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Functional asymmetry in elite female volleyball players: Crossover step blocking landing strategies quantified by symmetry angles

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ABSTRACT

The cross-step block is a key volleyball skill for stopping opponent attacks, yet it places substantial mechanical demands on the lower limbs during landing. This study compared lower-limb biomechanics and inter-limb symmetry between elite and amateur female volleyball players during rightward cross-step block landings.

Thirty-two female players participated in the study: 16 elite and 16 amateur athletes. Three-dimensional kinematics and kinetics during the landing buffering phase were analyzed using two-way repeated-measures ANOVA and one-dimensional statistical parametric mapping (SPM1D). Inter-limb symmetry of discrete variables was evaluated using the Symmetry Angle (SA).

Elite players showed greater ankle dorsiflexion and knee flexion during landing than amateur players. A significant group-by-side interaction was observed for ankle transverse-plane motion, with the elite group showing greater external rotation on the right side. In addition, elite players exhibited larger positive SA values for ankle sagittal-plane moments, indicating greater right-side loading in the dominant limb. By contrast, amateur players showed smaller kinetic asymmetry but also reduced joint excursion and a comparatively constrained landing pattern.

These findings suggest that elite female volleyball players use a task-specific asymmetric landing strategy characterized by greater sagittal-plane joint excursion and dominant-limb braking demands during impact attenuation. Training should emphasize eccentric control, unilateral ankle strength, and multi-planar control during impact attenuation to manage dominant-limb loading while maintaining sport-specific braking demands.

Keywords: Volleyball, Cross step, Block, Functional asymmetry, Injury prevention

INTRODUCTION

Blocking is one of the most important defensive skills in volleyball and often determines whether an attack is successfully stopped. During repeated jump-landing actions, athletes are exposed to high mechanical loads, especially in the lower limbs [20]. These loads become more complex in the cross-step block, which combines lateral movement, rapid deceleration, and landing under time pressure [33]. As a result, this action may increase the risk of ankle and knee injury if landing control is insufficient [5], [14].

Most previous studies on volleyball landing mechanics have focused on bilateral or vertical landing tasks [2]. However, the cross-step block is inherently asymmetric because the two limbs do not perform identical roles. One limb is often more responsible for braking and force absorption, whereas the other contributes more to balance and postural stabilization [33]. This task-specific asymmetry should not automatically be interpreted as poor movement quality; in some cases, it may represent an efficient strategy for performance. At the same time, excessive or poorly controlled asymmetry may increase joint loading and injury risk [2], [33].

Competitive level is an important factor shaping movement strategy [7], [11]. Elite athletes usually show better neuromuscular control, greater joint range of motion, and more efficient force attenuation during landing [27]. Amateur athletes, in contrast, may rely on stiffer movement patterns and reduced coordination flexibility [19]. These differences may be especially important in asymmetric tasks such as the cross-step block, yet this issue has not been sufficiently examined [11].

To quantify inter-limb asymmetry, the Symmetry Angle (SA) may offer advantages over conventional symmetry indices, particularly when paired values approach or cross zero. SA expresses bilateral asymmetry as an angular deviation and applies a correction when the calculated angle exceeds 90° [26] [40]. Therefore, SA provides a useful method for evaluating functional asymmetry in dynamic sports tasks.

The present study aimed to compare lower-limb kinematic and kinetic strategies, as well as inter-limb symmetry, between elite and amateur female volleyball players during the landing buffering phase of a rightward cross-step block. We hypothesized that elite players would demonstrate greater joint excursion and more pronounced functional asymmetry, reflecting a task-specific braking strategy for impact attenuation.

METHODS

Sample size estimation and justification

Drawing on the research of Garcia et al. and the power analysis conducted via G*Power 3.1 (Franz Faul Christian-Albrech, ts-Universität Kiel, Kiel, Germany) indicated that a minimum of 30 participants was required to detect significant effects (Effect size f=0.27, α=0.05, Power=0.8) [10], [38]. To account for potential attrition, 32 female volleyball players were recruited (16 elite and 16 amateur). The elite players (age: 21.75 ± 2.63 years, height: 176.00 ± 4.69 cm, body mass: 66.88 ± 11.09 kg) consisted of 16 female athletes, all of whom were certified as National Second-class athletes. Their technical proficiency was classified according to the 2025 revised edition of the Technical Standards for Athlete Grades issued by the General Administration of Sport of China (www.sport.gov.cn). The amateur players (age: 23.25 ± 1.26 years, height: 167.25 ± 5.32 cm, body mass: 58.08 ± 6.32 kg) comprised 16 participants who had accrued at least one year of volleyball experience.

To reduce experimental bias, all participants wore standardized laboratory footwear (EUR sizes 36–39), ensuring consistent traction and cushioning conditions across subjects. To preserve task-specific consistency, recruitment was limited to front-row players (outside hitters, middle blockers, and opposites) with substantial blocking experience. Liberos were excluded to reduce variability in landing strategies associated with position-specific role demands. Eligible participants were free of significant lower-extremity injury within the previous 6 months and had abstained from strenuous physical activity for at least 24 h before testing. No participant reported musculoskeletal or neurological disorders that might have affected motor performance. All participants were fully informed of the study objectives, experimental procedures, and potential risks, and written informed consent was obtained before participation. The experimental procedures were reviewed and approved by the Institutional Review Board of Ningbo University (TY2025074).

Experimental protocol

All testing was conducted in the Biomechanics Laboratory at Ningbo University. Reflective marker trajectories were recorded using a 10-camera Vicon motion capture system (Oxford Metrics Ltd., Oxford, UK) at 200 Hz. Tri-axial ground reaction forces (GRFs) were collected using two embedded Kistler force platforms (Kistler Instrumente AG, Winterthur, Switzerland), synchronized with the motion capture system at 2000 Hz.

