Accepted Article

J Musculoskelet Neuronal Interact 2026

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Associations of Lower-Extremity Alignment and Neuromuscular Control with Vertical Jump Height in Female Volleyball Athletes: A Cross-Sectional Study

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Abstract

Objectives: To examine associations between vertical jump height, clinical lower-extremity alignment, and field-based neuromuscular control in female volleyball athletes. **Methods**: Twenty-four female athletes participated in this analytical cross-sectional study. Jump height was measured using an optical timing system. Alignment was evaluated via quadriceps angle, femoral anteversion, Foot Posture Index, and navicular drop. Field-based functional control was assessed using the Y-Balance Test and timed single-leg squat test. Data were analyzed using false discovery rate-corrected correlations and exploratory robust multiple linear regression; the decision-tree model was retained as a descriptive visual analysis. **Results**: Jump height showed strong positive associations with single-leg squat ($r = .88$, $p < .001$) and Y-Balance scores ($r = .51$, $p = .011$), and inverse associations with quadriceps angle, Foot Posture Index, navicular drop, and femoral anteversion (all false discovery rate-adjusted $p <= .011$). In the exploratory robust multivariable model (R2 = .885), single-leg squat ($p = .019$) and Y-Balance score ($p = .042$) remained positively associated with jump height, whereas quadriceps angle did not reach statistical significance ($p = .101$). Decision-tree analysis was interpreted only as an exploratory visualization. **Conclusions**: Vertical jump height showed the clearest associations with unilateral functional performance, dynamic balance, and selected alignment characteristics. Low-cost clinical assessments may complement preseason athlete profiling and performance monitoring, although the findings should be interpreted as cross-sectional associations from a small Second League cohort.

Keywords: Lower-extremity Alignment, Quadriceps Angle, Single-leg Squat, Vertical Jump, Y-Balance Test

Introduction

Volleyball is a sport in which repeated explosive jumping underlies several decisive technical actions, particularly spiking and blocking, and jump capacity has long been regarded as a key performance characteristic across playing levels[1,2]. In female volleyball players, jump height appears especially relevant because differences in vertical reach can more directly influence offensive effectiveness and net-related actions[1]. Training studies and meta-analytic evidence further suggest that vertical jump performance is both trainable and performance-sensitive in volleyball populations, making it an important target for both athlete development and monitoring[3,4].

Although vertical jump height is often discussed in relation to strength and power, the literature suggests that jump performance in volleyball cannot be explained by a single physical domain. In female volleyball players, spike jump height has been linked to take-off mechanics and movement-specific factors rather than to isolated gross descriptors alone[5]. Likewise, studies examining anthropometric and body-composition correlates have

The authors have no conflict of interest.

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Edited by: G. Lyritis
Accepted 9 June 2026

reported that body fat may show negative associations with jump performance, whereas lower-limb dimensions and static structural characteristics often provide only partial explanatory value, particularly in relatively homogeneous athletic samples[6–8]. More recently, Daugherty et al.[9] reported that lower Q-angle and lower relative body fat were associated with better vertical jump performance, supporting the view that alignment-related features may be relevant when jump ability is studied in conjunction with performance variables. Taken together, these findings support a multifactorial interpretation in which jump performance reflects the interaction of body composition, segmental alignment, and force-production capacity rather than a purely anthropometric profile[6,9].

Excessive foot pronation has been proposed to alter tibial rotation and patellofemoral mechanics through distal-to-proximal kinetic-chain coupling, although contemporary evidence suggests that the strength of this association may vary across populations and measurement models[10–12], and induced hyperpronation has been shown to affect proximal lower-limb and pelvic alignment in standing[13]. Consistent with this kinetic-chain perspective, foot morphology and pronation-related measures have been linked with jump-related performance outcomes in some athletic and general active populations, although the magnitude and direction of these associations have not been entirely consistent across studies[14–16]. At the same time, dynamic balance and functional movement-control tests may capture neuromuscular qualities that are not reflected by static anthropometrics. The Y-Balance Test has demonstrated good reliability and broad applicability in physically active populations[17,18], and neuromuscular training that improves dynamic balance performance has been shown to enhance lower-extremity control in young female athletes[19]. Similarly, the single-leg squat has been described as a clinically useful task for identifying frontal-plane knee control and movement-quality deficits relevant to athletic function[20–22].

