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Body Composition, Bioelectrical Impedance Vector Analysis, And Pulmonary Function In Adolescent Swimming Athletes: A Cross-Sectional Study

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Abstract:
Background*: Swimming requires high ventilatory efficiency and adequate body composition for sports performance. The present study aimed to verify the relationship between body composition and pulmonary function in adolescent high-performance swimming athletes from a Higher Education Institution.*
Materials and Methods*: Cross-sectional study with 19 federated swimmers (12 males and 7 females), aged 10 to 22 years. Protocols applied included anthropometry, multifrequency bioelectrical impedance (Thera Science®), and spirometry (Minispir®). Statistical analysis used the Shapiro–Wilk test and Pearson/Spearman correlations.*
Results*: Male swimmers showed higher values of forced vital capacity (FVC: 4.99 vs. 3.30 L; $p<0.001$), forced expiratory volume in the first second (FEV_1: 4.41 vs. 3.06 L; $p=0.003$), and peak expiratory flow (PEF: 9.13 vs. 6.26 L/s; $p=0.005$), as well as greater fat-free mass (FFM: 55.4 vs. 37.4 kg; $p<0.001$) and skeletal muscle mass (SMM: 33.1 vs. 19.6 kg; $p<0.001$). Females exhibited higher body fat percentage (BF%: 26% vs. 14%; $p<0.001$). Bioelectrical impedance vector analysis (BIVA) significantly differentiated sexes ($T^2=37.5$; $p=0.001$). A strong positive correlation was observed between FFM and FEV_1 ($r=0.90$; $p<0.001$), total body water (TBW) and FEV_1 ($r=0.88$; $p<0.001$), and phase angle (PA) with FVC ($r=0.69$; $p<0.001$). Resistance showed a significant negative correlation with FVC ($r = -0.651$; $p=0.003$), FEV_1 ($r = -0.702$; $p=0.001$), and PEF ($r = -0.727$; $p<0.001$). Impedance also correlated negatively with FVC ($r = -0.648$; $p=0.003$), FEV_1 ($r = -0.700$; $p=0.001$), and PEF ($r = -0.725$; $p<0.001$).*
Conclusion: *The relationship between body composition and pulmonary function evidenced that greater lean mass, adequate hydration, and higher phase angle are associated with better respiratory performance in swimmers.*
Keywords: *Swimming; Spirometry; Bioelectrical impedance; Body composition; Hydration.*

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I. Introduction

The respiratory system plays a fundamental role in athletic performance, especially in endurance sports such as swimming. Ventilatory efficiency and adequate gas exchange are decisive for the supply of oxygen to muscle tissues during high-intensity efforts.[1] Specifically in swimming, inhalation must be strictly synchronized to maintain respiratory coordination with the stroke cycle, which reduces the duration of inspiratory time. This respiratory particularity is characterized by rapid inspiration, close to total lung capacity (TLC), accompanied by negative intrathoracic pressure, followed by prolonged expiration in the water.[2,3]

Due to the specific demands of swimming training, competitive athletes tend to present more pronounced adaptations in pulmonary function, characterized by higher static and dynamic lung volumes when compared with non-swimmers of the same age and height[4,5]. Scientific evidence suggests that in swimmers, the accumulation of years of systematic practice in this discipline is directly associated with increased forced vital capacity (FVC) and forced expiratory volume in the first second (FEV_1).[6,7]

In parallel, regional fat-free mass, particularly in the trunk and upper and lower limbs, is positively related to physiological fitness and the ability to generate force during swimming. This characteristic directly influences performance in middle-distance events such as the 200 meters, contributing to improved aerobic capacity and muscle strength, impacting speed directly, or indirectly through increased physiological indices related to maximal and submaximal cardiorespiratory fitness, reflecting the integration between body composition and pulmonary function in sports performance.[8]

In swimming in particular, monitoring body composition is an important tool for optimizing competitive performance. In sprint swimmers, body composition is strongly associated with performance in short-distance events. In men, performance is related to the balance between contractile and non-contractile tissue and high levels of muscle mass, whereas in women, the most decisive factor is high muscle mass combined with low body fat percentage. Moreover, predictive models based on body composition were able to explain 35.1% of the variability in male performance and 75.1% in female performance, indicating that measuring body composition can be a useful tool to guide training and optimize performance.[9] In recent years, bioelectrical impedance analysis (BIA) has been consolidated as a reliable method for assessing body composition in the sports context. The technique consists of applying a painless electric current between contact points, such as hands and feet, to measure body resistance and reactance, from which fat-free mass and body fat percentage are estimated using specific validated equations in the literature.[11]

