

Investigation of the Relationship Between Frontal Plane Knee Projection Angle and Dynamic Balance, Agility, and Ankle Dorsiflexion Mobility in Adolescent Female Volleyball Players

Sefa Haktan HATIK

sefahatik@sinop.edu.tr

Sinop University

İlker Can BÜYÜKKIRLI

Bahçeşehir University

Berkay Eren PEHLİVANOĞLU

Bahçeşehir University

Research Article

Keywords: Volleyball, Adolescent, Athletes, Biomechanical Phenomena, Postural Balance, Range of Motion, Articular

Posted Date: August 27th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10617844/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Background

This study aimed to examine associations between frontal plane knee projection angle (FPPA) during a single-leg squat and dynamic balance, agility, and ankle dorsiflexion mobility in adolescent female volleyball players.

Methods

Observational, cross-sectional, correlational study. A volleyball academy in İzmir, Türkiye. Sixty-six adolescent female volleyball players (median age, 13.0 years; range, 10–19 years). FPPA was assessed using two-dimensional video analysis. Dynamic balance, agility, and ankle dorsiflexion mobility were evaluated using the Lower Quarter Y-Balance Test, T-Test, and Weight-Bearing Lunge Test, respectively.

Results

FPPA was not significantly associated with the Y-Balance composite score ($r = -0.169$; 95% CI, -0.393 to 0.071 ; $p = 0.174$), T-Test time ($r = -0.158$; 95% CI, -0.393 to 0.088 ; $p = 0.205$), or Weight-Bearing Lunge Test value ($r = -0.093$; 95% CI, -0.341 to 0.162 ; $p = 0.456$). FPPA group differences were nonsignificant (Hedges' $g = 0.02$ – 0.34), and the regression model had low explanatory value ($F = 1.380$; $p = 0.245$; adjusted $R^2 = 0.028$). Height was modestly associated with FPPA after Holm–Bonferroni correction ($r = 0.346$; adjusted $p = 0.032$), but this was a secondary exploratory finding.

Conclusions

FPPA was not related to the assessed functional outcomes. The height association should be interpreted cautiously because biological maturation was not assessed and the wide age range may have introduced developmental heterogeneity. FPPA should not be used as a stand-alone functional screening measure. Adequately powered studies incorporating maturation assessment and study-specific measurement reliability are needed.

Trial registration

ClinicalTrials.gov, NCT07711236. Registered on 07 June 2026. Available at <https://clinicaltrials.gov/study/NCT07711236>

Background

Young athletes' development is influenced by growth- and maturation-related biomechanical changes and sports injuries [1]. Volleyball demands speed, strength, and explosive power through repeated jumping, landing, blocking, spiking, and rapid changes of direction [2]. Despite being a non-contact sport, volleyball has a considerable injury burden, with the ankle, knee, and shoulder among the most frequently affected anatomical regions. Knee injuries, particularly those involving the patellofemoral joint and anterior cruciate ligament, are an important concern in female athletes [3–5]. Patellofemoral joint and anterior cruciate ligament (ACL) injuries are particularly prominent [6], with most ACL injuries occurring through non-contact mechanisms. Adolescent female athletes are especially vulnerable because of anatomical, hormonal, and neuromuscular differences [3]. During this period, increased knee abduction angles and moments and reduced knee flexion during landing have been reported [7, 8]. Rapid growth and biological maturation may further compromise knee neuromuscular control when motor control and coordination do not adapt as rapidly as the musculoskeletal system [9]. These changes may also impair movement quality, dynamic balance, and overall neuromuscular performance [10]. Therefore, early identification of biomechanical indicators and related functional performance parameters associated with knee injury risk is clinically important in adolescent female volleyball players.

Non-contact volleyball injuries are multifactorial and may involve hormonal, biomechanical, anatomical, and psychological factors [11]. Lower-extremity biomechanics are particularly relevant to anterior cruciate ligament injury and patellofemoral pain [12]. Within this context, dynamic knee valgus (DKV) is a three-dimensional movement pattern characterized by hip internal rotation and adduction, knee abduction and internal rotation, anterior tibial translation, ankle eversion, and foot pronation [13]. DKV is considered an important risk factor for anterior cruciate ligament injury and patellofemoral pain [1]. Puberty-related changes in knee mechanics may further increase the relevance of assessing DKV in adolescent female athletes [9]. Therefore, evaluating frontal-plane knee mechanics associated with DKV may help identify biomechanical characteristics that predispose adolescent female volleyball players to knee injury.

Although three-dimensional (3D) motion analysis is the gold standard for assessing knee kinematics and kinetics, its cost, spatial requirements, and analytical complexity limit large-scale clinical screening [11, 14]. Two-dimensional (2D) methods offer a more accessible alternative for evaluating tasks such as the single-leg squat (SLS) [15]. Jamaludin et al. [14] reported good concurrent validity and reliability between 2D and 3D measurements during SLS tasks performed at 45° and 60° in physically active women. Kingston et al. [16] similarly found good reliability for 2D frontal-plane SLS measurements but emphasized their use as clinical screening tools rather than direct equivalents of 3D analysis. In adolescent female volleyball players, 2D SLS assessment may also provide information complementary to 3D analysis [17]. These findings support 2D SLS assessment as a practical method for examining frontal-plane knee control.

Lower-extremity biomechanics reflect kinetic-chain interactions among the hip, knee, and ankle; therefore, frontal plane projection angle (FPPA) may be related to other functional parameters. Restricted ankle dorsiflexion may limit anterior tibial translation during closed kinetic-chain movements, promote

compensatory frontal- and transverse-plane motion, and influence knee valgus mechanics [1, 18]. Dynamic balance may also be associated with FPPA because single-leg postural control and frontal-plane knee alignment involve similar neuromuscular demands, although evidence in young athletes remains inconsistent. Wilczyński et al. [1], for example, found no significant association between modified Star Excursion Balance Test performance and FPPA during single-leg squat and landing tasks. Although dynamic balance and agility are included in injury-related screening models for young female volleyball players, studies examining these variables together with FPPA remain limited [10]. Their combined assessment may therefore clarify the biomechanical and functional interactions underlying lower-extremity control.

