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Article

Numerical simulation of lower limb forces during basketball pivot movements investigating injury prevention strategies

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Abstract: Basketball is a dynamic sport characterized by high-intensity movements such as pivoting, cutting, and jumping, which place significant biomechanical stress on the lower limbs. These movements increase the risk of injury, particularly to the knee, ankle, and hip joints. This study investigates the biomechanical forces acting on the lower limbs during basketball pivot movements, explicitly focusing on injury prevention strategies. Using advanced biomechanical modeling techniques, including Motion Capture System (MCS), Force Plate Measurements (FPM), and electromyography (EMG), the study quantifies joint forces, muscle activation patterns, and Ground Reaction Forces (GRF) during pivoting, cutting, and jumping. A fatigue protocol was incorporated to examine how fatigue impacts force distribution and injury risk, with particular attention to Anterior Cruciate Ligament (ACL) strain and meniscal damage. Finite Element Analysis (FEA) and inverse dynamics modeling were employed to simulate the internal forces acting on the knee, ankle, and hip joints, providing insights into the injury mechanisms associated with basketball movements. The kinematic analysis reveals that jumping produces the highest knee flexion (52.3°) and extension (130.8°), with maximum angular velocity (332.7 deg/s) and acceleration (1456.8 deg/s^2), indicating the explosive nature of the movement. In the kinetic analysis, vertical GRF is highest during jumping, reaching 1897.4 N, while the knee joint reaction force peaks at 2876.3 N. A fatigue protocol was incorporated, showing that post-fatigue vertical GRF increased by 4%–5%, knee joint moments rose by 6%–8%, and quadriceps and hamstring activation dropped by 7%–8%. FEA highlighted that ACL stress is highest during jumping (23.1 MPa), with corresponding ACL strain at 9.7%. The results highlight that fatigue exacerbates joint loading and reduces muscle efficiency, increasing injury risks, especially during high-impact movements. This study provides practical recommendations for training regimens to enhance muscle coordination and reduce the likelihood of lower limb injuries among basketball players.

Keywords: biomechanical stress; biomechanical demands; training regimens; knee flexion; biomechanical forces; muscle coordination; movements; finite element analysis; anterior cruciate ligament

1. Introduction

Basketball is a high-intensity sport that requires rapid directional changes, explosive movements, and significant muscular coordination, placing substantial biomechanical demands on the lower limbs [1]. Movements such as pivoting, cutting, jumping, and sprinting are integral to basketball performance, but they also elevate the risk of injury, particularly to the knee, ankle, and hip joints [2,3]. The knee's Anterior Cruciate Ligament (ACL), menisci, and cartilage are especially vulnerable to the high shear and compressive forces generated during rapid directional changes and high-impact landings [4,5]. Injuries such as ACL tears, meniscal damage, and ankle sprains are common among basketball players and can lead to long-term physical impairments, significantly affecting a player’s performance and career longevity [6,7].

Among these movements, pivoting—characterized by a rapid change in direction while one foot remains planted—plays a central role in offensive and defensive maneuvers on the basketball court [8,9]. Despite its importance, pivoting poses considerable risks due to the complex forces it generates. The rotational stress on the knee joint and the body’s momentum expose the ACL to excessive strain, making it a common site of injury during pivoting and cutting movements [10,11]. Ankle sprains, particularly involving the Anterior Talofibular Ligament (ATFL), also frequently occur during rapid lateral movements, such as pivoting or cutting [12,13]. Understanding the biomechanical factors underlying these movements is essential for developing effective injury prevention strategies [14,15].

Advances in biomechanical modeling and numerical simulations have enabled more precise analyses of the forces acting on the lower limbs during dynamic sports movements [16]. These methods allow for quantifying Ground Reaction Forces (GRF), joint moments, and muscle activation patterns, providing insights into the distribution of stresses across the knee, ankle, and hip joints [17]. Such analyses are critical for understanding the injury mechanisms in basketball and designing interventions to reduce injury risks, particularly for the ACL, which bears the brunt of the shear and rotational forces during pivoting [18].

Previous research has examined the biomechanics of basketball movements, but few studies have explicitly focused on pivoting and the detailed forces acting on the lower limb joints [19,20]. Furthermore, there is limited understanding of how skill level, body composition, and fatigue influence joint loading and injury risk. Muscle activation patterns, particularly the co-contraction of the quadriceps and hamstrings, play a crucial role in stabilizing the knee during pivoting [21]. However, as players fatigue, muscle efficiency declines, increasing the risk of injury due to reduced joint stabilization [22].

This study aims to address these gaps by providing a comprehensive analysis of the forces acting on the lower limbs during basketball pivot movements. Using a combination of Motion Capture System (MCS), Force Plate Measurements (FPM), and electromyography (EMG), this study quantifies the kinematic and kinetic variables associated with pivoting, cutting, and jumping. Additionally, the study incorporates a fatigue protocol to evaluate how fatigue impacts force distribution and injury risk. Through Finite Element Analysis (FEA) and inverse dynamics modeling, the study simulates the internal and external forces acting on the knee, ankle, and hip joints, focusing on the ACL and meniscal injury risks [23–26].

The findings of this research will contribute to understanding the biomechanical demands of basketball pivoting and offer practical insights for injury prevention strategies. By identifying the key factors that influence joint loading, particularly under fatigue, the study provides evidence-based recommendations for training regimens to reduce injury risks and improve player safety.