Thus, analyzing body composition and pulmonary function in adolescent swimmers is justified, since the effects of sex hormones vary according to sex and directly influence breathing. In boys, higher testosterone levels favor increased muscle mass and the muscle-to-fat ratio, which contributes to reducing airway resistance. In girls, increased body mass index (BMI) associated with sexual maturation may exert a negative effect on respiratory function. [12] During adolescence, these particularities are intensified by the physical and hormonal changes typical of this stage, including accelerated growth in height and changes mediated by estrogen, testosterone, growth hormone, and somatomedin C concentrations. Such factors influence fat distribution, skeletal muscle mass gain, and bone density, so that males tend to develop more fat-free mass and skeletal tissue, while females present greater accumulation of adipose tissue, leading to distinct body patterns.[13]

These transformations also affect pulmonary function, since peak growth velocity is related to increases in FVC and FEV_1, resulting in better ventilatory capacity. Sexual dimorphism, initially subtle, becomes evident in this period, with boys acquiring more android body characteristics and girls more gynoid characteristics. A longitudinal study indicates that the age of pubertal onset and growth rate are strongly associated with pulmonary function in adulthood. Accelerated growth during puberty, for example, is associated with higher FVC, FEV_1, and forced expiratory flow between 25% and 75% (FEF25–75%) in boys, whereas in girls this effect is less evident. Conversely, late puberty may be associated with reduced pulmonary function in adolescent boys, suggesting a mismatch between linear growth and respiratory maturation.[14]

In this sense, understanding the relationship between pulmonary function and body composition variables in young athletes, such as regional lean mass, body fat percentage, and the muscle-to-fat ratio, may provide important insights to identify physiological adaptations resulting from systematic training. Furthermore, the integrated analysis of these variables may contribute to the development of individualized training strategies and monitoring of physical development, favoring performance improvement, prevention of ventilatory limitations, and enhancement of athletic condition in this age group.[15–17] Therefore, the present study aims to verify the relationship between body composition and pulmonary function in adolescent swimmers.

II. Material And Methods

Study Design and Sample

This work is an observational, cross-sectional, and analytical study conducted with high-performance federated swimming athletes (freestyle) from the team of Associação Educativa Evangélica (UniEVANGÉLICA), located in Anápolis (GO), Brazil. The athletes were between 10 and 22 years of age, with a history of participation in state and national competitions, and returned to activities immediately after the vacation period. The initial preparation phase was directed toward the development of aerobic power, a fundamental characteristic for the discipline. The program included six training days per week, distributed across two daily sessions: approximately two hours in the morning and four hours in the afternoon. In addition to specific swimming training, the routine encompassed complementary out-of-pool activities, such as 20 minutes of global stretching and joint mobility, followed by strength training sessions averaging one hour in duration, including resistance, strength, and power exercises. Periodization was structured into four main stages: aerobic power, specific training, pre-competitive, and competitive, allowing systematic progression of workload and preparation for the target competitions of the annual calendar.

Ethical Aspects

This study was approved by the Research Ethics Committee (CEP) of UniEVANGÉLICA under protocol nº 6.627.152 and followed Resolution nº 466/12 of the Brazilian National Health Council. All athletes signed the Informed Consent Form. For minors, both the Minor Assent Form and the Consent Form for parents or legal guardians were provided, ensuring that they could review the information and contact the researcher in case of questions before authorizing participation.

Participant Recruitment

Athlete recruitment took place between July and August 2024 during a meeting of the research team with the athletes, conducted during training sessions at the Aquatic Center located in Colégio Couto Magalhães, with authorization and collaboration from the manager and coach. The meeting was held in the warm-up room adjacent to the pool, during which all information and instructions regarding the study were provided. After expressing interest and signing the participation assent, an identification form was completed and evaluations were scheduled by two researchers from the team. The initial sample consisted of 29 athletes recruited by in-person invitation at the Aquatic Center, with 100% adherence to participation. However, 10 athletes were excluded: seven for not completing the evaluations and three for being adults, resulting in a final sample of 19 athletes, of whom seven were female and 12 male.

Inclusion and Exclusion Criteria

Inclusion criteria were athletes aged 10 to 22 years, affiliated with the Goiás Aquatic Federation (FAGO), with a history of participation in state and regional competitions, and at least 12 months of continuous training. Exclusion criteria were acute respiratory diseases such as sinusitis or bronchial asthma, self-reported heart disease, or recent osteomuscular injuries that could compromise participation in the evaluations. In addition, athletes who missed scheduled assessments or did not fully complete the established evaluation protocol were also excluded.