Although two-dimensional FPPA measurement during the single-leg squat has demonstrated clinical validity and reliability [14], evidence regarding its relationships with functional parameters remains limited and inconsistent, particularly in adolescent female volleyball players [1, 17]. Therefore, this study aimed to assess FPPA using two-dimensional video analysis during the single-leg squat and examine its relationships with dynamic balance, agility performance, and ankle dorsiflexion mobility in this population. It was hypothesized that FPPA would be significantly associated with dynamic balance, agility performance, and ankle dorsiflexion mobility, with lower FPPA values reflecting better functional performance and greater dorsiflexion mobility.

Methods

Study Design

This observational, cross-sectional, and correlational study examined the associations of frontal plane knee projection angle (FPPA) with dynamic balance, agility performance, and ankle dorsiflexion mobility in adolescent female volleyball players. No intervention was administered, and all variables were assessed by the same researcher during a single session under standardized field conditions. FPPA was evaluated using two-dimensional video analysis during the single-leg squat [19], dynamic balance using the Y-Balance Test [20], agility using the T-Test [21], and ankle dorsiflexion mobility using the Weight-Bearing Lunge Test [22]. Assessments were scheduled to minimize disruption to the athletes' training.

Written informed consent was obtained from all participants; additional written consent was obtained from the parents or legal guardians of participants younger than 18 years.

Participants

The sample comprised adolescent female volleyball players who regularly trained at AB Volleyball Academy in İzmir and voluntarily agreed to participate. Participants were recruited through convenience sampling. An a priori correlation-based power analysis conducted using G*Power version 3.1, with a two-tailed significance level of $\alpha = 0.05$, 80% power ($1 - \beta = 0.80$), and an expected moderate-to-large correlation of $r = 0.35$, indicated a minimum sample size of 62 participants. To account for missing data,

invalid measurements, and attrition, 70 athletes were recruited. Four participants were not included in the analyses because their assessments could not be completed according to the standardized protocol; therefore, data from 66 participants were analyzed (Fig. 1).

Inclusion criteria:

1. Female sex and age between 10 and 19 years.
2. Regular participation in volleyball training at least three days per week.
3. Having reached menarche [7].

Exclusion criteria:

1. A lower-extremity injury within the previous six months.
2. A history of lower-extremity surgery.
3. Use of medication that could affect balance, attention, or physical performance.
4. A neurological, orthopedic, or systemic condition that could affect physical performance.

Withdrawal criteria:

1. Occurrence of any injury during the study.
2. Development of pain, dizziness, excessive fatigue, or discomfort during the assessments.
3. Inability to complete the assessments according to the standardized protocol or the presence of incomplete data.

Outcome Measures

Data on participants' age, height, body mass, and body mass index (BMI) were collected. To standardize the test results, the dominant lower extremity was defined as the leg the participant preferred to use when kicking a ball [23]. The primary study variable was the frontal plane projection angle (FPPA) assessed during the single-leg squat test. Dynamic balance, agility performance, and ankle dorsiflexion mobility were considered secondary measures. This classification was adopted to structure the primary research question and define the statistical analysis plan more clearly.

Frontal Plane Projection Angle (FPPA)

FPPA was assessed using SparkMotion software [23]. It was calculated from the angle between a line connecting the anterior superior iliac spine (ASIS) to the midpoint of the patella and a line connecting the patellar midpoint to the midpoint between the medial and lateral malleoli; this angle was subtracted from 360°. Values $\geq 195^\circ$ were descriptively classified as increased FPPA. Frontal-plane video was recorded using an iPad mounted on a tripod 3 m from the participant and 1 m above the floor. Participants performed the single-leg squat with their arms crossed and a metronome-controlled tempo (2-s descent and 2-s ascent), reaching the deepest position possible while maintaining balance. FPPA was measured

at this position. After three practice trials, five consecutive squats were recorded, and the third recorded trial was analyzed [19, 24].

T – Test

Agility was assessed using the T-Test. Four cones were arranged in a T-shaped course, with the central cone (B) positioned 9.14 m from the starting cone (A) and cones C and D placed 4.57 m to the right and left of cone B, respectively. Starting from cone A, participants sprinted to cone B, shuffled laterally to touch cones C and D, returned to cone B, and backpedaled to cone A [25]. Time was recorded using a photocell timing system. After two familiarization trials, participants completed three valid trials separated by 3-min rest periods, and the fastest time was used for analysis [21, 25]. The T-Test course was arranged using four cones, and performance time was recorded using a photocell timing system (Fig. 3).

Y-Balance Test

Dynamic balance was assessed using the Lower Quarter Y-Balance Test (YBT-LQ), a standardized test that measures reach distances in the anterior, posteromedial, and posterolateral directions while maintaining single-leg balance [26]. Reach distances were recorded to the nearest 0.5 cm using the Y-Balance Test kit. Limb length was measured from the anterior superior iliac spine (ASIS) to the most distal point of the medial malleolus, and reach distances were normalized to limb length. After six practice trials, participants completed three valid trials in each direction; invalid trials were repeated, and the mean value for each direction was used in the analysis. The composite score was calculated as the sum of the three directional reach distances divided by three times the limb length and multiplied by 100 [20, 27].

Weight – Bearing Lunge Test (WBLT)

Ankle dorsiflexion mobility was assessed using the Weight-Bearing Lunge Test (WBLT). Participants faced the wall in a tandem stance, with the great toe and heel midline of the tested foot aligned perpendicular to the wall and the heel of the rear foot raised. With their hands on the wall, participants advanced the front knee until it touched the wall without lifting the heel of the tested foot. The tested foot was progressively moved away from the wall in 1-cm increments, and the greatest valid distance between the great toe and the wall was recorded in centimeters. Three valid trials were performed for each lower extremity, and their mean was used in the analysis. Trials involving heel lift, evident lower-extremity compensation, or loss of the required position were repeated [22, 28].

