Effects of Biomechanical Characteristics of Different Landing Modes in Basketball Players on Ankle Joint Injuries

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Abstract

Objective: To explore the effects of biomechanical characteristics of different landing patterns on ankle injuries in basketball players. Methods: Forty-two male national second-level basketball players were recruited as participants. The landing patterns were classified as forefoot landing after a running stop and two-leg takeoff (abbreviated as "forefoot landing") and rearfoot landing after a running stop and two-leg takeoff (abbreviated as "rearfoot landing"). A motion capture system and a three-dimensional force platform were used to collect and analyze the angles of the three joints (hip, knee, and ankle) at the instant of contact (IC), the peak joint angles during the cushioning phase, and the peak ground reaction force (GRF) during the cushioning phase under the two landing modes. Results: Compared with the rearfoot landing mode, the forefoot landing mode showed greater angles of hip flexion, hip adduction, knee flexion, knee varus, ankle dorsiflexion, and ankle internal rotation at IC ($P<0.05$). During the cushioning phase, the forefoot landing mode showed greater peak angles of ankle plantarflexion, hip flexion, and ankle inversion, whereas the rearfoot landing mode showed greater peak angles of ankle dorsiflexion, hip abduction, knee extension, and ankle internal rotation ($P<0.05$). Compared with the rearfoot landing mode, the forefoot landing mode showed a greater anterior peak GRF and a smaller lateral peak GRF ($P<0.05$). Conclusion: Different landing patterns in basketball players differ in joint angles at IC, peak joint angles during the cushioning phase, and peak GRF during the cushioning phase. The forefoot landing mode is more prone to ankle injury. Therefore, basketball players may appropriately strengthen training in the rearfoot landing mode during daily training, enhance strength training of relevant lower-limb muscle groups, and emphasize cushioning technique training during landing to further prevent ankle injuries.

Full Text

Effects of Biomechanical Characteristics of Different Landing Modes in Basketball Players on Ankle Joint Injuries

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Abstract: Objective To explore the effects of the biomechanical characteristics of different landing modes in basketball players on ankle joint injuries. **Methods** Forty-two male second-level basketball players were recruited as experimental subjects. The landing modes were divided into running sudden-stop take-off with both legs followed by forefoot landing (referred to as "forefoot landing") and running sudden-stop take-off with both legs followed by rearfoot landing (referred to as "rearfoot landing"). A motion-capture system and a three-dimensional force platform were used to collect and analyze the angles of the three joints (hip, knee, and ankle) at the instant of contact (IC) under the two landing modes, the peak joint angles during the cushioning phase, and the peak ground reaction force (GRF) during the cushioning phase. **Results** Compared with the rearfoot-landing mode, the forefoot-landing mode showed larger IC angles of hip flexion, hip adduction, knee flexion, knee varus, ankle dorsiflexion, and ankle internal rotation ($P < 0.05$); during the cushioning phase, the forefoot-landing mode showed larger peak angles of ankle plantarflexion, hip flexion, and ankle inversion, whereas the rearfoot-landing mode showed larger peak angles of ankle dorsiflexion, hip abduction, knee extension, and ankle internal rotation ($P < 0.05$); compared with the rearfoot-landing mode, the forefoot-landing mode had a larger peak forward GRF and a smaller peak outward GRF ($P < 0.05$). **Conclusion** Different landing modes in basketball players differ in IC joint angles, peak joint angles during the cushioning phase, and peak GRF during the cushioning phase. The forefoot-landing mode is more likely to cause ankle joint injury. Therefore, in daily training, basketball players may appropriately strengthen training in the rearfoot-landing mode, enhance strength training of lower-limb-related muscle groups, and emphasize cushioning technique training during landing, so as to further prevent ankle joint injuries.