Assessment Protocols

Data collection was performed in single sessions with each participant, averaging 45 minutes per volunteer, in the afternoon period (between 2:00 p.m. and 6:00 p.m.) to standardize physiological conditions and minimize circadian influences on results. All evaluations were conducted at the Aquatic Center of Colégio Couto Magalhães by trained professionals, following standardized preparation and evaluation protocols. The sequence of procedures was uniformly applied to all athletes, beginning with sociodemographic data collection, followed by anthropometric measurements, assessment of body composition by multifrequency bioelectrical impedance, and spirometry.

Anthropometric Measurements

Body mass was measured using a digital scale (G-Tech®, model Balgl10, São Paulo, Brazil), with accuracy of ±0.1 kg. Athletes were barefoot and wearing light clothing to minimize measurement interference. Height was measured using a non-extensible measuring tape fixed to a flat wall without baseboards, with athletes standing barefoot, in an upright position, heels against the wall, feet together, gaze directed to the horizon, and the vertex aligned with a rigid horizontal level, according to standardized anthropometric measurement protocols. BMI was calculated by dividing body mass by height squared.

Body Composition

Body composition was assessed using multifrequency bioelectrical impedance with the BIA Thera Science device (Thera Science®, Brasília, DF, Brazil), recognized for its reliability in estimating body compartments in active populations ativas[18]. To ensure accuracy, athletes were instructed to maintain a minimum four-hour fast, refrain from physical activity for 12 hours prior, empty the bladder 30 minutes before testing, and avoid caffeine or alcohol intake within 24 hours before assessment.

Bioelectrical variables included resistance (RΩ), reflecting opposition to current flow and related to total body water; resistance adjusted for height (R/H); reactance (XcΩ), associated with tissue capacitance and cell membrane integrity; reactance adjusted for height (Xc/H); impedance (ZΩ), the vector combination of R and Xc; and phase angle (PA°), considered an indicator of cell integrity and body cell mass proportion, and a marker of nutritional status.[19,20] Reference values for athletes indicate lower resistance and impedance due to higher lean mass, while reactance and phase angle tend to be higher, reflecting better cellular integrity and greater cell mass proportion. In well-trained athletes, phase angle may reach values up to 8.5°.

Analyzed body composition variables included fat-free mass (FFM, kg), skeletal muscle mass (SMM, kg), body fat (BF, kg and %), skeletal muscle mass index (SMMI), muscle-to-fat ratio (MFR). Hydration variables included total body water (TBW, L), intracellular water (ICW, L), and extracellular water (ECW, L). Interpretation was based on values reported by Vehrs et al. (2022), in which adolescent males aged 12–17 showed progressive reduction in BF%, from approximately 21% at age 12 to about 13% at age 17, whereas adolescent females in the same age range maintained more stable values between 24% and 27%[23].

Pulmonary Function

Pulmonary function was assessed by spirometry using a portable spirometer (Minispir®, Medical International Research – MIR, Rome, Italy) operated with WinspiroPRO software (Medical International

Research – MIR, Rome, Italy). Procedures followed guidelines of the American Thoracic Society/European Respiratory Society (ATS/ERS) [24]. Spirometric maneuvers were performed with athletes seated, using a nose clip, under direct supervision of a trained physiotherapist. At least three reproducible maneuvers were obtained. Measured respiratory parameters included FVC, FEV_1, FEV_1/FVC ratio, peak expiratory flow (PEF), and predicted values. Interpretation followed the criteria of the Brazilian Thoracic Society (SBPT) [25]. Predicted FEV_1 and FVC values were obtained using reference equations for the Brazilian population that account for age, sex, and height.

Data Analysis

The data obtained were organized in Microsoft Excel spreadsheets and subjected to statistical analysis using the Statistical Package for the Social Sciences – SPSS® software (version 27.0, IBM, Armonk, NY). Results were described as mean, standard deviation, frequencies, and percentages. The Shapiro–Wilk test verified the normality of numerical variables. Student's t-test (normal distribution) or Mann–Whitney test (asymmetric distribution) were used for group comparisons. Correlations between variables were verified using Spearman's correlation coefficient. The level of statistical significance was set at $p < 0.05$.