However, despite this growing body of work, relatively few studies have examined vertical jump height in competitive female volleyball players by jointly considering clinically accessible lower-extremity alignment measures and field-based neuromuscular control tests within the same analytical framework. Existing studies have often emphasized anthropometry, isolated performance variables, or instrumented biomechanical outputs, whereas the combined contribution of quadriceps angle, femoral anteversion, foot posture, navicular drop, dynamic balance, and single-leg squat performance remains insufficiently characterized in this population[6,9,15]. Therefore, this study aimed to examine the associations between vertical jump height and clinically accessible lower-extremity alignment measures together with field-based neuromuscular control tests in female volleyball athletes. Specifically, we evaluated whether quadriceps angle, femoral anteversion, foot posture index, navicular drop, Y-Balance performance, and single-leg squat performance were associated with vertical jump height when considered within the same analytical framework. We expected that athletes with better neuromuscular control and more favorable lower-extremity alignment profiles would demonstrate higher jump performance. These findings may be clinically and practically relevant for preseason screening, performance monitoring, and the planning of individualized training or corrective exercise strategies in volleyball players.

Materials and Methods

Study Design and Setting

This study was designed as an analytical cross-sectional observational investigation examining the associations between vertical jump height and selected indicators of lower extremity alignment and neuromuscular control in female volleyball athletes. Vertical jump height was defined as the primary outcome variable, whereas lower extremity alignment measures and field-based neuromuscular performance tests were treated as explanatory variables. The study was conducted in a standardized field-testing setting under the supervision of the research team and in accordance with the reporting principles recommended for cross-sectional observational studies.

Participants

Twenty-four female volleyball athletes voluntarily participated in the study. Participants were recruited from two Turkish Volleyball Federation Second League female volleyball teams available to the research team in Trabzon. All athletes were actively competing in registered teams and had at least 3 years of structured volleyball training experience. Data collection was performed in April–May 2025 during the spring period of the 2024–2025 competitive season. Athletes from these teams were invited to participate, and 24 eligible and consenting athletes completed the protocol and were included in the final analysis. The exact number of athletes initially approached or screened was not prospectively recorded. Athletes were excluded if they had a history of lower extremity surgery or any musculoskeletal injury within the 6 months preceding data collection. Lower extremity dominance was determined according to the self-reported preferred kicking leg. To reduce potential hormonal variation in neuromuscular performance, testing sessions were scheduled outside the early follicular phase of the menstrual cycle when feasible; menstrual cycle information was used only for scheduling purposes and was not included in the statistical analyses. The study protocol was approved by the Scientific Research Ethics Committee of Karadeniz Technical University Faculty of Medicine (approval no. 24237859-453), and all participants provided written informed consent before testing. All procedures were conducted in accordance with the Declaration of Helsinki.

Sample Size Determination

An a priori power analysis was performed using G*Power 3.1 to estimate the minimum required sample size for the primary correlation-based analyses. Assuming a moderate effect size (r = .50), a statistical power of 80%, and a two-sided alpha level of .05, the minimum required sample size was calculated as 23 participants[23]. Accordingly, 24 athletes were included in the final analysis. This calculation defined the sample-size basis for the primary correlation-based objective. The multivariable regression and decision-tree procedures were positioned as secondary exploratory analyses intended to describe whether the principal associations showed a consistent pattern within a parsimonious joint model and to provide an illustrative view of potential subgroup structure. Their interpretation was limited to exploratory, hypothesis-generating evidence rather than definitive prediction modeling.

Testing Procedures

All measurements were obtained during a single testing session using a standardized assessment sequence. Before data collection, participants completed a 15-min warm-up consisting of light jogging, progressive accelerations, and dynamic stretching exercises. All alignment, anthropometric, and performance assessments were administered by the same trained examiner to minimize inter-observer variability. The examiner used a standardized worksheet, objective numeric criteria, and the same test order for all athletes. The examiner was not blinded to previous measurements because all assessments were completed within the same session; this feature was considered when interpreting field-based observational findings. For bilateral alignment and anthropometric variables, right and left side measurements were obtained separately and averaged to derive a single participant-level mean value for statistical analysis.

Vertical Jump Assessment

Vertical jump height was measured using an optical timing-based system (Witty Jump, Microgate, Bolzano, Italy). Following the standardized warm-up, each participant performed 2 maximal countermovement vertical jumps with free arm swing, separated by 30 s of passive recovery. The protocol was kept to 2 trials to reduce fatigue within the broader field-testing session while retaining the best maximal effort. The highest jump height value was retained for analysis. Optical timing systems of this type have demonstrated high validity and reliability for estimating vertical jump height in athletic populations[24].

Lower Extremity Alignment Assessment

Lower extremity alignment was assessed using standardized clinical measures. Femoral anteversion was evaluated with the participant in the prone position and the tested knee flexed to 90°. While the pelvis was manually stabilized, the examiner palpated the greater trochanter and passively rotated the hip until maximal lateral prominence was identified. At that position, femoral anteversion was measured using a goniometer as the angle formed between the longitudinal axis of the tibia and a vertical reference line perpendicular to the floor[25]. Two measurements were obtained and averaged for analysis.

