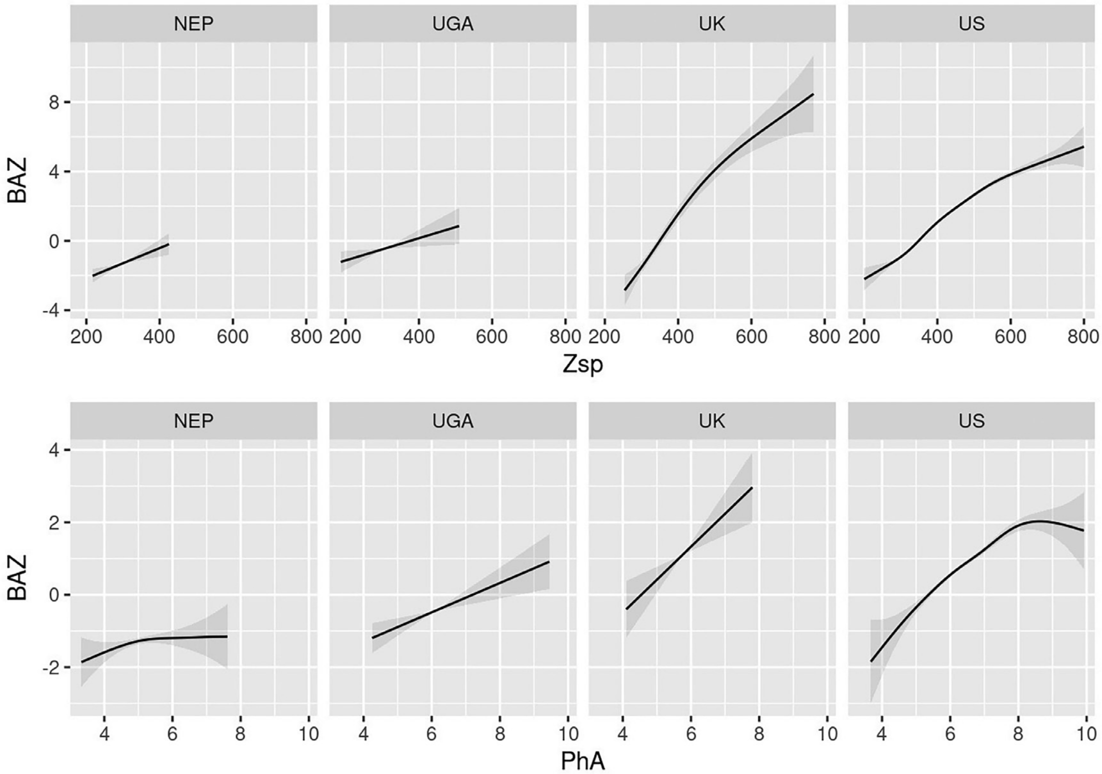


Fig. 3. *Specific* confidence ellipses in groups of different nutritional status according to HAZ. HAZ: height-for-age z scores; Rsp: specific resistance; Xcsp: specific reactance; NEP: Nepal; UGA: Uganda; UK: United Kingdom; US: United States.

according to the anthropometric indicator and the prevalent form of malnutrition in the population. Regression models showed that, in all population samples, HAZ was poorly associated with body composition differences, as indicated by the low levels of variance explained and the few significant associations with bioelectrical values.

Similar results have been observed in previous research [10]. Stunting typically originates early in life, before birth and is largely irreversible as height is more difficult to recover than weight [37]. As a consequence, different nutritional and lifestyle conditions during children's growth can led to variable expressions of weight and body composition (e.g. continued thinness or high fatness), whereas height does not change similarly. Such long-term relative stability of HAZ allows the use of stunting as a robust indicator of undernutrition at the population level. However, at the individual level, a low HAZ does not necessarily imply poor child well-being, even though some common determinants can be shared [38]. This may explain why the associations of HAZ with body composition were weak, as already observed by other authors [11,15,18], and also the inconsistent results of the literature [10,12], with some studies showing higher phase angles in stunted children [16] and others the opposite pattern ([39]; present study).