Keywords: basketball players; landing mode; biomechanics; ankle joint injury; forefoot landing; rearfoot landing

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Abstract: Objective To explore the effects of biomechanical characteristics of different landing modes on ankle joint injuries in basketball players. **Methods** A total of 42 second-class male basketball athletes were recruited as experimental subjects. According to their landing mode, they were divided into two types: running and sudden stop with both legs taking off and landing on the forefoot (referred to as forefoot landing)

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and running sudden-stop with double-leg takeoff and hindfoot landing (referred to as hindfoot landing). A motion-capture system and a three-dimensional force platform were used to collect and analyze the angles of the three joints (hip, knee, and ankle) at the instant of contact (IC) under the two landing modes, as well as the peak joint angles during the cushioning phase and the peak ground reaction force (GRF) during the cushioning phase. **Results** Compared with the hindfoot landing mode, the forefoot landing mode exhibited greater hip flexion, hip adduction, knee flexion, knee varus, ankle dorsiflexion, and ankle inversion angles at IC ($P < 0.05$). During the cushioning phase, the forefoot landing mode exhibited greater peak angles in ankle plantarflexion, hip flexion, and ankle inversion, whereas the hindfoot landing mode demonstrated greater peak angles in ankle dorsiflexion, hip abduction, knee extension, and ankle inversion ($P < 0.05$). Compared with the hindfoot landing mode, the forefoot landing mode had a larger peak GRF in the anterior direction and a smaller peak GRF in the lateral direction ($P < 0.05$). **Conclusion** Different landing modes in basketball players differ in IC joint angles, peak joint angles during the cushioning phase, and peak GRF during the cushioning phase, and ankle injuries are more likely to occur in the forefoot landing mode. Therefore, in daily training, basketball players may appropriately strengthen training in the hindfoot landing mode, enhance strength training of lower-limb-related muscles, and emphasize cushioning-skill training during landing, so as to further prevent ankle injuries.
Key words: basketball player; landing mode; biomechanics; ankle joint injury; forefoot landing; hindfoot landing

Basketball is a highly competitive and confrontational sport. During competition, athletes must frequently jump, stop suddenly, and turn, and these movements are accompanied by different forms of landing[1-2]. Because basketball players generally have greater muscle mass and body weight, they are subjected to large impact forces during landing and are highly prone to sports injuries, which can affect the course of a game and may even end an athlete's competitive career[3]. Surveys show that the vast majority of sports injuries occur during the landing phase in basketball players, with knee- and ankle-joint injuries being the most common[4-6]. At the moment of landing, athletes coordinate the joints of the lower limbs to adjust landing posture, thereby absorbing ground impact forces and reducing the risk of joint injury. Therefore, actively investigating the effects of different landing modes on athletes' joint injuries is of great significance. At present, existing studies mainly focus on knee injuries in basketball players, whereas relatively little attention has been paid to ankle injuries[7-8]. Accordingly, this study attempted to analyze the influence of the biomechanical characteristics of different landing modes in basketball players on ankle injury, with the aim of quantifying the biomechanical differences between forefoot landing and hindfoot landing, clarifying the loading characteristics of the ankle joint under different landing modes, and providing a scientific basis for precise prevention of ankle injury and training guidance for basketball players.

1 Subjects and Methods

1.1 Study Participants

Participants were recruited through promotional posters. The inclusion criteria were as follows: male basketball players with a Level II athlete rating; height > 180 cm; age ≥ 18 years; good physical health; no sports injuries; no history of lower-limb sports injury; and proficient mastery of the two experimental test movements. A total of 42 male Level II basketball players were ultimately recruited as participants, aged 18–25 years, with a mean age of (22.52 ± 0.82) years; height 181-187 cm, with a mean height of (183.98 ± 1.20) cm; body mass index 19-23 kg/m^2, with a mean of (21.67 ± 0.59) kg/m^2. In terms of landing habit, 25 participants habitually landed on the forefoot and 17 on the hindfoot. This study was approved by an ethics committee. All participants were informed of the experimental procedures and signed informed consent forms.