Participants' height, body mass, and basic information were recorded. Before testing, participants changed into standardized tight-fitting sportswear and indoor athletic shoes, then completed a standardized warm-up including dynamic stretching, high-knee drills, and integrative exercises to optimize performance [4], [29]. After the warm-up, movement protocols were reviewed, and familiarization trials were performed within the capture volume to encourage natural movement [37]. The marker points protocol followed the optimized 2392 model [12], [30]. Final adjustments and inspections of clothing and shoes were made to ensure a proper fit and comfort, to avoid interfering with the testing.

Limb dominance was determined by asking participants which limb they preferred to use for single-leg take-off and for braking during volleyball blocking actions. All participants identified the right limb as their preferred limb for these tasks; therefore, the right limb was defined as the dominant side [28], [39]. Participants performed a rightward cross-step block from a standardized defensive stance facing a regulation female volleyball net(www.fivb.com). Two force plates were placed to the right of the starting position. After an auditory cue, participants completed a standardized 3 m approach with minor step-length adjustments; the right and left limbs landed on Force Plates 1 and 2, respectively. Participants were instructed to complete the landing task naturally, and only the period from initial contact to maximum knee flexion was included in the analysis. At least five successful trials were recorded, with 2 min rest between trials to minimize fatigue [8].

A trial was considered valid if it met the following criteria: (1) fluid, habitual execution without slipping or hesitation; (2) participants performed the rightward cross-step block and were required to successfully touch the target ball without committing a foul (The vertical position of the target ball was individualized according to each participant's maximum jumping height measured before testing); (3) clean, isolated foot contact within the capture area of each force plate; and (4) continuous marker trajectories with synchronized kinetic and kinematic signals, confirmed in real time. The experimental workflow is shown in Figure 1.

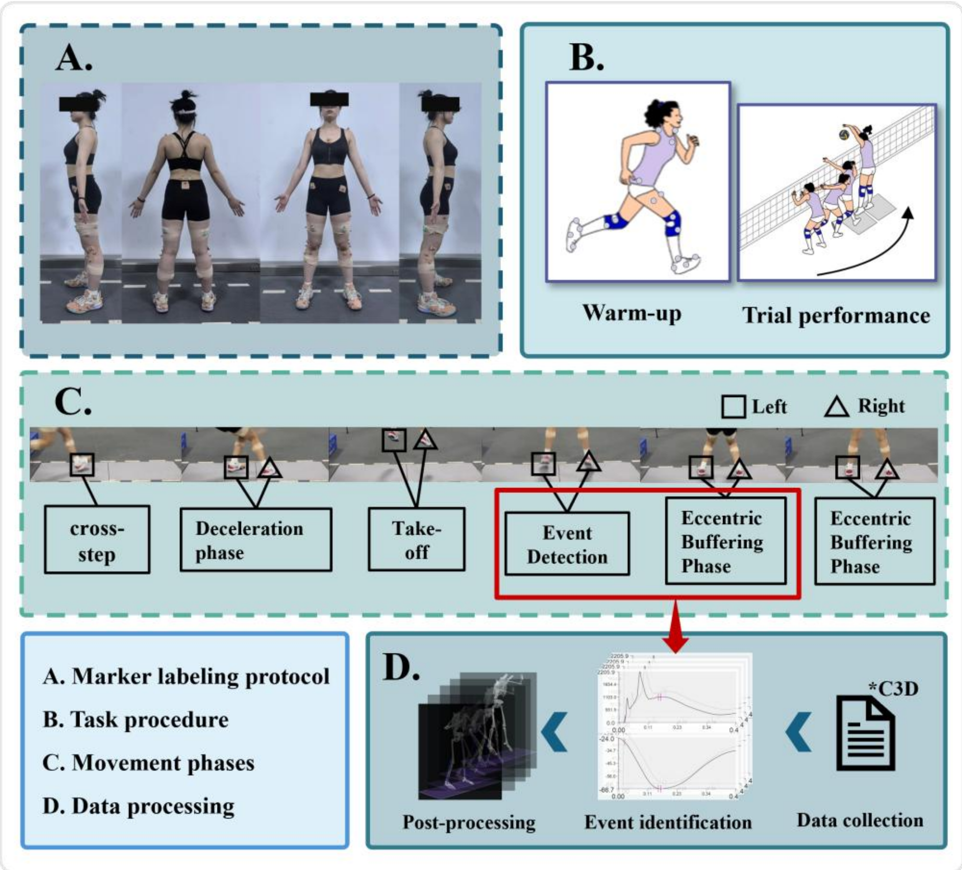

Fig.1. Experimental Procedure

Initial data processing

Based on established biomechanical definitions [8], [32], the landing cushioning phase was defined from initial contact (IC) to the instant of maximum knee flexion, with the peak flexion point determined separately for the left and right knees. All kinematic and kinetic analyses in the present study were restricted to this eccentric buffering phase, which primarily reflects impact absorption and inter-limb loading demands. Biomechanical differences between elite and amateur athletes were assessed by comparing dominant–non-dominant inter-limb asymmetries during this phase [31].

Marker labeling and event identification (e.g., foot strike and maximum knee flexion) were performed in Vicon Nexus (v2.12.1). C3D files were then exported to Visual3D (C-Motion, Germantown, MD, USA). A subject-specific full-body model was constructed and scaled using each participant's static calibration trial. Joint kinematics were calculated using the Visual3D model, and joint kinetics were obtained through inverse dynamics. Kinematic and kinetic data were filtered using a second-order low-pass Butterworth filter at 15 Hz. Time-series data were normalized to 101 points (0%–100% of the analyzed phase) via linear interpolation. Discrete biomechanical variables were calculated separately for each valid trial and then averaged across the five trials for each participant. SA was calculated from the paired left- and right-side values within each trial before the trial-level SA values were averaged. Joint moments are expressed as N·m/BW, whereas ground reaction forces are expressed as multiples of body weight (BW) [16].