Data Collection

All measurements were completed by the same researcher on the same day during a single session. Participants first completed a demographic information form, and the dominant lower extremity was identified. To minimize the potential effects of fatigue, assessments were administered in the following

order: FPPA, YBT-LQ, WBLT, and T-Test. Familiarization and recorded trials were conducted according to the test-specific protocols described above. A 2-min passive rest period was provided between tests. The assessment was discontinued if participants experienced pain, dizziness, excessive fatigue, or discomfort.

Statistical analysis

Continuous variables were assessed graphically and using the Shapiro-Wilk test and are presented as mean $\pm$ standard deviation (SD) or median (interquartile range [IQR]), as appropriate. BMI was calculated as body mass in kilograms divided by height in metres squared. Associations of FPPA with the Y-Balance composite score, T-Test time, and WBLT were specified as the primary correlation family. Associations with directional Y-Balance scores and anthropometric variables were considered exploratory. Spearman's rank correlation coefficients (r_s) were calculated with paired-bootstrap 95% confidence intervals based on 20,000 resamples. The Holm method was applied separately to the three primary correlations and the eight exploratory correlations. As a sensitivity analysis, the Holm method was also applied across all 11 correlations in a single family. Multiple linear regression was used to examine age, BMI, Y-Balance composite score, T-Test time, and WBLT as correlates of FPPA. Model fit was summarised using R^2 and adjusted R^2 ; multicollinearity was assessed using variance inflation factors (VIFs). Because residual normality was not fully supported, HC3 heteroscedasticity-consistent standard errors and confidence intervals were used for coefficient-level inference. A post hoc exploratory model examined the height-FPPA association after adjustment for age and BMI. Statistical significance was set at $p < 0.05$; exploratory findings were interpreted cautiously.

Results

Data from 66 adolescent female volleyball players were analysed. Median age was 13.0 years (IQR, 12.0–14.0; range, 11–18 years). Mean height, body mass, and recalculated BMI were 160.24 ± 9.59 cm, 50.02 ± 8.98 kg, and 19.39 ± 2.54 kg/m², respectively. Median FPPA was 196.5° (IQR, 187.3 – 201.0°). Mean Y-Balance composite score, T-Test time, and WBLT value were $68.59 \pm 11.52\%$, 12.82 ± 1.64 s, and 9.50 ± 3.57 cm, respectively (Table 1).

FPPA was not significantly associated with the Y-Balance composite score ($r_s = -0.169$, 95% CI -0.385 to 0.062 ; $p = 0.174$), T-Test time ($r_s = -0.158$, 95% CI -0.388 to 0.078 ; $p = 0.205$), or WBLT ($r_s = -0.093$, 95% CI -0.328 to 0.151 ; $p = 0.456$). All three primary correlations remained nonsignificant after Holm correction (all adjusted $p = 0.523$) and after the global Holm sensitivity correction across all 11 correlations (all adjusted $p = 1.000$; Table 2). The confidence intervals were compatible with small associations in either direction but did not support the hypothesised moderate relationships.

Among the exploratory correlations, height showed a positive association with FPPA ($r_s = 0.346$, 95% CI 0.108 to 0.560 ; $p = 0.004$). This association remained significant after correction within the eight exploratory tests (adjusted $p = 0.036$) and was borderline after the global Holm correction across all 11

correlations (adjusted $p = 0.049$). Limb length was positively associated with FPPA before correction ($r_s = 0.255$, 95% CI 0.021 to 0.466; $p = 0.039$) but not after correction. No significant corrected associations were observed for age, body mass, BMI, or the directional Y-Balance scores (Table 3). These exploratory findings should not be interpreted as evidence of a developmental or causal effect.

The prespecified multivariable model including age, BMI, Y-Balance composite score, T-Test time, and WBLT was not statistically significant using conventional inference ($F[5,60] = 1.380$, $p = 0.245$; $R^2 = 0.103$; adjusted $R^2 = 0.028$). The conclusion was unchanged with HC3 robust inference (Wald $F = 1.115$, $p = 0.362$), and none of the individual variables was significantly associated with FPPA (Table 4). VIF values ranged from 1.072 to 1.513, indicating no important multicollinearity.

In the post hoc exploratory model, height remained positively associated with mean FPPA after adjustment for age and BMI ($B = 0.507^\circ$ per cm, HC3 95% CI 0.128 to 0.886; $p = 0.010$; model $R^2 = 0.124$, adjusted $R^2 = 0.082$). However, the height coefficient was not statistically significant in median regression ($B = 0.346$, 95% CI -0.126 to 0.818; $p = 0.148$), indicating that the result was model-dependent and should be treated as hypothesis-generating rather than confirmatory.

A sensitivity analysis recalculating the Y-Balance composite score directly from the three directional reaches and limb length produced the same overall interpretation. The FPPA-Y-Balance association remained small and nonsignificant ($r_s = -0.195$; $p = 0.117$), and the multivariable model remained nonsignificant ($F[5,60] = 1.460$, $p = 0.217$; $R^2 = 0.108$; adjusted $R^2 = 0.034$).