The rest of the paper is organized as follows: Section 2 presents the theoretical framework, Section 3 presents the methodology, Section 4 presents the results and analysis, and Section 5 concludes the article

2. Theoretical framework

2.1. Biomechanical factors in basketball movements

Basketball is a high-intensity sport that involves a wide range of dynamic movements, including jumps, sprints, and rapid changes in direction, such as pivoting. These movements place significant biomechanical demands on the lower limbs, particularly the knee, ankle, and hip joints. Among these, pivoting movements are essential for quick directional changes on the court but often lead to substantial stresses due to the rotational forces they generate. The complexity of pivot movements lies in their co-occurring angular momentum, GRF, and muscular activation. As the player initiates a pivot, the lower limb must endure a sudden change in direction while maintaining stability, often placing the ACL and other knee structures at risk of injury [27–29].

Figure 1 illustrates a variety of basketball movements, such as sprinting, running, 45-degree cutting, and executing a lay-up, which highlight the distinct biomechanical demands of the sport. In sprinting and running (as shown in the second and third frames), the lower limbs endure repetitive compressive and tensile forces, increasing significantly during faster motions, such as sprinting. These forces pose stress risks to the knee and ankle joints, where proper muscle coordination and strength are essential to absorb and stabilize joint stresses, preventing injuries [30–34].

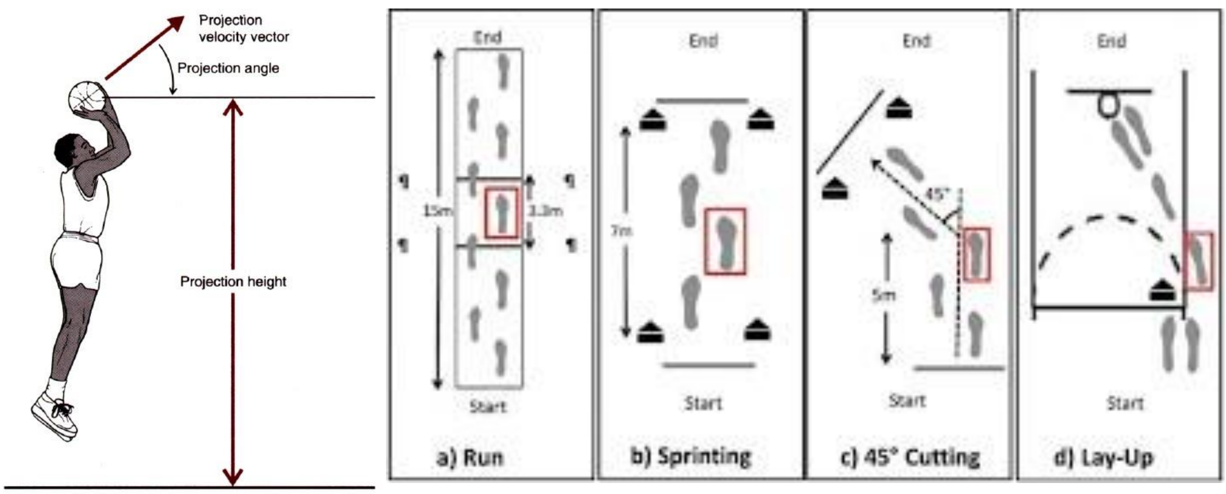

Figure 1. Basketball biomechanics.

In pivoting, as shown in the image's depiction of the 45-degree cutting movement, the knee experiences a high level of torsion as the foot remains planted while the upper body rotates, creating rotational stress. The coordination of muscles, particularly the quadriceps, hamstrings, and calves, is critical in maintaining knee stability during these motions. Imbalances or delayed muscle responses can lead to excessive ligament strain, increasing the risk of ACL injuries. Similarly, the ankle absorbs the force of rapid lateral movements, and inadequate technique or muscle strength can lead to common basketball-related injuries like ankle sprains. The combination of compressive, tensile, and shear forces acting on these joints during movements such as 45-degree cutting or lay-ups creates a substantial load, particularly in explosive moments, such as take-off or landing during a lay-up.

The hip joint plays a supportive role in these movements, facilitating trunk rotation and helping to maintain balance. However, the hip also contributes to the overall force distribution along the kinetic chain. Insufficient strength or flexibility in the hip muscles can alter force transmission through the knee and ankle, increasing injury susceptibility. The entire kinetic chain from the hip down to the foot must work harmoniously to ensure efficient and safe pivot movements.

Biomechanically, basketball pivoting is characterized by a combination of compressive, tensile, and shear forces, which fluctuate depending on the intensity and angle of movement. Understanding these forces is crucial for analyzing potential injury mechanisms. The complexity of basketball movements, such as those demonstrated in the image, illustrates the need for precise biomechanical analysis. Numerical simulations of these forces can model the stresses and strains on each joint during basketball movements, providing valuable insights for developing injury prevention strategies to mitigate the risks posed by these high-impact actions.

2.2. Force distribution in lower limbs

In basketball, lower limb forces during movements such as pivoting are distributed across various joints, primarily the knee, ankle, and hip. These forces fluctuate in magnitude and direction depending on the type of movement and the player’s biomechanical responses. The ability of the lower limbs to manage compressive, tensile, and shear forces is crucial for both performance and injury prevention. Pivoting, a pivotal movement in basketball, generates complex force patterns. The knee experiences rotational stress as it handles the player’s body weight and the forces generated from quick directional changes. The combination of vertical GRF and horizontal shear forces, particularly during a pivot, places significant stress on the ACL. Similarly, the ankle and hip joints are subjected to substantial forces, especially during rapid lateral or rotational movements. Proper muscle coordination, joint stability, and strength are required to manage these forces without injury.

The provided **Figure 2** helps illustrate the multiple axes of movement involved in force distribution. It shows the lower limb’s range of motion, including internal rotation, varus (adduction), flexion, and the forces acting along the anteroposterior, mediolateral, and superior-inferior directions.