Using Visual3D software, joint angles were determined based on a JCS defined by the mediolateral (X; flexion/extension), anteroposterior (Y; adduction/abduction), and longitudinal (Z; internal/external rotation) axes [3].

Joint angles and moments followed these conventions: positive (+) for dorsiflexion, hip flexion, and knee extension; negative (-) for plantarflexion, hip extension, and knee flexion. Frontal and transverse plane movements were defined as positive for abduction and external rotation, and negative for adduction and internal rotation across all joints.

Inter-limb symmetry for discrete variables was quantified using the Symmetry Angle (SA), following the method described by Zifchock et al [40]. Fundamentally, the SA conceptualizes the bilateral data (dominant vs. non-dominant) as a discrete point (X_{right}, X_{left}) within a 2D Cartesian coordinate space. A vector is formed by the line connecting the origin to this point. Any set of values will form an angle (α), which can be quantified as:

$$\alpha = \arctan\left(\frac{X_{left}}{X_{right}}\right) \quad (1)$$

In the case of perfect symmetry (where bilateral values are identical), the coordinate lies precisely on the angle bisector of the Cartesian system, and the resulting vector forms a 45° orientation with the horizontal axis. Any deviation (δ) from this identity line signifies a bilateral asymmetry; consequently, this deviation can be quantified as follows:

$$\delta = 45° - \alpha \quad (2)$$

As the positive and negative symmetry axes bisect the coordinate system, the angular deviation of any coordinate-based vector from these axes is bounded within ±90°. Data points within the gray shaded region exhibit deviation relative to the positive symmetry axis, while others align with the negative symmetry axis (see Figure 2.). Since the maximum deviation is constrained to 90°, the SA is quantified using the following equation:

$$SA = \frac{(45° - \arctan(\frac{X_{left}}{X_{right}}))}{90°} \times 100\% \quad (3)$$

Values falling within the diagonal-lined area of Figure 2 (i.e., $(45° - \arctan(\frac{X_{left}}{X_{right}})) > 90°$) would deviate from the appropriate symmetry axis. Consequently, if such values fall within this hatched region, they must be adjusted using the following equation:

$$SA = \frac{(45° - \arctan\left(\frac{X_{left}}{X_{right}}\right) - 180°)}{90°} \times 100\% \quad (4)$$

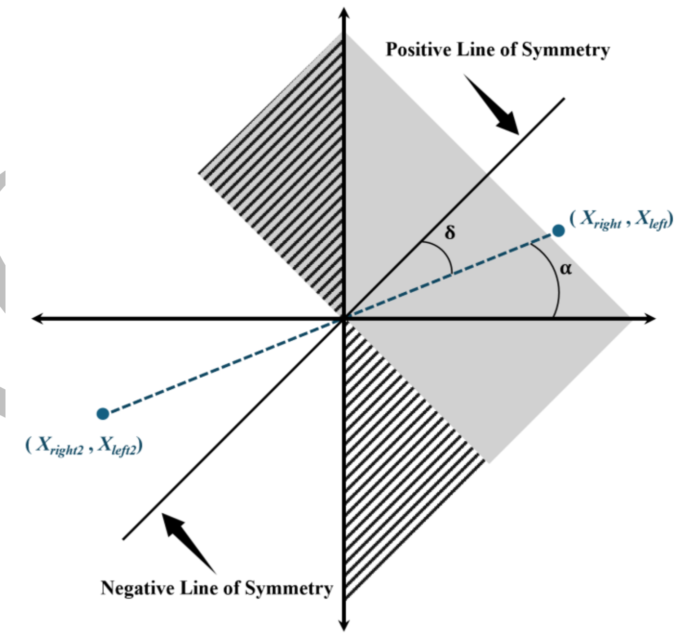

Fig. 2. Symmetry angle quantification Note: The angle formed between the X-axis and the vector composed of any pair of left and right values is defined as δ. Both positive coordinate pairs (Xright, Xleft) and negative pairs (Xright2, Xleft2) exhibit deviations relative to their corresponding axes of symmetry. Data points falling within the gray shaded region reflect a deviation from the positive axis of symmetry. In contrast, values in the remaining

regions are measured against the negative symmetry axis. For data points located within the diagonal-lined region, the corrected SA equation is applied to quantify the degree of asymmetry.

Statistical analysis

Statistical analyses were performed in Python 3.13. Data are presented as Mean (SD). Normality of all waveforms and discrete variables (peaks, SA) was assessed using Shapiro-Wilk tests. Accordingly, parametric or non-parametric One-Dimensional Statistical Parametric Mapping (SPM1D) was applied for time-series analysis. For discrete bilateral variables, a 2 × 2 mixed-design ANOVA was performed, with Group (elite vs. amateur) as the between-subject factor and Side (dominant right vs. non-dominant left) as the within-subject repeated-measures factor. The main effect of Group represented the overall difference between competitive levels, whereas the main effect of Side represented the difference between the dominant and non-dominant limbs. The Group × Side interaction tested whether side-to-side differences varied between the two competitive groups. When a significant interaction was identified, simple-effects analyses were conducted with appropriate adjustments for multiple comparisons. Effect sizes for ANOVA were interpreted using partial eta squared (η^2: 0.01, 0.06, and 0.14 for small, medium, and large, respectively).