Table 1
Participant Characteristics (n = 66)

Variable	Mean ± SD or Median (IQR)
Age (years)	13.0 (12.0–14.0)
Height (cm)	160.24 ± 9.59
Body mass (kg)	50.02 ± 8.98
BMI (kg/m ²)	19.39 ± 2.54
FPPA (°)	196.5 (187.3–201.0)
Y-Balance composite score (%)	68.59 ± 11.52
T-Test (s)	12.82 ± 1.64
WBLT (cm)	9.50 ± 3.57
<i>Note. BMI: body mass index; FPPA: frontal plane projection angle; IQR: interquartile range; SD: standard deviation; WBLT: Weight-Bearing Lunge Test.</i>	

Table 2
Primary Associations of FPPA With Functional Outcomes

Variable	r _s	Bootstrap 95% CI	Raw p	Holm p (primary family)	Global Holm p (11 tests)
Y-Balance composite score	-0.169	-0.385 to 0.062	0.174	0.523	1.000
T-Test time	-0.158	-0.388 to 0.078	0.205	0.523	1.000
WBLT	-0.093	-0.328 to 0.151	0.456	0.523	1.000
<i>Note. CI: confidence interval; r_s: Spearman's rank correlation coefficient; WBLT: Weight-Bearing Lunge Test.</i>					

Table 3
Exploratory Associations of FPPA With Directional Y-Balance and Anthropometric Variables

Variable	r _s	Bootstrap 95% CI	Raw p	Holm p (exploratory family)	Global Holm p (11 tests)
Y-Balance anterior	-0.009	-0.242 to 0.235	0.946	1.000	1.000
Y-Balance posteromedial	0.217	-0.011 to 0.431	0.080	0.464	0.697
Y-Balance posterolateral	-0.011	-0.259 to 0.236	0.930	1.000	1.000
Age	0.212	-0.028 to 0.435	0.087	0.464	0.697
Height	0.346	0.108 to 0.560	0.004	0.036	0.049
Body mass	0.219	-0.013 to 0.432	0.077	0.464	0.697
BMI	0.016	-0.221 to 0.251	0.897	1.000	1.000
Limb length	0.255	0.021 to 0.466	0.039	0.272	0.389
<i>Note. BMI: body mass index; CI: confidence interval; r_s: Spearman's rank correlation coefficient. Directional labels follow the raw spreadsheet and must be verified against the original assessment forms before submission.</i>					

Table 4
Multivariable Linear Regression Model for FPPA

Variable	B	HC3 95% CI	Standardised β	HC3 p	VIF
Age	0.962	-0.999 to 2.922	0.129	0.330	1.513
BMI	-0.116	-1.396 to 1.164	-0.024	0.857	1.072
Y-Balance composite score	-0.120	-0.451 to 0.210	-0.115	0.468	1.167
T-Test time	-1.040	-3.210 to 1.130	-0.142	0.342	1.476
WBLT	-0.584	-1.589 to 0.422	-0.173	0.250	1.160
<i>Note. Conventional model: $F(5,60) = 1.380$, $p = 0.245$, $R^2 = 0.103$, adjusted $R^2 = 0.028$. HC3 robust joint test: Wald $F = 1.115$, $p = 0.362$. BMI: body mass index; CI: confidence interval; VIF: variance inflation factor; WBLT: Weight-Bearing Lunge Test.</i>					

Table 5
Post Hoc Exploratory Model of Height and FPPA

Variable	B	HC3 95% CI	Standardised β	HC3 p	VIF
Height (cm)	0.507	0.128 to 0.886	0.404	0.010	1.919
Age (years)	-0.630	-3.055 to 1.796	-0.084	0.606	1.958
BMI (kg/m ²)	0.086	-1.208 to 1.379	0.018	0.895	1.028
<i>Note. Model $R^2 = 0.124$, adjusted $R^2 = 0.082$; conventional $F(3,62) = 2.930$, $p = 0.041$; HC3 robust joint test: Wald $F = 3.430$, $p = 0.022$. This model was post hoc and did not include a direct measure of biological maturation.</i>					

Discussion

This study examined whether frontal plane projection angle (FPPA) during the single-leg squat was associated with dynamic balance, agility, and ankle dorsiflexion mobility in adolescent female volleyball players. The primary analyses did not provide evidence of moderate associations between FPPA and the Y-Balance composite score, T-Test time, or Weight-Bearing Lunge Test (WBLT), and all three associations remained nonsignificant after both the prespecified Holm correction and the global correction across all correlation tests. The multivariable model also had low explanatory value, and its interpretation was unchanged when heteroscedasticity-consistent HC3 inference was used. Height showed a positive exploratory association with FPPA, but this finding was borderline after the global multiplicity correction and was not supported by median regression. Accordingly, the functional null findings are the principal

results of the study, whereas the height finding should be treated as hypothesis-generating rather than confirmatory.

The absence of an association between FPPA and Y-Balance performance extends previous evidence to adolescent female volleyball players. Wilczyński et al. [1] similarly found no significant relationship between frontal-plane knee alignment and modified Star Excursion Balance Test performance during single-leg tasks in young male football players. In physically active adolescent females, Bulow et al. [29] also reported that Y-Balance scores provided limited information regarding lower-extremity kinematics. Y-Balance reach performance is influenced by several task requirements, including ankle dorsiflexion, hip flexion, and multiplanar postural strategies [30], whereas FPPA represents a two-dimensional estimate of frontal-plane knee alignment at a specific point of the single-leg squat. Therefore, the two assessments may emphasize different components of lower-extremity function and should not be considered interchangeable. The formula-based sensitivity analysis for the Y-Balance composite score produced the same overall interpretation, supporting the stability of this primary finding.

FPPA was also not associated with T-Test performance. The T-Test integrates forward sprinting, lateral shuffling, backward running, acceleration, deceleration, and movement coordination, and is commonly used to characterize change-of-direction performance in female volleyball players [21, 31]. In contrast, FPPA was obtained during a controlled single-leg squat and does not reproduce the speed, external loading, or directional demands of the T-Test. Straub and Powers [32] reported that two-dimensional FPPA had only limited ability to predict frontal-plane knee moments during stepping, landing, and change-of-direction tasks, while Gomes et al. [33] showed that dynamic knee valgus may vary according to change-of-direction demands. These findings support a task-specific interpretation: change-of-direction performance and single-leg squat FPPA may provide complementary rather than redundant information. Future work should use synchronized frontal-plane assessment during standardized cutting and deceleration tasks when examining the relationship between knee alignment and agility performance.

