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Original Article

Comparative analysis of ankle injury kinematics and dynamics in basketball players: forefoot landing vs. rearfoot landing modes

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Abstract: Objective: To compare the differences in ankle joint parameters of basketball athletes between the forefoot and rearfoot landing and to investigate the injury mechanism of ankle joints in different landing modes. Methods: Twenty level II male basketball athletes were selected as subjects in this study. The landing movements of these athletes were assigned into a forefoot landing mode and a rearfoot landing mode. The former includes movements such as running emergency stop, two-leg jump and forefoot landing, while the latter includes actions such as running emergency stop, two-leg jump and rearfoot landing. The motion capture system and three-dimensional force measuring table were used for collecting the kinematic and dynamic data of the subjects. Results: The initial landing angles, including ankle dorsiflexion and medial ankle rotation of the forefoot were larger than those of the rearfoot (all $P<0.05$). Compared to those in the rearfoot landing mode, the forefoot landing exhibited a greater peak angle of ankle plantar flexion and ankle varus, as well as a smaller peak angle of ankle dorsiflexion and ankle internal rotation (all $P<0.05$). In comparison to the rearfoot landing mode, the forefoot landing showed a larger range of ankle varus and valgus, as well as a smaller range of ankle dorsiflexion and plantar flexion (all $P<0.05$). The ankle plantar flexion torque of forefoot landing was higher than that of rearfoot landing, while the peak ankle dorsiflexion torque of forefoot landing was smaller than that of rearfoot landing (all $P<0.05$). Compared to those in the rearfoot landing mode, the outward peak ground reaction force was smaller and the forward peak ground reaction was larger in forefoot landing mode (all $P<0.05$). No obvious differences were observed in other indicators between two landing modes. Conclusions: There are kinematic and dynamic differences between the forefoot and rearfoot landing. Forefoot landing may increase the risk of ankle injury during landing.

Keywords: Ankle, injury risk factor, landing mode, biomechanics, basketball

Introduction

The incidence of sports injuries among basketball players is high, and there are many risk factors for these injuries. During the process of intense physical contact and confrontation, basketball players often find themselves in an unusual position, and their joints throughout the body are subjected to constantly changing muscle forces. Every time a basketball player makes a technical move and takes off, the movement ends with the landing. Due to the greater body weight and muscle mass of the basketball players, they are prone to significant impact when landing, making them highly susceptible to sports injuries. Many studies have reported that in basketball players, the collision rate is highest in the knee and ankle joints [1, 2]. Athletes usually experience sudden lateral runs, squats or jumps after a straight run, which exerts a huge burden on the knee and ankle joints and affects their stability. In addition, after jumping, ankle injury may occur in the landing process. Another study with athletes from National Basketball Association as subjects reported that their ankles experienced the highest rate of injury, accounting for 61.6%, followed by knee injury, accounting for 48.8%, and calf injury, accounting for 12% [3]. McKay et al. investigated the injury situation of 10,000 basketball players and pointed out that they had a higher risk of sports injury when landing, most of which were concentrated in the lower limb joints, with the highest injury rate at the ankle joint, followed by the knee joint [4]. The reasons for these injuries are diverse. Approximately 45% of the ankle injuries in basketball players were attributed to landing, while other factors included collisions with opponents, sports equipment and facilities, and condition of the playing surface and environment. Drakos et al. reported the injuries of 1094 players in the National Basketball Association over 17 years and found that among the sports injuries, lateral ankle sprains were the most common, accounting for 13.2%, followed by patellar inflammation (11.9%), lumbar strain (7.9%), and hamstring sprains (3.3%) [5]. Messina et al. conducted a follow-up study on injuries in 100 high school basketball teams in the United States and found that the most common form of injury was sprain, with the ankle being the most common injury site, followed by the knee [6]. Ankle injuries affect the athletes themselves and may impact the results of the games. In severe cases, it could lead to the early termination of their basketball career.

