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Sprint and jump performance are determined by localized BIA - an ecological study in track and field adolescent athletes

Núbia Maria Oliveira[1*], Evandro Lázari[2], Catarina Nunes Matias[3], Gil Guerra-Júnior[1] and Ezequiel Moreira Gonçalves[1,4]

Abstract

Background Raw data obtained through bioelectrical impedance analysis (BIA) have been applied in different populations to assess body fluids and cell integrity. Assessing raw BIA parameters in specific muscles is an emerging method for evaluating muscle function. We investigated the associations of the BIA-derived variables of resistance (R), reactance (Xc) and phase angle (PhA) measured through whole-body (WB) and muscle-localized (ML) methods with performance in the countermovement jump (CMJ) and 50-meter (m) sprint.

Methods Thirty-one male track and field athletes (16.5 ± 1.6 years) were assessed. Fat-free mass (FFM) and Fat mass percentage (%FM) were determined by skinfold thickness. BIA at 50 kHz was employed to obtain the WB and ML (right thigh) parameters. The WB and ML-BIA parameters were adjusted by height (R/H, Xc/H) and segment length (R/L, Xc/L). The CMJ assessment was conducted via a contact mat; the software recorded the jump height. The 50-m sprint time was measured via two sets of photocells. Pearson's correlation and linear multiple regression were performed.

Results ML-PhA was inversely related to the 50-m sprint (β=-0.56) and by itself explained 29% of the sprint time variation. It remained a significant predictor even after adjusting for age, height, FFM and peak height velocity (PHV). ML-R/L was directly related to 50-m sprint (β = 0.48) and inversely related to CMJ performance (β=-0.54), explaining 20% and 27% of the variation in 50-m sprint and CMJ performance, respectively. Similarly, it remained a significant predictor in the adjusted models. Correlations between WB-BIA (PhA, R/H) and performance tests were found to be dependent on covariates.

Conclusions In this sample, the ML-BIA parameters of R/L and PhA were significantly associated with performance independent of age, height, FFM and PHV. Higher ML-PhA values were associated with better sprint times, whereas higher ML-R/L values were associated with worse sprint times and CMJ performance.

Keywords Bioelectrical impedance, Body composition, Phase angle, Countermovement jump

*Correspondence:
Núbia Maria Oliveira
nubiajapira@gmail.com
[1]Laboratory of Growth and Development, Center for Investigation in Pediatrics, School of Medical Sciences, State University of Campinas (UNICAMP), Campinas, Sao Paulo, Brazil
[2]School of Physical Education, Department of Sports Sciences, State University of Campinas (UNICAMP), Campinas, Sao Paulo, Brazil
[3]Center for Research in Sport, Physical Education, Exercise and Health (CIDEFES), Universidade Lusófona, Lisboa, Portugal
[4]Multiuser Laboratory of Biodynamics of Human Movement - Health Sciences Center, State University of Northern Parana (UENP), Jacarezinho, Parana, Brazil

Introduction

Among the factors contributing to sports success, athletes typically gain an advantage over their opponents by possessing greater muscular strength and power, as well as favorable body morphology and composition [1–4]. Higher strength and power levels often translate into greater speed, jump height and a reduced risk of injury [4–6]. Muscular power and speed are critical components of physical fitness in various track and field events [1]. Additionally, muscle quantity, size, and quality—often assessed through imaging techniques—are linked to performance [3, 7, 8]. Evaluating athletes' muscular function is, therefore, essential for success in sports, as it enables candidate screening, monitoring the efficacy of training programs, and assessing athletes' functional status. Consequently, accessible performance and muscular health indicators are needed in practical field settings to assist coaches and trainers in monitoring athletes throughout the preparation and recovery phases.

The assessment of raw data obtained through bioelectrical impedance analysis (BIA) has gained attention over the years, as it is a safe, practical, and non-invasive method [9]. Single-frequency BIA provides raw data on resistance (R), arising from extracellular and intracellular water distribution, and reactance (Xc), stemming from the ability of the cell membrane to take an electric load and release it after a brief delay [10]. The phase angle (PhA) is obtained by geometrically quantifying the angular transformation of the ratio between Xc and R [10], and its positive relationship to muscle function markers, such as strength and power, has been documented in several studies involving people in disease states, athletes, and healthy individuals [11–14].