Keeping in mind the low explained variance of the observed relationships and hence the importance of factors not included in the model - such as household and mother's characteristics, diet, infectious diseases - some significant tendencies can be perceived. HAZ was positively related to Zsp in the US and UK samples (characterized by higher values of HAZ), but unrelated or negatively related in the Ugandan and Nepalese ones, whereas it was negatively related or unrelated to PhA in the US and UK samples, but



	F	p
Zsp	52.26	p<0.005
PhA	6.46	p<0.005
Exp.Var.	14.60 %	

	F	p
Zsp	24.83	p<0.005
PhA	52.59	p<0.005
Exp.Var.	12.4%	

	F	p
Zsp	324.50	p<0.005
PhA	59.09	p<0.005
Exp.Var.	82.7%	

	F	p
Zsp	1975.8	p<0.005
PhA	297.6	p<0.005
Exp.Var.	70.9%	

Fig. 4. Results of cubic splines regression results between BAZ values and bioelectrical predictors.
Filled areas show the 95% C.I. about the regression mean estimated with the corresponding spline. BAZ: BMI-for-age z scores; Zsp: specific vector length; PhA phase angle; NEP: Nepal; UGA: Uganda; UK: United Kingdom; US: United States.

positively related in the Ugandan and Nepalese ones. This suggests that both extremes of stature variability, highlighted by different population samples, are characterized by relatively higher body fat (as indicated by Zsp), and lower ICW/ECW ratio or body cell mass and cell membrane quality (as contextually suggested by PhA). Body fat preservation at the detriment of fat-free tissue has been already observed among other samples of undernourished children [17,40], similar to the 'thin-fat phenotype' described in South Asian neonates and children [13,14,41,42], and could be viewed as an ultimate survival strategy [17,43], likely modulated by proximate factors, such as alimentary habits and physical activity levels. On the other side, in higher income countries, such as the US and UK, diet is broadly characterized by highly caloric foods, that, along with common sedentary habits, induce fat accumulation, but also allow skeletal development [44].

BIA parameters explained a greater proportion of variance in BAZ, particularly in the US and UK samples, that is among populations mainly affected by overweight and obesity, where bioelectrical variability almost completely explains weight variability. A clear and predictable increase of Zsp, indicating %FM increase, appears particularly evident with increasing BAZ, especially in the UK and US samples, along with an increase of phase angle. Considering that a correlation of PhA with fat-free mass has been described previously in adults [24,45], this highlights that obesity, as defined by BMI, incorporates higher levels of both FM and FFM, consistent with other pediatric studies [46,47].

The positive relation between BAZ and phase angle, similarly observed in other studies [12], in this research was particularly clear in the analysis of Ugandan (5–10 years old) and Nepalese children (5–6 years old), where differences between confidence ellipses were more related to PhA than vector length. This observation is consistent with the greater variability in FFM than in FM among undernourished children, already discussed in relation to stunting and observed among wasted Cambodian [17] or Chinese [19] children, and among relatively thin (BMI below 50th percentile) US children and adolescents [20].

Among the strengths of this study, it is the first to analyze body composition assessed by BIA in relation to the full spectrum of malnutrition assessed by anthropometry in large samples of children and adolescents from four different continents, including remote and difficult settings. This allowed us to attribute associations with bioelectrical outcomes directly to undernutrition on one side and obesity on the other, independent of environmental or genetic factors.