Previous studies showed that currently, the common methods for evaluating and analyzing the risk factors of injury were the simultaneous combination of kinematics and dynamics. A biological study examining the sudden stop and takeoff stage of basketball players [7] revealed that the lower limb involved in takeoff experienced higher loads during landing. Specifically, the ankle joints were particularly vulnerable to injury during the landing impact phase when they were subjected to maximum inward and outward rotation [8]. At present, most of the existing literature focuses on knee joint injuries at landing, but little attention has been paid to ankle joint injuries while landing. Moreover, there are limited biomechanical studies on landing injuries of basketball players, especially ankle joint injuries [9]. Therefore, this study conducted kinematic and dynamic analysis of the ankle joint at landing from the perspective of sports biomechanics to analyze the dynamic force changes of the ankle joint. In addition, we explored the biomechanical factors that cause ankle joint injuries while landing and the mechanisms of ankle joint injuries during the landing process of basketball players from a biological perspective. This study aimed at providing a basis for athletes and coaches to reduce the risks of injury during training and games, which is also conductive to the performance of players.

Materials and methods

General information

The twenty male basketball athletes were recruited as subjects from Yuncheng University. Inclusion criteria: basketball players who were national level II athletes; players with a height of over 180 cm and in good health condition; players with no history of sports injuries and lower limb injuries; players who were informed of the experiment and signed an informed consent. Exclusion criteria: players who had skeletal muscle injury within the past 6 months; players participated in vigorous activities within 24 hours before the experimental tests; players who did not understand or master the movements required in the tests. This trial was authorized by the Ethics Committee of Yuncheng University (Ethics approval number: 202211).

Experimental apparatus

A total of 10 cameras with Vicon motion capture systems (Vicon V5 cameras, Vicon Motion Systems, Oxford, UK) were used to collect the kinematic parameters of lower limb joints during the movements, with a collection frequency of 200 Hz. Two Kistler three-dimensional (3D) force measuring platforms (AMTI BP600900) were used to collect the dynamic parameters of lower limb joints during the movements, with a collection frequency of 1200 Hz.

Experimental indexes

The movements were required to be completed through a forefoot landing and rearfoot landing, respectively. Forefoot landing process included running emergency stop, two-leg jump, and forefoot landing. Rearfoot landing process also started with running emergency stop and two-leg jump, but ended with rearfoot landing.

The detected time was from the initial contact moment to the maximum knee flexion. The kinematic indexes in this study included the angle of ankle at the time of initial contact, the range of ankle movement, and the peak angle of ankle. Dynamic indicators included the peak torque of ankle and the peak ground reaction force.

Definition of kinematics indexes: the X axis of the coordinate system in 3D space was consistent with the direction of the sagittal axis, and the forward direction was positive, while backward was negative. The Y-axis was aligned with the frontal axis, with the inward as positive and the outward as negative. The Z-axis was aligned with the vertical axis direction, with internal rotation as positive and external rotation as negative. In 3D space composited by Vicon infrared motion capture system and Kistler dynamometer, the direction of the subject's running approach forward was the positive direction of the X-axis, the direction on the subject's left side was the Y-axis positive direction, and the direction of the subject's vertical upward jump was the positive direction of the Z-axis.

Definition of dynamic indicators: The direction of 3D ankle torque was consistent with the direction of 3D ankle angle. The vertical ground reaction force in 3D space was defined as follows. The X-axis was the forward and backward directions of the runway, with a positive value for the forward direction and a negative value for the backward direction. The Y-axis was the inner and outer directions of the runway, with positive values for inward and negative values for outward. The Z-axis was the vertical direction of the runway plane, with positive values for upwards and negative values for downwards. To mitigate the impact of body weight on the measurements, the ground reaction force and ankle torque were standardized by body weight, as BW and Nm/kg, respectively.

Data processing

The subjects in this study repeated each action for three times, and the average was calculated. The Vicon Nexus 2.6 software was used to name the infrared reflective marker balls collected by the infrared motion capture system. Expurgation and supplement of the collected reflective balls were performed if necessary, in order to avoid more or fewer points. The experimental movements of the subjects were captured in time frames, from the moment of initial contact to the moment of maximum knee flexion during the landing impact stage. The experimental action data were input into the software for the modeling of lower limb joints. There were 7 skeletal links in the established model, body pelvic joints, human left and right thigh joints, human left and right calf joints, and human left and right foot joints. The joint angle, joint torque, and ground reaction force of ankle joint was calculated through the reverse dynamic method.

