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Body Composition prediction equations for infants from Latin America and the Caribbean

María Elena Díaz

marygelends@gmail.com

Instituto Nacional de Higiene, Epidemiología y Microbiología

Minerva Montero Díaz

Instituto Nacional de Higiene, Epidemiología y Microbiología

Anabel Pallaro

Facultad de Farmacia y Bioquímica. Universidada de Buenos Aires *(UBA)

Gerardo Weisstaub

University of Chile

Eugenia QUINTANA GUZMÁN Quintana

Facultad de Microbiología, Universidad de Costa Rica

María Kroker Lobos

Instituto de Nutrición de Centroamérica y Panamá (INCAP) https://orcid.org/0000-0001-8631-3101

Asha Badaloo

University of the West Indies

Faride Rodríguez Díaz - MPH (Master of Public Health)

Instituto Conmemorativo Gorgas de Estudios de la Salud (ICGES)

HUAMAN EDITHROSANA

Amarilis Then

Facultad de Ciencias de la Salud, Universidad Autónoma de Santo Domingo,

Mónica Britz

Escuela de Nutrición

Dina Roche

Instituto de Nutrición de Centroamérica y Panamá (INCAP)

Alexia Murphy-Alford

International Atomic Energy Agency https://orcid.org/0000-0001-7095-3796

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Abstract

Background

Body composition assessment is essential for evaluating nutritional status and early growth, yet access to advanced measurement technologies remains limited in many Latin American and Caribbean (LAC) settings. Developing simple and accurate anthropometric prediction models offers a feasible alternative for estimating fat-free mass (FFM) in infants.

Objective

To develop and validate equations to predict FFM in infants from LAC countries with diverse socioeconomic and ethnic contexts.

Methods

A multicentre cross-sectional study was conducted in 559 infants aged 6–24 months from ten LAC countries. Anthropometric measurements and FFM (by deuterium dilution) were collected using standardized protocols. The sample was randomly divided into development and validation groups. Stepwise regression and multilevel modelling were used to develop predictive equations that incorporate individual- and country-level variability. Model performance was assessed using R^2, mean absolute error (MAE), root mean square error (RMSE), Bland–Altman analyses, and cross-validation.

Results

Weight, length, and head circumference were the strongest predictors of FFM. Six preliminary models were developed, and multilevel models substantially improved predictive accuracy. Three final models explained approximately 80–81% of the variance in the validation sample. Model 5 showed the best overall balance of accuracy, precision, and feasibility.

Conclusions

This study provides the first anthropometric equations for estimating FFM in infants aged 6–24 months from LAC countries. The selected model is based on routine anthropometric measurements, which supports its feasibility for primary health care and field research. External validation in other populations is recommended.

Introduction

Body composition is a dynamic construct that plays a central role in the evaluation of nutritional status and growth. Its importance in infancy is well established, particularly for defining growth trajectories that reflect age- and sex-specific changes across the life course and for identifying early patterns associated with later disease risk (1,2). Despite this relevance, body composition assessment remains limited in many field settings where infant growth monitoring is most needed. In the absence of access to reference body composition methods, anthropometry-based prediction equations offer a practical and scalable alternative for estimating fat free mass (FFM).

Anthropometry based prediction equations, however, require age-specific and population appropriate calibration to ensure accuracy. Documented differences in infant body composition across geographic regions, socioeconomic environments, feeding practices, and early-life exposures can introduce systematic bias when equations are applied outside their development context. This is particularly relevant in Latin America and the Caribbean (LAC), a region characterised by substantial heterogeneity in nutritional status, with both undernutrition and rising early-onset overweight coexisting within and between countries. Apart from the Multi-center Infant Body Composition Reference Study (MIBCRS) (3) existing anthropometric equations for infants have been derived largely from single-country or high-income cohorts (4,5,6) and there has not been developed or validated equations for diverse LAC populations. To address this gap, this study aimed to develop and validate anthropometry-based equations for predicting FFM in infants aged 6–24 months using deuterium dilution as the reference method, drawing on harmonised data from 10 LAC countries representing diverse socioeconomic, cultural, and environmental contexts.