During basketball movements like pivoting, these axes are highly engaged:

- Mediolateral and Anteroposterior Forces: As the figure indicates, forces acting side-to-side (mediolateral) and front-to-back (anteroposterior) are critical in movements like cutting and sprinting. When pivoting, the knee and ankle must stabilize against these forces, with the knee particularly vulnerable to lateral forces that can cause ligament strain, such as an ACL tear.
- Rotational and Varus Movements: The internal rotation depicted in the image highlights the knee’s rotational mechanics during pivoting. Excessive internal rotation and varus (adduction) stress can overburden the ligaments, especially when a player’s foot is planted during a pivot. This rotational force can lead to significant knee injuries if not adequately absorbed by surrounding muscles.

- Flexion and Superior-Inferior Forces: During flexion, as shown in the figure, the knee joint undergoes significant compressive forces along the superior-inferior axis. This is particularly important during jumping and landing movements in basketball. High compressive forces on the knee, combined with torsional stress from pivoting, increase the risk of meniscal injuries and cartilage degradation.

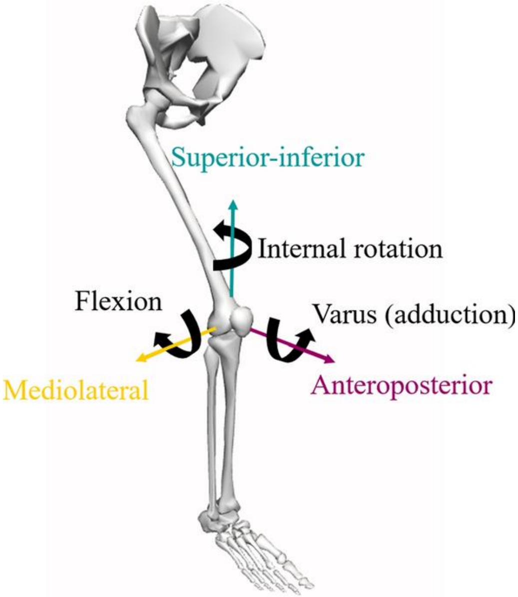

Figure 2. Multiple axes of movement involved in force distribution.

The complexity of basketball movements, especially in pivots, requires an integrated biomechanical understanding of how these forces interact. Each movement involves a dynamic redistribution of forces through the lower limb joints, where the knee, ankle, and hip must coordinate to avoid overload on any single structure. Using this model of movement axes, the figure visually complements the biomechanical factors, illustrating how internal rotation, flexion, and other movements contribute to overall force distribution.

Injury prevention strategies must, therefore, focus on optimizing muscle strength and joint flexibility to manage these forces effectively. Numerical simulations can further help model these dynamic force distributions, offering insights into how specific movements, such as pivoting or cutting, impact joint health over time. This understanding aids in designing training regimens that enhance biomechanical efficiency and reduce the risk of injury during high-stress basketball movements.

2.3. Injury mechanisms

In basketball, fast-paced, high-impact movements such as pivoting, sprinting, and cutting expose players to various injury risks, especially to the lower limbs. The mechanisms behind these injuries are rooted in the complex biomechanical forces acting on the joints, muscles, and ligaments. Understanding the injury mechanisms is essential for developing strategies to mitigate these risks and improve player safety. One of the most common injuries in basketball is the ACL tear (**Figure 3**), particularly during pivoting or cutting movements. The ACL stabilizes the knee against anterior translation and rotational forces, but rapid changes in direction or sudden deceleration, as seen in a pivot, can cause the ligament to rupture. The ACL is most vulnerable when the foot is planted, and the knee undergoes internal rotation and valgus (outward) stress. The combination of GRD and the player's body momentum contributes to the strain, which, if not adequately absorbed by surrounding muscles, leads to an ACL injury. Fatigue, poor muscle coordination, or incorrect landing techniques amplify these risks.

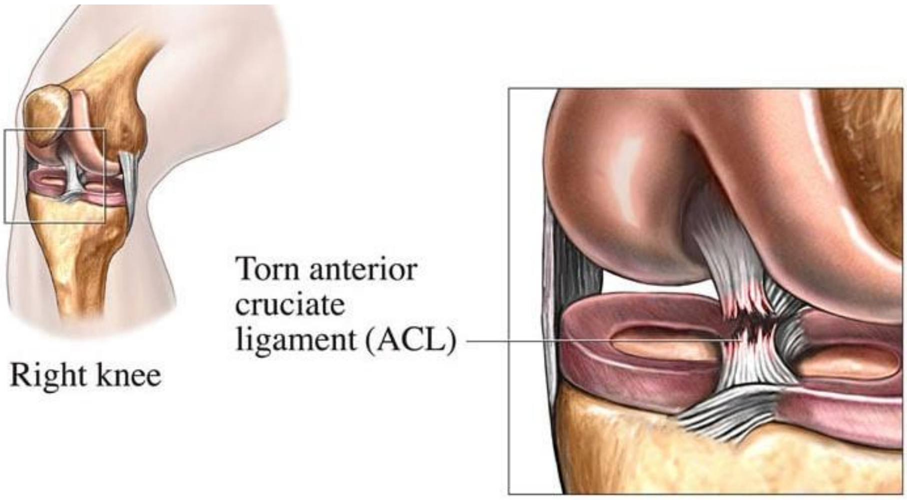

Figure 3. ACL tear.

From **Figure 4** is the Ankle sprains are another frequent injury associated with the rapid lateral movements of basketball. The lateral ligaments of the ankle, particularly the ATFL, are commonly injured during movements that involve sudden changes in direction. A player may land awkwardly on the outside of the foot after a jump or pivot, creating an inversion movement that overstretches these ligaments. Ankle sprains can also result from improper force distribution during lateral movements, where the stabilizing muscles fail to react quickly enough to absorb the impact forces.