Bioelectrical impedance vector analysis was performed using the BIVA software (2002, Antonio Piccoli and Giordano Pastori, Department of Medical and Surgical Sciences, University of Padova, Italy). Confidence ellipses were compared using Hotelling's T^2 test with the corresponding univariate analysis test (F-test), and similarity between confidence ellipses was determined by Mahalanobis distance (D). Tolerance ellipses were established from the vectors of the total sample of athletes for the 95%, 75%, and 50% intervals. Vectors positioned within the 75% tolerance ellipse were considered normohydrated, above as dehydrated, and below as hyperhydrated.[26]

III. Results

The study included 19 swimming athletes specialized in freestyle events, of whom 7 (36.8%) were female and 12 (63.2%) male. Table 1 presents the sample characterization. Male athletes showed higher values of body mass (Δ=14.9 kg, p=0.004) and height (Δ=17.38 cm, p<0.001) compared to female athletes. Mean age was similar between groups (p=0.299), and BMI showed no significant difference (p=0.335).

Table 1. Characterization of swimming athletes (n=19).

Variables	Female (n = 07)	Male (n = 12)	ES	p*
	Average ± SD	Average ± SD		
Age (years)	13.57 ± 2.15	15.18 ± 1.70	0.38	0.299
Body mass (kg)	50.90 ± 10.80	65.80 ± 8.65	1.52	0.004
Height (cm)	156.29 ± 10.61	173.67 ± 5.70	2.04	<0.001
BMI (kg/m^2)	20.63 ± 2.61	21.77 ± 2.30	0.46	0.335
Maturity offset (years)	-0.28 ± 1.60	3.43 ± 1.47	0.77	<0.001

**BMI: Body mass index; ES: effect size. Data for p <0.05.*

In Table 2, regarding pulmonary function, male athletes presented significantly higher values in PEF (Δ=2.87 L/s; p=0.005; ES=1.40), FVC (Δ=1.69 L; p<0.001; ES=1.93), and FEV_1 (Δ=1.35 L; p=0.003; ES=1.72) compared with female athletes. The remaining pulmonary function variables remained similar between groups, with no statistically significant differences.

Table 2. Comparison of pulmonary function according to sex in swimming athletes (n=19)

Pulmonary function	Total (n=19)	Male (n = 12)	Female (n = 7)	ES	p*
		Average ± SD	Average ± SD		
PEF (L/s)	8.07 ± 2.63	9.13 ± 2.72	6.26 ± 1.03	1.40	0.005
FVC (L)	4.37 ± 1.24	4.99 ± 1.07	3.30 ± 0,62	1.93	<0.001
FVC_{PRED} (%)	113.49 ± 13.23	115.74 ± 15.75	109.98 ± 6.91	0.47	0.392
FVC_1 (L)	3.91 ± 1.05	4.41 ± 0.95	3.06±0.58	1.72	0.003
FEV_{1PRED} (%)	121.65 ± 16.53	124.17 ± 19.86	117.33 ± 7.90	0.45	0.400
FEV_1/FVC	0.90 ± 0.08	0.83 ± 0.00	0.87 ± 0.01	5.67	0.310
FEV_1/FVC_{PRED}	0.85 ± 0.02	0.89 ± 0.09	0.92 ± 0.05	0.41	0.400
TEF (s)	2.53 ± 1.40	2.35 ± 1.35	2.83 ± 1.54	0.16	0.482

**PEF: peak expiratory flow; FVC: forced vital capacity; FVCpred: predicted forced vital capacity; FEV_1: forced expiratory volume in the first second; EFT: expiratory flow time. Data for p <0.05.*

Table 3 presents the comparison of body composition variables of swimming athletes stratified by sex. Among the bioelectrical variables, male athletes showed significantly lower values of R (Δ=149.65 Ω; p<0.001;

ES=2.46) and Z (Δ=149.22 Ω; $p<0.001$; ES=2.45), while PA was higher (Δ=1.38°; p=0.004; ES=1.50). Male athletes also showed bioelectrical impedance vectors characterized by significantly higher values of resistance normalized by height (R/H) (Δ=129.19 Ω; $p<0.001$; ES=0.81). In contrast, reactance normalized by height (Xc/H) showed no significant difference between sexes (Δ=5.81 Ω; p=0.113), indicating no relevant effect for this variable.

Regarding body composition variables, FFM (Δ=18.06 kg; $p<0.001$; ES=2.55), SMM (Δ=13.48 kg; $p<0.001$; ES=4.31), SMMI (Δ=2.95; $p<0.001$; ES=3.29), and MFR (Δ=2.87; p=0.009; ES=1.59) were significantly higher in males, while BF (Δ=18.6 kg; p=0.023; ES=1.12) and BF% (Δ=12.34%; $p<0.001$; ES=2.71) were lower. Concerning hydration status, female athletes showed lower values of ECW (Δ=4.86 L; p=0.001; ES=2.00), ICW (Δ=8.91 L; $p<0.001$; ES=3.64), and TBW (Δ=13.75 L; $p<0.001$; ES=2.87).