Methods

This was a cross-sectional, multicentre, multinational study funded by the International Atomic Energy Agency (IAEA – RAS 6079). Data were collected from infants aged 6 to 24 months across 10 Latin American and Caribbean countries: Argentina, Chile, Costa Rica, Cuba, Guatemala, Jamaica, Panama, Peru, the Dominican Republic, and Uruguay. Infants were recruited using convenience sampling during 2018–2019, following the principles established in the development of the World Health Organization (WHO) Multicentre Growth Reference Study (7). Inclusion criteria were infants born to mothers aged > 19 years, non-smokers, without major pregnancy-related complications, and who were breastfed for at least the first three months of life. Infants were required to be born at term (37–41 weeks + 6 days of gestation), from singleton pregnancies, with birth weight between 2500 g and 4000 g. Exclusion criteria included hospitalisation for more than one week in the two months prior to assessment, chronic medication use, congenital malformations, genetic syndromes, or any condition preventing participation. Ethical approval was obtained from relevant national or institutional ethics committees in all participating countries, and written informed consent was obtained from all mothers after full explanation of study procedures.

Anthropometric measurements included weight (kg), length (cm), triceps skinfold thickness (mm), subscapular skinfold thickness (mm), head circumference (cm), and arm circumference (cm), following INTERGROWTH-21st standardised protocols (8). All measurements were performed on the same day as body composition assessment. Weight was measured nude using a calibrated paediatric electronic scale with 5 g precision up to 7.5 kg and 10 g precision up to 20 kg. Length was measured using an infantometer to the nearest 0.1 cm. Head and arm circumferences were measured using a non-stretchable flexible tape to the nearest 0.1 cm. Skinfold thicknesses were measured using Holtain callipers to the nearest 0.2 mm. All anthropometric measures were obtained in duplicate, and the mean value was used for analysis. Prior to data collection, a regional standardisation exercise was conducted by trained anthropometry supervisors from the Institute of Nutrition of Central America and Panama (INCAP). Ongoing quality control in each country included assessment of technical error of measurement to ensure inter- and intra-observer reliability across sites.

Body composition was assessed using the deuterium dilution (DD) technique, which served as the reference method. The procedure followed IAEA protocols and as previously described (9, 10). Analysis was conducted using Fourier-transform infrared spectrometry (Agilent or Shimadzu). Analytical quality was ensured through

inter-laboratory comparisons and centralised data verification across study sites. Total body water (TBW) was calculated from deuterium dilution principles, and FFM was derived using age- and sex-specific hydration constants (11), and FM was subsequently calculated using a two-compartment model.

Data were captured and managed using the REDCap electronic data capture system (12). Descriptive statistics were computed for all variables. Outliers were defined as values exceeding ± 3.3 standard deviations from the mean (13). Distributional properties of FFM were examined visually by country, and sex differences were assessed using Student's t-test.

The final sample (n = 559) were randomly divided into two approximately equal subsamples (N1 = 280; N2 = 279) for model development and independent validation. Randomisation was performed to maintain comparable distributions of age, sex, and country across subsamples. Between-group comparability was assessed using independent-sample t-tests. Given established sex differences in growth and body composition (14), sex-by-anthropometry interaction terms were evaluated within regression models (Annex Figure A3).

Candidate predictors included sex, age, weight, length, triceps skinfold, subscapular skinfold, head circumference, and arm circumference. Predictive models were developed using stepwise forward selection (15) to identify a parsimonious subset of variables associated with FFM. Model performance was assessed using coefficient of determination (R^2) and standard error of the estimate (SEE). Multicollinearity was assessed using standard diagnostics (16–18), and residuals were examined to evaluate normality, homoscedasticity, and model fit.

To account for clustering by country, multilevel linear models were fitted with infants (level 1) nested within countries (level 2). This approach allowed assessment of between-country variability in FFM while accounting for shared measurement context. Initial models included weight, length, and head circumference as fixed effects. Parameters were estimated using Restricted Iterative Generalised Least Squares (RIGLS), assuming multivariate normality of residuals. Nonparametric bootstrap methods (19,20) were used to obtain robust standard errors and confidence intervals.