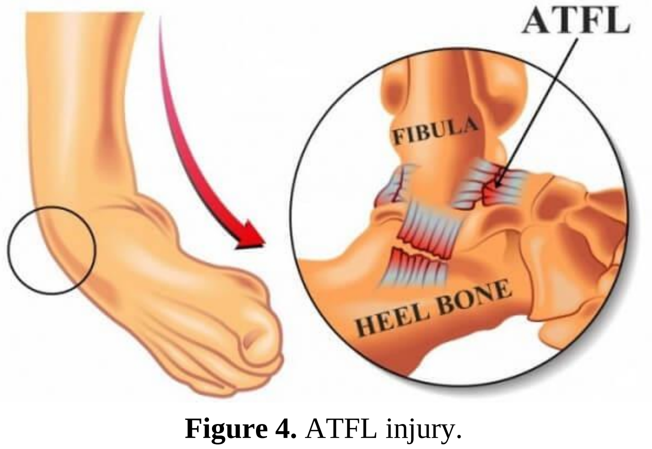

Figure 4. ATFL injury.

Knee cartilage injuries, including meniscal tears, are also prevalent, often exacerbated by repetitive pivoting and high-impact landings. The menisci are shock absorbers between the femur and tibia, distributing compressive forces across the knee joint. However, these forces can lead to meniscal damage during sharp pivots or landings from jumps, particularly when combined with rotation. The risk is further increased when these movements occur at high speeds or when a player is off-balance.

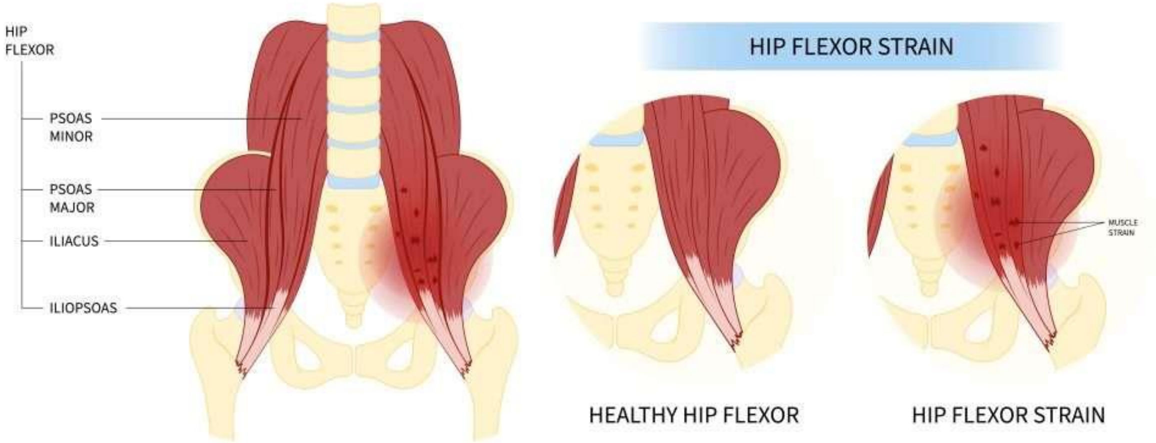

Figure 5. Hip injury.

Hip injuries (**Figure 5**), though less common than knee and ankle injuries, can occur due to overuse or poor mechanics in the lower kinetic chain. Hip flexor strains or labral tears are often the result of imbalanced force distribution between the lower back and the lower limbs. These injuries typically occur when the hip joint is forced into extreme ranges of motion, such as during aggressive lunging or pivoting. Tightness in the hip flexors or weakness in the gluteal muscles can lead to improper force transmission, increasing the risk of injury. Fatigue plays a significant role in injury mechanisms. As players tire, their ability to coordinate movements and absorb shock diminishes, leading to compensatory strategies that place additional stress on the joints. For example, a fatigued player may land more heavily or with less control, increasing the risk of knee and ankle injuries. Fatigue also affects muscle activation timing, which is critical for joint stabilization, particularly during high-speed directional changes.

3. Methodology

3.1. Population

This study involved 17 participants, all basketball players recruited from various universities in China. The participants were selected based on their active involvement in competitive basketball, ensuring that they were familiar with the high-intensity demands of the sport, particularly the dynamic movements of pivoting, sprinting, and cutting. The selection criteria included players aged between 18 and 25 years, with at least three years of competitive basketball experience at the collegiate level. All participants were male, reflecting the demographics of the competitive basketball teams from which they were drawn.

The participants had an average height of 1.83 m (ranging from 1.78 to 1.89 meters) and an average body weight of 78.2 km (ranging from 71.5 to 84.6 kilograms).

These physical characteristics were essential for understanding how body mass and stature influence lower limb force distribution during basketball movements. Each player underwent pre-screening to ensure they had no current lower limb injuries or significant medical conditions that could affect their movement patterns or increase their injury risk during the study.

The players were from different provinces across China, representing a geographically diverse sample, although most were from the northern and eastern regions, where basketball is a popular sport at the university level. This diversity provided a broad understanding of how biomechanical factors and force distribution could vary slightly across players with different backgrounds and training environments. The study design aimed to include participants of varied skill levels, from intermediate to advanced, to observe how the mechanics of basketball movements might change with experience. The participants' training regimens were also considered, with all players participating in at least five weekly training sessions, incorporating drills that emphasized pivoting and cutting maneuvers.