Quadriceps angle was measured in a bilateral weight-bearing standing position with the knees fully extended. A standard goniometer was aligned with its fulcrum positioned at the midpoint of the patella, the stationary arm directed toward the anterior superior iliac spine, and the moving arm aligned with the tibial tuberosity. To improve measurement stability, 3 readings were obtained for each side and averaged[25].

Static foot posture was assessed using the Foot Posture Index-6, a validated clinical tool consisting of 6 observational criteria scored from -2 to +2 [26]. Item scores were summed to obtain the total foot posture score for each side. Navicular mobility was assessed using the navicular drop test. The vertical position of the navicular tuberosity relative to the floor was first measured in a seated non-weight-bearing position and then reassessed during relaxed bipedal standing. The difference between the 2 measurements was recorded as the navicular drop value[27,28]. In the present study, Foot Posture Index and navicular drop values were treated as complementary indicators of static foot alignment and medial longitudinal arch behavior under load.

Neuromuscular Control Assessment

Dynamic postural control was assessed using the Y-Balance Test. Participants maintained single-leg stance on the dominant limb while reaching as far as possible with the contralateral limb in the anterior, posteromedial, and posterolateral directions. After familiarization, 3 successful trials were recorded in each direction. Reach distances were averaged and used to calculate a composite Y-Balance score normalized to limb length according to the standard formula[17,18,29].

Unilateral functional control was further assessed with a timed single-leg squat test. After a familiarization trial, participants performed the test on the dominant limb, matching the laterality used for the Y-Balance Test. Participants were instructed to perform as many controlled partial single-leg squats as possible within 30 s while maintaining approximately 45° of knee flexion. The non-stance limb remained elevated throughout the trial. Repetitions were not counted if balance was lost or if excessive compensatory movement was observed. No video-based scoring was used; the total number of correctly completed repetitions was recorded by the examiner. This test has shown acceptable intra-rater and inter-rater reliability as a field-based measure of movement quality[30,35]. Because the timed score may also reflect pacing, lower-limb strength endurance, and task familiarity, it was interpreted as a practical field indicator of unilateral functional control rather than an isolated measure of neuromuscular control alone.

Anthropometric Assessment

Anthropometric and body composition measurements were obtained to characterize the physical profile of the sample. All anthropometric assessments were performed according to the standards of the International Society for the Advancement of Kinanthropometry[31]. Body composition was evaluated using bioelectrical impedance analysis with a Tanita BC-601 analyzer (Tanita Corp., Tokyo, Japan), consistent with the general principles and limitations of bioelectrical impedance methods[32]. To enhance consistency, all measurements were performed by the same trained examiner under standardized testing conditions. In the analytical framework of the present study, anthropometric variables were used for sample characterization and exploratory screening, whereas the primary multivariable model focused on biomechanical alignment and field-based functional control indicators.

Outcome and Predictor Definitions

The primary outcome variable was vertical jump height (cm). The candidate biomechanical and functional explanatory variables were single-leg squat repetitions, Y-Balance composite score, mean quadriceps angle, mean femoral anteversion angle, mean Foot Posture Index score, and mean navicular drop value. Bilateral variables were averaged before analysis to generate participant-level mean scores. Additional anthropometric variables were retained for descriptive characterization and exploratory screening but were not emphasized in the final multivariable model. The regression model was constructed as a parsimonious exploratory joint model from the strongest clinically interpretable variables rather than as a fully prespecified confirmatory prediction model.

Statistical Analysis

All statistical analyses were performed using Python 3.11 with pandas, NumPy, SciPy, statsmodels, scikit-learn, and matplotlib. Continuous variables were summarized using sample size, minimum and maximum values, mean, standard deviation, median, and interquartile range, as appropriate. Distributional characteristics were examined using the Shapiro–Wilk test together with skewness, kurtosis, and median absolute deviation-based outlier screening. Bivariate associations between vertical jump height and candidate explanatory variables were evaluated using Pearson product–moment correlation coefficients for approximately normally distributed variables and Spearman rank-order correlation coefficients when distributional assumptions were less appropriate. The multiplicity family for false discovery rate correction consisted of the six primary biomechanical and functional correlations reported in Table 2.