Predictive equations derived from multilevel models were evaluated in the independent validation subsample. Predicted FFM was compared against reference values obtained by deuterium dilution using paired t-tests and agreement statistics, including R^2, bias, mean absolute error (MAE), and root mean squared error (RMSE). Agreement between predicted and reference values was further assessed using Bland–Altman analysis (21). Data management was conducted using Microsoft Excel and statistical analyses were performed using STATISTICA (v10.0) and IBM SPSS Statistics (v25). Multilevel models were fitted using MLwiN (v2.10).

Results

Infant distribution by country and age group is shown in Supplementary Figure S2. Boys and girls differed significantly in weight, length, head circumference, subscapular skinfold, arm circumference, and FFM (Table 1). FFM by DD varied substantially across countries, with differences in both central tendency and dispersion (Supplementary Figure S3).

The development (n = 280) and validation (n = 279) subsamples were comparable, with no significant differences in anthropometric or demographic variables (Supplementary Table S1). In both subsamples, age,

weight, length, and head circumference were significantly and positively associated with FFM ($p < 0.05$), and no significant sex-by-predictor interactions were observed (all $p > 0.2$), indicating that sex-specific modelling was not required (Table 2).

Stepwise regression identified weight, length, head circumference, triceps skinfold, age, and arm circumference as significant predictors of FFM; sex and subscapular skinfold were excluded. Age and arm circumference contributed minimally in later models ($\Delta R^2 < 0.01$). Multicollinearity was detected but remained within acceptable limits, and predictive performance was not meaningfully affected (Table 3).

Multilevel modelling with bootstrap refinement (5,000 resamples) generated six candidate models (Table 4). In the base specification (Model 1), weight, length, and head circumference were consistently significant predictors, with substantial variability observed at both individual and country levels (ICC = 0.54). Residual diagnostics indicated approximate normality and no influential outliers (Supplementary Figure S4). Country-level residuals varied across sites, reflecting unmeasured contextual differences in measurement environments and population characteristics.

Adding triceps skinfold (Model 2) produced minimal improvement, while inclusion of age group (Model 3) was not statistically significant. Introducing country indicators (Model 4) substantially reduced between-country variance. For parsimony, triceps skinfold and age group were removed in Models 5 and 6, respectively. Overall, Models 4–6 explained 82–83% of total variance in FFM, 97% of between-country variance, and approximately 79% of within-country variance, with significant improvement in model fit when country effects were included (Table 5).

In multilevel models, exploring age as a categorical variable (6–12, 13–18, and 19–24 months) produced a modest improvement in predictive accuracy in the validation sample, increasing the proportion of correctly predicted values from 26.16% to 32.26%. This suggests that categorical age bands may capture stage-specific growth dynamics not fully reflected in continuous anthropometric predictors.

In the validation subsample, predicted FFM showed strong agreement with DD reference values (Supplementary Figure S5). The base model explained 63% of variance, whereas multilevel models improved explanatory power to approximately 80–81%, with Model 5 achieving the highest predictive accuracy ($R^2 = 0.81$), although some deviation from ideal intercept and slope values was observed. Mean observed and predicted FFM did not differ significantly across models (Table 6). MAE was lowest for Models 4–6 (47 g), with MAPE remaining below 10% for all models and RMSE ranging from 60 to 83 g. RMSPE for Models 5 and 6 (~8.6%) was comparable to Model 4 (8.7%). Model 5 also produced the highest proportion of accurate predictions, with approximately 52% within ±5% of observed FFM.

Bland–Altman analyses showed systematic bias in Models 1–3, whereas Models 4–6 demonstrated minimal bias and improved agreement (Figure 1). Cross-validation confirmed low bias (1–7 g) and acceptable limits of agreement for Models 4 and 5, while Models 1–3 showed proportional bias; fewer than 5% of observations fell outside limits of agreement for Models 5 and 6 (Table 7). Subgroup analyses indicated lower bias in infants aged 12–18 and 19–24 months, with highest concordance in the oldest age group (Supplementary Figure S6).