The lack of association between FPPA and WBLT should be interpreted in the context of inconsistent previous evidence. A systematic review and meta-analysis reported an association between reduced ankle dorsiflexion and dynamic knee valgus [34], and studies in asymptomatic adults and men reported relationships between dorsiflexion mobility and FPPA [35, 36]. Conversely, Hassan et al. [18] found no significant relationship between ankle dorsiflexion and FPPA in participants with patellofemoral pain or healthy controls. Da Costa et al. [37] further demonstrated that passive ankle dorsiflexion does not necessarily correspond to the dynamic dorsiflexion strategy used during the single-leg squat. Differences in population, task, and measurement approach may contribute to these contrasting findings. The present result does not indicate that ankle mobility is irrelevant to lower-extremity mechanics; rather, it indicates that isolated WBLT performance was not closely coupled with FPPA in this sample.

The prespecified regression model, comprising age, BMI, Y-Balance composite score, T-Test time, and WBLT, explained little of the variability in FPPA, and none of the included variables was independently associated with FPPA. This conclusion remained unchanged with HC3 robust inference. The low adjusted R^2 indicates that the selected field-based measures did not constitute a comprehensive explanatory model of frontal-plane knee alignment. Variables not measured in the present study may account for additional variability. Jamaludin et al. [38] reported significant relationships between knee frontal-plane angle and non-dominant hip extensor strength ($r = -0.56$, $p = 0.02$) and dominant hip adductor strength ($r = -0.51$, $p = 0.04$) during a 45° single-leg squat among physically active females without excessive dynamic knee valgus. Among females with excessive dynamic knee valgus, knee frontal-plane angle for both legs was significantly related to non-dominant hip abductor strength during a 60° single-leg squat [38]. In adolescent female volleyball players, Sahin et al. [39] found moderate positive correlations between Beighton score and peak knee valgus during double-leg vertical-jump landing ($r = 0.487$, $p = 0.014$), single-leg drop landing ($r = 0.478$, $p = 0.016$), and single-leg squat ($r = 0.439$, $p = 0.028$). Because hip strength and generalized joint hypermobility were not assessed in the present study, their contributions to FPPA variability cannot be determined from the current data.

Height was positively correlated with FPPA in the exploratory analyses. The association remained significant when the eight exploratory correlations were corrected as a separate family, but it was only borderline when all 11 correlations were corrected together. Height also remained associated with mean FPPA after adjustment for age and BMI using HC3 robust linear regression, whereas the corresponding median regression coefficient was not statistically significant. This model dependence reduces confidence in the robustness of the finding. Previous studies have described associations of stature, growth, or maturation with lower-extremity alignment and knee mechanics [7, 8, 40, 41], but biological maturation was not directly assessed in the present study. The observed height-FPPA association therefore cannot be attributed to maturation, changes in center-of-mass position, or a developmental mechanism. It should be considered an exploratory signal requiring confirmation in larger studies with direct maturation measures.

From a clinical and field-assessment perspective, the present findings indicate that Y-Balance performance, T-Test time, and WBLT should not be used as proxies for FPPA during the single-leg squat in adolescent female volleyball players. Two-dimensional FPPA can provide a practical estimate of frontal-plane knee alignment, but its interpretation remains task specific and does not substitute for broader assessment of strength, trunk and pelvic control, movement strategy, or sport-specific deceleration mechanics [14, 16, 17, 38]. Because injury occurrence was not measured prospectively, the current data also do not support conclusions regarding injury prediction. The contribution of the study is therefore not the identification of a single screening determinant, but the demonstration that commonly used field tests and single-leg squat FPPA appear to capture only partially overlapping aspects of lower-extremity function in this population.

Limitations

This study has several limitations. First, the cross-sectional design precludes causal or developmental inference and does not permit evaluation of injury prediction. Second, the sample-size calculation was based on an expected correlation of $r = 0.35$, whereas the observed primary correlations were small. The study was therefore not adequately powered to exclude small associations, and the confidence intervals should be considered alongside the nonsignificant p values. Third, participants were recruited by convenience from a single volleyball academy, and the findings may not generalize to male athletes, other sports, symptomatic athletes, or players at different competitive levels.

Fourth, FPPA was measured by a single assessor, and no study-specific intra-rater or inter-rater reliability analysis was available. Consequently, the magnitude of assessor-related measurement error could not be quantified, despite the known assessor and task sensitivity of two-dimensional FPPA measurement [14, 16, 23]. Fifth, hip strength and generalized joint hypermobility were not assessed, although both have been associated with knee frontal-plane angle or peak knee valgus during single-leg squat tasks in physically active females and adolescent female volleyball players [38, 39]. Sixth, the broad age range of the analysed sample (11–18 years) probably included athletes at different stages of biological maturation, but maturation status and time since menarche were not directly measured. This limits interpretation of the exploratory height association. Seventh, all assessments were completed in one session and in a fixed order, with the T-Test administered last; cumulative fatigue or within-session variation may therefore have influenced performance. Finally, FPPA was derived from a two-dimensional single-leg squat assessment and should not be generalized to three-dimensional knee mechanics or to landing, cutting, and high-velocity sport tasks.

Conclusions

FPPA during the single-leg squat was not significantly associated with dynamic balance, agility performance, or ankle dorsiflexion mobility in adolescent female volleyball players after correction for multiple testing. The observed associations were small, although small effects cannot be excluded with the present sample size. These field-based functional tests should therefore not be interpreted as substitutes for task-specific assessment of frontal-plane knee alignment. The positive association between height and FPPA was exploratory, borderline under global multiplicity correction, and model dependent; it does not support causal or maturation-related conclusions. Larger studies incorporating direct biological maturation measures, proximal neuromuscular variables, task-matched movement analysis, and study-specific assessor reliability are needed.

