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ORIGINAL ARTICLE

Physical Fitness Profile of Elite Female Volleyball Players: an Observational Study Correlating Bioimpedance Vector Analysis (BIVA) with Field-Based Testing

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Abstract

Background Body composition and physical performance assessments are crucial for optimizing athletic performance in volleyball. This observational study aimed to provide preliminary comprehensive physical fitness profiles of elite female volleyball players, integrating bioimpedance vector analysis (BIVA) with established field-based fitness tests.

Methods Twenty-four elite female volleyball players (23.4 ± 3.7 years) underwent assessment for body composition parameters using the BIA 101 BIVA Pro (Akern, Italy). Field-based performance evaluations included handgrip strength, 20 m shuttle run test (for cardiorespiratory fitness), T-test (for change of direction speed), and sit-and-reach (for flexibility). BIVA was employed to assess hydration status and cell mass properties. This cross-sectional study adhered to STROBE guidelines.

Results Mean weight and height were 72.6 ± 6.2 kg and 182.7 ± 5.4 cm, respectively. BIVA analysis indicated that players generally clustered within the 75% tolerance ellipse, suggesting body composition characteristics consistent with elite athletic performance. Significant correlations were observed between phase angle (PhA 6.8° ± 0.4°) and handgrip strength (HGS 33.2 ± 4.8 kg) ($r = 0.73$, $P < 0.001$), and between 20 m shuttle run test performance (level 9.8 ± 1.2) and resistance-reactance (R-Xc) graph positioning ($r = –0.64$, $P < 0.001$). Positional differences were identified for several body composition and performance metrics. For instance, outside hitters demonstrated significantly higher estimated aerobic capacity (SRT levels) compared to middle blockers and setters, while middle blockers exhibited greater strength values (e.g., higher PhA than setters and liberos).

Conclusions These initial findings provide preliminary BIVA patterns and physical performance parameters for elite female volleyball players, acknowledging the study's sample size limitations. Phase angle emerges as a promising marker associated with strength capacity. The integrated application of BIVA and field-based assessments offers a practical, initial framework for monitoring training adaptations and informing individualized training approaches in elite volleyball. Further research with larger, more diverse cohorts is warranted to confirm and expand upon these findings.

Keywords Bioimpedance vector analysis · Volleyball · Female athletes · Body composition · Physical performance · Phase angle

Introduction

Elite volleyball performance primarily hinges on the ability to execute repeated, high-intensity actions such as explosive jumps, rapid accelerations, and multidirectional movements. While brief periods of lower-intensity activity and recovery are inherent to the game's rhythm, the capacity to perform and sustain these high-intensity efforts is paramount [37]. Optimizing performance within this demanding physiological landscape necessitates a comprehensive understanding of athletes' physical characteristics. Therefore, detailed

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physiological profiling – encompassing assessments of body composition, neuromuscular strength, aerobic and anaerobic capacities, agility, and flexibility – is essential for guiding training, monitoring adaptations, and maximizing athletic potential in volleyball players [18].

Body composition assessment is a cornerstone in evaluating athletic preparedness and tracking training efficacy [4]. Bioelectrical impedance analysis (BIA) is a practical, non-invasive field tool providing information on body water compartments and cellular characteristics [5, 7]. Its fundamental principle involves measuring the opposition of biological tissues to an electrical current. Specifically, resistance (R) is the opposition to current flow through ion-rich intra- and extracellular fluids, inversely related to total body water. Reactance (Xc) reflects the capacitive properties of cell membranes and tissue interfaces, correlating with body cell mass, membrane integrity, and cellular function [21]. The phase angle (PhA), mathematically derived from the relationship between Xc and R (arctan Xc/R), integrates information on cellular quantity and quality, serving as a global indicator of cell membrane integrity and function [21, 27]. In athletes, higher PhA values often reflect greater muscle mass, enhanced cellular integrity, and superior physiological status [8, 14], positioning PhA as a valuable biomarker of athletic condition and training adaptation [25].

Bioimpedance Vector Analysis (BIVA) represents an advancement over traditional BIA methods that often rely on population-specific prediction equations. BIVA utilizes the raw, directly measured bioelectrical properties – R and Xc, standardized for conductor length (height) as R/h and Xc/h – to qualitatively assess body fluid status and body cell mass without the inherent limitations of regression equations [22, 33].

While BIVA offers crucial insights into body composition and cellular status, it does not directly measure functional capacity. Therefore, integrating BIVA with field-based physical performance tests provides a more holistic assessment profile, particularly relevant to volleyball's specific demands. Handgrip strength (HGS) is a reliable and practical measure of upper body isometric strength, correlating with overall muscle strength and PhA in various populations [27, 35]. Cardiorespiratory fitness, vital for recovery between high-intensity bouts, can be estimated using the 20 m shuttle run test (SRT) [17]. Change of direction speed (CODS), a physical attribute critical for rapid defensive movements and transitions in volleyball, is commonly assessed via the T-test. While often referred to as a test of agility, its primary outcome is a measure of an athlete's ability to rapidly accelerate, decelerate, and change direction [29].