BIA can be performed via the traditional tetrapolar method, which involves four electrodes, two on the hands and two on the feet [9], to measure whole-body (WB) parameters. Alternatively, it is possible to assess the bioelectrical properties of specific muscles [15]. The muscle-localized BIA (ML-BIA) parameters may provide more detailed physiological data on the composition and function of muscle tissue. In young men, BIA measures obtained from the anterior thigh showed associations with ultrasound muscle quality measures [16]. Despite being an emerging method, ML-BIA has demonstrated significant physiological relevance. In states of muscle injury, a decrease in the R parameter reflects localized fluid accumulation, whereas reductions in Xc and PhA indicate disruptions in cellular membrane integrity [17]. Additionally, ML-PhA was positively associated with muscle power in young women [13].

Sprinting and jump tests are common field measurements for evaluating functional and muscular capacity, forming integral components of various track and field events [1, 18–20]. Sprinting requires high levels of force production in the shortest time possible; additionally, significant vertical forces are essential to sustain high speeds [1, 21, 22]. Similarly, rapid force generation is necessary for jumping to propel the athlete's center of mass upwards or forwards [23]. As a result, the countermovement jump (CMJ) test is widely employed to assess lower-body power and evaluate qualities related to sprint performance [18]. To our knowledge, no investigations have analyzed whether BIA parameters obtained from specific muscles have the potential to act as performance indicators in an athletic population, namely, at the pediatric level. Adolescence is a crucial phase of human development characterized by hormonal and metabolic changes that drive rapid and substantial shifts in body composition (lean mass, fat mass, bone mineral content, body water) and physical fitness [24, 25]. Therefore, it is important to investigate the potential of raw BIA parameters as predictors of muscle performance in this age range.

Thus, this cross-sectional study aims to investigate the associations of raw bioimpedance-derived parameters, measured via the WB and the ML approach, with performance in the CMJ and 50-meter (m) sprint time in adolescent track and field athletes. We hypothesize that both WB and ML-PhA will show a direct association with CMJ and an inverse association with 50-m sprint time. In contrast, R will demonstrate an inverse association with CMJ and a direct association with 50-m sprint time. We also assume that the parameters obtained through muscle-localized analysis will be better predictors of performance than those obtained through the traditional WB method.

Methods

Study design and sample size

This cross-sectional study was conducted during the physical assessment week at the ORCAMPI track and field training center in Campinas, SP, Brazil. Each participant was evaluated once and underwent anthropometric and BIA assessments, followed by performance tests. Evaluations were conducted in the morning (9:00–11:00 a.m.) and afternoon (2:00–5:00 p.m.) based on participants' availability. Participants were instructed to fast for at least three hours prior to the assessments.

The sample size calculation (G*Power 3.1.9.7, Franz Faul, Germany) was conducted considering a large effect size, suitable for a multiple regression model with continuous independent and dependent variables, a 5% type I error rate, and 80% power. The results revealed that this study's ideal sample size was $n=29$.

The sample comprised thirty-one competitive [26] male track and field athletes (aged 16.5±1.6 years) with a training experience of 24.6±15.1 months who met the following inclusion criteria: i) aged >13 and ≤19 years;

ii) ≥8 months of training; and iii) ≥6 h of training per week and iv) without any injuries that would limit the performance in the tests. Among the total sample, 19.4% were jumpers, 54.8% were sprinters, 12.9% were decathletes, 6.5% were middle- and long-distance runners, and 6.5% were in training school. The study was approved by the Ethics Committee of the State University of Campinas under protocol number 6.735.234 and was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent. For minors, informed consent to participate was obtained from their parents or legal guardians after they were thoroughly informed about all study procedures.

Anthropometric measurements

Participants were wearing minimal clothing (shorts) for the evaluation. Total body mass and height were determined using a digital scale with a stadiometer (Prix – Toledo 2096PP, Sao Bernardo do Campo, SP, Brazil) to the nearest 0.1 kg and the nearest 0.1 cm, respectively. Body mass index (BMI) was calculated as weight in kilograms divided by the square of height in meters. The length of the right thigh was measured from the greater trochanter to the knee joint space via a non-extendable and malleable metric tape (Sanny, TR4013, Sao Bernardo do Campo, SP, Brazil) [27].