The main limitation of the research is related to the lack of a wider representation of body composition variability in human populations and of international bioelectrical references that would allow the contextual interpretation of body composition in all population groups. Indeed, this is one of the objectives of the BIA International data project [30]. Another limit is related to the lack of results from dilution techniques that would have been useful to disentangle the variability of PhA in terms of ICW or ECW

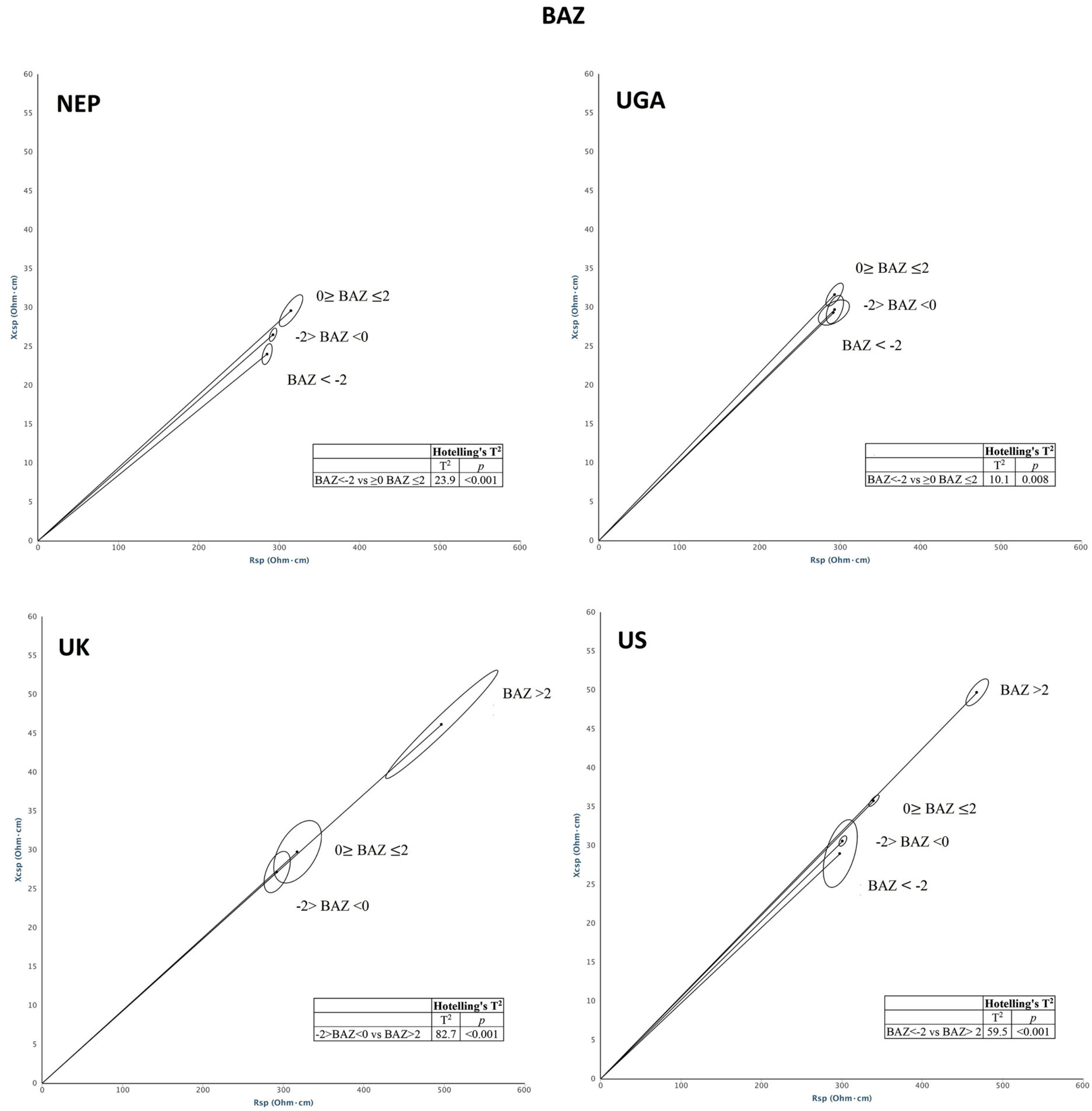


Fig. 5. *Specific* confidence ellipses in groups of different nutritional status according to BAZ. BAZ: BMI-for-age z scores; Rsp: specific resistance; Xcsp: specific reactance; NEP: Nepal; UGA: Uganda; UK: United Kingdom; US: United States.

variation. Also, the use of different bioimpedance devices hampers the direct comparison of bioelectrical values among samples. However, this limit should cancel out in the comparison of within-sample bioelectrical-anthropometric relationships carried out in this study. The potential effect of imprecision on age [48] among undernourished children was negligible, as in the Nepalese sample age was known to the day and in the Ugandan sample it has proven to be irrelevant [32].