Finally, trunk and hamstring flexibility, considered relevant for injury prevention [15, 20], was assessed using the sit-and-reach test.

Despite the recognized importance of these individual components and the potential utility of integrating BIVA with performance testing, comprehensive reference data specifically for elite female volleyball players remain scarce. Existing literature often focuses on anthropometry, HGS [3, 13], or segmental BIA [11] in various volleyball cohorts. However, a significant gap exists in establishing whole-body BIVA parameters alongside a battery of relevant field performance tests within a well-defined elite female population. Moreover, the distinct physical demands of different playing positions (e.g., libero vs. middle blocker) necessitate position-specific analyses [18], yet such integrated, positional BIVA and performance data are largely unavailable for elite female players.

While BIVA offers crucial insights into body composition and cellular status, it does not directly measure functional capacity. Therefore, integrating BIVA with field-based physical performance tests provides a more holistic assessment profile, particularly relevant to volleyball's specific demands. Therefore, the primary aims of this observational study were threefold: (1) to establish preliminary descriptive BIVA parameters (R/h, Xc/h, PhA) and field-based physical performance profiles (HGS, SRT, T-test, flexibility) for elite female volleyball players; (2) to investigate the correlational relationships between BIVA parameters and these key performance indicators; and (3) to identify potential differences in BIVA characteristics and physical performance across distinct playing positions, while acknowledging the limitations of sample size for robust subgroup comparisons. This investigation seeks to provide initial reference data and insights for coaches, sports scientists, and clinicians working with elite female volleyball players, ultimately aiding in the optimization of training and performance monitoring strategies, by exploring the relationships between raw bioelectrical parameters and functional outcomes under standardized, field-based conditions.

Methods

Study Design and Participants

This cross-sectional observational study was conducted in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. Twenty-four elite female volleyball players (age: 23.4 ± 3.7 years; competitive experience: 11.3 ± 2.6 years) from a single professional team competing in the national first division were recruited for participation. Participants were categorized by playing position: outside hitters (n = 7), middle blockers (n = 6), opposite hitters (n = 3), setters (n = 4), and liberos (n = 4). All participants had a minimum of five years of competitive volleyball experience, were free from injury or illness during the testing period, and were in the mid-competition phase of their season. The study was carried out in accordance with the ethical requirements established by the Catholic University's research governance policies and adhered to the principles of the Declaration of Helsinki. All participants were informed about the nature, purpose, and procedures of the study and voluntarily provided written informed consent before participation. They were also informed of their right to withdraw from the study at any time without consequences. Personal data were collected and processed in compliance with the General Data Protection Regulation.

Anthropometric Measurements

Height was measured to the nearest 0.1 cm using a Seca stadiometer (Seca, Hamburg, Germany) with participants standing barefoot. Body mass was assessed to the nearest 0.1 kg using a calibrated electronic scale (Seca, Hamburg, Germany) with participants wearing minimal clothing. All anthropometric measurements were conducted by the same experienced researcher following standardized procedures [19].

Bioelectrical Impedance Analysis (BIA)

Bioelectrical impedance measurements were performed using the BIA 101 BIVA Pro (Akern, Florence, Italy), which operates at a single frequency of 50 kHz and provides resistance (R), reactance (Xc), and phase angle (PhA) values. Measurements were conducted in accordance with established guidelines [22] to ensure data reliability and to minimize the influence of confounding variables, particularly hydration status. To this end, participants abstained from food and drink for at least 4 h before testing, avoided strenuous exercise for 12 h prior, and emptied their bladders immediately before assessment. These standardized procedures are designed to bring athletes to a comparable state of euhydration.

Participants were positioned supine on a non-conductive examination table with limbs abducted at a 30–45° angle. After cleansing the skin with alcohol, four disposable electrodes (Biatrodes Akern Srl, Florence, Italy) were placed: two on the dorsal surface of the right hand (one on the distal metacarpus and one between the distal prominences of the radius and ulna) and two on the dorsal surface of the right foot (one on the distal metatarsus and one between the medial and lateral malleoli) (National Institutes of Health [NIH], 1994).

The BIVA approach was applied by plotting the standardized resistance (R/h) and reactance (Xc/h) values on the R-Xc graph, using the 50%, 75%, and 95% tolerance ellipses from the reference healthy female population described by Piccoli et al. [34]. It is critical for the reader to note that this reference, while a historical standard, is based on a mixed-age sample (15–85 years). More recent, large-scale research has provided updated, adult-specific reference ellipses [9] which demonstrate a significant leftward shift on the R-Xc graph. Consequently, the qualitative interpretation of the absolute position of this study's vectors against the 1995 ellipses must be made with considerable caution. The 1995 reference is presented here as it was the established standard at the time of the original data analysis. Importantly, the core findings of this study—namely the correlational analyses between BIVA parameters and physical performance, and the comparisons between playing positions—are internal to the cohort and thus remain valid irrespective of the reference population used for qualitative plotting.

Field-Based Physical Fitness Assessments

All physical fitness assessments were conducted in a controlled indoor environment within a one-week period. Participants completed a standardized 15-minute warm-up including jogging, dynamic stretching, and sport-specific movements before testing.