Abbreviations

2D

two-dimensional

3D

three-dimensional

ACL

anterior cruciate ligament
ASIS
anterior superior iliac spine
BMI
body mass index
CI
confidence interval
DKV
dynamic knee valgus
FPPA
frontal plane projection angle
IQR
interquartile range
SD
standard deviation
SEBT
Star Excursion Balance Test
SLS
single-leg squat
VIF
variance inflation factor
WBLT
Weight-Bearing Lunge Test
YBT-LQ
Lower Quarter Y-Balance Test

Declarations

Ethics approval and consent to participate

The study was approved by the Sinop University Human Research Ethics Committee at the meeting dated June 12, 2026, with decision no. 2026/272. The study was conducted in accordance with the principles of the Declaration of Helsinki, and written informed consent was obtained from all participants before participation. Additional written consent was obtained from the parents or legal guardians of participants younger than 18 years.

Consent for publication

Written informed consent for publication of the images was obtained from the participants and their parents or legal guardians.

Competing interests

The authors declare that they have no competing interests.

Use of artificial intelligence-assisted tools

Artificial intelligence-assisted tools were used only for Turkish-to-English translation, language editing, and preparation of Fig. 1 based on the authors' study workflow. The authors reviewed and approved all AI-assisted outputs and take full responsibility for the manuscript.

Funding

No funding was received for this study.

Author Contribution

Conceptualization: SHH, İCB. Methodology: SHH, İCB, BEP. Software: İCB. Validation: BEP. Formal analysis: SHH, BEP. Investigation: SHH, İCB. Resources: SHH, İCB. Data curation: SHH, İCB. Writing – original draft: SHH, İCB. Writing – review & editing: SHH, BEP. Visualization: SHH, İCB. Supervision: SHH, BEP. Project administration: SHH. Funding acquisition: BEP.

Acknowledgement

The authors would like to thank all participants for their valuable contributions to this study.

Data Availability

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

References

1. Wilczyński B, Radzimiński Ł, Sobierajska-Rek A, Zorena K. Association between selected screening tests and knee alignment in single-leg tasks among young football players. *Int J Environ Res Public Health*. 2022;19(11):6719. 10.3390/ijerph19116719.

2. Akoğlu AS, Adın RM, Ada AM, Bayrakçı Tunay V, Erden Z. Comparison of functional movement, balance, vertical jumping, hip strength and injury risk in adolescent female volleyball players with and without chronic ankle instability. *Med (Kaunas)*. 2025;61(9):1547. 10.3390/medicina61091547.
3. Sassi LB, Miguel AC, Serafim TT, de Menezes FS, Martins TB, Okubo R. Understanding ACL injuries in volleyball: A systematic review of epidemiology and risk factors. *Front Sports Act Living*. 2025;7:1675136. 10.3389/fspor.2025.1675136.
4. Chalabiyev N, Basaran S, Deniz V, Adaş Ü, Sariyildiz A. Beyond muscle activation: The role of biomechanical properties of muscles in determining dynamic knee valgus in female volleyball players. *BMC Sports Sci Med Rehabil*. 2026;18(1):249. 10.1186/s13102-026-01681-1.
5. Crowell KR, Nokes RD, Cosby NL. Weak hip strength increases dynamic knee valgus in single-leg tasks of collegiate female athletes. *J Sport Rehabil*. 2021;30(8):1220–3. 10.1123/jsr.2021-0043.
6. Giustino V, Messina G, Patti A, Padua E, Zangla D, Drid P, et al. Effects of a postural exercise program on vertical jump height in young female volleyball players with knee valgus. *Int J Environ Res Public Health*. 2022;19(7):3953. 10.3390/ijerph19073953.
7. Butcher AJ, Ward S, Clissold T, Richards J, Hébert-Losier K. Maturation and biomechanical risk factors associated with anterior cruciate ligament injury: Is there a link? A systematic review. *Phys Ther Sport*. 2024;68:31–50. 10.1016/j.ptsp.2024.06.002.
8. Ramachandran AK, Pedley JS, Moeskops S, Oliver JL, Myer GD, Lloyd RS. Changes in lower limb biomechanics across various stages of maturation and implications for ACL injury risk in female athletes: A systematic review. *Sports Med*. 2024;54(7):1851–76. 10.1007/s40279-024-02022-3.
9. Zoellner A, Whatman C. The association between biological maturity and injury in young females participating in sport: A systematic review. *Phys Ther Sport*. 2026;80:101843. 10.1016/j.ptsp.2025.08.007.
10. Erol M, Gozlukaya Girginer F, Seyhan S, Acar G, Cerit G, Uzun M, et al. Predicting injury risk in young female volleyball players through movement and jump assessments. *Front Public Health*. 2025;13:1658046. 10.3389/fpubh.2025.1658046.
11. Paz GA, de Freitas Maia M, Santana HG, Miranda H, Lima V, Willson JD. Knee frontal plane projection angle: A comparison study between drop vertical jump and step-down tests with young volleyball athletes. *J Sport Rehabil*. 2019;28(2):153–8. 10.1123/jsr.2017-0204.
12. Powers CM. The influence of abnormal hip mechanics on knee injury: A biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40(2):42–51. 10.2519/jospt.2010.3337.
13. Yalfani A, Ahmadi M, Asgarpour A. The effect of kinetic factors of dynamic knee valgus on patellofemoral pain: A systematic review and meta-analysis. *J Bodyw Mov Ther*. 2024;37:246–53. 10.1016/j.jbmt.2023.11.001.
14. Jamaludin NI, Sahabuddin FNA, Rasudin NS, Shaharudin S. The concurrent validity and reliability of single leg squat among physically active females with and without dynamic knee valgus. *Int J Sports Phys Ther*. 2022;17(4):574–84. 10.26603/001c.35706.