The fat mass percentage %FM was determined by measurement of tricipital and calf skinfold thickness (mm). Measures were taken at two seconds using a Harpenden calliper (British Indicators Ltd, Weybridge, England). The evaluation followed the ACSM recommendations [27]. The following published [28] equation was used:

$$\%\mathrm{FM}_{\mathrm{boys}}: \ 0.735^{*}(\mathrm{tricipital} + \mathrm{calf}) + 1.0$$

$$\mathrm{Fat-free\ mass\ (FFM)\ was\ calculated\ as\ follows:}$$
$$\mathrm{FFM} = \mathrm{body\ mass} \times (1 - 100/\%\mathrm{FM})$$

Peak height velocity (PHV)

The chronological age (years) and body height (cm) were used to calculate the PHV (in years). Using the individual classification, participants with negative predictive PHV were classified as pre-PHV, and those with positive values were classified as post-PHV. The following equation [29] was used:

$$\mathrm{PHV\ boys}: -7.999994 + [0.0036124 \times (\mathrm{age} \times \mathrm{height})]$$

Whole-body and muscle-localized BIA analysis

A tetrapolar device operating at 50 kHz (Quantum II, RJL systems, Detroit, Michigan) was used obtain the WB and ML bioimpedance measures. The analysis was conducted in a climate-controlled room, and the participants were instructed to follow the recommendations described in the literature (previous exercise, food, and beverage consumption) [9]. The skin of each participant was cleaned with alcohol. For the WB analysis, two electrodes were placed on the surface of the right hand, and two others were placed on the right foot, according to the recommended protocol [9]. The ML analysis was conducted on the right thigh; two electrodes were positioned 5 and 10 cm distal from the anterior-inferior iliac spine, and the other two were positioned proximally and 5 cm above the upper pole of the patella, respectively, as previously described [13]. Raw variables were obtained, and for the analysis, the WB-R and Xc values were adjusted by height (in meters), whereas the ML-R and Xc values were adjusted for segment length (in meters). The PhA was calculated as PhA = arc-tangent (Xc/R) × (180°/π) to assess cellular integrity and quality [9].

The reproducibility of the parameters provided by BIA was determined by the coefficient of variation (CV) and the technical error of measurement (TEM) based on the test-retest method performed on 15 volunteers. The %CV values calculated from our BIA device for WB and ML-BIA were 0.2 and 1.2 for R and 0.8 and 1.5 for Xc, respectively. The TEMs for WB and ML-BIA were 2.7 Ω and 1.5 Ω for R and 1.1 Ω and 0.4 Ω for Xc, respectively.

Performance tests

Performance was evaluated via the CMJ and a 50-m sprint test. Before performing the tests, the athletes completed a 10-minute warm-up, including 5 min of running at a moderate pace, followed by 5 min of active lower limb stretching. The CMJ assessment was conducted using a contact mat (Jump System Pro, CEFISE, Nova Odessa, SP, Brazil). Athletes were already familiar with this task, routinely used during assessment weeks. Each participant performed one submaximal jump, followed by two valid attempts, with a 2-minute interval between attempts.

Each trial was conducted while the participants stood with their hands on their hips. During each trial, the participants quickly bent downward and performed a fast upward push to achieve the highest possible jump. The Jump System 1.0 software recorded the CMJ height, and the best of the two attempts was selected for analysis.

The 50-m sprint is one of the most commonly used distances for sprint testing in track and field assessments, covering the acceleration phase and reaching or closely approaching maximum speed [19, 22]. The 50-m sprint test was conducted on a synthetic track, with sprint time measured to an accuracy of 0.01 s via two sets of photocells (Speed Test 6.0, CEFISE, Nova Odessa, SP, Brazil) positioned at the 0-m and 50-m marks. The participants performed two attempts with a 3-minute

interval between them, and the fastest recorded time was selected for analysis.

Statistical analysis

The data analysis was conducted using the SPSS software version 25.0 (IBM, Chicago, Illinois) and OriginPro version 2024 (OriginLab Corporation, Northampton, MA). Descriptive data of the sample are presented as mean ± SD or median and interquartile range (IQ). Data normality was assessed using the Shapiro–Wilk test. Variables that did not adhere to a normal distribution were transformed into log10 (CMJ and ML-R/L) and bloom scores (%FM, 50-m sprint). We performed a general linear model to test the effect of athletes' disciplines on the variables of interest (BIA parameters, body composition and performance tests). Pearson's correlation coefficient was employed to examine associations among BIA parameters (WB-R/H, Xc/H, PhA; ML-R/L, Xc/L, PhA), performance tests (CMJ, 50-m sprint), body composition (FFM, %FM), and descriptive characteristics (age, height, PHV). We subsequently performed partial correlations between PhA (WB and ML), body composition and performance tests, controlling for age, height, and PHV. We tested correlations for WB-R/H, Xc/H, ML-R/L, Xc/L, body composition and performance tests, controlling for age and PHV. The strength of the correlation coefficients (r) was interpreted as follows: 0 to 0.3 = small; 0.31 to 0.49 = moderate; 0.5 to 0.69 = large; 0.7 to 0.89 = very large; 0.9 to 1.0 = near-perfect correlation [30]. Multiple linear regression via the enter method was conducted to test whether WB and ML-BIA parameters that remained significant in partial correlations could predict CMJ and 50-m sprint performance. For all analyses, the significance level was set at $p < 0.05$.