Handgrip Strength (HGS)

Handgrip strength (HGS) was assessed using a Jamar Plus + digital dynamometer (Patterson Medical, Warrenville, IL, USA), following standardized procedures recommended in the literature to ensure consistency and comparability [28, 39, 40]. Participants were seated upright in a standard chair with their feet flat on the floor, shoulders adducted and in a neutral position, elbow flexed at 90 degrees, and the forearm and wrist maintained in a neutral position, adhering to common testing protocols [39, 40]. The dynamometer handle was adjusted to ensure a comfortable and secure grip for each participant, accommodating variations in hand size [39]. Following one non-recorded familiarization trial per hand, participants performed three maximal isometric contractions for approximately 3–5 s with each hand [39, 40]. Trials were alternated between the left and right hands, with a 60-second rest period enforced between consecutive trials on the same hand to minimize fatigue, as recommended for reliable measurements [39, 40]. Standardized verbal encouragement (e.g., "Squeeze as hard as you can!") was provided during each maximal effort trial, as this can influence maximal output [28, 40]. The peak force (highest value) achieved across the three trials for each hand was recorded in kilograms (kg), reflecting the maximal strength capacity [39]. For data analysis, the mean of the peak values obtained from the left and right hands was utilized.

20 m Shuttle Run Test (SRT)

Cardiorespiratory fitness was assessed using the 20 m multistage shuttle run test, following the 1-minute stage protocol established by Léger et al. [17]. Participants were required to run back and forth between two lines set 20 m apart, aiming to touch the line coincident with auditory signals emitted from a calibrated audio device. The test commenced at a speed of 8.5 km/h and the required running speed increased by 0.5 km/h every minute, corresponding to the completion of each stage [17]. Participants received a warning if they failed to reach the line in time with the signal; the test was terminated when a participant failed to reach the line concurrently with the audio signal for two consecutive shuttles despite maximal effort, or when they withdrew voluntarily due to exhaustion [16, 17]. Performance was recorded as the final stage number and number of shuttles completed within that stage. This performance score was used to determine the maximal speed achieved, which was subsequently used to estimate maximal oxygen uptake (VO_{2max}) in mL/kg/min using the corrected regression equation for adults proposed by Léger et al. [17].

T-Test

Change of direction speed (CODS) was evaluated using the T-test protocol described by Pauole et al. [29]. Four cones were arranged in a T-shape, with cone A and B placed 9.14 m apart, and cones C and D placed 4.57 m to the left and right of cone B, respectively. Starting at cone A, participants sprinted forward to cone B, side-shuffled left to cone C, side-shuffled right to cone D, side-shuffled left back to cone B, and backpedalled to cone A. Electronic timing gates (Microgate, Bolzano, Italy) were used to record completion time. After two familiarization trials, participants completed three test trials with a 3-minute recovery period between attempts. The best time was recorded in seconds.

Flexibility Assessment

Following the warm-up procedures, hamstring and lower back extensibility was assessed using the classic sit-and-reach test protocol, a widely adopted field measure primarily reflecting hamstring extensibility rather than lumbar flexibility [24, 31]. Participants sat on the floor with legs fully extended, knees kept straight throughout the test, and the soles of their feet placed flat against a standardized sit-and-reach box. With hands stacked one on top of the other, palms facing down, and arms fully extended forward, participants slowly and smoothly reached forward along the measuring scale as far as possible, exhaling during the forward flexion [31]. Participants were instructed to hold the position of maximal reach momentarily without bouncing, while the assessor ensured the knees remained in full extension. Following two practice attempts for familiarization, three formal trials were performed. The maximum distance reached by the fingertips, representing the best score of the three trials, was recorded to the nearest centimetre [24].

Data Analysis

All statistical analyses were performed using IBM SPSS Statistics (Version 28.0; IBM Corp., Armonk, NY, USA). Descriptive statistics for all variables are presented as mean ± standard deviation (SD).

The normality of data distribution for all variables was assessed using the Shapiro-Wilk test. For the primary outcome variables (anthropometric characteristics, BIVA parameters, and physical performance measures), the assumption of normality was met (all $P > 0.05$), allowing for the use of parametric tests for group comparisons and correlations.

To examine the relationships between BIVA parameters (R/h, Xc/h, PhA) and physical performance measures (handgrip strength, estimated VO_{2max}, T-test time, Sit-and-Reach score), Pearson's product-moment correlation coefficients (r) were calculated. The strength of correlations was interpreted as follows: negligible (0.00–0.09), weak (0.10–0.39), moderate (0.40–0.69), strong (0.70–0.89), and very strong (0.90–1.00).

To compare anthropometric characteristics, BIVA parameters, and physical performance measures across the five distinct playing positions (outside hitters $n = 7$, middle blockers $n = 6$, opposite hitters $n = 3$, setters $n = 4$, and liberos $n = 4$), an appropriate approach for group comparisons was employed, considering the unequal group sizes. First, the assumption of homogeneity of variances was assessed for each variable using Levene's test ($P < 0.05$ was considered a violation of homogeneity).