Statistical methods

SPSS 23.0 software was used for analyzing the data collected in this study. The measured data were presented in form of mean ± standard deviation (SD). The comparison of parameters between two landing modes was conducted by paired t test. The enumerated data were presented in the form of [n (%)], and χ^2 partition test was used for the comparison. $P<0.05$ was considered as statistically significant.

Results

General information

According to the inclusion and exclusion criteria, 20 male national level II basketball players from Yuncheng University were included in this study. The basketball players had an average age of 22.30±2.74 years, an average height of 182.57±3.06 cm, and an average weight of 76.96±9.11 kg. All of the athletes successfully completed the experimental tests of movements required in this study.

Comparison of the initial landing angle of ankle

As seen in the **Table 1**, there was no significant difference in ankle varus between the two modes. Compared to those in the rearfoot landing mode, the ankle dorsiflexion and medial ankle rotation in the forefoot landing mode were obviously greater, and statistical differences were observed.

Comparison of the peak angle of ankle

As seen in the **Table 2**, the differences were found in the peak angle of ankle dorsiflexion, ankle plantar flexion, ankle varus and ankle internal rotation between two landing modes. There were no differences in ankle valgus and ankle external rotation between the two models.

Table 1. Comparison of the initial landing angle of ankle between the foretoot and rearfoot landing modes (°)

Modes	Ankle dorsiflexion	Medial ankle rotation	Ankle varus
Forefoot landing	-17.18±4.95	3.35±0.25	2.61±0.97
Rearfoot landing	11.71±6.97	1.68±0.72	1.95±0.80
t value	10.690	6.929	1.660
P value	<0.001	<0.001	0.114

Table 2. Comparison of the peak angle of ankle between the forefoot and rearfoot landing modes (°)

Modes	Ankle dorsiflexion	Ankle plantar flexion	Ankle varus	Ankle valgus	Ankle internal rotation	Ankle external rotation
Forefoot landing	26.12±3.53	-36.95±5.14	11.03±3.95	-9.25±1.86	9.06±2.92	-5.31±1.75
Rearfoot landing	32.97±6.84	-30.05±4.78	7.96±2.89	-10.37±1.91	12.83±3.59	-4.70±1.43
t value	2.841	3.109	2.771	1.328	2.576	0.854
P value	0.012	0.006	0.013	0.201	0.019	0.405

Table 3. Comparison of the range of ankle motion between the forefoot and rearfoot landing modes (°)

Mode	Ankle dorsiflexion and plantar flexion	Ankle varus and valgus	Ankle internal and external rotation
Forefoot landing	36.18±5.91	24.63±4.16	15.82±2.97
Rearfoot landing	44.05±6.17	20.01±3.94	17.01±5.48
t value	2.913	2.550	0.604
P value	0.009	0.020	0.554

Comparison of range of ankle motion

As seen in **Table 3**, the range of ankle dorsiflexion and plantar flexion in the rearfoot landing mode was significantly greater, while the range of ankle varus and valgus in the rearfoot landing mode was significantly lower than those in the forefoot landing mode. There were no differences in the range of ankle internal and external rotation between the two modes.

Comparison of the peak ankle torque

As seen in **Table 4**, the peak ankle dorsiflexion torque in the forefoot landing mode was obviously less than that in rearfoot landing mode, while the peak ankle plantar flexion torque in the forefoot landing mode was larger than that in rearfoot landing mode. There were no significant differences in the peak ankle varus torque, ankle valgus torque, ankle internal rotation torque, or ankle external rotation torque between the two modes.

Comparison of the peak ground reaction force

As seen in **Table 5**, compared to those in rearfoot landing mode, the peak forward ground reaction force in forefoot landing mode was larger, while the peak outward ground reaction force was smaller, with statistical differences. There were no statistical differences in vertical ground reaction force, backward ground reaction force, or inward ground reaction force between the two modes.