3.2. Simulation setup

This study's simulation setup (**Table 1**) was designed to replicate the dynamic movements involved in basketball, explicitly focusing on pivoting maneuvers. The primary goal was to model the forces acting on the lower limbs—particularly the knee, ankle, and hip joints—during these movements. The simulation environment was developed using advanced biomechanical modeling software, which allowed for the integration of MCS data and FPM to generate accurate representations of player movements and the associated stresses on the joints.

i) Assumptions Regarding Movement

Key assumptions were made regarding the types of movements involved to standardize the simulation. Pivoting, cutting, and rapid direction changes were the focus, as these movements significantly strain the lower limbs. A typical pivot movement was a 45-degree turn with the player's foot planted while the upper body rotated to initiate the directional change. The duration of the pivot movement was assumed to be between 0.3 and 0.5 s, reflecting the quick nature of basketball maneuvers.

In addition, the simulation assumed that players performed these movements at maximum effort, as would be expected during competitive gameplay. The model incorporated a wide range of motion, including full flexion and extension of the knee and internal and external hip rotation. These assumptions were critical in capturing the complexity of the joint movements and their impact on force distribution across the lower limbs.

ii) Movement Speed

The simulation assumed that players executed pivot movements at speeds ranging from 3.5 to 5.0 m per second, reflecting the average sprint speed of competitive basketball players during cutting and pivoting maneuvers. This range was selected based on existing literature on basketball biomechanics and reflects the intensity of in-game movements. Faster movements generate higher GRF, which increases the load on the joints, mainly when a pivot is initiated at the moment of deceleration.

For this simulation, acceleration was assumed to be consistent, leading into the pivot, with a rapid deceleration occurring when the foot was planted. The deceleration phase, which is critical in understanding injury mechanisms, was modeled to account for the sudden reduction in speed that often accompanies cutting and pivoting. This deceleration produces high shearing and rotational forces at the knee, which the simulation aimed to replicate.

iii) Environmental Factors

Environmental factors, such as the playing surface, were also accounted for in the simulation. The surface was modeled as a standard hardwood basketball court with a friction coefficient of 0.6, which is typical for indoor courts. The friction between the player's shoes and the surface was critical in determining how forces were transmitted through the lower limbs during the pivot. High friction can increase rotational stress on the knee as the foot remains planted while the body continues to rotate. Additionally, environmental assumptions included a standard atmospheric pressure and temperature within an indoor basketball court, where the temperature was set at 20℃. These conditions were considered to provide a neutral environment that would not significantly influence the physiological performance of the players.

Table 1. Simulation setup.

Category	**Details**
Movement Type	Pivot, Cutting, Directional Changes
Pivot Angle	45 degrees
Movement Duration	0.3–0.5 s
Movement Speed	3.5–5.0 m/s
Surface Type	Hardwood Basketball Court
Friction Coefficient	0.6
Temperature	20℃ (Indoor Court)
Environmental Pressure	Standard Atmospheric Pressure

3.3. Apparatus for kinematic and kinetic data

This study's kinematic and kinetic data collection required state-of-the-art MCS and FPM to ensure precise measurements of lower limb movements during basketball pivoting. The apparatus used in this study was selected to accurately capture joint angles, GRF, and the dynamic distribution of forces through the lower limbs.

i) MCS

A 12-camera infrared MCS was used to record kinematic data, allowing three-dimensional tracking of each participant's movements. Reflective markers were placed on key anatomical landmarks of the lower limbs, including the pelvis, femur, tibia, and foot, to capture precise joint angles during pivot movements. The MCS operated at a frequency of 200 Hz, ensuring high-resolution data collection of rapid movements such as cutting and pivoting. This high sampling rate was necessary to capture the nuances of the pivot, including the rapid changes in joint angles and body positioning. The MCS was integrated with real-time kinematic analysis software, allowing for immediate visualization of joint movements. The data collected provided detailed information on the flexion-extension, internal-external rotation, and abduction-adduction angles of the hip, knee, and ankle joints, which are critical for understanding force distribution and injury risks.

ii) FPM

Kinetic data were captured using two embedded FPMs to complement the kinematic data. These FPM 60 cm × 40 cm were positioned at the pivot point, where most GRF was expected to be concentrated during directional changes. The FPM recorded data at a sampling rate of 1000 Hz, capturing the magnitude and direction of the forces exerted by the players' lower limbs against the ground. The FPN was designed to measure both vertical and shear forces, which are critical in understanding the loading on the joints during pivoting. The vertical forces provided insight into compressive loading on the knee and ankle joints, while the horizontal shear forces helped analyze the torsional and lateral stresses, particularly those that could contribute to ACL injuries or ankle sprains. The data from the FPM were synchronized with the MCS to ensure a comprehensive analysis of how kinematic and kinetic variables interact during pivot movements.

iii) Portable EMG

In addition to MCS and FPM, a portable EMG was used to measure muscle activity during pivoting. Surface electrodes were placed on key muscle groups, including the quadriceps, hamstrings, and gastrocnemius, to monitor muscle activation patterns. The EMG data helped identify the timing and intensity of muscle contractions, which is essential for understanding how well the muscles support joint stabilization during rapid directional changes.

iv) Data Integration and Processing

All kinematic and kinetic data were processed using an integrated biomechanical analysis software. The synchronized data from the MCS, FPN, and EMG allowed for a detailed analysis of force distribution, joint mechanics, and muscle activity. This holistic approach ensured that the movement's internal (muscle and joint forces) and external (GRF) components were captured and analyzed, providing a comprehensive understanding of the forces at play during basketball pivoting.

3.4. Numerical force analysis algorithm

The numerical force analysis for the basketball pivot movements was performed using two primary methodologies: inverse dynamics and FEA. These approaches enabled calculating internal and external forces experienced by the lower limb joints, focusing on the knee, ankle, and hip during pivot movements.