If Levene's test indicated homogeneity of variances ($P > 0.05$), a one-way Analysis of Variance (ANOVA) was conducted. For significant ANOVA results, post-hoc pairwise comparisons were performed using the Tukey-Kramer test, which is specifically recommended for situations with unequal group sizes while maintaining acceptable Type I error rates.

If Levene's test indicated non-homogeneity of variances ($P < 0.05$), Welch's ANOVA was utilized, as it is robust to violations of the homogeneity of variances assumption. For significant Welch's ANOVA results, post-hoc pairwise

Table 1 Descriptive characteristics of participants by playing position

Position (*n*)	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m²)	Experience (years)
Outside Hitters (7)	22.7 ± 3.1	183.6 ± 3.9[a]	73.1 ± 5.4[a]	21.7 ± 1.3	11.3 ± 2.7
Middle Blockers (6)	24.3 ± 4.2	188.5 ± 4.1[b, c, d]	78.4 ± 5.8[e, f]	22.0 ± 1.2	10.8 ± 3.1
Opposite Hitters (3)	25.2 ± 3.8	185.1 ± 3.3[a]	75.3 ± 4.9[a]	22.0 ± 1.0	12.3 ± 2.1
Setters (4)	23.0 ± 4.0	179.4 ± 2.7	69.8 ± 3.2	21.6 ± 0.8	11.5 ± 2.8
Liberos (4)	22.4 ± 3.5	173.2 ± 2.5	65.1 ± 3.5	21.7 ± 0.9	10.8 ± 2.4
Total (24)	**23.4 ± 3.7**	**182.7 ± 5.4**	**72.6 ± 6.2**	**21.8 ± 1.0**	**11.3 ± 2.6**

Notes: Values are mean ± SD

[a] Significantly taller/heavier than Liberos ($P<0.05$)

[b] Significantly taller than Liberos ($P<0.001$)

[c] Significantly taller than Setters ($P=0.003$)

[d] Significantly taller than Outside Hitters ($P=0.035$)

[e] Significantly heavier than Liberos ($P=0.002$)

[f] Significantly heavier than Setters ($P=0.041$)

Table 2 Bioimpedance vector analysis parameters by playing position

Position (*n*)	*R*/h (Ω/m)	Xc/h (Ω/m)	Phase Angle (°)	*R*-Xc Graph Position
Outside Hitters (7)	271.4 ± 18.3	27.8 ± 2.1	6.9 ± 0.3	Mid-left quadrant
Middle Blockers (6)	258.1 ± 15.7	27.4 ± 2.3	7.1 ± 0.3[a, b]	Lower-left quadrant
Opposite Hitters (3)	261.3 ± 14.2	27.5 ± 1.8	7.0 ± 0.2	Lower-left quadrant
Setters (4)	282.6 ± 16.5	28.1 ± 2.0	6.7 ± 0.3	Upper-right quadrant
Liberos (4)	288.7 ± 17.4	27.6 ± 1.9	6.5 ± 0.3	Upper-right quadrant
Total (24)	**272.4 ± 19.3**	**27.7 ± 2.0**	**6.8 ± 0.4**	Within 75% tolerance ellipse

Notes: Values are mean ± SD. R/h = resistance standardized for height; Xc/h = reactance standardized for height

[a] Significantly higher PhA than Setters ($P=0.039$)

[b] Significantly higher PhA than Liberos ($P=0.012$)

comparisons were performed using the Games-Howell test, which is suitable for unequal group sizes and unequal variances.

For all statistically significant pairwise comparisons derived from the post-hoc analyses, Cohen's *d* effect sizes were calculated to quantify the magnitude of the differences. Effect sizes were interpreted as: small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$), and large ($d \geq 0.8$).

Statistical significance for all analyses, including normality and homogeneity tests, was set at an alpha level of $P<0.05$.

Bioelectrical impedance vector analysis (BIVA) tolerance ellipses (50%, 75%, 95%) based on a reference healthy female population [34] were utilized for the graphical representation and qualitative interpretation of individual R/h and Xc/h vector distributions, generated using dedicated BIVA software [32].

Results

The findings of this study are presented across four main sub-sections: participant characteristics and anthropometry, bioimpedance vector analysis (BIVA) parameters, physical performance measures, and correlations between BIVA parameters and physical performance. Detailed descriptive statistics for all variables, segmented by playing position, are provided in Tables 1 and 2, and 3.

Participant Characteristics and Anthropometry

The twenty-four elite female volleyball players had a mean (± SD) age of 23.4 ± 3.7 years, height of 182.7 ± 5.4 cm, body mass of 72.6 ± 6.2 kg, and BMI of 21.8 ± 1.0 kg/m². Their average competitive experience at a high level was 11.3 ± 2.6 years (Table 1).

One-way ANOVA (or Welch's ANOVA, as appropriate) revealed statistically significant differences across playing positions for height ($F(4, 19)=8.74$, $P<0.001$) and body mass ($F(4, 19)=6.23$, $P=0.002$). Levene's test indicated homogeneity of variances for height ($P=0.187$) but not for body mass ($P=0.015$), hence a Welch's ANOVA was used for body mass.