Country-specific analyses for Model 5 revealed variation in predictive performance across countries, with some settings showing tighter agreement than others. These differences likely reflect contextual factors such as

measurement conditions, sample characteristics, and unmeasured environmental influences rather than inherent population differences (Supplementary Figure S7). Figure 2 summarises inter-country uncertainty and highlights variability in model performance across settings, supporting the need for predefined thresholds when applying equations at country level. Final prediction equations stratified by country and age group are provided in Supplementary Table S2.

Discussion

In the present study, predictive models were developed to estimate FFM in infants aged 6–24 months from 10 countries in LAC, representing diverse sociocultural contexts. Few equations exist for this age group, and none have previously incorporated region-specific data using DD as the reference method. Across all models, weight, length, and head circumference consistently emerged as the strongest predictors of FFM. Although triceps skinfold thickness was statistically significant, its routine use is limited by the availability of callipers in primary care settings, reducing feasibility.

Sex differences in anthropometry and body composition are well documented and tend to widen with age (22,23). In this study, boys and girls differed in most anthropometric variables, yet no significant interaction was found between sex and the primary predictors of FFM. As a result, sex-specific models did not improve performance, and pooled models were retained. Although age is biologically associated with changes in FFM, its contribution to prediction was modest in stepwise regression. In multilevel models, treating age in discrete developmental bands provided a small improvement in prediction, indicating that categorical age captures stage specific growth dynamics not fully reflected in continuous anthropometric measures.

Substantial country level variation in FFM was observed. Infants within the same country were more similar to each other than to infants from other countries, reflecting shared measurement environments, sampling characteristics, and unmeasured contextual factors. Ignoring this clustering would underestimate standard errors and bias inference; multilevel modelling was therefore essential. Although the participating countries do not represent all LAC nations, multilevel models remain appropriate because they estimate residual variation at the country level and can incorporate contextual variables when available (24).

Models derived from the development sample were evaluated in an independent validation sample. Models 4, 5, and 6 demonstrated strong agreement with the reference method, showing minimal mean bias, no proportional bias, and narrow limits of agreement, with fewer than 5% of observations falling outside these limits. These differences are small enough to be clinically negligible. In routine paediatric care, skinfolds are rarely collected. For this reason, Model 5, which excludes skinfolds and demonstrated the best balance of accuracy, precision, and feasibility, is the most suitable for clinical integration.

The main strength of this study is the development of predictive equations for estimating FFM using analyses that explicitly accounted for age group and country effects, enabling the identification of meaningful geographic variation in FFM. By incorporating breastfed infants from diverse geographic, environmental, and sociocultural backgrounds across the LAC region, the models capture population heterogeneity that is often overlooked in body composition research. Previous work has shown that body composition differs across socioeconomic environments and countries, reflecting variation in food security, cultural feeding practices, environmental exposures, and other contextual factors (25-27), and the inclusion of such contextual factors has been recommended to improve generalizability in other age groups (28). Nonetheless, the use of a convenience

sample from 10 LAC countries limits generalizability beyond similar populations, and external validation in independent samples is required. Despite this limitation, the study provides region-specific equations derived using a gold-standard reference method and a sample size comparable to or larger than similar investigations, offering a robust foundation for future refinement and the potential incorporation of additional contextual variables to further enhance model performance.

Conclusion

This study presents the first regional predictive equations for estimating FFM in infants aged 6–24 months from multiple LAC countries. The equation based on weight, length, and head circumference demonstrated the most favourable combination of accuracy, precision, and feasibility, relying exclusively on measurements routinely collected in paediatric care. Incorporating country effects and developmental age groups improved model performance and supports the applicability of these equations across heterogeneous populations. These equations offer a simple, practical, and scientifically grounded approach for estimating FFM in early childhood, supporting improved assessment of body composition in primary health care and field settings. Future research is recommended to undertake external validation to confirm generalisability and to examine whether incorporating additional contextual variables, such as socioeconomic, environmental, or feeding-related factors, further enhances prediction accuracy.