15. Willson JD, Davis IS. Utility of the frontal plane projection angle in females with patellofemoral pain. *J Orthop Sports Phys Ther.* 2008;38(10):606–15. 10.2519/jospt.2008.2706.
16. Kingston B, Murray A, Norte GE, Glaviano NR. Validity and reliability of 2-dimensional trunk, hip, and knee frontal plane kinematics during single-leg squat, drop jump, and single-leg hop in females with patellofemoral pain. *Phys Ther Sport.* 2020;45:181–7. 10.1016/j.ptsp.2020.07.006.
17. Erdman A, Loewen A, Dressing M, Wyatt C, Oliver G, Butler L, et al. A 2D video-based assessment is associated with 3D biomechanical contributors to dynamic knee valgus in the coronal plane. *Front Sports Act Living.* 2024;6:1352286. 10.3389/fspor.2024.1352286.
18. Hassan KA, Youssef RSEE, Mahmoud NF, Eltagy H, El-Desouky MA. The relationship between ankle dorsiflexion range of motion, frontal plane projection angle, and patellofemoral pain syndrome. *Foot Ankle Surg.* 2022;28(8):1427–32. 10.1016/j.fas.2022.08.003.
19. Pişirici P, Sakul BU. Investigation of the functional and biomechanical effect of instrument-assisted soft tissue mobilization technique in individuals with asymptomatic dynamic knee valgus: Randomized controlled trial. *J Bodyw Mov Ther.* 2024;39:263–9. 10.1016/j.jbmt.2024.02.040.
20. Zheng Y, Feng R, Hu W, Huang P. Investigation of inter-rater and test-retest reliability of Y balance test in college students with flexible flatfoot. *BMC Sports Sci Med Rehabil.* 2024;16(1):40. 10.1186/s13102-024-00819-3.
21. Wright WC, Aguiar EJ, Winchester LJ, Fedewa MV, Fields AD, Esco MR. The interrelationships of three change of direction ability tests in elite female volleyball players: An exploratory study. *Sports (Basel).* 2025;13(10):339. 10.3390/sports13100339.
22. Cady KP, De Ste Croix M, Deighan M. Effect of sex and lateral ankle sprain history on dorsiflexion range of motion asymmetry during the weight bearing lunge test. *Int J Sports Phys Ther.* 2024;19(6):714–23. 10.26603/001c.117775.
23. Ramirez MM, Negrete R, Hanney WJ, Kolber MJ. Quantifying frontal plane knee kinematics in subjects with anterior knee pain: The reliability and concurrent validity of 2D motion analysis. *Int J Sports Phys Ther.* 2018;13(1):86–93. 10.26603/ijsp.20180086.
24. Asaeda M, Mikami Y, Matsumoto A, Araki T, Ueda K, Maeda N, et al. Biomechanical changes in the lower limb after a quadriceps fatigue task in association with dynamic knee valgus. *Cureus.* 2025;17(7):e87390. 10.7759/cureus.87390.
25. Cereda F. Physical fitness profile of elite female volleyball players: An observational study correlating bioimpedance vector analysis (BIVA) with field-based testing. *J Sci Sport Exerc.* 2025. 10.1007/s42978-025-00340-0.
26. Plisky P, Schwartkopf-Phifer K, Huebner B, Garner MB, Bullock G. Systematic review and meta-analysis of the Y-Balance Test Lower Quarter: Reliability, discriminant validity, and predictive validity. *Int J Sports Phys Ther.* 2021;16(5):1190–209. 10.26603/001c.27634.
27. Zajac B, Olszewski M, Mika A. Influence of protocol variables on outcomes of the star excursion balance test group (SEBT, mSEBT, YBT-LQ) in healthy individuals: A systematic review. *Front Physiol.* 2024;15:1415887. 10.3389/fphys.2024.1415887.

28. Tourillon R, M'Baye M, Smith M. Restoring ankle dorsiflexion range of motion in athletes: An individualized clinical decision-making system. *Front Sports Act Living*. 2025;7:1677383. 10.3389/fspor.2025.1677383.
29. Bulow A, Bellemare A, Anderson JE, Leiter JRS, MacDonald PB, Peeler JD. Lower extremity kinematics of the Y-Balance Test in healthy and ACL-injured adolescent females. *Int J Sports Phys Ther*. 2021;16(2):381–92. 10.26603/001c.21529.
30. Kang MH, Kim GM, Kwon OY, Weon JH, Oh JS, An DH. Relationship between the kinematics of the trunk and lower extremity and performance on the Y-Balance Test. *PM R*. 2015;7(11):1152–8. 10.1016/j.pmrj.2015.05.004.
31. Oliveira JP, Marinho DA, Jacinto P, Sampaio T, Morais JE. Characterization of physical performance and change of direction deficit across age groups in young female volleyball players. *BMC Sports Sci Med Rehabil*. 2025;17(1):209. 10.1186/s13102-025-01264-6.
32. Straub RK, Powers CM. Does the 2D frontal plane projection angle predict frontal plane knee moments during stepping, landing, and change of direction tasks? *Int J Sports Phys Ther*. 2022;17(7):1259–70. 10.26603/001c.39612.
33. Gomes BB, Cardoso R, Fernandes RA, Ferreira RA. Impact of neuromuscular fatigue on dynamic knee valgus in female basketball players. *Life (Basel)*. 2025;15(5):816. 10.3390/life15050816.
34. Lima YL, Ferreira VMLM, de Paula Lima PO, Bezerra MA, de Oliveira RR, Almeida GPL. The association of ankle dorsiflexion and dynamic knee valgus: A systematic review and meta-analysis. *Phys Ther Sport*. 2018;29:61–9. 10.1016/j.ptsp.2017.07.003.
35. Wyndow N, De Jong A, Rial K, Tucker K, Collins N, Vicenzino B, et al. The relationship of foot and ankle mobility to the frontal plane projection angle in asymptomatic adults. *J Foot Ankle Res*. 2016;9(1):3. 10.1186/s13047-016-0134-9.
36. Nakagawa TH, Petersen RS. Relationship of hip and ankle range of motion, trunk muscle endurance with knee valgus and dynamic balance in males. *Phys Ther Sport*. 2018;34:174–9. 10.1016/j.ptsp.2018.10.006.
37. da Costa GV, de Castro MP, Sanchotene CG, Ribeiro DC, de Brito Fontana H, Ruschel C. Relationship between passive ankle dorsiflexion range, dynamic ankle dorsiflexion range and lower limb and trunk kinematics during the single-leg squat. *Gait Posture*. 2021;86:106–11. 10.1016/j.gaitpost.2021.03.015.
38. Jamaludin NI, Sahabuddin FNA, Hanafi H, Shaharudin S. The relationship of hip strength and dynamic knee valgus during single leg squat in physically active females. *J Bodyw Mov Ther*. 2024;40:1238–42. 10.1016/j.jbmt.2024.07.045.
39. Sahin S, Erdman A, McGinley J, Loewen A, Ellis HB, Wyatt C, et al. The relationship between Beighton score and biomechanical risk factors among adolescent, female volleyball players. *Phys Ther Sport*. 2024;70:84–9. 10.1016/j.ptsp.2024.10.003.
40. Sharma R, Khorwal G, Vaibhav V, Singh B, Meshram R. Quadriceps angle measurement in adolescents with short stature: Exploring the relationship between postural alignment and lower