Post-hoc analyses (Tukey-Kramer for height, Games-Howell for body mass) indicated:

Middle blockers were significantly taller than liberos ($P<0.001$, Cohen's $d=2.14$), setters ($P=0.003$, $d=1.67$), and outside hitters ($P=0.035$, $d=1.05$). They were also significantly heavier than liberos ($P=0.002$, $d=1.95$) and setters ($P=0.041$, $d=1.15$).

Table 3 Physical performance measures by playing position

Position (*n*)	Handgrip Strength (kg)	Relative HGS (kg/kg)	20 m Shuttle Run (level)	Estimated VO_{2max} (mL/kg/min)	*T*-Test (s)	Sit-and-Reach (cm)
Outside Hitters (7)	33.6 ± 3.5	0.46 ± 0.06	10.7 ± 0.9[b, c]	49.3 ± 2.1	9.54 ± 0.31[d]	33.2 ± 4.8
Middle Blockers (6)	35.7 ± 4.2[a]	0.46 ± 0.04	9.1 ± 1.1	44.8 ± 2.3	10.42 ± 0.36[d]	30.5 ± 5.3
Opposite Hitters (3)	36.8 ± 3.9[a]	0.49 ± 0.05	9.5 ± 0.8	45.9 ± 1.9	10.21 ± 0.29[d]	32.8 ± 4.2
Setters (4)	31.4 ± 3.1	0.45 ± 0.04	9.4 ± 0.7	45.6 ± 1.7	9.82 ± 0.27[d]	34.1 ± 5.6
Liberos (4)	29.1 ± 3.5	0.45 ± 0.04	10.3 ± 1.0	48.1 ± 2.2	9.18 ± 0.24	33.8 ± 4.9
Total (24)	**33.2 ± 4.8**	**0.45 ± 0.05**	**9.8 ± 1.2**	**46.7 ± 2.6**	**9.83 ± 0.53**	**32.7 ± 5.1**

Notes: Values are mean ± SD, Relative HGS refers to the Handgrip Strength (kg) divided by body weight (kg)

[a] Significantly higher HGS than Liberos ($P<0.05$)

[b] Significantly higher SRT level than Middle Blockers ($P=0.008$)

[c] Significantly higher SRT level than Setters ($P=0.031$)

[d] Significantly slower T-Test time (higher value) than Liberos ($P<0.001$)

Opposite hitters were significantly taller than liberos ($P=0.001$, $d=1.88$) and heavier than liberos ($P=0.015$, $d=1.57$).

As expected, liberos represented the shortest and lightest playing position group. No significant differences were observed for age, BMI, or competitive experience across positions ($P>0.05$).

Bioelectrical Impedance Vector Analysis

The mean bioelectrical parameters for the entire cohort were R/h = 272.4 ± 19.3 Ω/m, Xc/h = 27.7 ± 2.0 Ω/m, and PhA = 6.8° ± 0.4° (Table 2). Qualitative assessment using the Piccoli et al. [34] tolerance ellipses showed that 87.5% of the players' individual impedance vectors were located within the 75% tolerance ellipse. However, as noted in the methods, this finding should be interpreted cautiously due to the outdated nature of this reference population. When considered against more recent, adult-specific references, the vectors of this athletic cohort would likely plot more centrally or to the right of the reference ellipse, a pattern typically associated with higher lean mass and lower relative fluid content compared to the general population. The primary value of the BIVA parameters in this study therefore lies in the correlational and comparative analyses rather than their absolute position on the graph.

Levene's test indicated non-homogeneity of variances for PhA across positions ($P=0.038$), therefore Welch's ANOVA was used, confirming a statistically significant difference in PhA among playing positions ($F(4, 19)=3.85$, $P=0.021$).

Post-hoc Games-Howell comparisons revealed that middle blockers exhibited significantly higher PhA values compared to setters ($P=0.039$, Cohen's $d=1.05$) and liberos ($P=0.012$, $d=1.52$). No other significant positional differences were found for R/h or Xc/h.

Physical Performance Measures

Results of the field-based physical fitness assessments are presented in Table 3. The mean performance results for the group were: handgrip strength (HGS) = 33.2 ± 4.8 kg; 20 m shuttle run test (SRT) performance = level 9.8 ± 1.2 (estimated $VO_{2max}=46.7 \pm 2.6$ mL/kg/min); T-test change of direction speed time = 9.83 ± 0.53 s; and Sit-and-Reach flexibility = 32.7 ± 5.1 cm.

Significant differences between playing positions were found for HGS, SRT level, and T-test time, but not for flexibility.

Handgrip Strength (HGS): Levene's test indicated homogeneity of variances ($P=0.065$), and ANOVA showed significant differences ($F(4, 19)=4.51$, $P=0.011$). Post-hoc Tukey-Kramer tests indicated that opposite hitters (36.8 ± 3.9 kg) and middle blockers (35.7 ± 4.2 kg) had significantly higher HGS compared to liberos (29.1 ± 3.5 kg) ($P=0.031$, $d=1.50$ for opposite hitters vs. liberos; $P=0.048$, $d=1.25$ for middle blockers vs. liberos). No other significant HGS differences were observed. However, when HGS was normalized for body mass, these differences were substantially attenuated, with relative strength values being more comparable across all positions (Table 3), suggesting that the differences in absolute strength were largely attributable to the differences in body mass.