Symmetry Angle (SA) was compared between groups using independent t-tests, Welch's t-tests, or Mann-Whitney U tests based on normality and variance homogeneity. For the nine kinematic variables, the Benjamini-Hochberg (FDR) procedure adjusted p-values to control for multiple comparisons. Cohen's d quantified between-group effect sizes (0.2, 0.5, and 0.8). Significance was set at $\alpha = 0.05$.

RESULTS

Given that the crossover step block is characterized by pronounced laterality and sport-specific demands, the main effect of limb side is considered a baseline reflection of the inherent task constraints. Therefore, the present study centers on the main effect of expertise group and the Group × Side interaction [19], [33].

Lower limb joint kinematics

The expertise group had a significant effect on peak ankle plantar/dorsiflexion angle (F (1,30) =4.192, p=0.045, η^2=0.065), with elite athletes showing greater bilateral peak ankle dorsiflexion than amateur athletes. A significant Group × Side interaction was found for ankle internal/external rotation (F (1,30) =6.425, p=0.014, η^2=0.097); post hoc analysis showed greater external rotation in the right ankle than the left in the elite group (p=0.009), and greater right-ankle external rotation in the elite group than in the amateur group (p=0.032).

The expertise group also affected peak knee flexion/extension angle (F (1,30) =10.203, p=0.002, η^2=0.145), with elite athletes exhibiting greater bilateral knee flexion. A significant main effect of side was observed for knee abduction/adduction (F (1,30) =10.830, p=0.002, η^2=0.147), with both groups showing greater right-knee abduction and left-knee adduction.

For the hip, significant side effects were found for peak abduction/adduction (F (1,30) =22.082, p<0.001, η^2=0.269) and internal/external rotation (F (1,30) =8.443, p=0.005, η^2=0.123). In both groups, the left hip showed greater peak abduction and internal rotation than the right.

SPM1D analysis showed a significant expertise-group effect on ankle sagittal-plane trajectories during 10%–40% of the impact attenuation phase, with elite athletes displaying greater bilateral dorsiflexion. A Group × Side interaction was observed for ankle transverse-plane trajectories during 40%–100%, with greater right-ankle external rotation in the elite group. Group effects were also found for knee sagittal-plane trajectories during 20%–100%, with elite athletes showing greater bilateral knee flexion, and for knee frontal-plane trajectories during the first 8%, with elite athletes showing greater bilateral abduction.

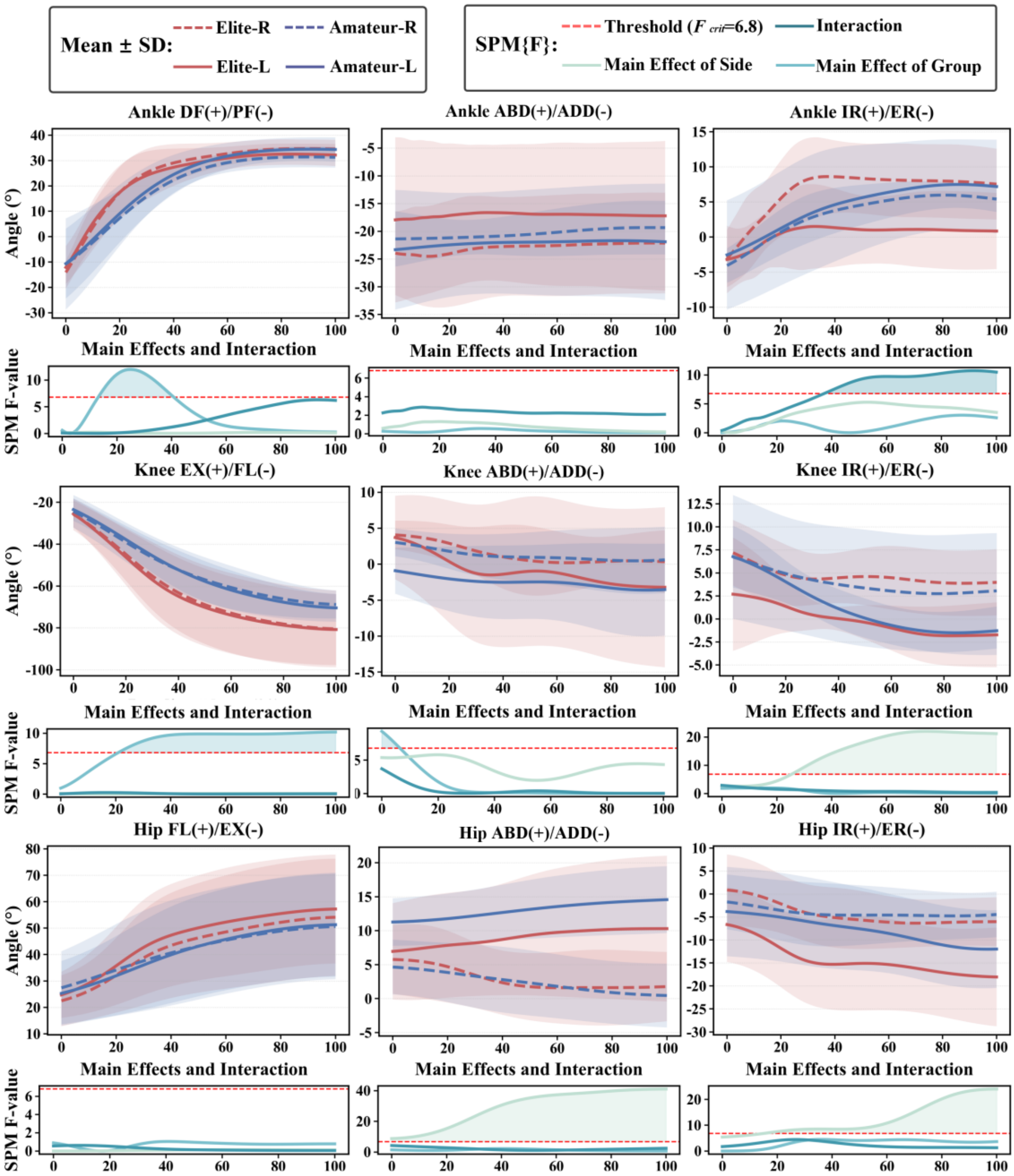

Fig. 3. Three-dimensional kinematic profiles of the ankle, knee, and hip joints during the impact attenuation phase. Note：SPM{F} was employed to analyze the continuous kinematic trajectories during landing.