Table 1 Descriptive characteristics of the sample ($n = 31$)

	Mean ± SD/ Median(IQ)
Age (years)	16.5 ± 1.6
PHV(years)	2.5 ± 1.3
Weight (kg)	65.3 ± 7.8
Height (m)	1.8 ± 0.1
BMI (kg/m^2)	21.3 ± 1.7
FM (%)	11.2 (3.6)
FFM (kg)	57.4 ± 6.1
WB-R/H (Ω/m)	275.5 ± 27.3
WB-Xc/H (Ω/m)	38.0 ± 3.5
WB-PhA (°)	8.0 ± 0.8
ML-R/L(Ω/m)	97.7 (17.2)
ML-Xc/L(Ω/m)	35.8 ± 5.0
ML-PhA (°)	20.8 ± 2.9
50-m Sprint (s)	6.4 (0.6)
CMJ (cm)	38.9 (14.4)

SD = Standard Deviation; IQ = Interquartile range; PHV = Peak Height Velocity; BMI = Body Mass Index; FM = Fat Mass; FFM = Fat-Free Mass; H = Height; L = Length; CMJ = Countermovement Jump

Results

There was no effect of athletes' disciplines on the variables of interest: 50-m sprint ($F[df = 3,27] = 1.57$; $p = 0.219$), CMJ ($F = 2.10$; $p = 0.123$), WB-PhA ($F = 0.74$; $p = 0.973$), ML-PhA ($F = 1.02$; $p = 0.397$), WB-R/H ($F = 1.65$; $p = 0.201$), WB-Xc/H ($F = 2.16$; $p = 0.117$), ML-R/L ($F = 0.04$; $p = 0.988$), and ML-Xc/L ($F = 0.775$; $p = 0.518$). The supplementary table shows the descriptive characteristics of the sample split by discipline. Table 1 displays the descriptive characteristics of the total sample.

A heatmap illustrating the relationships between the variables of interest is presented in Fig. 1. Regarding the 50-m sprint, a direct correlation was observed with the ML-R/L and WB-R/H ($r = 0.48$ [0.15;0.71] and 0.37 [0.01;0.64], respectively). Additionally, an inverse correlation of the 50-m sprint with CMJ, ML-PhA, and FFM (r = -0.52 [-0.74;-0.21], -0.56 [-0.76;-0.25] and −0.44 [-0.69;-0.10], respectively) was noted. Furthermore, regarding CMJ, a direct correlation was found with WB-PhA, ML-PhA, and FFM ($r = 0.49$ [0.17;0.72], 0.39 [0.04;0.65] and 0.66 [0.40;0.82], respectively), along with an inverse correlation with WB-R/H and ML-R/L (r = -0.62 [-0.80;-0.35] and −0.54 [-0.75;-0.23], respectively).

WB-PhA was directly correlated with FFM ($r = 0.66$ [0.40;0.82]). WB-R/H and MR/R/L were inversely related to FFM (r = -0.87 [-0.94;-0.75] and −0.50 [-0.73;-0.18], respectively). ML-R/L and ML-Xc/L were positively correlated with %FM ($r = 0.36$ [0.01;0.64], 0.52 [0.20;0.74]).