20 m Shuttle Run Test (SRT) Level: Levene's test indicated homogeneity of variances ($P=0.122$), and ANOVA showed significant differences ($F(4, 19)=5.23$, $P=0.006$). Post-hoc Tukey-Kramer tests revealed that outside hitters (10.7 ± 0.9 level) demonstrated significantly higher SRT levels compared to middle blockers (9.1 ± 1.1 level) ($P=0.008$, $d=1.57$) and setters (9.4 ± 0.7 level) ($P=0.031$, $d=1.45$).

T-Test Time: Levene's test indicated homogeneity of variances ($P=0.088$), and ANOVA showed highly significant differences ($F(4, 19)=9.15$, $P<0.001$). Post-hoc Tukey-Kramer tests confirmed that liberos (9.18 ± 0.24 s)

Table 4 Pearson correlation coefficients between BIVA parameters and physical performance measures

BIVA Parameter	Handgrip Strength	Estimated VO_2max	T-Test	Sit-and-Reach
R/h (Ω/m)	–0.61**	–0.64**	0.40*	–0.32
Xc/h (Ω/m)	0.37	0.18	–0.12	0.25
Phase Angle (°)	0.73**	0.58**	–0.45*	0.38

Notes: R/h = resistance standardized for height; Xc/h = reactance standardized for height

$^{*}P<0.05$. $^{**}P<0.01$

recorded significantly faster T-test times (indicating superior change of direction speed)) than all other positions: outside hitters ($P<0.001$, $d=1.34$), middle blockers ($P<0.001$, $d=1.88$), opposite hitters ($P<0.001$, $d=1.82$), and setters ($P=0.001$, $d=1.46$).

Sit-and-Reach Flexibility: No significant differences were found across playing positions ($F(4, 19)=1.87$, $P=0.156$).

Correlations between BIVA Parameters and Physical Performance

Statistically significant correlations were identified between BIVA parameters and key physical performance measures (Table 4).

PhA exhibited a strong positive correlation with HGS ($r=0.73$, $P<0.001$) and a moderate positive correlation with estimated VO_2max ($r=0.58$, $P=0.003$).

R/h showed moderate negative correlations with HGS ($r = –0.61$, $P=0.001$) and estimated VO_{2max} ($r = –0.64$, $P<0.001$).

Weaker but significant correlations were observed between R/h and T-test time ($r=0.40$, $P=0.048$), and between PhA and T-test time ($r=–0.45$, $P=0.026$).

No significant correlations were found between any BIVA parameters (R/h, Xc/h, PhA) and the Sit-and-Reach flexibility measure (all $P>0.05$).

Xc/h did not correlate significantly with any of the assessed physical performance measures (all $P>0.05$).

Discussion

This study provides a comprehensive assessment of elite female volleyball players, integrating BIVA with standard field-based physical performance tests. The primary findings establish preliminary reference points for BIVA parameters and key performance metrics within this specific athletic population, reveal significant correlations between bioelectrical characteristics and functional capacity, particularly between phase angle (PhA) and handgrip strength (HGS), and delineate distinct physiological profiles based on playing position. These results contribute valuable initial data for optimizing training and monitoring strategies in elite volleyball.

BIVA Patterns in Elite Female Volleyball Players

The BIVA results indicate that the cohort possessed hydration levels and body cell mass generally appropriate for elite athletes. While these qualitative assessments rely on standardized pre-testing conditions rather than direct hydration markers, the clustering of vectors within the 75% tolerance ellipse of a reference population [6, 25] suggests this interpretation. The mean PhA of 6.8° is notably higher than values typically reported for sedentary females [2], reinforcing the utility of PhA as an indicator of athletic status [14]. Comparing this value to recently established athlete-specific percentiles [8], a mean PhA of 6.8° places this cohort near the 50th percentile for female team sport athletes, suggesting typical, healthy cellular characteristics for this group.

The observed positional differences in PhA, although based on very small subgroups and thus exploratory in nature, with middle blockers demonstrating significantly higher values than liberos and setters (moderate to large effect sizes: $d=1.05$ and $d=1.52$, respectively), likely reflect the varying physiological demands. Middle blockers, requiring substantial strength and power for explosive actions like blocking and attacking, would be expected to possess greater muscle mass and potentially higher cellular density/integrity, manifesting as a higher PhA [11, 21]. Conversely, the lower PhA in liberos and setters might signify adaptations favoring characteristics like agility and rapid reactivity over maximal muscle mass [18], aligning with their respective defensive and playmaking roles. This preliminary positional differentiation mirrors findings in male athletes where BIVA parameters vary according to role-specific demands [5, 23], warranting further investigation in larger cohorts.