1.2 Methods

1.2.1 Pre-experimental Preparations and Instruments

Before the experiment, the research staff measured and registered each participant' s name, height, body mass, lower-limb length, knee width, ankle width, and other information, and entered these data into the experimental equipment system. After information collection, participants changed into standardized sportswear and laboratory test shoes, and ensured that they were not wearing hats, glasses, jewelry, or other items. They then performed warm-up exercises, including: dynamic warm-up (10 min): high-knee running (3 sets $\times$ 30 s), lunge leg presses (3 sets $\times$ 20 s on each side), ankle-joint circumduction (3 sets $\times$ 15 repetitions on each side), and knee-joint circumduction (3 sets $\times$ 15 repetitions on each side); sport-specific movement practice (15 min): in an area outside the force platform, one basketball specialist coach demonstrated the movements of "running sudden-stop double-leg takeoff—forefoot landing" and "running sudden-stop double-leg takeoff—hindfoot landing." The movement standards were clarified: for forefoot landing, at the instant of ground contact, the forefoot (metatarsal heads 1–5) must contact the ground first and the hindfoot (heel) must be off the ground; for hindfoot landing, at the instant of ground contact, the hindfoot (heel) must contact the ground first and the forefoot must be off the ground. Participants practiced each type of movement 10 times, until

The coach confirmed that the movement met the standard and that the participant could repeat it stably.

This study used internationally adopted biomechanical experimental equipment: a Vicon Vantage V16 infrared motion-capture system (Vicon, UK), equipped with 16 infrared cameras. The camera sampling frequency was set to 200 Hz; the capture volume covered a 3 m × 5 m experimental area; and the positioning accuracy reached 0.1 mm. The system was used to collect joint-position and angle data during participants' movements. Two Kistler 9287B three-dimensional force plates (Kistler, Switzerland), with platform dimensions of 400 mm × 600 mm, were used. The sampling frequency was set to 1,000 Hz, the measuring range was $±$5,000 N, and the resolution was 0.1 N. These force plates were used to collect ground reaction force (GRF) data during landing. Before the experiment, the force plates were statically calibrated using Kistler' s dedicated calibration tool by loading a 50 kg standard weight, ensuring that the force-value error was <0.5%. Other auxiliary tools included Vicon Nexus 2.6 data acquisition and analysis software for integrating motion-capture and force-plate data, Kistler Bioware 5.0 force-data analysis software, dedicated reflective markers (diameter 14 mm, height 8 mm, reflectivity $ $90%), and standardized experimental shoes (brand: ASICS; model: GEL-Basketball 360; outsole hardness: 60 ± 5 Shore A).

1.2.2 Experimental Procedure and Experimental Data Collection

1) Static data acquisition

Reflective markers for the infrared motion-capture system were affixed and secured to the participants' bodies. With reference to the required positions of bony surface landmarks, 20 infrared reflective markers were selected as follows: left and right anterior superior iliac spines and posterior superior iliac spines (4); lateral midpoints of the left and right thighs (2); medial and lateral femoral condyles of the left and right legs (4); lateral midpoints of the left and right shanks (2); medial malleoli of the left and right tibiae and lateral malleoli of the left and right fibulae (4); centers of the left and right second and third metatarsophalangeal joints (2); and left and right calcanei (2). The participants stood with both feet on two force plates, looking straight ahead, with the shoulders and back upright and both arms abducted. Using the static calibration module of Vicon Nexus 2.6 software, the operator automatically identified all reflective markers under the participant' s static condition. A personalized lower-limb skeletal model was established based on the participant' s basic information, such as lower-limb length. The model fitting error was required to be <1 mm; if the error exceeded the standard, the marker positions were readjusted and calibration was repeated.