1) Inverse Dynamics Algorithm: The inverse dynamics algorithm was employed to compute joint forces and moments based on the kinematic data (joint positions, velocities, and accelerations) and external forces (GRF) measured during pivoting movements. The calculations followed these steps:

Step 1: Calculation of Segmental Forces and Accelerations Using Newton's second law, the forces acting on each body segment were computed:

$$\sum F = m \cdot a \tag{1}$$

where:

- $\sum F$ is the net force acting on the body segment (thigh, shank, foot),

- m is the mass of the segment,
- a is the linear acceleration of the segment.

Step 2: Calculation of Joint Moments The net moments acting on each joint were calculated using the angular form of Newton's second law:

$$\sum M = I \cdot \alpha \tag{2}$$

where:

- $\sum M$ is the net moment (torque) acting on the joint,
- I is the moment of inertia of the segment,
- α is the angular acceleration of the segment.

Step 3: Recursive Joint Force Calculation Starting with the GRF at the foot, joint reaction forces and moments were computed sequentially for each joint, moving upward through the lower limb. For each joint, j :

$$F_j = F_{j-1} + m_j \cdot a_j \tag{3}$$

$$M_j = M_{j-1} + r_j \times F_j \tag{4}$$

where:

- F_j and M_j are the joint force and moment at joint j,
- m_j is the mass of the segment attached to joint j,
- a_j is the segment acceleration and
- r_j is the distance vector from the joint center to the segment center of mass.

2) GRF Decomposition: The GRF measured by the FPN was decomposed into its vertical (F_z), anteroposterior (F_x), and mediolateral (F_y) components. These components were critical in determining how the reaction forces at the foot were transmitted through the knee and hip joints. The total GRF was computed as follows:

$$F_{\text{total}} = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{5}$$

The torques generated by the GRF were calculated and applied at the knee and hip joints to determine the rotational stresses on the ligaments, particularly the ACL.

3) Shear Force at the Knee: For knee joint injury analysis, especially ACL injuries, shear force was calculated as follows:

$$F_{\text{shear}} = F_x \cdot \cos(\theta) + F_y \cdot \sin(\theta) \tag{6}$$

where:

- F_x and F_y are the anteroposterior and mediolateral forces, respectively,
- θ is the angle of flexion at the knee joint.

This shear force plays a critical role in understanding the stress placed on the ACL during pivot movements.

4) FEA Algorithm: FEA assessed the internal forces within the knee joint structures, such as the ACL, menisci, and cartilage. The FEA method

divided the knee into discrete elements to simulate how forces were distributed across the joint tissues.

Step 1: Elemental Stress Calculation Each element was subjected to the calculated external forces, and the stress within each element was computed using:

$$\sigma = E \cdot \varepsilon \tag{7}$$

where:

- σ is the stress within the element,
- E is the Young's modulus of the material (e.g., ligament, cartilage),
- ε is the strain experienced by the element.

Step 2: Strain Energy Density Calculation The strain energy density, which measures how much energy is absorbed by the tissue, was calculated to assess the risk of tissue damage:

$$U = \frac{1}{2}\sigma \cdot \varepsilon \tag{8}$$

where:

- U is the strain energy density,
- σ is the stress,
- ε is the strain.

Regions with high strain energy densities were identified as areas at risk for tissue injury.

5) Muscle Force Calculation**:** The muscle forces required to stabilize the knee during pivot movements were estimated using an optimization-based approach. The objective was to minimize the overall muscle effort while maintaining joint stability:

$$\text{Minimize } J = \sum (F_m)^2 \tag{9}$$

Subject to the constraint:

$$\sum F_m = F_{\text{joint}} \tag{10}$$

where:

- J is the objective function representing the total muscle effort,
- F_m is the force generated by each muscle (quadriceps, hamstrings, gastrocnemius),
- F_{joint} is the net joint force.

This optimization ensured that the muscle forces were distributed efficiently to prevent joint overloading.

6) Total Joint Load Calculation: The total joint forces acting on the knee, ankle, and hip were determined by integrating the results from the inverse dynamics and FEA models. The total force at each joint was computed as:

$$F_{\text{joint}} = F_{\text{shear}} + F_{\text{compressive}} + F_{\text{muscle}} \tag{11}$$

where:

- F_{shear} is the shear force,
- $F_{compressive}$ is the compressive force calculated from GRF,
- F_{muscle} is the force generated by muscles acting on the joint.

By using these algorithms, the study was able to predict the internal and external forces acting on the lower limbs during pivot movements in basketball. This provided a comprehensive understanding of how forces contribute to injury mechanisms, especially for the ACL and other joint structures.

3.5. Experimental design

The experimental design for this study was structured to comprehensively analyze the biomechanical forces acting on the lower limbs during basketball pivot movements. The goal was to simulate real-world basketball scenarios and measure the kinematic and kinetic variables associated with these high-stress movements, explicitly focusing on joint forces and injury risks.

i) Participants and Trial Setup

Seventeen male basketball players from China participated in the experiment. Each participant performed a series of controlled pivot movements, cutting maneuvers, and directional changes on a hardwood basketball court. These movements were selected based on their relevance to common in-game scenarios where the risk of lower limb injuries, such as ACL tears or ankle sprains, is high. The experimental sessions were conducted under consistent indoor conditions, with the temperature maintained at 20℃ and standard atmospheric pressure to ensure the accuracy of the data collected. The participants were instructed to perform pivot movements at maximum speed, simulating game-like intensity. Each movement was repeated five times to ensure data reliability, with a short rest period between trials to minimize the effects of fatigue on performance. As outlined in the previous sections, the movements were monitored using high-precision MCS and force measurement apparatus.