Table 3. Comparison of body composition according to sex in swimming athletes (n=19)

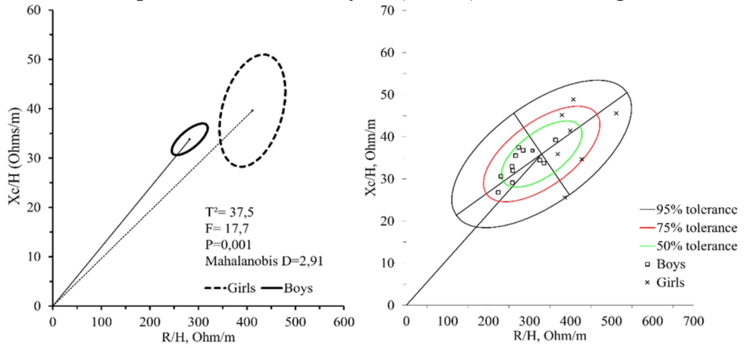
Variables	Total (n=19)	Male (n = 12)	Female (n = 7)	ES	p*
		Média ± DP	Média ± DP		
Bioelectrical					
R (ohms)	544.86 ± 97.45	489.72 ± 74.30	639.37 ± 43.22	2.46	<0.001
R/H	329.76 ± 77.39	282.16 ± 42.74	411.35 ± 48.21	0.81	<0.001
Xc (ohms)	59.84 ± 9.36	58.70 ± 6.77	61.80 ± 13.10	0.30	0.501
Xc/H	35.93 ± 6.19	33.79 ± 3.69	39.60 ± 8.07	0.42	0.113
Z (ohms)	548.24 ± 97.35	493.26 ± 74.37	642.48 ± 43.44	2.45	<0.001
PA (º)	6.39 ± 1.07	6.90 ± 0.67	5.52 ± 1.12	1.50	0.004
Body composition					
FFM (kg)	48.75 ± 11.51	55.41 ± 8.21	37.35 ± 5.76	2.55	<0.001
SMM (kg)	28.09 ± 7.43	33.06 ± 3.86	19.58 ± 2.17	4.31	<0.001
BF (kg)	10.60 ± 4.56	8.84 ± 3.26	13.62 ± 5.10	1.12	0.023
BF (%)	18.17 ± 7.49	13.62 ± 4.18	25.96 ± 4.89	2.71	<0.001
SMMI	9.88 ± 1.74	10.97 ± 1.19	8.02 ± 0.44	3.29	<0.001
MFR	3.40 ± 2.44	4.46 ± 2.51	1.59 ± 0.49	1.59	0.009
Hydration					
ECW (L)	15.16 ± 3.42	16.96 ± 2.74	12.10 ± 2.05	2.00	0.001
ICW (L)	21.03 ± 5.10	24.31 ± 3,02	15.40 ± 1.70	3.64	<0.001
TBW (L)	36.20 ± 8.41	41.26 ± 5.71	27.51 ± 3.65	2.87	<0.001

**R: resistance; R/H: resistance by height; Xc: reactance; Xc/H: reactance by height; Z: impedance; PA: phase angle; FFM: fat-free mass; SMM: skeletal muscle mass; BF: body fat; SMMI: skeletal muscle mass index; MFR: muscle-to-fat ratio; ECW: extracellular water; ICW: intracellular water; TBW: total body water. Data for p<0.05.*

As shown in Figure 1, bioelectrical impedance vector analysis (BIVA) revealed statistically significant differences in the confidence ellipses between male and female swimming athletes (T^2=37.5; F=17.7; p=0.001). Mahalanobis distance (D=2.91) confirmed a separation between groups, indicating distinct body composition patterns between sexes, as illustrated in Figure 1A.

The tolerance ellipse (Figure 1B) showed that most athletes were within the 75% tolerance ellipse, indicating that they were normohydrated and had muscle mass within the expected range. Only three female athletes had their vectors positioned outside the 75% ellipse: one in the upper left quadrant and another in the right quadrant toward dehydration, and one in the lower right quadrant toward hyperhydration and a lower proportion of body cell mass.

Figure 1. Bioelectrical impedance vector analysis (BIVA) of swimming athletes stratified by sex



R/H: resistance normalized by height; (Ohm/m): unit of electrical resistance per meter; Xc/H: reactance normalized by height; T^2: Hotelling's T^2 statistic; F: F statistic; p: probability value; D: Mahalanobis distance.