Tab. 1. Peak joint angles of the ankle, knee, and hip in sagittal, frontal, and transverse planes during the buffering phase of the crossover step block (Mean ± SD, unit: °).

Joint Angle (°)	Plane	Elite Left (SD)	Elite Right (SD)	Amateur Left (SD)	Amateur Right (SD)	ANOVA *p*-level	F (η^2)	*p*-side	F (η^2)	*p*-int	F (η^2)
Ankle	Sagittal Plane	32.96 (4.29)	35.17 (3.73)	28.11 (21.71)	23.96 (21.94)	**0.045***	4.192 (0.065)	0.805	0.061 (0.001)	0.421	0.656 (0.011)
	Frontal Plane	-18.71 (14.98)	-25.62 (8.58)	-25.34 (10.76)	-22.63 (3.77)	0.484	0.495 (0.008)	0.420	0.660 (0.011)	0.068	3.459 (0.054)
	Transverse Plane	-0.70 (9.00)	8.48 (7.70)	5.03 (11.85)	2.79 (6.59)	0.992	0.001 (0.001)	0.129	2.371 (0.038)	**0.014***	6.425 (0.097)
Knee	Sagittal Plane	-80.78 (17.49)	-80.46 (18.91)	-70.43 (6.79)	-68.83 (6.91)	**0.002***	10.203 (0.145)	0.781	0.078 (0.001)	0.854	0.034 (0.001)

	Frontal Plane	-3.04 (12.63)	4.05 (4.21)	-3.36 (7.17)	2.36 (4.92)	0.616	0.254 (0.004)	**0.002***	10.380 (0.147)	0.731	0.119 (0.002)
	Transverse Plane	2.08 (6.61)	6.88 (4.83)	6.13 (4.81)	5.38 (6.61)	0.436	0.615 (0.010)	0.217	1.555 (0.025)	0.093	2.914 (0.046)
Hip	Sagittal Plane	57.55 (21.49)	54.40 (23.10)	51.30 (20.30)	50.60 (20.62)	0.352	0.881 (0.014)	0.720	0.130 (0.002)	0.819	0.052 (0.001)
Hip	Frontal Plane	10.81 (11.30)	3.90 (7.97)	14.71 (5.01)	2.83 (6.27)	0.483	0.450 (0.008)	**<0.001***	22.082 (0.269)	0.218	1.551 (0.025)
Hip	Transverse Plane	-16.87 (13.96)	-3.60 (11.09)	-9.05 (13.37)	-5.23 (7.49)	0.297	1.108 (0.018)	**0.005***	8.443 (0.123)	0.113	2.588 (0.041)

Note: Statistical significance $p<0.05$ is denoted by boldface type and an asterisk (*).

Lower limb joint kinetics

For peak ankle plantarflexion/dorsiflexion moment, a significant Group × Side interaction was found ($F(1,30)=5.552$, $p=0.022$, $\eta^2=0.084$). The elite group showed a greater plantarflexion moment in the right ankle than in the left ($p=0.001$), whereas no side difference was observed in the amateur group ($p=0.198$). The expertise group also affected ankle adduction/abduction moments ($F(1,30)=8.740$, $p=0.004$, $\eta^2=0.127$). Significant side effects were observed for ankle adduction/abduction moment ($F(1,30)=142.203$, $p<0.001$, $\eta^2=0.703$) and ankle internal/external rotation moment ($F(1,30)=125.580$, $p<0.001$, $\eta^2=0.677$). The elite group showed a greater right-ankle adduction moment than the left, whereas the amateur group showed greater right-ankle abduction and internal rotation moments.

For peak knee flexion/extension moment, a significant Group × Side interaction was found ($F(1,30)=4.664$, $p=0.035$, $\eta^2=0.072$). The elite group showed a greater right-knee extension moment than the left ($p<0.001$), while no side difference was observed in the amateur group ($p=0.193$). For knee internal/external rotation moment, a significant Group × Side interaction was also observed ($F(1,30)=12.356$, $p=0.001$, $\eta^2=0.171$), with the elite group showing side-specific asymmetry ($p=0.007$) and a greater left-knee external rotation moment than the amateur group ($p=0.04$).

For hip adduction/abduction moment, a significant Group × Side interaction was identified ($F(1,30)=6.954$, $p=0.011$, $\eta^2=0.104$). In the elite group, the right-hip abduction moment was greater than the left ($p=0.006$), and the elite right-hip abduction moment was greater than the peak hip adduction moment in the amateur group ($p<0.001$).