Conclusions

This research generated novel findings on the relationship between anthropometric indicators of malnutrition and body composition variability.

The relationship between nutritional status (defined on the basis of anthropometry) and body composition (defined on the basis of BIVA) varied according to the anthropometric indicator and the population cluster, as the samples from Uganda and Nepal were more characterized by undernutrition, and those in the US and UK more affected by obesity. In all populations, HAZ was weakly associated with BIVA variation, whereas BAZ showed a positive relation with bioelectrical indicators of fat and muscle mass, and particularly in the case of %FM (as highlighted by US and UK samples). Indicators of fat mass tended to vary less than markers of muscle mass among undernourished children (as highlighted by Ugandan and Nepalese samples), whereas they varied more than muscle mass among children with overweight or obesity (as highlighted by UK and US samples). From a methodological point of view, *specific* BIVA was shown to be a suitable method to be used in association with anthropometric indices in order to evaluate body composition in malnourished children. For this purpose, reference values representing multipopulational bioelectrical variability would be helpful.

Financial Support

The research in Nepal was supported by the Wellcome Trust Strategic Award for the Population Biology of Maternal and Newborn Survival (085417/Z/08/Z), the Bill & Melinda Gates Foundation (OPP1113344), the UCL International Child Health Group Research Fund 2016-17, the UCL Chadwick Trust Travelling Fellowship 2018, and the Stiftung fiat panis Dr. Hermann Eiselen Doktorandenförderung 2017. The research in Uganda was supported by the Fondazione Banco di Sardegna (Italy), Grant/Award Number (n ° 2013.1193). Stefano Cabras was partly funded by the Ministerio de Ciencia e Innovación of Spain Project PID2022-138201NB-I00.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Elisabetta Marini: Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization. **Silvia Stagi:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Stefano Cabras:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Ornella Comandini:** Writing – review & editing, Investigation. **Jude Thaddeus Ssensamba:** Writing – review & editing, Investigation. **Mary Fewtrell:** Writing – review & editing, Investigation. **Laura Busert-Sebela:** Writing – review & editing, Investigation. **Naomi M. Saville:** Writing – review & editing, Investigation. **Carrie P. Earthman:** Writing – review & editing, Investigation. **Analiza M. Silva:** Writing – review & editing, Methodology, Conceptualization. **Jonathan C.K. Wells:** Writing – review & editing, Methodology, Conceptualization.

Acknowledgments

Authors wish to acknowledge parents and children or adolescents that participated in the study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nut.2024.112550.