Table 4 presents the correlations between body composition, hydration, and bioelectrical variables with pulmonary function parameters. A positive and significant correlation was observed between fat-free mass ($r=0.888$; $p<0.001$), skeletal muscle mass ($r=0.823$; $p<0.001$), total body water ($r=0.864$; $p<0.001$), and FEV_1. Phase angle also showed a positive correlation with FVC ($r=0.692$; $p=0.001$) and FEV_1 ($r=0.681$; $p=0.001$). In contrast, the electrical parameters of resistance and impedance exhibited negative correlations with FVC, FEV_1, and PEF, suggesting that lower values of these variables are associated with greater respiratory efficiency. Furthermore, a significant association was observed between body fat percentage and predicted FEV_1/FVC ratio ($r=0.645$; $p=0.003$).

Table 4. Correlation between bioelectrical, body composition, and hydration variables versus pulmonary function variables (n=19)

Variable	FVC (L) r (p)	FVC_{PRED} (% r (p)	FEV_1 (L) r (p)	VEF_{1PRED} (%) r (p)	PEF (L/s) r (p)	FEV_1/FVC_{PRED} (%) r (p)
R (ohms)	-0.651 (0.003)	—	-0.702 (0.001)	-0.532 (0.019)	-0.727 (<0.001)	0.763 (<0.001)
Z (ohms)	-0.648 (0.003)	-0.530 (0.020)	-0.700 (0.001)	—	-0.725 (<0.001)	0.760 (<0.001)
PA°	0.692 (<0.001)	0.561 (0.012)	0.681 (0.001)	0.499 (0.029)	0.664 (0.002)	-0.681 (0.001)
FFM (kg)	0.888 (<0.001)	0.601 (0.006)	0.901 (<0.000)	0.630 (0.004)	0.864 (<0.001)	-0.902 (<0.001)
SMM (kg)	0.819 (<0.001)	0.494 (0.032)	0.823 (0.000)	0.456 (0.050)	0.782 (<0.001)	-0.926 (<0.001)
SMMI	0.599 (0.007)	—	0.632 (0.004)	—	0.646 (<0.003)	-0.750 (<0.001)
ECW (L)	0.851 (<0.001)	—	0.878 (<0.001)	0.649 (0.003)	0.857 (<0.001)	-0.858 (<0.001)
ICW (L)	0.853 (<0.001)	0.536 (0.018)	0.856 (<0.001)	0.553 (0.014)	0.835 (<0.001)	-0.910 (<0.001)
TBW (L)	0.864 (<0.001)	0.567 (0.011)	0.876 (<0.001)	0.599 (0.007)	0.855 (<0.001)	-0.901 (<0.001)
BF (%)	—	—	—	—	—	0.645 (0.003)
MFR	—	—	—	—	—	-0.490 (0.033)

FVC: forced vital capacity; PRED: predicted; FEV_1: forced expiratory volume in the first second; PEF: peak expiratory flow; R: resistance; Z: impedance; PA: phase angle; FFM: fat-free mass; SMM: skeletal muscle mass; SMMI: skeletal muscle mass index; ECW: extracellular water; ICW: intracellular water; TBW: total body water; BF: body fat; MFR: muscle-to-fat ratio; r: correlation coefficient.

IV. Discussion

The findings of this study revealed significant sex differences in lung function and body composition among adolescent swimmers. In spirometric parameters, males presented higher absolute values of FVC, FEV_1, and PEF, differences that attenuated after adjustment for height, highlighting the influence of somatic growth. Regarding body composition, boys exhibited greater FFM, SMM, and MGR, whereas girls presented higher %BF and a relatively greater proportion of body water. This morphofunctional profile was directly associated with maturational stage, reflecting greater predominance of lean mass and more efficient ventilation in boys, and higher fat accumulation and water differentiation in girls. In summary, the differences observed reflect pubertal particularities between sexes, which distinctly influence body composition and ventilatory performance in high-performance adolescent athletes. Vectorial analysis of bioimpedance (Z) revealed sex-specific patterns, with no overlap of confidence ellipses. Strong positive correlations were observed between FFM, SMM, TBW, and ventilatory parameters, while resistance (R) and impedance (Z) showed significant negative correlations. Phase angle (PA°) was positively associated with FVC and FEV_1.

With respect to lung function, the higher absolute values of FVC, FEV_1, and PEF in males may be attributed to greater thoracic development and respiratory musculature, resulting from sexual dimorphism and biological maturation[27]. These findings are consistent with literature reporting favorable chronic adaptations in swimmers, including increased pulmonary and thoracic compliance, higher lung volumes, and improved ventilatory efficiency, especially when training is systematic from childhood or adolescence[4,6,27]. Such adaptations enhance athletic performance and reflect a cardiorespiratory profile compatible with elite-level performance.