For anterior-posterior GRF, a significant Group × Side interaction was found ($F(1,30)=6.812$, $p=0.011$, $\eta^2=0.102$). In the elite group, the right side showed posterior force and the left side anterior force ($p=0.002$); right-side GRF was also greater in the elite than in the amateur group ($p<0.001$). A significant side effect was found for mediolateral GRF ($F(1,30)=791.562$, $p<0.001$, $\eta^2=0.929$), with the right-limb lateral GRF greater than the left-limb medial GRF in both groups. Vertical GRF was affected by both group ($F(1,30)=10.343$, $p=0.002$, $\eta^2=0.147$)

and side ($F(1,30)=5.589$, $p=0.021$, $\eta^2=0.085$), with higher values in the amateur group and on the right side.

SPM1D analysis of kinetics showed a Group × Side interaction for ankle sagittal-plane moments during 4%–38% of impact attenuation, with elite athletes showing greater right- than left-ankle plantarflexion moments. Group effects were also observed for ankle frontal-plane moments during the initial 50% and transverse-plane moments during 1%–38%, with elite athletes showing greater right-ankle plantarflexion/internal-rotation moments and greater left-ankle external-rotation moments than amateur athletes.

For the knee, a significant Group × Side interaction was observed in transverse-plane moments during 1%–75%, with elite athletes showing right-knee internal and left-knee external rotation moments, whereas amateur athletes showed the opposite pattern; the elite right-knee internal-rotation moment was significantly greater. At the hip, a Group × Side interaction was found during 5%–20%, with elite athletes showing greater right- than left-hip abduction moments. A terminal group effect was observed for hip transverse-plane moments during 97%–100%, with elite athletes showing greater bilateral external-rotation moments.

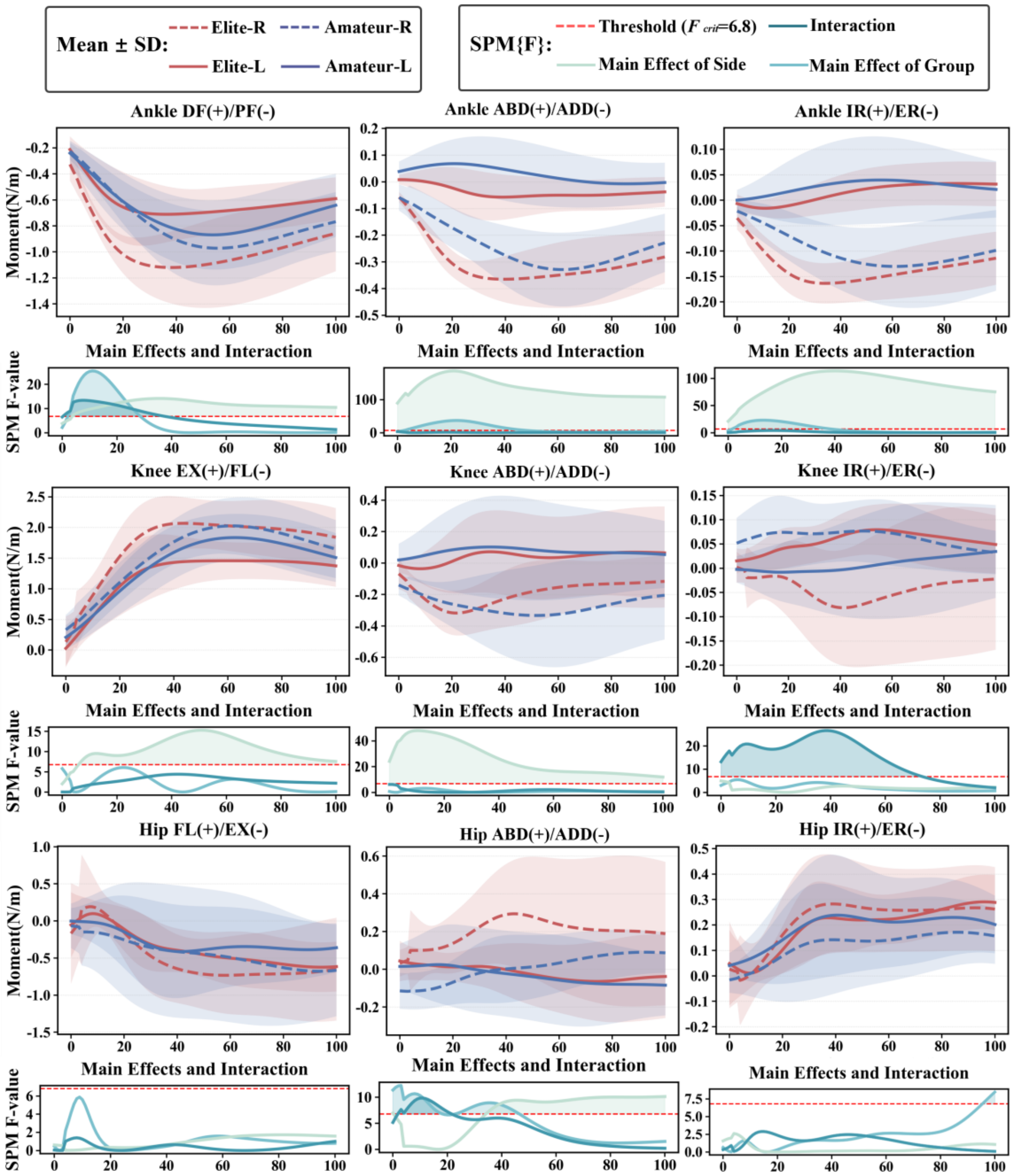

Fig. 4. Tri-planar kinetic profiles of the ankle, knee, and hip joints during the impact attenuation phase. Note：The kinetic data during the impact attenuation phase were analyzed using SPM{F}.

Tab. 2. Peak joint moments of the ankle, knee, and hip in three anatomical planes and peak ground reaction forces (GRF) during the buffering phase of the crossover step block (Mean ± SD).