2) Dynamic data acquisition

Participants began their approach run from the starting line. Running speed was controlled at 3.0 ± 0.5 m/s and adjusted in real time using feedback from the "speed monitoring module" of the Vicon system. When they reached the force-plate area, both feet stepped onto the force plates simultaneously and stopped abruptly, with a braking distance <0.5 m. They then jumped vertically upward, with a flight height $ $30 cm as monitored in real time by the system. During landing, the forefoot-landing pattern was used: the forefoot contacted the ground first and the rearfoot was off the ground. The two feet landed separately on the two force plates, with one force plate corresponding to each foot. After each trial, the participant returned to the starting line and rested for 30 s. Testing was repeated three times. The coefficients of variation for flight height and approach-run speed across the three trials were required to be <10%; if this standard was not met, one additional trial was added.

Rearfoot landing: the movement procedure was the same as for forefoot landing, except that the landing pattern was changed to rearfoot landing, in which the rearfoot contacted the ground first and the forefoot was off the ground. Testing was likewise repeated three times, and the three trials meeting the consistency criteria were selected for subsequent analysis.

1.3 Criteria for Determining Landing Pattern

Landing pattern was determined from the vertical displacement, namely the Z-axis coordinate, of the calcaneus marker and the second metatarsal marker recorded by the Vicon system.

Forefoot landing: at the instant of contact (IC), the Z-axis coordinate of the second metatarsal marker first reached the height of the force-plate surface, indicating initial contact, while the Z-axis coordinate of the calcaneus marker remained above the surface, indicating no contact.

Rearfoot landing: at IC, the Z-axis coordinate of the calcaneus marker first reached the height of the force-plate surface, indicating initial contact, while the Z-axis coordinate of the second metatarsal marker remained above the surface, indicating no contact. Two experimenters made independent judgments. The inter-rater agreement had a Kappa value >0.85. In cases of disagreement, confirmation was reached through consultation using slow-motion video of the movement.

1.4 Data Processing

1.4.1 Data Preprocessing Vicon Nexus 2.6 software was used to process the raw data: invalid frames caused by reflective-marker occlusion were removed, and missing data were completed using linear interpolation, with a missing rate <5%; joint-angle data were filtered using a fourth-order Butterworth low-pass filter, with the cutoff frequency set to 10 Hz, in accordance with the filtering standard for lower-limb motion data; GRF data were filtered using a fourth-order Butterworth low-pass filter, with the cutoff frequency set to 50 Hz.

1.4.2 Phase Division and Definition of Characteristic Time Points IC was defined as the moment at which the vertical ground reaction force (GRF) of the force plate first exceeded 50 N, excluding interference from environmental noise. The cushioning phase was defined as the period from IC to the moment when the knee-joint flexion angle reached its maximum value. This was determined from the knee-joint angle time-series curve recorded by the Vicon system; the time corresponding to the peak of the curve was taken as the endpoint of the cushioning phase.

1.4.3 Calculation of Joint Angles The Euler angle method was used to calculate the hip, knee, and ankle joint angles. The anatomical neutral position of the human body was taken as 0°. The positive and negative definitions of joint angles were as follows: hip-joint flexion and adduction were positive, whereas extension and abduction were negative; knee-joint flexion and varus were positive, whereas extension and valgus were negative; ankle-joint dorsiflexion and internal rotation were positive, whereas plantarflexion and external rotation were negative.

1.4.4 Method for Modeling Lower-Limb Segments Based on a rigid-body segment model, the lower limb was divided into seven rigid-body segments: pelvis, left thigh, right thigh, left shank, right shank, left foot, and right foot. The center-of-mass position of each segment was determined using the proportional method, referring to the center-of-mass parameters for lower-limb segments of adult males in *Biomechanics of Human Movement*: thigh

The center of mass was located at 43.3% of thigh length, the shank center of mass at 43.4% of shank length, and the foot center of mass at 50% of foot length. The marker coordinates recorded by the Vicon system were used to calculate the spatial position and angle of each segment, thereby obtaining joint-angle data.