Single-leg squat repetitions, Y-Balance score, and quadriceps angle were subsequently entered into an exploratory robust multiple linear regression model because they represented the strongest clinically interpretable functional and alignment indicators while keeping the number of model parameters limited for the sample size. Robust HC3 standard errors were used to provide more reliable inference under small-sample conditions and potential heteroscedasticity, with p values and confidence intervals calculated using the model residual degrees of freedom. Model fit was summarized using R^2, adjusted R^2, model significance, and in-sample root mean square error for the observed-versus-predicted display. Multicollinearity was assessed using variance inflation factor values, and model diagnostics included inspection of residual patterns, leverage, and Cook's distance. In addition, an exploratory decision-tree regression model was generated using scikit-learn DecisionTreeRegressor with the squared-error criterion, maximum depth set to 3, minimum samples per leaf set to 2, and random_state = 42. The decision tree was retained only as a descriptive visualization of sample-specific patterns; it was not treated as a validated predictive model. Statistical significance was set at $p < .05$.

Results

Descriptive characteristics of the main study variables

The final analytical sample consisted of 24 participants with complete data on all variables included in the main analyses, and no enrolled participant was excluded from the final analytical dataset after consent and eligibility confirmation. Baseline cohort characteristics are presented in Table 1. The mean age was 18.38 years (SD = 1.31), mean training experience was 4.60 years (SD = 1.68), mean body mass was 59.78 kg (SD = 7.87), mean body height was 170.42 cm (SD = 8.99), and mean body mass index was 20.22 kg/m^2 (SD = 1.46). Selected body-composition variables, including right and left leg fat percentage and leg muscle mass, were also summarized to characterize the cohort. Mean vertical jump height was 31.68 cm (SD = 3.74), and mean single-leg squat performance was 27.25 repetitions (SD = 6.86). The average Y-Balance score was 84.62 (SD = 7.42), whereas the mean quadriceps angle, Foot Posture Index, navicular drop, and femoral anteversion values were 19.17° (SD = 3.48), 3.14 (SD = 1.78), 0.79 cm (SD = 0.24), and 14.50° (SD = 3.35), respectively (Table 1). These values indicate variability across the principal performance and biomechanical measures. As illustrated in Figure 1A, several of the retained variables were moderately to strongly interrelated, supporting a focused examination of

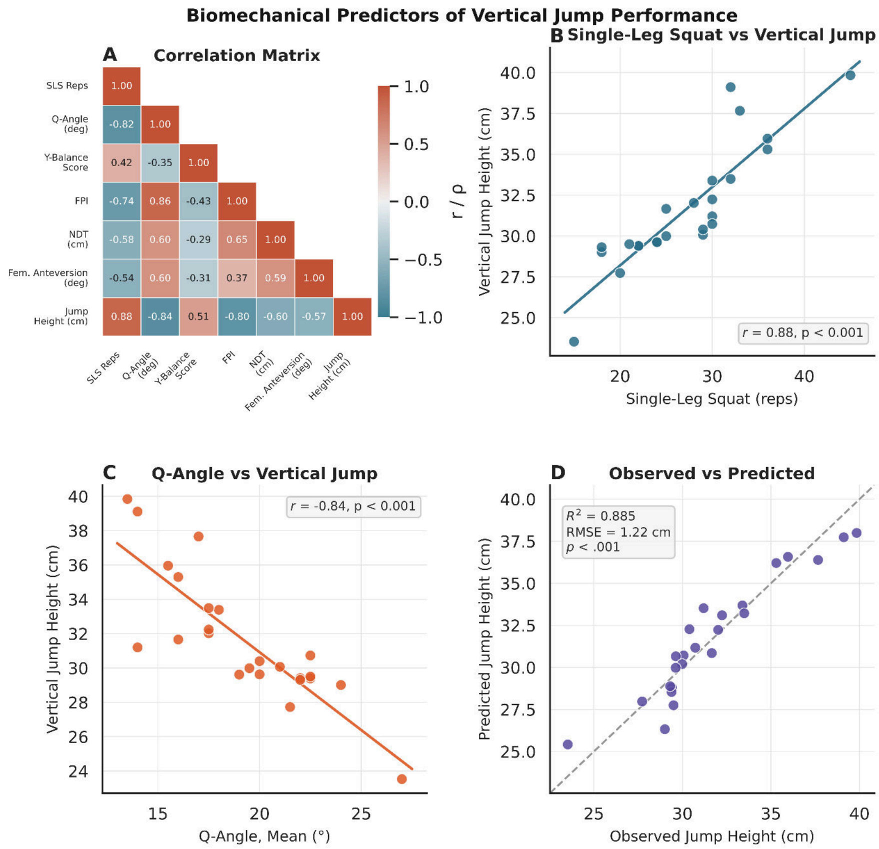

Figure 1. Graphical summary of the associations between vertical jump height and principal biomechanical variables. Note. (A) Correlation matrix illustrating the interrelationships among the retained lower-extremity alignment and field-based functional control variables. Coefficients represent Pearson r unless Spearman ρ was used for Y-Balance associations. (B) Scatter plot demonstrating the strong positive association between unilateral functional performance (single-leg squat repetitions) and vertical jump height. (C) Scatter plot demonstrating the inverse association between frontal-plane alignment (mean quadriceps angle) and vertical jump height. (D) Plot of observed versus predicted vertical jump height values derived from the exploratory robust multiple linear regression model. The R^2 and RMSE values shown in the panel represent in-sample descriptive fit and were not treated as validation metrics.