Joint Moment (N·m/kg)	Plane	Elite Left (SD)	Elite Right (SD)	Amateur Left (SD)	Amateur Right (SD)	ANOVA *p*-level	F (η_2)	*p*-side	F (η_2)	*p*-int	F (η_2)
Ankle	Sagittal Plane	-0.78 (0.21)	-1.18 (0.30)	-0.91 (0.29)	-0.99 (0.29)	0.672	0.181 (0.003)	**0.001**	11.927 (0.165)	**0.022**	5.552 (0.084)
	Frontal Plane	-0.07 (0.09)	-0.41 (0.09)	0.04 (0.15)	-0.34 (0.14)	**0.004**	8.740 (0.127)	**<0.001**	142.203 (0.703)	0.550	0.362 (0.006)
	Transverse Plane	0.03 (0.05)	-0.19 (0.03)	0.04 (0.01)	-0.14 (0.08)	0.106	2.692 (0.043)	**<0.001**	125.580 (0.677)	0.242	1.398 (0.023)
Knee	Sagittal Plane	1.73 (0.31)	2.33 (0.41)	1.93 (0.04)	2.09 (0.47)	0.871	0.027 (0.001)	**<0.001**	14.274 (0.192)	**0.035**	4.664 (0.072)
	Frontal Plane	0.10 (0.33)	-0.32 (0.14)	0.10 (0.36)	-0.40 (0.31)	0.549	0.363 (0.006)	**<0.001**	38.146 (0.388)	0.603	0.273 (0.005)
	Transverse Plane	0.09 (0.07)	-0.05 (0.19)	0.01 (0.13)	0.10 (0.10)	0.279	1.191 (0.019)	0.415	0.674 (0.011)	**0.001**	12.356 (0.171)

Hip	Sagittal Plane	-0.73 (0.42)	-0.65 (1.17)	-0.49 (0.67)	-0.54 (1.00)	0.422	0.653 (0.011)	0.936	0.006 (0.001)	0.763	0.092 (0.002)
	Frontal Plane	0.01 (0.29)	0.39 (0.34)	-0.03 (0.30)	-0.03 (0.24)	**0.003**	9.397 (0.135)	**0.010**	7.059 (0.105)	**0.011**	6.954 (0.104)
	Transverse Plane	0.34 (0.14)	0.31 (0.22)	0.03 (0.23)	0.19 (0.22)	0.145	2.179 (0.035)	0.226	1.495 (0.024)	0.432	0.625 (0.010)
GRF	Anterior-posterior GRF	0.15 (0.49)	-0.32 (0.53)	0.33 (0.48)	0.47 (0.33)	**<0.001**	17.880 (0.229)	1.931	0.170 (0.031)	**0.011**	6.812 (0.102)
	Medio-lateral GRF	-0.27 (0.07)	0.45 (0.11)	-0.33 (0.10)	0.46 (0.13)	0.359	0.853 (0.014)	**<0.001**	791.562 (0.929)	0.171	1.920 (0.031)
	Vertical GRF	1.85 (0.78)	2.31 (0.54)	2.46 (0.78)	2.81 (0.83)	**0.002**	10.343 (0.147)	**0.021**	5.589 (0.085)	0.723	0.126 (0.002)

Note: A two-way ANOVA was conducted to analyze the tri-planar kinetic profiles of the ankle, knee, and hip joints during the impact attenuation phase. Significant differences ($p < 0.05$) are denoted by bold text with an asterisk (*).

Inter-limb symmetry

No significant between-group differences were found in kinematic SA values for the ankle, knee, or hip. In contrast, kinetic SA differed between groups for ankle plantar/dorsiflexion moment ($t=3.29$, $p=0.023$, $d=1.163$). The elite group showed a positive bias (14.69 ± 14.09), whereas the amateur group showed a near-symmetrical pattern (-0.65 ± 12.21). No other kinetic SA variables differed significantly between groups ($p>0.05$).

Tab. 3. Comparison of Symmetry Angle

Joint	Plane	Elite Mean (SD)		Amateur Mean (SD)		*p*-value		Cohen's d	
		Kinematic	Kinetic	Kinematic	Kinetic	Kinematic	Kinetic	Kinematic	Kinetic
Ankle	SP	2.14(2.20)	14.69(14.09)	-2.81(6.69)	-0.65(12.21)	0.132	**0.023**	0.994	1.163
	FP	9.89(36.29)	43.63(56.22)	4.16(22.66)	18.32(69.26)	0.101	0.509	0.189	0.401
	TP	18.73(17.95)	-16.35(70.59)	2.67(39.65)	-19.20(54.59)	0.102	0.720	0.526	0.045
Knee	SP	-0.34(7.22)	9.12(7.92)	0.25(7.16)	2.55(7.16)	0.777	0.090	-0.082	0.868
	FP	13.31(37.90)	-39.58(32.92)	-18.5(51.91)	-15.67(47.69)	0.128	0.304	0.700	-0.584
	TP	12.58(21.61)	-7.21(44.59)	-1.99(41.61)	17.59(39.82)	0.339	0.304	0.439	-0.586
Hip	SP	-3.24(4.13)	20.57(31.89)	-1.13(4.26)	0.80(40.27)	0.128	0.509	-0.503	0.544
	FP	-7.30(38.77)	20.36(31.12)	-27.67(22.10)	0.35(48.45)	0.537	0.304	0.632	0.491
	TP	-25.33(30.32)	-8.02(28.19)	-34.94(46.17)	-1.65(29.23)	0.553	0.720	0.246	-0.221

Note. Kinematic and Kinetic SA values of the bilateral ankle, knee, and hip joints in elite and amateur groups. SP, Sagittal plane; FP, Frontal plane; TP, Transverse plane. Raw P-values were adjusted using the Benjamini-Hochberg procedure to control for false discovery rates. Significant findings ($p < 0.05$) are denoted by bold typeface and an asterisk (*)

DISCUSSION

Kinematic variations

The present study showed that elite players landed with greater ankle dorsiflexion and knee flexion than amateur players during the buffering phase. This pattern reflects a deeper cushioning strategy characterized by greater sagittal-plane joint excursion during landing [11]. In contrast, the amateur group displayed a more constrained landing pattern, which is consistent with a stiffer and less adaptable movement strategy. Such reduced joint excursion indicates a comparatively constrained or stiffer landing pattern [15], [24].