Age was directly related to CMJ, ML-PhA, WB-PhA, FFM, and height ($r = 0.69$ [0.44;0.84], 0.44 [0.10;0.68], 0.45 [0.12;0.70], 0.49 [0.16;0.72] and 0.39 [0.04;0.65], respectively) and inversely related to the 50-m sprint (r = -0.46 [-0.70;-0.12]) and WB-R/H (r = -0.46 [-0.70;-0.12]). Height was directly related to CMJ ($r = 0.48$ [0.15;0.71]), ML-PhA ($r = 0.37$ [0.02;0.64]), and FFM ($r = 0.73$ [0.52;0.87]) and inversely related to the 50-m sprint (r = -0.48 [-0.71;-0.15]), ML-R/L (r = -0.36 [-0.63;-0.01]), and WB-R/H (r = -0.53 [-0.74;-0.21]). PHV was directly correlated with CMJ ($r = 0.72$ [0.50; 0.85]), WB-PhA ($r = 0.47$ [0.14; 0.70]), ML-PhA ($r = 0.47$ [0.14; 0.71]), and FFM ($r = 0.64$ [0.38; 0.81]), and inversely correlated with 50-m sprint (r = -0.52 [-0.74; -0.21]) and WB-R/H (r = -0.55 [-0.76; -0.24]).

Considering the impact of age, height and PHV on this sample's performance tests and BIA parameters, we conducted partial correlations. The correlations between performance tests with PhA and body composition were controlled for age and height, while for the correlations of performance tests with BIA parameters (R, Xc), adjustments were made only for age, as these parameters are

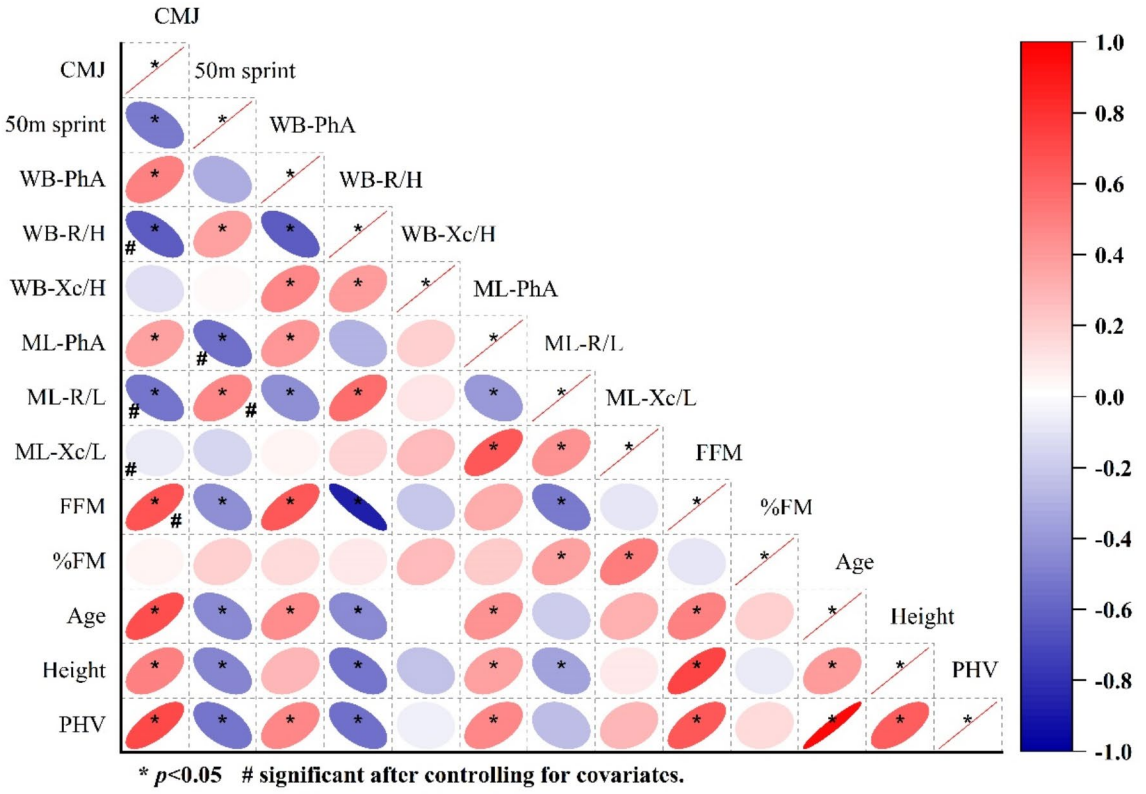

Fig. 1 Heatmap of correlations: Performance tests, BIA parameters, body composition, and sample characteristics (age, height, PHV)
Legend: CMJ = Countermovement Jump; L = Length; H = Height; FM = Fat Mass; FFM = Fat-Free Mass; PHV = Peak Height Velocity