their association with vertical jump performance. Table 1 includes baseline cohort characteristics together with the main biomechanical and functional variables.

Associations between vertical jump height and biomechanical variables

Bivariate analyses showed that vertical jump height was strongly and positively associated with single-leg squat repetitions, $r = .88$, $p < .001$, and moderately positively associated with Y-Balance score, $r = .51$, $p = .011$ (Table 2). In contrast, jump height was inversely associated with quadriceps angle, $r = -.84$, $p < .001$, Foot Posture Index, $r = -.80$, $p < .001$, navicular drop, $r = -.60$, $p = .002$, and femoral anteversion, $r = -.57$, $p = .004$. All six associations remained statistically significant after false discovery rate correction based on the six-test family reported in Table 2. The positive association between single-leg squat performance and jump height is shown in Figure 1B, whereas the inverse association between quadriceps angle and jump height is displayed in Figure 1C. The correlation matrix in Figure 1A further indicates that these biomechanical predictors were not independent of one another, which justified cautious joint evaluation in an exploratory multivariable model.

Multivariable and tree-based modeling of vertical jump height

An exploratory robust multiple regression model was fitted to evaluate the joint associations of single-leg squat repetitions, Y-Balance score, and quadriceps angle with

Table 1. Baseline characteristics and descriptive statistics of the main study variables.

Variable	n	Min	Max	M	SD
Age (years)	24	18.00	20.00	18.38	1.31
Training experience (years)	24	3.00	8.00	4.60	1.68
Body mass (kg)	24	48.00	80.00	59.78	7.87
Body height (cm)	24	156.00	185.00	170.42	8.99
Body mass index (kg/m^2)	24	18.10	23.60	20.22	1.46
Right leg fat percentage (%)	24	18.60	34.20	27.11	3.41
Left leg fat percentage (%)	24	17.10	33.90	27.08	3.39
Right leg muscle mass (kg)	24	6.30	8.90	7.64	0.60
Left leg muscle mass (kg)	24	6.20	8.60	7.44	0.59
Vertical Jump Height (cm)	24	23.53	39.84	31.68	3.74
Single-Leg Squat repetitions (n)	24	15.00	45.00	27.25	6.86
Y-Balance Test Score	24	72.90	103.30	84.62	7.42
Quadriceps Angle mean (deg)	24	13.50	27.00	19.17	3.48
Foot Posture Index mean	24	0.50	7.50	3.14	1.78
Navicular Drop Test mean (cm)	24	0.30	1.35	0.79	0.24
Femoral Anteversion mean (deg)	24	8.00	20.00	14.50	3.35

Note. n = sample size; Min = minimum; Max = maximum; M = mean; SD = standard deviation; deg = degrees; BMI = body mass index. "Quadriceps Angle mean," "Foot Posture Index mean," "Navicular Drop Test mean," and "Femoral Anteversion mean" represent participant-level averages of right and left side measurements. Single-leg squat performance is reported as the number of correctly completed repetitions.

Table 2. Bivariate associations between vertical jump height and the main alignment and neuromuscular variables.

Predictor	Method	Effect size	*p*	FDR-adjusted *p*
Single-Leg Squat repetitions (n)	Pearson	0.880	< .001	< .001
Quadriceps Angle mean (deg)	Pearson	-0.842	< .001	< .001
Foot Posture Index mean	Pearson	-0.800	< .001	< .001
Navicular Drop Test mean (cm)	Pearson	-0.601	.002	.003
Femoral Anteversion mean (deg)	Pearson	-0.572	.004	.004
Y-Balance Test Score	Spearman	0.512	.011	.011

Note. Effect size values represent correlation coefficients (Pearson r or Spearman ρ, as applicable). FDR-adjusted p values were calculated using the false discovery rate procedure across the six primary biomechanical and functional correlations displayed in this table. Positive coefficients indicate that higher values of the predictor were associated with greater vertical jump height, whereas negative coefficients indicate that higher values of the predictor were associated with lower vertical jump height. "Quadriceps Angle mean," "Foot Posture Index mean," "Navicular Drop Test mean," and "Femoral Anteversion mean" represent the average of right and left side measurements.