A notable finding was the larger right-side external rotation in the elite group during the later landing buffering phase. Rather than representing a simple movement error, this may reflect a task-specific adjustment that contributes to controlling horizontal momentum and managing inter-limb loading during impact attenuation [11], [18]. In the cross-step block, athletes must decelerate lateral momentum within a constrained landing space. Elite players may therefore use controlled frontal- and transverse-plane adjustments to meet the braking demands of the task [25].

The greater knee abduction observed in elite athletes during the early landing phase should also be interpreted in the context of the movement task. Although knee abduction is often discussed as a potential injury-related pattern, in this setting it may function as part of a coordinated braking strategy combined with deep flexion. This combination reflects a task-specific braking configuration involving both sagittal- and frontal-plane joint motion [17]. Nevertheless, repeated exposure to such asymmetrical loading may still increase cumulative stress on the dominant limb over time [1], [34]. Further research incorporating joint loading estimates, muscle activity, and prospective injury monitoring is needed to clarify its mechanical and clinical significance.

Kinetic variations

Kinetic results indicated that elite players adopted a more task-specific braking strategy. Elite athletes showed greater ankle and knee moments, particularly on the dominant side, indicating greater eccentric braking demands during landing [6], [22]. These findings indicate greater dominant-limb joint moment demands in the elite group. The amateur group showed lower joint moments and smaller directional changes, consistent with a comparatively constrained braking pattern [23], [35].

The ankle findings were especially important. Elite athletes demonstrated greater dominant-side plantarflexion moment demand and a clear asymmetry in sagittal-plane kinetics. This pattern implies that the dominant ankle played a major role in resisting forward and downward momentum during landing [14]. Such a strategy may be beneficial for performance because it supports rapid stabilization after lateral approach. However, it may also increase fatigue-related overload in the dominant lower limb if repeated frequently without adequate strength and recovery [9].

Ground reaction force data further reflected the task-specific demands of the crossover block [33]. The elite group showed greater posterior braking-force demands but lower peak vertical ground reaction force than the amateur group, indicating distinct horizontal and vertical loading characteristics [31]. However, these findings do not establish superior overall cushioning because loading rate, impulse, and joint-specific energy absorption were not assessed.

Symmetry differences

The symmetry results suggest that bilateral equality is not necessarily the optimal strategy for this task. In kinematic variables, no major group differences were found in SA values, indicating that both groups adopted broadly similar inter-limb joint-angle patterns. However, kinetic SA showed a clear difference in ankle sagittal-plane moments, with elite players presenting a stronger positive bias. This indicates that the dominant limb carried a greater proportion of braking demand during landing.

This finding supports the idea that functional asymmetry can be beneficial in highly specialized sport actions [34]. In the cross-step block, the two limbs do not serve identical roles. One limb may act as the primary braking limb, while the other contributes more to balance and postural control [13]. For elite athletes, this division of labor may improve performance efficiency and help maintain stability in a fast and constrained movement environment [21].

At the same time, the observed asymmetry may have clinical implications. Repeated dominant-limb loading may increase the risk of overuse injury, especially in the ankle and lower-leg musculature. Therefore, asymmetry should not be viewed simply as either good or bad. Instead, it should be interpreted relative to task demands, performance requirements, and cumulative training load [21], [36].

Limitations and Future Directions

Although the approach distance and task instructions were standardized, approach velocity and jump height were not quantified, limiting our ability to confirm comparable task-execution characteristics between groups. In addition, the lack of EMG data and potential marker-related artifacts may affect interpretation. Future studies should include larger cohorts across competitive levels, integrate muscle synergy analysis, and examine trunk–arm coordination to clarify mechanisms for reducing joint shear and improving sport-specific conditioning.

CONCLUSION

Elite female volleyball players used a deeper landing strategy during the rightward cross-step block, characterized by greater ankle dorsiflexion, greater knee flexion, and stronger dominant-side braking demand. Amateur players showed a comparatively constrained or stiffer landing pattern. The results suggest that functional asymmetry is a task-specific feature of this landing maneuver, but may also increase dominant-limb loading. Training should therefore balance performance development with strategies to manage fatigue and reduce overuse risk.

Statements and Declarations

Ethics approval and consent to participate: Prior to the study, all participants provided written informed consent following a comprehensive explanation of the objectives, procedures, and associated risks. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Ningbo University (TY2025074).

Consent to participate: Informed consent was obtained from all individual participants included in the study. The study was conducted in accordance with ethical guidelines, with all participants (or their legal guardians) fully apprised of the research protocols and risks.

Consent for publication: Not applicable.

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Abbreviations

SA, Symmetry Angle

ACL, Anterior Cruciate Ligament

CoM, center of mass

SI, Symmetry Index

PF, Plantarflexion

DF, Dorsiflexion

EX, Extension

ABD, Abduction

ADD, Adduction

ER, External rotation

IR, Internal rotation

FL, Flexion

SP, Sagittal plane

FP, Frontal plane

TP, Transverse plane

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