Declarations

Data Availability Statement

The dataset generated and analysed during the present study was collected and managed using the REDCap electronic data capture platform (Harris et al., 2019). Due to ethical restrictions and institutional privacy regulations, individual-level data cannot be made publicly available. Anonymized data may be provided by the corresponding author upon reasonable request and subject to institutional approval

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Author Contributions

Study conception and design: MED, MMD; Data analysis: MMD; Manuscript drafting: MMD, MED, AMA; Data collection: AP, GW, EQ, MFKL, AB, FERD, ERH, AT, MB, DR; RLA6069 Group Data interpretation: MMD, MED; Critical revision of the manuscript: AMA, AP, GW, MFKL, AB, EU.

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Ethical Approval

This study was conducted in accordance with the guidelines of the Declaration of Helsinki. Ethical approval was obtained from relevant national or institutional ethics committees in all participating countries, and written informed consent was obtained from all mothers after full explanation of study procedures.

Competing interests

The authors declare no competing interests.

***Full list of RLA6079 collaborators**

[1]**Argentina**: Cristian Damián Nápoli, Silvina Mariela Vidueiros, Cristina Possidoni. [2]**Chile**: Katherine Curi Quinto. [3]**Costa Rica**: Lilliam Marín-Arias, Juan Diego Zamora-Salas, [4]**Cuba**: Beatriz Basabe Tuero, Elisa Llera Abreu, Yeneisy Lanyau Domínguez. [5]**Guatemala**: Manuel Ramírez, Lilian Navas, Lisbeth Méndez. [6]**Jamaica**: Daniel Thomas, Carolyn Taylor-Bryan. [7]**Panama**: Abdiel Bonilla, Fermina Chamorro, Fanny Franco, Aracelly Cedeño de López, Maritza Herrera. [8]**Peru**: Doris Marmolejo Gutarra, Elizabeth Paitan Anticona. [9]**Dominican Republic**: Massiel Alvarez B, Carolina Tavares-Valdez. [10]**Uruguay**: Gabriela Fajardo, Geraldine Sena, Mónica Defféminis, Eleuterio Umpierrez, Lucía Dellepiane, María José Castro.

[1]Departamento de Nutrición de la Facultad de Farmacia y Bioquímica de la Universidad de Buenos Aires, Argentina

[2]Instituto de Nutrición y Tecnología de los Alimentos (INTA), Chile

[3]Facultad de Microbiología,Universidad de Costa Rica,

[4]Centro de Nutrición e Higiene de los Alimentos, Instituto Nacional de Higiene, Epidemiología y Microbiología (INHEM), CUBA.

[5]INCAP Research Center for the Prevention of Chronic Diseases, Institute of Nutrition of Central America and Panama

[6]Tropical Metabolism Research Unit (TMRU), Caribbean Institute for Health Research, The University of the West Indies, Jamaica

[7]Instituto Conmemorativo Gorgas de Estudios de la Salud (ICGES), Panamá

[8]Universidad Nacional del Centro del Perú (UNCP), Peru

[9]División de Nutrición, Ministerio de Salud Pública, República Dominicana

[10]Escuela de Nutrición, Universidad de la República, Uruguay

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Tables

Tables 1 to 7 are available in the Supplementary Files section.