Physical Performance Profiles and Positional Specialization

The physical performance data confirmed the high athletic standard of the participants and underscored the physiological specialization inherent in elite volleyball. The mean HGS (33.2 kg, Table 3) is consistent with data from other elite female volleyball players in Latin America [3] but notably higher than reported values for Indian inter-university [13] and some Italian professional cohorts [11], potentially reflecting differences in training levels, genetics, or assessment protocols.

The positional differences in performance were pronounced, with significant effects supported by moderate to large Cohen's *d* values. Outside hitters exhibited superior aerobic capacity, achieving significantly higher 20 m shuttle run test levels compared to middle blockers ($d=1.57$) and setters ($d=1.45$), aligning with time-motion analyses that indicate greater court coverage and repeated high-intensity efforts for this position [37]. While the absolute strength capacity was higher in opposite hitters and middle blockers (with moderate to large effect sizes when compared to liberos), the analysis of relative strength suggests this is largely a reflection of their greater body mass. This finding implies that, when scaled to body size, the functional strength capacity is more uniform across positions, even though absolute power remains critical for the offensive and net-play roles. Liberos displayed exceptional change of direction speed, recording significantly faster T-test times than all other positions (large effect sizes, d ranging from 1.34 to 1.88), which directly reflects the need for rapid multi-directional movement and quick reaction times inherent to their specialized defensive function [18]. The absence of significant positional differences in flexibility suggests this attribute might be less critical for positional differentiation compared to strength, power, or aerobic capacity in elite volleyball. This could reflect a more uniform level of development across the team, or perhaps indicate that a sufficient baseline functional range of motion, important for injury prevention and general movement, is achieved by all players regardless of their specialized role. These findings collectively emphasize the importance of tailoring conditioning programs to the specific physiological demands of each playing position.

Relationship between Bioelectrical Parameters and Performance

Among the observed associations, the correlation between PhA and handgrip strength (HGS) emerges as particularly relevant ($r=0.73$, $P<0.001$). While this represents a moderate-to-strong relationship, the interpretation must be approached with caution due to the limited sample size and the cross-sectional nature of the data. Nonetheless, these findings align with previous studies linking PhA to muscle strength across diverse populations, including athletes and clinical cohorts [27, 11, 10]. PhA integrates resistance and reactance—two raw bioelectrical parameters—which reflect intracellular hydration and membrane capacitance, respectively [21]. As such, PhA is increasingly recognized as a marker of muscle quality, membrane integrity, and functional status [36].

Moderate correlations were also observed between PhA and estimated VO_{2max} ($r=0.58$, $P=0.003$), and between R/h and both aerobic capacity and HGS ($r = -0.64$ and -0.61, respectively), consistent with prior work suggesting that lower resistance values are indicative of greater lean mass and improved physiological efficiency [21, 27]. These associations imply that BIVA-derived metrics may provide useful, albeit indirect, insight into aerobic capacity. Weaker, yet statistically significant, correlations were found between PhA and change of direction speed ($r = -0.45$, $P=0.026$), whereas no associations were observed with flexibility, indicating that bioelectrical markers alone cannot comprehensively reflect all components of volleyball-specific performance. Interestingly, the weak-to-moderate negative correlation between PhA and T-test time ($r = -0.45$) suggests a link between cellular integrity and change of direction speed, a finding that warrants further exploration.

Practical Applications

The integration of BIVA and field testing offers significant practical value for athlete monitoring and program individualization. BIVA, particularly PhA, provides a rapid, non-invasive means to track changes in cellular status that correlate with strength and, to some extent, aerobic fitness. Monitoring PhA longitudinally could potentially offer insights into training adaptation, recovery status, and readiness, complementing traditional performance metrics [1]. For instance, deviations from individual baseline PhA values or established normative ranges [8] might signal inadequate recovery, excessive fatigue, or changes in muscle status, prompting adjustments to training load or nutritional strategies [12, 38]. The established positional profiles provide benchmarks for evaluating athletes and can inform the design of position-specific conditioning programs aimed at enhancing relevant physical capacities (e.g., change of direction speed for liberos, aerobic endurance for outside hitters, strength/power for blockers/opposite hitters). This comprehensive approach moves beyond simple body mass or BMI tracking, offering a more nuanced understanding of an athlete's physiological state [7].

Strengths, Limitations, and Future Directions

This study's strengths include its focus on an elite female athletic population, the combined assessment of BIVA and relevant performance tests, standardized measurement protocols, and the analysis of positional differences supported by robust statistical methods. However, limitations must be acknowledged. The cross-sectional design prevents establishing causality. Furthermore, data were collected during the mid-competition phase; consequently, the observed profiles and relationships reflect this specific time point and might differ during other phases of the annual training cycle (e.g., pre-season, off-season) due to variations in training load, fatigue, and physiological adaptation.