References

[1] United Nations Children's Fund (UNICEF), World Health Organization (WHO), International Bank for Reconstruction and Development/The World Bank. Levels and trends in child malnutrition: UNICEF / WHO / World Bank Group Joint Child Malnutrition Estimates: Key findings of the 2023 edition. New York: UNICEF and WHO; 2023. Accessed May 2024. https://www.who.int/data/gho/data/themes/topics/joint-child-malnutrition-estimates-unicef-who-wb.
[2] Global Nutrition Report. 2022 Global Nutrition Report: Stronger commitments for greater action, Bristol, UK: Development Initiatives; 2022.
[3] Joosten KF, Hulst JM. Prevalence of malnutrition in pediatric hospital patients. Curr Opin Pediatr 2008;20(5):590–6.
[4] Lara-Pompa NE, Hill S, Williams J, Macdonald S, Fawbert K, Valente J, et al. Use of standardized body composition measurements and malnutrition screening tools to detect malnutrition risk and predict clinical outcomes in children with chronic conditions. Am J Clin Nutr 2020;112(6):1456–67.
[5] World Health Organization. Malnutrition. Accessed on 27 March https://www.who.int/en/news-room/fact-sheets/detail/malnutrition.
[6] WHO. Physical status: the use and interpretation of anthropometry. Report of a WHO Expert Committee. World Health Organ Tech Rep Ser. 1995;854:1–452.
[7] Wells JCK. The evolutionary biology of human body fat: thrift and control. Cambridge: Cambridge University Press; 2010.
[8] Briend A, Garenne M, Maire B, Fontaine O, Dieng K. Nutritional status, age and survival: the muscle mass hypothesis. Eur J Clin Nutr 1989;43(10):715–26.
[9] Roche S, Lara-Pompa NE, Macdonald S, Fawbert K, Valente J, Williams JE, et al. Bioelectric impedance vector analysis (BIVA) in hospitalised children; predictors and associations with clinical outcomes. Eur J Clin Nutr 2019;73(10):1431–40. https://doi.org/10.1038/s41430-019-0436-7.
[10] Wells JCK. Body composition of children with moderate and severe undernutrition and after treatment: a narrative review. BMC Med 2019;17(1):215. https://doi.org/10.1186/s12916-019-1465-8.
[11] Konyole SO, Omollo SA, Kinyuru JN, Owuor BO, Estambale BB, Ritz C, et al. Associations between stunting, wasting and body composition: a longitudinal study in 6- to 15-month-old Kenyan children. The Journal of nutrition 2023;153(4):970–8. https://doi.org/10.1016/j.tjnut.2023.02.014.
[12] Franco-Oliva A, Ávila-Nava A, Rodríguez-Aguilar EA, Trujillo-Mercado A, García-Guzmán AD, Pinzón-Navarro BA, et al. Association between phase angle and the nutritional status in pediatric populations: a systematic review. Front Nutr 2023;10:1142545. https://doi.org/10.3389/fnut.2023.1142545.
[13] D'Angelo S, Yajnik CS, Kumaran K, Joglekar C, Lubree H, Crozier SR, et al. Body size and body composition: a comparison of children in India and the UK through infancy and early childhood. J Epidemiol Community Health 2015;69(12):1147–53. https://doi.org/10.1136/jech-2014-204998.
[14] Buksh MJ, Hegarty JE, Griffith R, Alsweiler JM, McKinlay CJ, Harding JE, et al. Relationship between BMI and adiposity among different ethnic groups in 2-year-old New Zealand children. Br J Nutr 2019;121(6):670–7. https://doi.org/10.1017/S000711451800380X.
[15] Jensen SM, Mølgaard C, Ejlerskov KT, Christensen LB, Michaelsen KF, Briend A. Validity of anthropometric measurements to assess body composition, including muscle mass, in 3-year-old children from the SKOT cohort. Maternal & child nutrition 2015;11(3):398–408. https://doi.org/10.1111/mcn.12013.