1.4.5 Extraction of GRF peak values From the GRF time-series curves recorded by the force plates, the peak GRF values during the cushioning phase were extracted in the anterior direction (X axis, run-up direction), lateral direction (Y axis, perpendicular to the run-up direction), and vertical direction (Z axis, vertical direction). The mean GRF in the corresponding direction from the two force plates was taken as the participant' s GRF peak-value data.

1.5 Observation indicators

The hip, knee, and ankle joint angles of the participants under the two landing modes were collected and compared; the peak hip, knee, and ankle joint angles during the cushioning phase under the two landing modes were collected and compared; and the GRF peak values during the cushioning phase under the two landing modes were collected and compared.

1.6 Statistical analysis

SPSS 23.0 was used to process and analyze the experimental data. The Shapiro-Wilk test was used to test the normality of measurement data, and Levene' s test was used to verify homogeneity of variance. After confirming that the data had homogeneous variance and followed a normal distribution, the data were expressed as ($\bar{x} \pm s$), and paired t tests were used. $P < 0.05$ was considered statistically significant. Cohen' s d was used to evaluate the effect size of the paired t test. The criteria were: $|d| < 0.2$ indicated a trivial effect, $0.2 \leq |d| < 0.5$ a small effect, $0.5 \leq |d| < 0.8$ a medium effect, and $|d| \geq 0.8$ a large effect.

2 Results

2.1 IC hip joint angles under different landing modes

Comparison of IC hip flexion angles and hip adduction angles between the two landing modes showed statistically significant differences ($P < 0.05$). Compared with rearfoot landing, forefoot landing showed larger IC hip flexion and hip adduction angles ($P < 0.05$), as shown in Table 1.

Table 1 Comparison of IC hip joint angles under different landing modes ($\bar{x} \pm s$)

Tab. 1 Comparison of IC hip joint angles in different landing modes ($\bar{x} \pm s$)

Group	Hip adduction angle	Hip flexion angle	Hip internal rotation angle
Forefoot landing	$3.56° \pm 1.03°$	$40.23° \pm 3.85°$	$0.98° \pm 0.30°$
Rearfoot landing	$1.38° \pm 0.42°$	$32.79° \pm 2.63°$	$-1.08° \pm 0.31°$
t	12.701	10.341	1.502
P	< 0.001	< 0.001	0.137
Cohen' s d	3.92	3.19	0.46

2.2 IC knee joint angles under different landing modes

Comparison of IC knee flexion angles and knee varus angles between the two landing modes showed statistically significant differences ($P < 0.05$). Compared with rearfoot landing, forefoot landing showed larger IC knee flexion and knee varus angles ($P < 0.05$), as shown in Table 2.

Table 2 Comparison of IC knee joint angles under different landing modes ($\bar{x} \pm s$)

Tab. 2 Comparison of IC knee joint angles for different landing modes ($\bar{x} \pm s$)

Group	Knee varus angle	Knee flexion angle	Knee internal rotation angle
Forefoot landing	$2.57° \pm 0.43°$	$-23.14° \pm 2.68°$	$-6.15° \pm 1.16°$
Rearfoot landing	$1.35° \pm 0.35°$	$-18.96° \pm 2.34°$	$-6.09° \pm 1.02°$
t	14.260	−7.614	−0.252
P	< 0.001	< 0.001	0.802
Cohen' s d	4.40	2.35	0.08

2.3 IC ankle joint angles under different landing modes

Comparison of IC ankle dorsiflexion angles and ankle internal rotation angles between the two landing modes showed statistically significant differences ($P < 0.05$). Compared with rearfoot landing, forefoot landing showed larger IC ankle dorsiflexion and ankle internal rotation angles ($P < 0.05$), as shown in Table 3.