Table 3. Robust multiple regression model for vertical jump height.

Predictor	B	Robust SE (HC3)	t	*p*	95% CI	VIF
Constant	20.141	8.350	2.412	.026	[2.723, 37.559]	—
Single-Leg Squat repetitions	0.256	0.100	2.560	.019	[0.047, 0.465]	3.17
Y-Balance Test Score	0.141	0.065	2.168	.042	[0.005, 0.277]	1.21
Quadriceps Angle mean (deg)	-0.387	0.225	-1.717	.101	[-0.856, 0.082]	3.00

Note. HC3 = heteroscedasticity-consistent standard errors (type HC3); CI = confidence interval; VIF = variance inflation factor. Unstandardized regression coefficients (B) are reported. "Quadriceps Angle mean" represents the average of right and left side measurements. Robust standard errors were used to reduce sensitivity to heteroscedasticity and small-sample bias. The p values and confidence intervals were calculated using residual degrees of freedom for the HC3-based t tests. Model fit statistics are as follows: N = 24, RÇ = .885, adjusted RÇ = .868, model p < .001, in-sample RMSE = 1.22 cm, and Durbin–Watson = 2.16.

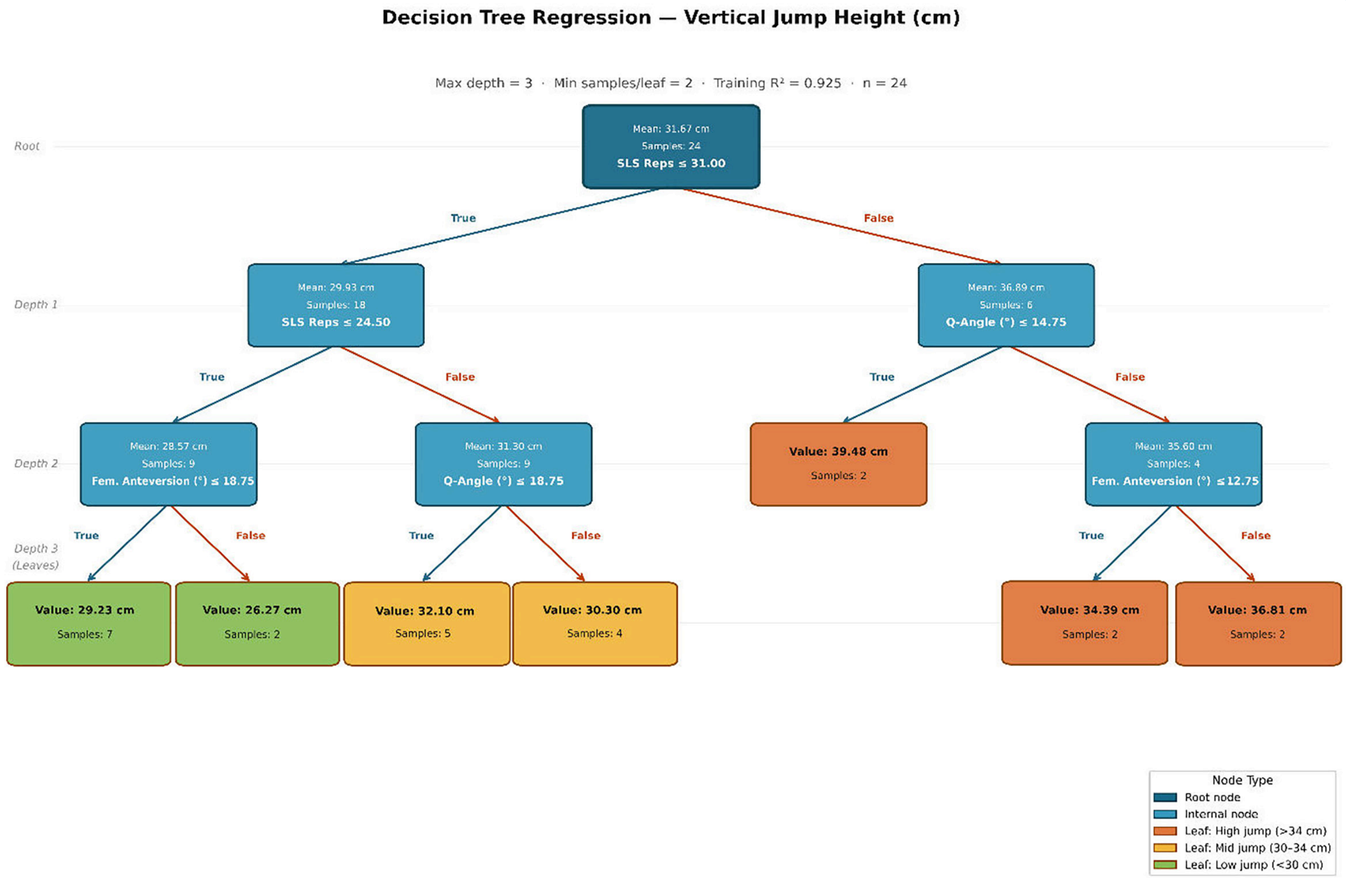

Figure 2. Decision Tree Regression. Note. Exploratory decision-tree regression model illustrating the hierarchical segmentation of vertical jump height across biomechanical and functional profiles. In the present sample, single-leg squat performance formed the first split, followed by mean quadriceps angle and mean femoral anteversion in subsequent branches. The model is presented as a descriptive, hypothesis-generating visualization of sample-specific patterns, with threshold values interpreted as exploratory reference points for future validation rather than generalizable screening cut-offs.

vertical jump height (Table 3). The model showed strong in-sample fit, $R^2 = .885$, adjusted $R^2 = .868$, model $p < .001$. Within this model, single-leg squat repetitions remained positively associated with jump height, B = 0.256, 95% CI [0.047, 0.465], p = .019, and Y-Balance score also showed a positive association, B = 0.141, 95% CI [0.005, 0.277], p = .042. Quadriceps angle retained a negative coefficient, B = -0.387, 95% CI [-0.856, 0.082], although this estimate did not meet the conventional threshold for statistical significance, p = .101. As shown in Figure 1D, the observed and predicted values were closely aligned, with an in-sample RMSE of 1.22 cm. The decision-tree visualization shown in Figure 2 identified a sample-specific first split around single-leg squat performance, with quadriceps angle and femoral anteversion contributing to later subgroup separation. This tree was interpreted as an exploratory visual summary of the dataset rather than as confirmatory evidence or a validated prediction model.

Discussion

The present study showed that vertical jump height in female volleyball athletes was closely associated with field-based functional control and selected lower-extremity alignment variables. Within the exploratory robust model, single-leg squat performance and Y-Balance score were positively associated with jump height, whereas quadriceps angle retained an inverse coefficient after the functional variables were included. This general pattern is consistent with the central role of jumping in volleyball performance and with previous work indicating that successful jump actions in female volleyball depend on coordinated force production, task-specific mechanics, and efficient lower-extremity control rather than on a single isolated trait[1,2,5].