The sample size, while sufficient for initial profiling and correlation analysis, is limited for robust positional subgroup comparisons and originates from a single team, potentially impacting generalizability. While robust statistical methods (e.g., Welch's ANOVA, Tukey-Kramer, Games-Howell) were employed to account for unequal group sizes and heterogeneity of variances, it is acknowledged that tests for normality in very small subgroups (e.g., $n=3$, $n=4$) may have limited power to detect subtle deviations from a normal distribution. Therefore, the interpretation of positional differences, while supported by effect sizes, should be done with appropriate caution regarding the precise p-values for these smaller subgroups. Furthermore, the study cohort was drawn from a single professional team within one national league. While this ensures a homogenous elite level, team-specific training philosophies or prevalent playing styles might influence the observed profiles, potentially limiting direct extrapolation to all elite female volleyball populations globally. A primary limitation of this study lies in the lack of a direct biological marker for hydration status, such as urine specific gravity. Despite the implementation of rigorous standardisation protocols to achieve a comparable level of euhydration among participants, minor individual differences in hydration may have influenced BIA readings. This limitation restricts the possibility of definitively confirming the cohort's absolute hydration status. However, this limitation must be considered in light of the study's primary aims—namely, to establish a preliminary normative profile and to explore the correlational, rather than predictive, validity of BIVA parameters in relation to functional performance among elite athletes. The methodological approach aligns with current practices in the field, where BIVA serves as a practical, field-based assessment tool. For example, research by Petri et al. [30] on bodybuilders and by Campa et al. [7] on former athletes demonstrates the effective application of BIVA in yielding insights into body composition, even in the absence of direct hydration markers. Notably, the study by Campa et al. [7] highlighted a strong correlation between changes in BIVA vectors and fat mass variations confirmed by Dual-energy X-ray absorptiometry (DEXA). This evidence reinforces the interpretation of BIVA parameters—particularly phase angle—as indicators of cellular attributes such as mass and integrity, rather than mere fluid balance. This perspective substantiates the observed association between phase angle and handgrip strength. Although the absence of a hydration biomarker constitutes a recognised limitation, it does not undermine the principal conclusions regarding the relationship between bioelectrical properties and physical performance. Future investigations should incorporate direct measures of hydration to enhance the robustness of these findings and enable more refined interpretations of BIVA vector shifts.

Related to this qualitative interpretation, the BIVA vectors were plotted against the 50%, 75%, and 95% tolerance ellipses derived from the reference healthy female population described by Piccoli et al. [34]. While this was the established reference for many years, it was based on a mixed-age sample (15–85 years). Recent large-scale research [9] has provided updated, specific tolerance ellipses for adults (18–65 years), showing a significant leftward shift compared to the 1995 data. Consequently, the positioning of this cohort's vectors, reported here relative to the 1995 ellipses (e.g., clustering within the 75% ellipse), should be interpreted with caution. Relative to the newer 2023 adult reference ellipses, these vectors would likely plot slightly more towards the right side of the R-Xc graph. This primarily impacts the absolute qualitative comparison against the reference population but does not invalidate the internal findings of this study, such as the strong correlation observed between PhA and HGS, the relationships with estimated VO_{2max}, or the significant differences identified between playing positions within this specific cohort. Additionally, the 20 m shuttle run test, while widely used, has limitations for volleyball players due to its primary focus on cardiorespiratory capacity rather than explosive power or anaerobic endurance. Future research could explore the use of more sport-specific intermittent tests like the Yo-Yo Intermittent Recovery Test.

Future research should prioritize longitudinal studies to track BIVA parameters, performance, and potentially training load variables across different phases of the volleyball season (e.g., preparatory, competitive, transition) [12, 38]. This would clarify the sensitivity of PhA and BIVA vector displacement to training adaptation, fatigue, and recovery. Investigating larger, multi-center cohorts representing diverse competitive levels would strengthen normative data and improve generalizability. Further exploring the relationship between BIVA parameters and direct measures of volleyball-specific power (e.g., jump height, spike velocity) and anaerobic capacity would also be valuable. Finally, comparing BIVA with criterion body composition methods in this population could further elucidate the relationship between bioelectrical properties and underlying tissue composition. Future studies evaluating BIVA qualitatively should utilize these updated adult reference ellipses for more accurate classification.

Conclusions

This observational study provides preliminary reference data on BIVA parameters and field-based physical performance in elite female volleyball players. Moderate-to-strong associations were observed between PhA and handgrip strength, as well as between bioelectrical resistance and aerobic capacity. However, when handgrip strength was normalized for body mass, inter-positional differences were substantially reduced—highlighting the importance of relative, rather than absolute, strength metrics for a more accurate evaluation of athletic function.

The findings suggest that PhA may serve as a non-invasive marker of strength-related cellular characteristics, with potential utility for monitoring training status. Nonetheless, these interpretations should be viewed as exploratory, given the limited sample size, cross-sectional design, and reliance on a single team cohort. While positional differences in BIVA and performance profiles were identified, further validation in larger, multi-club samples is essential before generalizing these trends.

Overall, the integrated application of BIVA and field-based testing represents a practical, low-burden strategy for initial athlete profiling. Future longitudinal research is needed to assess the sensitivity of BIVA parameters—particularly PhA—to training adaptations, recovery, and seasonal variability in elite volleyball populations.

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Data Availability The data that support the findings of this study are not publicly available.

Declarations

Ethics Approval and Consent to Participate This is an observational study. The University Territorial Ethics Committee has confirmed that no ethical approval is required.

Competing Interests The author has no relevant financial or non-financial interests to disclose.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

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