Figures

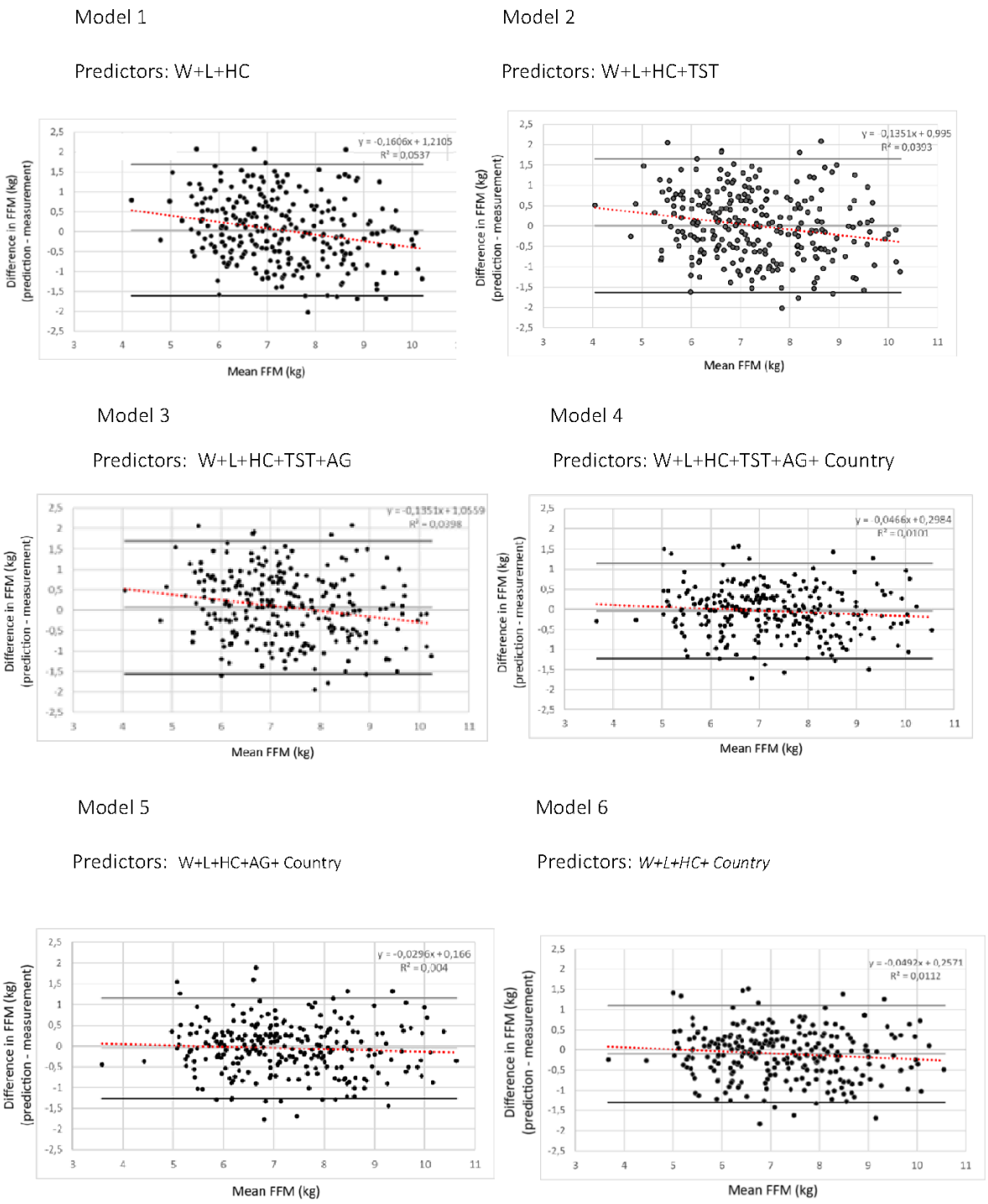


Figure 1

Bland-Altman plots[1] in the validation sample to determine the levels of agreement between the FFM (kg) obtained directly by the deuterium dilution method and that predicted by the predictive equations

[1]Central lines represent mean difference (mean) between methods. Mean ± 2 S.D. lines represent upper and lower limits of agreement. The red line and equation in each plot represent the linear regression between the differences (y) and the mean of the two measurement methods (x), its correlation (r) and significance (p). W:

weight (kg); L: length (cm): HC: head circumference (cm); TST: triceps skinfold thickness (mm); AC: arm circumference (cm) and A: age (months);