One of the most meaningful findings of the present study was the prominence of field-based functional variables, particularly single-leg squat performance and Y-Balance score. This pattern is clinically plausible. The Y-Balance Test has repeatedly demonstrated good to excellent reliability as a measure of dynamic postural control[17,33], and training approaches that improve dynamic balance have also been shown to enhance functional performance in female athletes[19,34]. Likewise, the single-leg squat is widely used to characterize frontal-plane knee control and segmental coordination, and previous studies support its clinical validity and reliability when appropriately performed and rated[21,35]. In the present protocol, the single-leg squat score represented the number of controlled repetitions completed within 30 s; it therefore captured a field-based combination of unilateral control, pacing, and strength endurance. Although dynamic balance and jump performance are not interchangeable constructs, volleyball-specific work suggests that postural control remains relevant to jump-related function, especially in athletes repeatedly exposed to unilateral loading and repeated landing demands[36,37]. In this setting, higher scores on unilateral control and dynamic balance tests appeared to accompany better vertical jump performance.

The alignment-related findings add another layer to this pattern. Quadriceps angle showed the strongest inverse bivariate association among the alignment measures, whereas femoral anteversion, foot posture, and navicular drop were more prominent at the bivariate level. In the multivariable model, the quadriceps angle coefficient remained negative after single-leg squat and Y-Balance scores were included, although the estimate became less precise. This pattern is compatible with shared variance between static frontal-plane alignment and dynamic functional control. The variance inflation factor values did not indicate severe multicollinearity, yet the overlap among quadriceps angle, single-leg squat performance, and other alignment measures suggests that static alignment and movement-control patterns may represent partly connected aspects of lower-extremity function. Recent reviews describe the Q-angle as a biomechanically meaningful descriptor of knee loading and frontal-plane control in female athletes, although its relationship with performance varies across study designs and populations[38,39]. A similar issue applies to foot alignment. Contemporary literature supports the idea that excessive foot pronation can alter tibial and femoral rotation and patellofemoral mechanics[40,41], while recent meta-analytic evidence indicates that flatfoot is not necessarily accompanied by lower jump height despite measurable differences in jump biomechanics[42]. The inverse associations observed in the present sample are therefore more consistent with differences in mechanical organization and force-transfer efficiency than with a direct performance penalty attributable to any single static alignment feature. This interpretation also aligns with reports of lower-extremity biomechanical asymmetries during landing tasks in women's collegiate volleyball, where alignment-related factors are considered part of the broader organization of repeated jump-land actions[43].