already adjusted for height and segment length. ML-R/L (r = -0.58; p<0.01) showed a large correlation with CMJ, while R/H (r = -0.48; p=0.007), ML-Xc/L (r = -0.38; p=0.040), and FFM (r=0.43; p=0.021) showed moderate correlations. For the 50-m sprint, only ML-PhA (-0.41; p=0.029) and ML-R/L (r=0.45; p=0.012) remained significant, showing moderate correlations. We also tested the associations while controlling for PHV, and the results were similar: ML-R/L, ML-Xc/L, R/H, and FFM remained correlated with CMJ (r = -0.53, p=0.002; r = -0.39, p=0.033; r = -0.39, p=0.032; r=0.37, p=0.042). Additionally, ML-PhA (r = -0.42, p=0.020) and ML-R/L (r=0.42, p=0.020) remained correlated with the 50-m sprint.

After controlling for age and height, we also examined the explanatory power of the BIA parameters that remained correlated with the 50-m sprint and CMJ (Table 2). ML-PhA explained 29% of the variation in 50-m sprint performance in the unadjusted model and remained a significant predictor even after adjusting for age, height, FFM and PHV (p<0.05). ML-R/L explained 20% and 27% of the variation in 50-m sprint and CMJ performance, respectively, and remained a significant predictor in the adjusted models (p<0.05). Despite the significant correlation of ML-Xc/L with CMJ when controlling for age, height and for PHV, it was not a significant predictor in the linear models. In addition, the WB-R/H also lost explanatory power in the adjusted models.

Discussion

The present study revealed large and moderate associations of ML-PhA and ML-R/L with the 50-m sprint, and a large association of ML-R/L with CMJ. These relationships remained significant even after controlling for age, height, FFM, and PHV. In contrast, associations between WB-BIA parameters (PhA, R/H) and performance were not independent of covariates in this sample. The indirect association of ML-PhA with 50-m sprint time presently observed aligns with previous research demonstrating associations between WB-PhA and sprint time in soccer athletes [31]. Additionally, when we performed a

Table 2 Unadjusted and adjusted linear models to test BIA parameters as performance predictors

	50-m sprint (bloom)						
	beta	**CI 95%**		**S.E**	**β**	***p***	**r^2 adjust.**
ML-PhA[a]	-0.187	-0.292	-0.081	0.052	-0.556	**0.001**	**0.29**
ML-PhA[b]	-0.126	-0.243	-0.008	0.057	-0.375	**0.037**	**0.34**
ML-PhA[c]	-0.132	-0.247	-0.016	0.056	-0.393	**0.027**	**0.35**
ML-R/L(log)[a]	8.355	2.500	14.210	2.863	0.476	**0.007**	**0.20**
ML-R/L(log)[d]	6.523	0.158	12.888	3.102	0.372	**0.045**	**0.30**
ML-R/(log)[c]	6.794	0.564	13.025	3.037	0.387	**0.034**	**0.34**
	CMJ (log)						
	beta	**CI 95%**		**S.E**	**β**	***p***	**r^2 adjust.**
ML-R/L(log)[a]	-0.955	-1.521	-0.388	0.277	-0.539	**0.002**	**0.27**
ML-R/L(log)[d]	-0.560	-1.013	-0.107	0.221	-0.316	**0.017**	**0.65**
ML-R/L(log)[c]	-0.580	-1.048	-0.112	0.228	-0.328	**0.017**	**0.63**
ML-Xc/L[a]	-0.001	-0.008	0.006	0.004	-0.053	0.779	-0.03
ML-Xc/L[d]	-0.004	-0.009	0.001	0.002	-0.190	0.142	**0.60**
ML-Xc/L[c]	-0.004	-0.009	0.001	0.003	-0.209	0.127	**0.58**
WB-R/H[a]	-0.002	-0.003	-0.001	0.001	-0.624	**< 0.01**	**0.37**
WB-R/H[d]	0.000	-0.002	0.001	0.001	-0.131	0.599	**0.58**
WB-R/H[c]	-0.001	-0.003	0.001	0.001	-0.218	0.393	**0.56**

[a]crude model; [b]adjusted by age, height and FFM; [c]adjusted by PHV and FFM; [d]adjusted by age and FFM; S.E = Standard Error; β = standardized beta. **Bold values are statistically significant ($p < 0.05$)**

stepwise multiple regression analysis including variables correlated with sprint capacity, ML-PhA emerged as the primary predictor.