Discussion

The ankle joint is a uniaxially flexed joint and can perform dorsiflexion and plantar flexion in the sagittal plane, varus and valgus in the coronal plane, and inward and outward rotation in the horizontal plane. The ankle joint can withstand approximately 5 times the body weight during normal walking and 13 times the body weight during running and jumping [10]. During the process of normal upright walking, it is in a static state, where the movement of ankle joint transitions between dorsiflexion and plantar flexion, while under dynamic situations such as running, jumping and other movements, the range of ankle joint movement would correspondingly increase. When running, there were three landing modes based on the contacts between feet and the ground, the rearfoot landing, midfoot landing, and forefoot landing. Research has shown that people have a greater degree of plantar flexion in the ankle joint when landing with the forefoot, while the ankle joint has a greater degree of dorsiflexion when landing with the rearfoot [11]. Compared to running, the landing movement after jumping has a

Table 4. Comparison of the peak ankle torque between the forefoot and rearfoot landing modes (Nm/kg)

Mode	Ankle dorsiflexion	Ankle plantar flexion	Ankle varus	Ankle valgus	Ankle internal rotation	Ankle external rotation
Forefoot landing	0.67±0.21	-3.15±0.24	0.49±0.16	-0.25±0.08	0.23±0.11	-0.10±0.04
Rearfoot landing	0.93±0.25	-2.53±0.38	0.39±0.11	-0.27±0.05	0.34±0.15	-0.09±0.05
t value	2.518	4.362	1.629	0.670	1.870	0.494
P value	0.022	<0.001	0.121	0.511	0.078	0.627

Table 5. Comparison of the peak ground reaction force between the forefoot and rearfoot landing modes (BW)

Mode	Vertical ground reaction force	Forward ground reaction force	Backward ground reaction force	Inward ground reaction force	Outward ground reaction force
Forefoot landing	3.56±0.59	1.45±0.07	-1.33±0.05	0.94±0.03	-0.09±0.02
Rearfoot landing	3.48±0.62	1.32±0.05	-1.31±0.02	0.93±0.02	-0.13±0.03
t value	0.296	4.779	1.174	0.877	3.508
P value	0.771	<0.001	0.256	0.392	0.003

greater impact on the ankle joint. Therefore, the change in kinematics of the ankle joint while jumping is particularly important.

The results of kinematics and dynamics of the ankle joint are different in various movements. When walking, the body weight constantly changes in standing positions, achieving energy exchange. By analyzing the leverage model, it was found that at a certain speed, an increase in the ratio of ankle joint stiffness to leg length would lead to a decrease in the time taken for the back heel to lift [12]. When running, regardless of the landing pattern, the maximum peak force and load ratio in the vertical direction are higher than those in the front, rear, left, or right directions, indicating that forefoot landing imposes higher joint loads on the ankle joint compared to rearfoot landing. Yeadon et al. conducted a comparative analysis of in situ jumping movements and approach jumping movements. Their results pointed out that approach jumping movements could increase ankle joint force and torque, as well as elongate initial muscle length, and a higher approach speed was helpful for the stabilization of the ankle joint, increasing the explosive nature of jumping [13].

There were differences in kinematics between these two landing modes in basketball players. This study showed that on the sagittal plane, forefoot landing showed a larger initial landing angle of ankle plantar flexion, while rearfoot landing showed a larger initial landing angle of ankle dorsiflexion. This is consistent with previous researches results [14]. Compared with rearfoot landing, forefoot landing had a greater ankle varus angle on the coronal plane and a greater ankle inward rotation angle on the horizontal plane. These indicate that during forefoot landing, the ankle joint is in a plantar flexion state upon initial contact, accompanied by varus and inward rotation, which helps to maintain the ankle joint below the center of gravity. Wright et al. found that a larger plantar flexion angle in the ankle joint upon initial landing was associated with an increased risk of sprain [15], which is similar to the results of this study. In addition, this study showed that in the sagittal plane, the range of motion of the ankle joint while forefoot landing was smaller than those while rearfoot landing. In the coronal plane, the ankle joint had a larger range of varus and valgus movements in the forefoot landing mode. These results indicate that the lower limb joint flexion range of motion is smaller while forefoot landing, making the initial landing in a relatively upright manner, which increases the load on the lower limb joints. The dorsiflexion degree of the ankle joint was small, and the range of motion of the ankle varus and valgus was large, which also compromised the ankle joint's ability to absorb impact, leading to instability during landing, and an increased risk of ligament damage and ankle joint injuries. These results are consistent with those of a previous study [16].