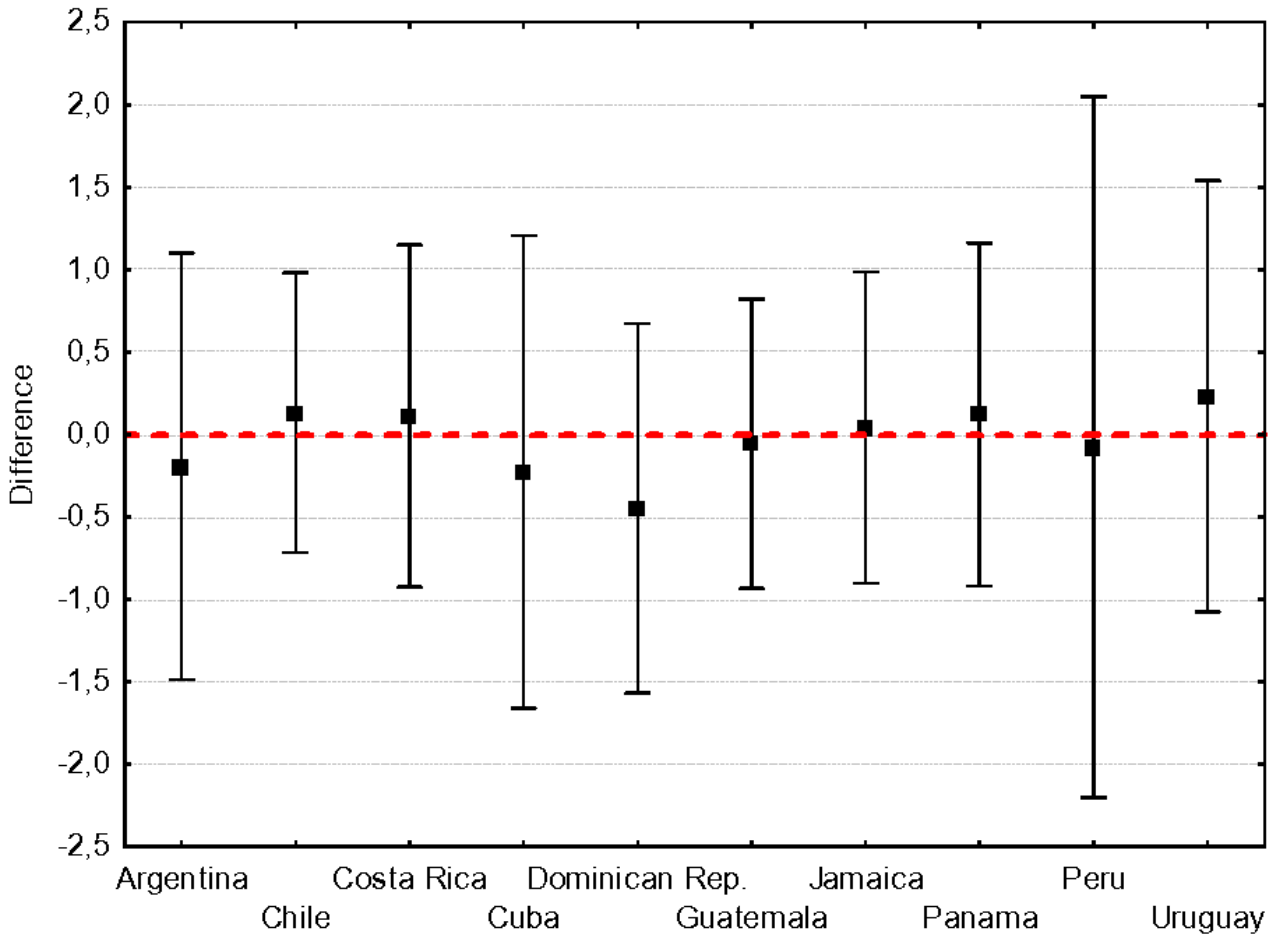


Figure 2

Country-specific estimation of uncertainty (mean difference ± 2 SD) in FFM prediction within the validation sample.

Supplementary Files

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