[16] Macena ML, Silva Júnior AED, Praxedes DRS, Leite FMB, Silva Neto LGR, Pureza IROM, et al. Association between phase angle and height-to-age index classifications of children under five years of age. Clin Nutr ESPEN 2021;44:367–71. https://doi.org/10.1016/j.clnesp.2021.05.013.
[17] Skau JKH, Grenov B, Chamnan C, Chea M, Wieringa FT, Dijkhuizen MA, et al. Stunting, wasting and breast-feeding as correlates of body composition in Cambodian children at 6 and 15 months of age. Br J Nutr 2019;121(6):688–98. https://doi.org/10.1017/S0007114518003884.
[18] Ramel SE, Zhang L, Misra S, Anderson CG, Demerath EW. Do anthropometric measures accurately reflect body composition in preterm infants? Pediatr Obes 2017;12(Suppl 1):72–7.
[19] Zhu Y, Ye H, Feng Y, Pan LY, Fu HH, Liu YM, et al. Assessment of nutritional status in paediatric outpatients using bioelectrical impedance analysis and anthropometric z-scores. J Paediatr Child Health 2021;57(8):1274–80. https://doi.org/10.1111/jpc.15450.
[20] Freedman DS, Wang J, Maynard LM, Thornton JC, Mei Z, Pierson RN, et al. Relation of BMI to fat and fat-free mass among children and adolescents. Int J Obes (Lond) 2005;29(1):1–8. https://doi.org/10.1038/sj.ijo.0802735.
[21] Wilkes M, Thornton J, Horlick M, Sopher A, Wang J, Widen EM, et al. Relationship of BMI z score to fat percent and fat mass in multiethnic prepubertal children. Pediatr Obes 2019;14(1):e12463. https://doi.org/10.1111/ijpo.12463.
[22] Miranda-Alatriste PV, Colin-Ramirez E, Inda Icaza P, Ponce-Martínez X, Shor Mochón A, Martinsanchez Vázquez N, et al. Association between BMI z-score and body composition indexes with blood pressure and grip strength in school-age children: a cross-sectional study. Sci Rep. 2024;14(1):5477. https://doi.org/10.1038/s41598-024-55875-z.
[23] Wang Z, Deurenberg P, Wang W, Pietrobelli A, Baumgartner RN, Heymsfield SB. Hydration of fat-free body mass: review and critique of a classic body-composition constant. Am J Clin Nutr 1999;69(5):833–41. https://doi.org/10.1093/ajcn/69.5.833.
[24] Buffa R, Saragat B, Cabras S, Rinaldi AC, Marini E. Accuracy of specific BIVA for the assessment of body composition in the United States population. PLoS One 2013;8(3):e58533. https://doi.org/10.1371/journal.pone.0058533.
[25] Norman K, Stobäus N, Pirlich M, Bosy-Westphal A. Bioelectrical phase angle and impedance vector analysis. clinical relevance and applicability of impedance parameters. Clin Nutr 2012;31(6):854–61. https://doi.org/10.1016/j.clnu.2012.05.008.
[26] Heymsfield SB, Gonzalez MC, Lu J, Jia G, Zheng J. Skeletal muscle mass and quality: evolution of modern measurement concepts in the context of sarcopenia. Proc Nutr Soc 2015;74(4):355–66. https://doi.org/10.1017/S0029665115000129.
[27] Marini E, Campa F, Buffa R, Stagi S, Matias CN, Toselli S, et al. Phase angle and bioelectrical impedance vector analysis in the evaluation of body composition in athletes. Clin Nutr 2020;39(2):447–54. https://doi.org/10.1016/j.clnu.2019.02.016.
[28] Wells JC, Williams JE, Ward LC, Fewtrell MS. Utility of specific bioelectrical impedance vector analysis for the assessment of body composition in children. Clin Nutr 2021;40(3):1147–54. https://doi.org/10.1016/j.clnu.2020.07.022.