This study revealed that the range of flexion activity of the ankle joint in the forefoot landing mode was smaller than that of the rearfoot landing mode, which is consistent with results reported by John et al. [17]. Dakin et al. found that during landing, the ankle joint had the smallest range of motion among the lower limb joints, and excessive joint movement could lead to ankle joint damage, such as sprains or Achilles tendon ruptures [18]. The results of this study showed that the ankle joint had a greater tendency of varus and inward rotation in the forefoot landing mode, as well as a greater range of motion in the coronal plane. These may cause injuries to the ankle joint of basketball players when landing, which is consistent with the research results of Fong et al. [19]. It can be seen that compared to those in the rearfoot landing mode, the forefoot landing mode had a greater risk of ankle joint injuries. The reasons might be that the ankle joint is in a plantar flexion state during forefoot landing, and the range of motion for lower limb joint flexion during the landing process was smaller. In addition, the ankle joint exhibits a larger range of motion for varus and valgus movements, along with a greater trend of varus and inward rotation.

There were also differences in terms of dynamics between the two landing modes in basketball players. This study only found the difference in the sagittal plane for the joint torque between the two landing modes. The forefoot landing mode had a greater ankle plantar flexion torque, while the rearfoot landing mode had a greater ankle dorsal flexion torque, which is similar to the report of Kotsifaki et al. [20]. Wright et al. found that a plantar flexion torque that occurred in the ankle joint during the landing stage increased the risk of ankle joint injuries [21]. When the ankle joint lands in a plantar flexion state with the forefoot as the contact area, it results in a significant increase in the force arm of the subtalar joint. This, in turn, leads to an elevated torsional torque on the ankle joint, making it more susceptible to varus forces and increasing the risk of ankle injury [22]. The forefoot landing mode also could produce a significant plantar flexion torque, which not only increases the risk of ankle joint injury, but also enhances the risk of Achilles tendon injury. Moreover, the forefoot landing mode had greater forward ground reaction force, while the rearfoot landing mode had the greater outward ground reaction force. Both landing modes were subjected to a backward ground reaction force during the landing process, indicating that the contact between the foot and the ground while landing generated a force that hindered forward movement, and the forefoot landing mode exhibited a greater magnitude of backward ground reaction force, which is consistent with the research results of Kulmala et al. [23]. In the vertical direction, the forefoot landing mode had a greater vertical ground reaction force, which is similar to the research results of Thompson et al. [24]. It can be seen that the forefoot landing mode can increase the risk of ankle injuries in basketball players.

The limitations of this study are as follows. First, the ground surface in the laboratory setting, where the basketball players in this study performed, may differ from the surfaces encountered during actual outdoor training or competition venue. Second, this study focused on kinematics and dynamics analysis but did not include electromyography measurements. Third, we only included two common test movements in this study, and there are various of other movements in playing basketball.

In conclusion, there are differences in the term of kinematics and dynamics between the forefoot landing mode and the rearfoot landing mode. The landing mode followed by running emergency stop and take-off has a larger ankle plantar flexion angle, varus angle, ankle plantar flexion torque, vertical ground reaction force and, horizontal ground reaction force, as well as a smaller ankle flexion range of motion. All of these factors can contribute to an increased risk of ankle joint injuries. The findings of this study offer some experimental evidence that can contribute to the prevention of ankle injury and the reduction of injury risk in basketball athletes during training and competition.

Disclosure of conflict of interest

None.

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