All athletes included in this study specialized in crawl swimming. This style is characterized by predominance of aerobic metabolism and high ventilatory efficiency requirements, particularly in middle- and long-distance events. Studies indicate that crawl specialists develop distinct morphofunctional adaptations, including greater vital capacity, increased upper-limb strength, and body composition conducive to buoyancy and propulsion. The characteristic breathing pattern of crawl, with unilateral inspiration and short apnea periods during submerged expiration, imposes substantial demands on the ventilatory system, favoring positive pulmonary adaptations over time[28].

Regarding BIA, in this study, male athletes presented a mean body fat (BF) of 13.6%, whereas female athletes showed an average of 25.9%. A similar pattern was observed for MGR, higher in males, indicating closer alignment with the expected profile for the sport. PA° is a widely recognized marker of cell integrity and functional status. In this study, males presented mean values consistent with adequate cell integrity, suggesting greater cell mass and better hydration status—desirable features for performance[28].

These results are consistent with Martins et al. (2021), who found that young soccer players with higher phase angle (PA) values demonstrated better performance in 10- and 30-meter sprints and greater sprint repeatability, even after adjusting for age and body composition[26]. This body profile is also associated with better hydrodynamic performance and lower resistance (R) in water, while higher TBW indicates fluid balance, essential for sustaining performance and preventing fatigue. Studies in adolescent athletes reinforce that the development of FFM and SMM is directly linked to biological maturation, including sexual and skeletal development[30,31].

Furthermore, longitudinal evidence supports these findings. Reis et al. (2021) observed swimmers across 13 weeks of training and found that, in the final three weeks preceding competition—characterized by progressive training load reduction—vector shortening, increased PA, and reduced %BF occurred, reflecting improved hydration and cell integrity. These adaptations were mirrored by improved 50-meter freestyle performance, suggesting that PA is sensitive to physiological adaptations to training load adjustment and recovery. Thus, PA emerges not only as a marker of cell integrity and density but also as a noninvasive tool to monitor athletic condition and performance in swimmers[28].

Biological maturation exerts a significant influence on bioimpedance (Z) parameters, as early-maturing athletes tend to exhibit higher TBW and specific vector patterns[32]. Differences between sexes observed in this study, particularly in FFM and PA°, may be partially explained by maturational stage and training history, both of which directly modulate bioelectrical variables. Supporting this interpretation, Cattem et al. (2024) found that adolescent athletes showed progressive reductions in resistance (R) and reactance, along with significant PA increases over one year, highlighting training-induced bioelectrical adaptations in a sex-dependent manner. Growth spurts were associated with increases in FFM, SMM, and PA, particularly near peak height velocity[33]. Therefore, BIVA and PA interpretation in youth should consider biological development stage and training history, avoiding bias when comparing individuals of the same chronological age but with different maturational and training exposure.

The results point to a more favorable body profile in males, with greater muscle mass and lower relative fat, directly impacting movement efficiency, strength, and buoyancy. The higher PA° observed in boys suggests superior cell integrity and nutritional status, consistent with greater lean body mass and fluid content[34]. Moreover, the integration of body composition with functional measures, such as muscle strength, may enhance performance assessment. Cattem et al. (2021) demonstrated that adolescents with higher handgrip strength and older than 13 years presented vector displacements consistent with greater hydration and cell mass, suggesting that combining BIVA with strength measures yields robust insights into biological maturity and athletic potential[35].

Vector analysis revealed displacement towards the left and upward in the RXc graph, a pattern indicative of greater cell density and adequate hydration. Most athletes clustered within the 75% tolerance ellipse, suggesting normohydration consistent with reference populations. These findings align with previous elite-athlete studies in soccer, volleyball, and cycling, which also demonstrated vectors consistent with greater cell mass and intact membranes[18,36]. In this study, male and female swimmers exhibited distinct patterns without overlap of confidence ellipses, a separation statistically supported by Hotelling's T^2 and Mahalanobis distance. Female vectors shifted toward reduced hydration and lower cell mass compared with males. Similar patterns have been observed in other sports, such as handball, where BIVA distinguished athletes from non-athletes[37].

Male swimmers presented mean vectors in the R/Xc graph shifted further left compared with females, denoting lower electrical resistance (R) and, consequently, higher lean body mass proportion—a finding consistent with athletic morphology often reported in strength- and power-based sports[38]. Female athletes, though with smaller displacements, still maintained vectors within zones compatible with healthy, physiologically active body composition[28].