Key factors contributing to sprint performance include muscular volume, enzymatic activity concentration in muscle cells for energy production, and muscular activation capacity for effective force and power production [21, 32]. Furthermore, in the 50-m sprint, the acceleration phase is highly prominent, requiring high levels of propulsive force to achieve greater speeds [22]. In this aspect, the muscles of the lower limbs play a significant role, with muscle mass being essential in this phase, where overcoming inertia and increasing stride length are fundamental [21, 33]. Taken together, the associations we found between ML-PhA and 50-m sprint have a sound rationale, as PhA has been shown to reflect muscular and cellular characteristics that positively impact performance, including strength, power, and DXA measures of fat free mass [13, 31, 34–36]. Additionally, PhA has been shown to predict intracellular water values [37] assessed by dilution techniques and reductions in this compartment have been associated with decreases in strength [38].

Body composition and muscle quality are also important for the sprint ability, as evidenced by studies indicating that lower fat levels are associated with better sprint capacity, likely due to reduced resistance in propelling the body forward [39, 40]. Emerging evidence shows that BIA parameters obtained from specific body parts can potentially reflect tissue composition and muscle quality [13, 16, 41]. Previous research has indicated that ML-BIA parameters are correlated with echo intensity [16], a measure of muscle quality provided by ultrasound that is also related to muscle strength [42]. More specifically, PhA values were negatively associated with echo intensity values in older men [41].

Conversely, the R parameter was positively associated with higher echo intensity values, indicating elevated levels of noncontractile and poorly hydrated tissues [16]. Thus, the indirect relationship of ML-PhA with sprint time and the positive contribution of ML-R/L to lower sprint times and reduced CMJ performance observed in our study are logical findings and may suggest a potential capability of ML-BIA to reflect tissue quality and function. However, it is worth noting that the correlations between the raw BIA parameters and ultrasound measures of muscle quality mentioned above were conducted via multifrequency devices with different physical configurations and electrode positions. These factors may influence the raw BIA values, thus limiting comparisons between studies [43]. Moreover, it is necessary to determine whether BIA parameters obtained from unifrequency devices, such as the one used in the present study, show the same correlations.

The WB and ML-R parameters showed very large and moderate inverse associations with the FFM, respectively. FFM represents functional mass and positively contributes to strength and force production [44]. This finding reinforces our hypothesis that the R parameter is inversely related to muscle performance in this sample, as higher lean mass, which contains the muscles, leads to lower R values due to its richness in water and electrolytes [9, 10]. Additionally, the ML-R/L showed a moderate positive correlation with %FM. Although %FM did

not correlate with performance in our study, it is considered a nonfunctional mass, with increasing amounts of FM mechanically and metabolically hindering sports performance [3, 45]. Finally, the above relationships emphasize the synergetic effect between the physiological components of the human body, strengthening the bonds between tissues and fluids to achieve the performance goal.

An association between whole body and segmented PhA with CMJ performance was previously reported in adolescent athletes [46]. Thus, we anticipated similar results. In our research, the ML-PhA was derived from the anterior thigh, encompassing the knee extensor muscles, which play a critical role in CMJ performance by contributing to force generation and acceleration of the body's center of mass [23, 47]. These aspects are closely linked to muscle quality and function, which may be reflected by PhA [12, 13, 41]. Additionally, relative increases in lean mass and leg lean mass, along with reductions in fat mass measured by DXA, have been positively associated with improvements in CMJ performance in male athletes [48]. As previously shown, these aspects of body composition can also be reflected by PhA [13, 35, 36]. However, although we observed a moderate correlation between WB and ML-PhA with CMJ, these relationships disappeared when we controlled for covariates. The WB-R/H initially emerged as a predictor of CMJ even when controlling for age or PHV; however, after adjusting for FFM in the linear model, its explanatory power was lost.

Only ML-R/L remained a significant predictor of CMJ after adjusting for all covariates in the model. Additionally, when we performed a stepwise linear regression, ML-R/L emerged as a significant predictor of CMJ with PHV, explaining 61% of the variation in CMJ performance. These results may be attributed to the strong correlations of FFM and PHV with CMJ, as the R parameter is strongly influenced by fat-free mass [49], and given that the association of WB-R/H with CMJ was dependent on FFM, maybe a segmented measure of FFM would similarly affect the significant association of ML-R/L with CMJ. Besides that, the R parameter appears to be crucially linked to muscle performance and should be considered alongside PhA.