Table 3 Comparison of IC ankle joint angles under different landing modes ($\bar{x} \pm s$)

Tab. 3 Comparison of IC ankle joint angles for different landing modes ($\bar{x} \pm s$)

Group	Ankle internal rotation angle	Ankle inversion angle	Ankle dorsiflexion angle
Forefoot landing	$3.32° \pm 0.65°$	$2.26° \pm 0.56°$	$-18.30° \pm 3.64°$
Rearfoot landing	$1.86° \pm 0.51°$	$2.18° \pm 0.42°$	$12.66° \pm 3.35°$
t	11.452	0.741	−7.389
P	< 0.001	0.461	< 0.001
Cohen' s d	3.53	0.23	2.28

2.4 Peak hip joint angles during the cushioning phase under different landing modes

Comparison of the peak hip flexion and hip abduction angles during the cushioning phase between the two landing modes showed statistically significant differences ($P < 0.05$). During the cushioning phase, the peak hip flexion angle was greater in the forefoot landing mode, while the peak hip abduction angle was greater in the rearfoot landing mode ($P < 0.05$), as shown in Table 4.

2.5 Peak knee joint angles during the cushioning phase under different landing modes

Comparison of the peak knee extension angle during the cushioning phase between the two landing modes showed a statistically significant difference ($P < 0.05$). Compared with the forefoot landing mode, the rearfoot landing mode showed a larger peak knee extension angle ($P < 0.05$), as shown in Table 5.

Table 4 (Tab. 4). Comparison of the peak hip joint angles during the buffering phase of two different landing modes ($\bar{x} \pm s$)

Group	Hip extension angle	Hip abduction angle	Hip external rotation angle	Hip flexion angle	Hip adduction angle	Hip internal rotation angle
Forefoot landing	2.86°±0.83°	−7.65°±0.64°	−7.53°±1.32°	49.23°±3.93°	8.13°±1.25°	6.22°±1.18°
Rearfoot landing	−3.15°±0.92°	−8.87°±0.68°	−7.86°±1.54°	43.58°±3.56°	7.86°±1.18°	6.15°±1.12°
t	1.159	8.467	1.054	6.905	1.018	0.279
P	0.095	<0.001	0.295	<0.001	0.312	0.781
Cohen's d	0.36	2.61	0.33	2.14	0.31	0.09

Table 5 (Tab. 5). Comparison of the peak knee joint angles during the buffering phase of two different landing modes ($\bar{x} \pm s$)

Group	Knee extension angle	Knee valgus angle	Knee external rotation angle	Knee flexion angle	Knee varus angle	Knee internal rotation angle
Forefoot landing	−3.65°±0.83°	−3.09°±0.75°	−11.56°±2.53°	−73.95°±6.55°	5.16°±1.32°	−1.95°±0.60°
Rearfoot landing	−6.93°±1.39°	−2.87°±0.71°	−12.26°±2.85°	−75.38°±7.06°	4.92°±1.22°	−2.08°±0.62°

Group	Knee extension angle	Knee valgus angle	Knee external rotation angle	Knee flexion angle	Knee varus angle	Knee internal rotation angle
t	−13.130	−1.381	1.190	0.962	0.865	0.976
P	<0.001	0.171	0.237	0.339	0.389	0.332
Cohen's d	4.06	0.43	0.37	0.30	0.27	0.30

2.6 Peak Ankle Joint Angles During the Buffering Phase Under Different Landing Modes

Comparison of the peak ankle dorsiflexion, ankle plantarflexion, ankle inversion, and ankle internal rotation angles between the two landing modes during the buffering phase showed statistically significant differences ($P < 0.05$). The forefoot-landing mode had larger peak ankle plantarflexion and ankle inversion angles, whereas the rearfoot-landing mode had larger peak ankle dorsiflexion and ankle internal rotation angles ($P < 0.05$), as shown in Table 6.