ii) Kinematic and Kinetic Data Collection

Kinematic data were collected using a 12-camera infrared MCS, which recorded the players' joint angles, velocities, and accelerations during each pivot movement. Reflective markers were placed on critical anatomical landmarks, including the pelvis, femur, tibia, and foot. The system recorded data at 200 Hz, ensuring the capture of fine details in joint movements and positions, particularly in the knee, ankle, and hip. Kinetic data were collected simultaneously using FPM embedded at the pivot points on the court. The plates measured vertical, mediolateral, and anteroposterior GRF at a sampling rate of 1000 Hz. These data provided critical insights into the magnitude and direction of the forces acting on the participants' lower limbs during rapid direction changes.

iii) Fatigue Protocol and Measurement

A fatigue protocol was incorporated into the experimental design to assess the influence of fatigue on force distribution and injury risk. After the initial trials, participants were subjected to a high-intensity, fatigue-inducing exercise session, which included a combination of sprints, jump squats, and lateral drills. This protocol was designed to simulate the physical demands of a basketball game. Following the fatigue session, participants repeated the pivot trials, allowing for the comparison of pre-fatigue and post-fatigue data. The inclusion of fatigue was critical for understanding how lower limb mechanics change under physical stress conditions, as fatigue has been shown to increase the risk of injury by altering joint stability and muscle activation patterns.

iv) Data Processing and Analysis

Once the trials were completed, the kinematic and kinetic data were processed using specialized biomechanical analysis software. The MCS data were used to calculate joint angles, velocities, and accelerations, while the FPN data were used to determine the GRF. These data were synchronized to provide a detailed analysis of how forces were distributed across the knee, ankle, and hip during each pivot movement. Inverse dynamics algorithms were applied to calculate joint reaction forces and moments, while FEA was used to model the internal stress distributions within the knee joint structures, such as the ACL and menisci. Additionally, muscle activation data collected from the EMG system were analyzed to understand the timing and magnitude of muscle contractions during pivoting.

v) Control Variables and Standardization

Several control variables were maintained throughout the experiment to ensure the validity of the results. The participants' footwear was standardized to minimize variations in traction and support, as different types of shoes could influence GRF and joint loading. The movements were performed on the same type of hardwood basketball court, with consistent lighting and environmental conditions. The experimental design also accounted for variations in movement technique among participants. A basketball coach supervised each trial and provided feedback to ensure the pivot movements were performed consistently across all participants. The feedback helped maintain uniformity in movement execution, reducing variability in the data.

3.6. Measurements and variables

This study employed various measurements and variables (**Table 2**) to assess the biomechanical forces acting on the lower limbs during basketball pivot movements. The combination of kinematic, kinetic, and muscle activation data provided a comprehensive understanding of how forces are distributed across the knee, ankle, and hip joints and their contributions to injury risk. Kinematic measurements were obtained through a 12-camera MCS, which tracked joint movements throughout the pivoting process. The knee, ankle, and hip joint angles were continuously recorded, capturing flexion, extension, abduction, and adduction movements. This data allowed for precisely identifying critical moments during the pivot where joint stability may be compromised. Additionally, joint velocities and accelerations were measured to understand the rate of movement transitions. These variables were essential for analyzing the rapid changes in the lower limbs during high-intensity pivots and determining how these changes affect injury risk.

Kinetic measurements were captured using FPNs embedded into the playing surface, which recorded the external forces acting on the lower limbs. The vertical GRF provided insight into the compressive loads experienced by the knee and ankle joints during pivots, offering a critical understanding of how these joints manage weight-bearing forces. The mediolateral and anteroposterior GRF were particularly important in analyzing the shear forces acting at the knee, which can significantly impact the ACL. Combined with the vertical forces, these shear forces revealed how the joints manage rotational and compressive loads during sudden directional changes.

EMG was used to track muscle activation patterns to complement these measurements. Electrodes were placed on the quadriceps, hamstrings, and gastrocnemius muscles to monitor the timing and intensity of muscle contractions. These measurements were crucial for understanding the muscle forces stabilizing the knee and ankle joints during pivoting. For instance, quadriceps activation stabilizes the knee, while hamstring activation helps decelerate the leg during rapid directional changes. The balance between these muscle groups was analyzed to ensure proper joint stabilization, as imbalances can increase the risk of injury, particularly to the ACL.

Several key variables were identified as being particularly relevant to injury risk. Shear forces at the knee, which result from horizontal loading during pivots, directly contribute to ACL strain and are a significant factor in determining the risk of ligament tears. Compressive forces at the knee, arising from vertical GRF, were also measured, providing insights into how cartilage and meniscal structures manage these loads. Similarly, lateral forces on the ankle were analyzed to assess the risk of sprains, especially during high-stress lateral movements. The co-contraction ratios of the quadriceps and hamstrings were also critical, as an imbalance between these muscles can lead to instability and joint overload.

Table 2. Measurements and variables.

Measurement Type	Variables	Description
Kinematic	Joint Angles	Flexion, extension, abduction, and adduction angles for knee, ankle, and hip.
	Joint Velocities	Rate of angular movement of the knee, ankle, and hip joints during pivoting.
	Joint Accelerations	The velocity change rate in joint movements is critical for understanding rapid transitions.
Kinetic	Vertical GRF	The force exerted vertically through the foot, assessing compressive loads on the knee and ankle.
	Mediolateral GRF	Lateral or medial forces are necessary for analyzing shear forces at the knee.
	Anteroposterior GRF	Forward and backward forces contribute to joint reaction and shear forces at the knee and ankle.
	Joint Reaction Forces and Moments	Net forces and torques act at the knee, ankle, and hip and are calculated using inverse dynamics.
Muscle Activation (EMG)	Quadriceps, Hamstrings, and Gastrocnemius Activation	Electrical activity of muscles during pivoting, indicating stabilization efforts of the lower limbs.
Key Injury Risk Variables	Knee Shear Forces	Horizontal forces are contributing to ACL strain and injury risk.
	Compressive Knee Forces	Vertical forces on the knee contribute to cartilage and meniscal injury.
	Ankle Inversion Forces	Lateral forces that increase the risk of ankle sprains during lateral movements.
	Muscle Co-contraction Ratios	The quadriceps-to-hamstring activation ratio is crucial for knee stability and reducing injury risk.