Anthropometric and body-composition characteristics provide useful context for these findings. These measures were collected to describe the sample and to support exploratory screening, while the final analytical model focused on biomechanical alignment and field-based functional variables. Previous studies have reported that higher body fat and body mass are associated with poorer jump or broader fitness outcomes in female volleyball players[8,44], whereas the explanatory value of morphology appears to vary according to training status and sample homogeneity. Ćopić et al.[7] showed that body composition and muscle strength predicted jumping performance differently in elite female volleyball players and nontrained women, suggesting that the importance of morphological characteristics changes across athletic populations. More recent profiling work in young female team-sport athletes likewise indicates that volleyball players may share relatively similar body-composition ranges while differing more clearly in selected functional performance measures[45]. The present results fit within this broader view: in a trained and relatively homogeneous volleyball sample, field-based functional control variables showed clearer associations with jump height than general anthropometric descriptors.

Taken together, the correlation, robust regression, and exploratory tree-based analyses point toward an integrated interpretation of jump performance. Volleyball jumping is a whole-chain task in which take-off mechanics, stretch-shortening behavior, and intersegmental coordination interact[2,5,46]. The decision-tree model provided a descriptive visualization of this pattern, with single-leg squat performance appearing as the first split in the present sample. Because the decision tree was exploratory and unvalidated, the observed thresholds were interpreted only as sample-specific descriptive reference points and were not presented as screening cut-offs. Practical training responses can include progressive single-leg squat variations, hip abductor and external rotator strengthening, landing-control drills, dynamic balance tasks, and foot-ankle control exercises, particularly when lower unilateral control is accompanied by higher quadriceps angle or pronation-related findings. This emphasis is consistent with contemporary sports-performance literature showing that proprioceptive and neuromuscular training can improve balance-related qualities and, in many contexts, support jump-related performance development[34,47,48].

Several features of the study frame the interpretation of these findings. The cross-sectional design describes associations at a single assessment point, and the sample consisted of 24 Second League female volleyball athletes. This sampling frame provides a focused view of a specific athletic group, while limiting direct extension to other competitive levels, age groups, and playing positions. Playing-position distribution, weekly training exposure, hormonal contraceptive use, and exact menstrual-cycle adherence were not included as statistical covariates, leaving room for residual variation related to training and biological status. The alignment measures were clinical rather than instrumented, and the field assessments were performed by a single examiner. The timed single-leg squat count also reflects pacing, endurance, and task familiarity alongside movement control. The laterality strategy paired dominant-limb dynamic tests with averaged bilateral alignment measures, which may reduce sensitivity to asymmetry-specific patterns. The decision-tree model served as a visual exploratory summary of the present sample rather than a validated prediction tool. Larger longitudinal studies with playing-position stratification, seasonal follow-up, instrumented biomechanical assessment, and internal or external validation of prediction-oriented models would help clarify the stability and practical value of these associations.

Ethics approval

The study protocol was approved by the Scientific Research Ethics Committee of Karadeniz Technical University Faculty of Medicine (approval no. 24237859-453). All procedures were conducted in accordance with the principles of the Declaration of Helsinki.

Consent to participate

Written informed consent was obtained from all participants prior to data collection.

Authors' contributions

M.G. developed the study hypothesis, conducted the literature review, and performed the measurements. S.K. performed the statistical analyses. H.N.O. contributed to the measurements and data collection. A.F.O. contributed to the literature review, drafted the discussion section and accepts responsibility for the integrity of the data analysis. All authors have reviewed and approved the final version of the manuscript.

Acknowledgments

The authors would like to thank the athletes and coaching staff for their voluntary participation and cooperation.

This manuscript was derived from the doctoral thesis of the first author, Melike Gültekin, conducted at the Department of Anatomy, Health Sciences Institute, Karadeniz Technical University, under the supervision of Dr. Ali Faruk Özyaşar.

The authors used ChatGPT (OpenAI; model: GPT-5.5 Thinking) to support language editing, structural organization, and drafting refinement of the manuscript. No artificial intelligence system was used as an author or as a substitute for scientific judgment. All study design decisions, data analyses, interpretation of the findings, and final content verification were performed by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the manuscript.

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