limb mechanics. Cureus. 2023;15(8):e43953. 10.7759/cureus.43953.

41. Froehle AW, Edwards B, Peterson MJ, Meyerson B, Duren DL. Effects of pubertal growth variation on knee mechanics during walking in female and male adolescents. Am J Hum Biol. 2023;35(5):e23853. 10.1002/ajhb.23853.

Figures

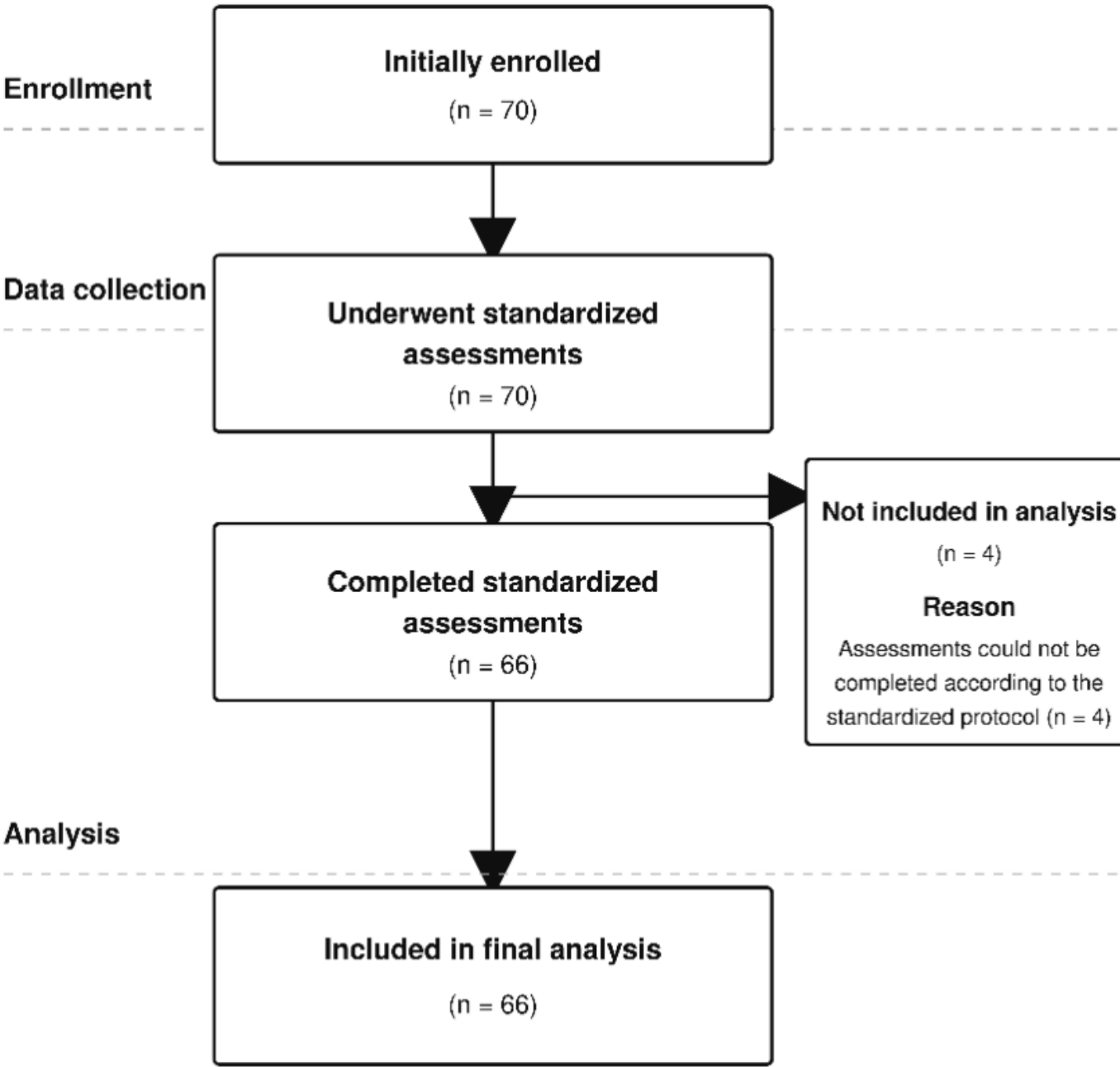


Figure 1



Figure 2

Representative two-dimensional assessment of the frontal plane projection angle during the single-leg squat. FPPA was determined from the alignment of the anterior superior iliac spine, midpoint of the patella, and midpoint between the medial and lateral malleoli using SparkMotion software.



Figure 3

T-Test setup used to assess agility performance. The course consisted of four cones arranged in a T-shaped configuration, and completion time was recorded using a photocell timing system.