[29] Stagi S, Silva AM, Jesus F, Campa F, Cabras S, Earthman CP, Marini E. Usability of classic and specific bioelectrical impedance vector analysis in measuring body composition of children. Clin Nutr 2022;41(3):673–9. https://doi.org/10.1016/j.clnu.2022.01.021.
[30] Silva AM, Campa F, Stagi S, Gobbo LA, Buffa R, Toselli S, et al. The bioelectrical impedance analysis (BIA) international database: aims, scope, and call for data. Eur J Clin Nutr 2023;77(12):1143–50. https://doi.org/10.1038/s41430-023-01310-x.
[31] CIA. The World Factbook 2024. Washington, DC: Central Intelligence Agency; 2024. Accessed June 2024 https://www.cia.gov/.
[32] Comandini O, Cabras S, Ssensamba JT, Bukenya JN, Cipriano A, Carmignani G, et al. Nutritional status of Ugandan school-children: The effect of age imprecision. Am J Phys Anthropol 2019;170(1):88–97. https://doi.org/10.1002/ajpa.23895.
[33] WHO. Child growth standards: Length/height-for-age, weight-forage, weight-for-length, weight-for-height and body mass index-for-age: Methods and development. Geneva: WHO, Publications; 2006. p. 1–336.
[34] de Onis M, Onyango AW, Borghi E, Siyam A, Nishida C, Siekmann J. Development of a WHO growth reference for school-aged children and adolescents. Bulletin of the World Health Organization 2007;85(9):660–7. https://doi.org/10.2471/BLT.07.043497.
[35] Hastie T, Tibshirani R, Friedman JH, Friedman JH. The elements of statistical learning: data mining, inference, and prediction. New York: Springer; 2009.
[36] Benjamin DJ, Berger JO, Johannesson M, Nosek BA, Wagenmakers EJ, Berk R, et al. Redefine statistical significance. Nat Hum Behav 2018;2(1):6–10. https://doi.org/10.1038/s41562-017-0189-z.
[37] de Onis M, Branca F. Childhood stunting: a global perspective. Matern Child Nutr 2016;12(Suppl 1):12–26. https://doi.org/10.1111/mcn.12231.
[38] Leroy JL, Frongillo EA. Perspective: what does stunting really mean? A critical review of the evidence. Adv Nutr. 2019;10(2):196–204. https://doi.org/10.1093/advances/nmy101.
[39] Marino LV, Meyer R, Johnson M, Newell C, Johnstone C, Magee A, et al. Bioimpedance spectroscopy measurements of phase angle and height for age are predictive of outcome in children following surgery for congenital heart disease. Clin Nutr 2018;37(4):1430–6. https://doi.org/10.1016/j.clnu.2017.06.020.
[40] Wells JC, Hawton K, Darch T, Lunn PG. Body composition by 2H dilution in Gambian infants: comparison with UK infants and evaluation of simple prediction methods. Br J Nutr 2009;102(12):1776–82. https://doi.org/10.1017/S0007114509991255.
[41] Van Steijn L, Karamali NS, Kanhai HH, Ariëns GA, Fall CH, Yajnik CS, et al. Neonatal anthropometry: thin-fat phenotype in fourth to fifth generation South Asian neonates in Surinam. Int J Obesity 2009;33(11):1326–9.
[42] Yajnik CS, Fall CHD, Coyaji KJ, Hirve SS, Rao S, Barker DJP, et al. Neonatal anthropometry: the thin-fat Indian baby. The Pune Maternal Nutrition Study. Int J Obes 2003;27:173–80.
[43] Owino VO, Kasonka LM, Sinkala MM, Wells JK, Eaton S, Darch T, et al. Fortified complementary foods with or without alpha-amylase treatment increase hemoglobin but do not reduce breast milk intake of 9-mo-old Zambian infants. Am J Clin Nutr 2007;86(4):1094–103. https://doi.org/10.1093/ajcn/86.4.1094.
[44] Wu S, Zhang Y, De Luca F. The effect of a high-calorie diet on bone growth is mediated by the insulin receptor. Bone 2019;122:166–75. https://doi.org/10.1016/j.bone.2019.02.021.
[45] Gonzalez MC, Barbosa-Silva TG, Bielemann RM, Gallagher D, Heymsfield SB. Phase angle and its determinants in healthy subjects: influence of body composition. Am J Clin Nutr 2016;103(3):712–6. https://doi.org/10.3945/ajcn.115.116772.
[46] Haroun D, Wells JC, Williams JE, Fuller NJ, Fewtrell MS, Lawson MS. Composition of the fat-free mass in obese and nonobese children: matched case-control analyses. Int J Obes (Lond) 2005;29(1):29–36. https://doi.org/10.1038/sj.ijo.0802834.
[47] Wells JC, Fewtrell MS, Williams JE, Haroun D, Lawson MS, Cole TJ. Body composition in normal weight, overweight and obese children: matched case-control analyses of total and regional tissue masses, and body composition trends in relation to relative weight. Int J Obes (Lond) 2006;30(10):1506–13. https://doi.org/10.1038/sj.ijo.0803402.
[48] Comandini O, Cabras S, Marini E. Birth registration and child undernutrition in sub-Saharan Africa. Public Health Nutr 2016;19(10):1757–67. https://doi.org/10.1017/S136898001500333X.