According to BIVA methodological guidelines, vector shifts parallel to the major ellipse axis represent hydration state changes, while shifts parallel to the minor axis indicate cell mass modifications[32]. In this study, no vectors exceeded the 95% tolerance limits, indicating that all athletes fell within bioelectrical normality for their age and training status. In crawl swimmers, BIVA has similarly revealed vectors shifted leftward and upward in the RXc plot, reflecting higher cell density and adequate hydration—physiological traits of high performance[38]. This reinforces BIVA's utility as a sensitive tool for monitoring training-related physiological changes, especially when combined with spirometric and anthropometric data.

BIVA was crucial for qualitative interpretation of nutritional and hydroelectrolytic status through tolerance ellipses. Observed vector displacements—shortening and upward shifts—indicated adequate hydration and membrane integrity, consistent with profiles expected in adolescent athletes. Cattem et al. (2021) also associated shorter vectors with better functional condition and greater cell mass in adolescents[35]. Similarly, Campa et al. (2020) emphasized morphological traits, such as mesomorphism, positively associated with PA° and leftward RXc vector displacement, supporting the findings in this swimmer cohort[36].

Recent studies also highlight hormonal and physiological factors—such as the menstrual cycle in women—as influences on BIVA vectors and body composition parameters. Although not directly assessed here, literature recommends considering such variations in serial evaluations, particularly in female athletes[39]. The combined use of BIVA with quantitative BIA has proven effective, as proposed by Piccoli et al. (2002)[26] and updated by Campa et al. (2019)[18], by enabling refined interpretation of physiological changes in young, developing populations.

Body composition variables were closely related to lung function in the swimmers assessed. Strong positive correlations between FFM, SMM, and expiratory volumes (FEV_1 and FVC) reinforce the role of contractile tissue in ventilatory performance, consistent with literature associating muscle mass with respiratory efficiency in athletes[32,35]. Differences in body mass and height are expected due to biological maturation, especially during puberty, when boys tend to develop greater linear growth and muscle mass. These factors are associated with enhanced aquatic performance[34].

Komici et al. (2022), assessing 435 athletes across sports, found that FFM and muscle mass were independently and positively associated with FVC and FEV_1 in both sexes, whereas waist-to-height ratio showed an inverse association with these parameters in males only[40]. These findings reinforce that high lean mass levels are central determinants of ventilatory function in athletes, and that body fat distribution can negatively impact respiratory performance.

Similarly, water volumes (total, intra- and extracellular) were significantly associated with spirometric variables, suggesting hydration status influences ventilatory mechanics under effort. Conversely, resistance (R) and impedance (Z) presented negative correlations with FVC, FEV_1, and PEF, suggesting that lower values reflect greater conductivity, potentially associated with higher cell mass and improved respiratory function. Phase angle (PA) consistently correlated positively with lung parameters, confirming its role as a marker of cell integrity and functional capacity[30]. Finally, the association between %BF and predicted FEV_1/FVC ratio suggests that fat accumulation may negatively impact ventilatory function, a finding reported in several sports and deserving attention in monitoring developing athletes[32,36].

Among study limitations, the small sample size (n=19) restricts generalizability. Moreover, lack of longitudinal monitoring prevents evaluation of fluctuations across training cycles, competitions, or maturational stages. No direct hormonal markers were used to assess maturational status, which could have enriched analysis. However, the study's strength lies in integrating spirometry, BIA, and BIVA—methodologies rarely explored in Brazilian adolescent swimmers. This combination of noninvasive methods provides clinically and athletically relevant data with high applicability in Sports Physiotherapy, contributing to training monitoring and individualized interventions.

V. Conclusion

The present study demonstrated that male athletes exhibited a morphofunctional profile closer to the ideal for swimming, with greater muscle mass, lower body fat percentage, higher phase angle, and superior pulmonary function. Female athletes, although maintaining parameters within the normal range, showed higher body fat percentage and a greater relative proportion of body water. Furthermore, correlation analyses revealed that fat-free mass, skeletal muscle mass, and body water compartments were strongly associated with ventilatory capacity, while phase angle emerged as a relevant marker of cell integrity and respiratory performance. In contrast, resistance and impedance showed negative correlations with spirometric indices, reinforcing their usefulness as indirect indicators of body composition. Taken together, the integration of spirometry and bioimpedance may be useful for physiological monitoring, allowing individualized and targeted training strategies to optimize competitive performance.

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