Table 6 (Tab. 6). Comparison of the peak ankle joint angles during the buffering phase of two different landing modes ($\bar{x} \pm s$)

Group	Ankle dorsiflexion angle	Ankle plantarflexion angle	Ankle inversion angle	Ankle eversion angle	Ankle internal rotation angle	Ankle external rotation angle
Forefoot landing	23.58°±3.39°	−38.63°±5.32°	11.49°±1.59°	−9.82°±2.11°	9.85°±1.36°	−5.11°±1.10°
Rearfoot landing	31.25°±3.57°	−27.46°±4.73°	8.20°±1.41°	−10.07°±2.36°	13.25°±1.55°	−4.85°±1.08°
t	−10.097	−10.169	10.033	0.512	−10.686	−1.093
P	<0.001	<0.001	<0.001	0.610	<0.001	0.278
Cohen's d	3.11	3.13	3.10	0.16	3.29	0.34

2.7 Peak GRF of the Three Lower-Limb Joints

The peak forward GRF and peak outward GRF differed significantly between the two landing modes ($P < 0.05$). Compared with the rearfoot-landing mode, the forefoot-landing mode had a larger peak forward GRF and a smaller peak outward GRF ($P < 0.05$), as shown in Table 7.

Table 7 (Tab. 7). The peak ground reaction force of two different landing modes in the buffering stage ($\bar{x} \pm s$)

Group	Vertical	Forward	Backward	Inward	Outward
Ground reaction force (forefoot landing) / kN	3.56±0.51	1.39±0.10	−1.32±0.31	0.95±0.13	−0.08±0.03
Ground reaction force (rear foot landing) / kN	3.41±0.47	1.28±0.08	−1.25±0.28	0.93±0.12	0.13±0.03
t	1.402	5.567	−1.086	0.733	−32.078
P	0.082	<0.001	0.140	0.233	<0.001
Cohen’ s d	0.43	1.72	0.33	0.23	9.89

3 Discussion

After the limbs are subjected to severe impact, the instantaneous load borne by the joints can easily exceed the physiological threshold of the tissues, increasing the risk of joint injury [9-12]. Basketball players must frequently perform jumping, sudden stopping, and change-of-direction movements; intense physical confrontation can readily cause joint sports injuries, among which ankle-joint injuries are the most common [13-15]. Moreover, landing mode is a key factor affecting joint loading and injury. Therefore, exploring the biomechanical characteristics of different landing modes is of great significance for preventing ankle-joint injuries [16].

When an athlete jumps to a certain height, a tremendous impact force is generated at the instant of ground contact, which can easily induce joint and muscle injuries. Previous related studies

It has been pointed out that changes in joint angles are closely related to lower-limb injuries[17]. The results of this study show that, during forefoot landing, the peak ankle dorsiflexion angle in the sagittal plane and the IC ankle dorsiflexion angle were larger. According to biomechanical principles, when the ankle is dorsiflexed, the Achilles tendon and ligaments are markedly stretched; when the load they bear exceeds physiological limits, ligament strain or tearing is likely to occur[18]. The results of this study also show that, during forefoot landing, the peak ankle inversion angle in the coronal plane was larger; when the inversion angle exceeds the tolerance range of the joint capsule and ligaments, ankle inversion sprain is likely to be induced[19]. In addition, this study found that, during forefoot landing, the IC ankle internal-rotation angle and the peak ankle internal-rotation angle were larger, and the soft tissues around the ankle joint are prone to injury under complex torsional forces. The results of this study further show that, during rearfoot landing, the peak ankle dorsiflexion angle was larger, indicating that during rearfoot landing, the ankle joint can disperse GRF to the lower-limb joint chain through dorsiflexion during the landing-buffering process, thereby reducing local loading of the ankle joint[20]. In addition, during rearfoot landing, the peak ankle inversion angle was smaller, which may further reduce the risk of ankle inversion sprain. The results of this study also show that, during forefoot landing, hip flexion, hip adduction, the peak hip-flexion angle, as well as knee flexion and knee varus angles were larger; larger hip flexion, hip adduction, knee flexion, and knee varus angles during landing significantly alter the transmission pathway of the lower-limb force line, causing the ankle joint to additionally bear abnormal stresses from the hip and knee joints, increasing ankle loading and leading to ankle injury. In addition, theoretically, an increase in the hip-flexion angle is beneficial for sagittal-plane cushioning of the lower limb; however, during normal landing, GRF should be transmitted along the vertical path of heel–tibia–femur–pelvis. During forefoot landing, increased hip adduction and knee varus angles shift the force line toward the midline of the body, causing the GRF absorbed by the hip and knee joints to be unable to disperse along the normal pathway. Instead, abnormal stress on the medial side of the ankle joint is increased, indirectly increasing ankle loading and the risk of ankle injury. By contrast, during rearfoot landing, the peak hip-abduction angle was larger, which can effectively maintain body stability during landing, disperse GRF, reduce the impact force borne by the ankle joint, and thereby lower the risk of ankle injury.