Corroborating this, a study involving young resistance-trained females concluded that changes in the R parameter, both total and segmented, corresponded with changes in lean soft tissue following a resistance-training intervention [50] while fewer associations were observed for Xc and PhA. Nevertheless, it should be noted that this study was conducted with a female sample, and we are aware of the influence of sex on body characteristics, physiological traits, and body composition. This, in turn, can impact BIA parameters [51] and potentially affect which parameters have the best relationship with performance in each sex. Despite all this, the R parameter obtained in specific muscles has demonstrated sensitivity to muscle adaptations after a training period [52] and to states of recovery from muscle injury in young adult soccer players [17]. Finally, another important factor to consider in comparison to these studies is that our sample consisted of adolescents. In this age group, maturation and growth influence the composition and hydration of tissues, and chemical maturity—referring to the chemical stability of lean mass—has not yet been fully achieved [25], which may have impacted our results.

Although its potential in a field of novelty and where evidence is scarce, this study has limitations that should be considered. The cross-sectional study design precludes establishing a cause–and–effect relationship; thus, future investigations should consider a longitudinal design. Additionally, it would be valuable to investigate ML-BIA in other muscles relevant to these specific tasks, such as the hip and posterior thigh and leg muscles, to determine whether ML-BIA has the potential to provide a more comprehensive assessment of muscle function [21, 23, 47]. Even though skinfold measurements were conducted by an experienced evaluator, enhancing the reliability of whole-body FFM and %FM estimation, a reference method for body composition assessment and segmented quantification of tissues such as DXA is lacking. In addition, this study combined athletes from different track and field disciplines to achieve the minimum 80% statistical power for analyzing associations of BIA parameters (R and PhA) with performance tests. This target was met for most analyses, except for the model of ML-R/L as a predictor of the 50-m sprint (67%) and the correlation between ML-PhA and CMJ (62%). Despite including athletes from various disciplines, we conducted a statistical test to assess the effects of sports modality on the variables of interest, and no significant effect was found. However, future studies should consider investigating each discipline separately.

It should also be noted that the wide range of training experience among the athletes may be an influential factor. However, when we analyzed ML-PhA and ML-R/L, controlling for PHV and training experience (in months), they remained significant predictors of the 50-m sprint ($\beta = 0.39$ and 0.36; $p = 0.047$ and 0.025, respectively). Similarly, ML-R/L was also a significant predictor of CMJ ($\beta = 0.39$; $p = 0.001$). Additionally, despite instructing the athletes to follow the recommendations described in the literature regarding hydration, exercise, and pre-evaluation nutrition, their hydration status before the evaluations was not measured. This factor should be considered in future investigations involving athletes, as it can impact BIA results. Finally, this study consists of a male-only sample, which does not allow these results to

be extrapolated to females owing to the different physiological and body characteristics previously discussed.

Conclusions

The raw bioimpedance-derived parameters of PhA and R obtained through the ML method were associated with 50-m sprint capacity and CMJ performance in adolescent track and field athletes. Higher ML-PhA values were linked to better sprint times, whereas higher ML-R/L values were associated with poorer sprint times and CMJ performance. The correlations between WB-BIA parameters and performance tests did not persist after controlling for covariates. ML-BIA appears to be a promising practical tool that can be easily applied by coaches to assess and monitor athletes' functional capacity, which can inform better training methods and performance optimization strategies.

Abbreviations

BIA	Bioelectrical Impedance Analysis
R	Resistance
Xc	Reactance
PhA	Phase Angle
WB	Whole–body
ML	Muscle–Localized
CMJ	Countermovement Jump
FFM	Fat Free Mass
FM	Fat Mass
H	Height
L	Length
BMI	Body Mass Index
CV	Coefficient of Variation
TEM	Technical Error of Measurement
SD	Standard Deviation
IQ	Interquartile Range
PHV	Peak Height Velocity

Supplementary Information

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Supplementary Material 1

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Not applicable.

Author contributions

N.M.O., C.N.M., and E.M.G. designed the study; N.M.O. and E.L. collected the data; N.M.O. performed the data analysis; N.M.O., E.L. and G.G.J. interpreted the data; N.M.O. wrote the manuscript; E.M.G., C.N.M. and G.G.J. substantively revised the manuscript. All the authors have read and approved the final version of the manuscript.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study was approved by the Ethics Committee of the State University of Campinas under protocol number 6.735.234 and was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent. For minors, informed consent to participate was obtained from their parents or legal guardians after they were thoroughly informed about all study procedures.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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