In addition, according to the impulse–momentum theorem, GRF can generate a large impulse over a short period, causing the ankle joint to bear a large impact force and inducing ankle cartilage wear, ligament tearing, and even fractures[21-25]. The results of this study show that forefoot landing had a larger peak anterior GRF and a smaller peak outward GRF, suggesting that landing modes differ in terms of GRF: the anterior ground reaction force is greater during forefoot landing, whereas the outward ground reaction force is greater during rearfoot landing. The results of this study also show that both movements had relatively large peak posterior GRF, indicating that when the foot contacts the ground, a force that impedes forward motion is generated. Therefore, during forefoot landing, the strong anteroposterior force makes the forefoot repeatedly contact the ground, with the metatarsal bones and ankle joint continuously subjected to horizontal impacts, causing metatarsal and ankle injuries; during rearfoot landing, the vertical GRF additionally received can easily injure the calcaneus and knee joint. Thus, from the peak ground reaction force during the buffering phase in the two different landing modes, it can be found that the forefoot-landing mode is more likely to increase the risk of ankle injury, whereas rearfoot landing is more likely to increase the risk of knee injury. In addition, vertical GRF is a core kinetic indicator for quantifying the intensity of landing impact; its peak value directly reflects the maximum vertical load borne by the lower limb and is closely related to risks such as articular cartilage wear and ligament injury. However, the results of this study show that the difference in peak vertical GRF between forefoot landing and rearfoot landing was not statistically significant. This may be because the impact load is mainly determined by drop height, body mass, and cushioning efficiency. In this study, the participants' jump height was standardized, body-mass differences were small, and both landing modes achieved basic cushioning through flexion of the lower-limb joints, ultimately resulting in no significant difference in total vertical load.

4 Conclusion

There are differences between basketball players' different landing modes in IC joint angles, peak joint angles during the buffering phase, and peak GRF during the buffering phase, and the forefoot-landing mode is more likely to lead to ankle injury. Therefore, in daily training, basketball players may appropriately strengthen training in the rearfoot-landing mode, reinforce strength training of relevant lower-limb muscle groups, emphasize cushioning-skill training during landing, and improve joint stability during landing, so as to further prevent ankle injuries. However, this study still has limitations. It was limited to male second-level athletes, whereas basketball players of different sexes and competitive levels may differ in physical function, movement habits, and biomechanical characteristics, which may affect the representativeness and generalizability of the results. Therefore, future studies should use multicenter and multichannel sampling, expand the range of research participants, and further verify the influence of different landing modes on ankle injuries in basketball players. In addition, this study mainly focused on differences in joint angles and ground reaction forces among basketball players using different landing modes, and did not collect electromyographic activity data of key lower-limb muscle groups or body-center-of-mass parameter data. In the future, collection of relevant data should be increased to explore in depth the joint injury mechanisms and overall movement-mechanics logic of different landing modes.

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Note: Figure translations are in progress. See original paper for figures.