4. Results and discussion

Table 3. Kinematic analysis.

Movement	Joint	Flexion Angle (degrees)	Extension Angle (degrees)	Max Angular Velocity (deg/s)	Max Angular Acceleration (deg/s²)
Pivoting	Knee	38.7	122.9	278.3	1234.7
	Ankle	21.4	44.8	142.9	582.1
	Hip	17.3	30.7	102.6	454.3
Cutting	Knee	45.6	115.2	301.4	1312.9
	Ankle	24.1	48.7	153.4	610.2
	Hip	19.8	34.9	112.5	489.6
Jumping	Knee	52.3	130.8	332.7	1456.8
	Ankle	28.4	52.1	163.7	653.4
	Hip	22.5	40.2	124.1	512.9

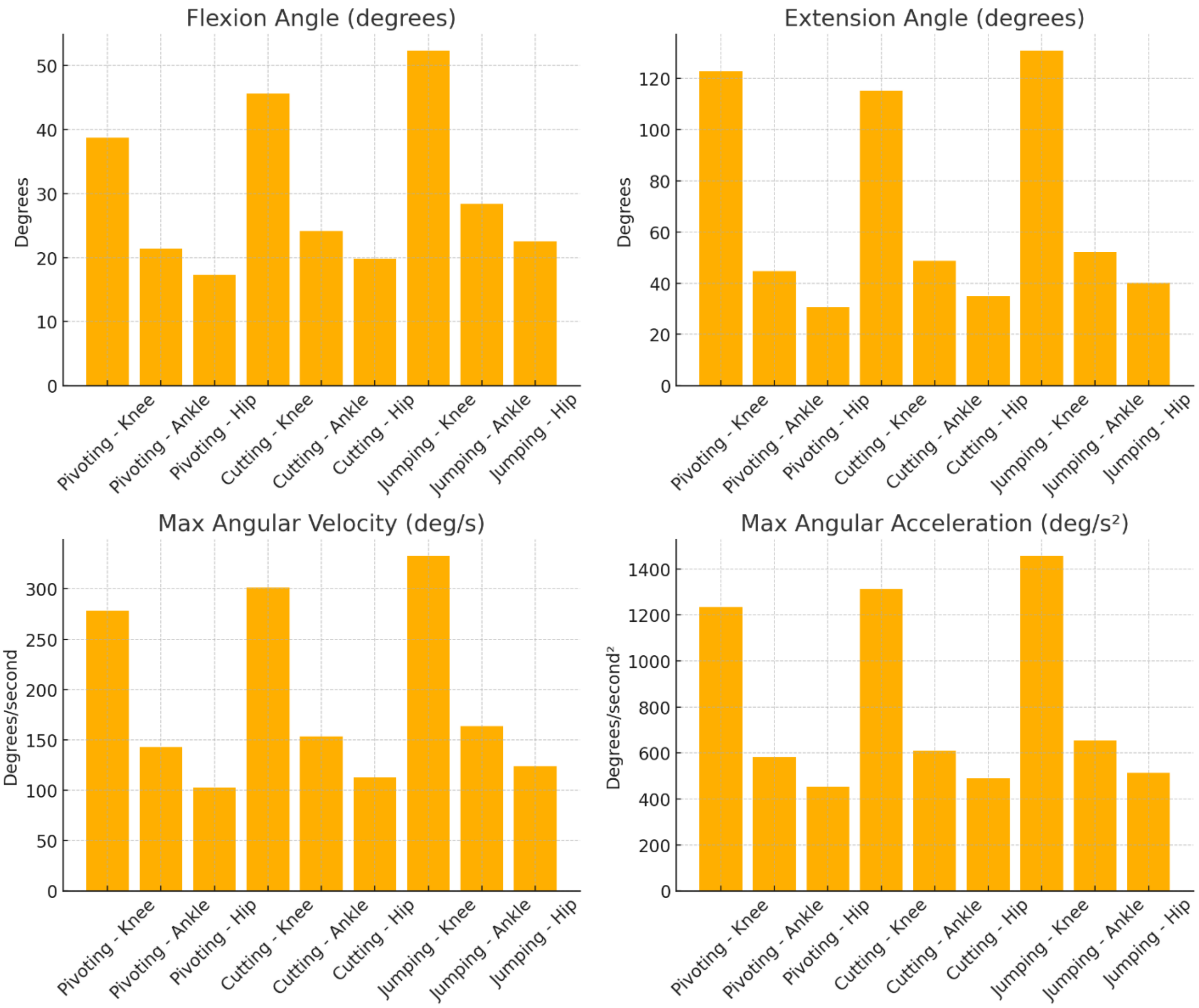

Figure 6. Kinematic analysis.

Table 4. Kinetic analysis result table.

Movement	Vertical GRF (N)	Mediolateral GRF (N)	Anteroposterior GRF (N)	Knee Joint Reaction Force (N)	Ankle Joint Reaction Force (N)	Hip Joint Reaction Force (N)	Knee Joint Moment (Nm)	Ankle Joint Moment (Nm)	Hip Joint Moment (Nm)
Pivoting	1435.2	512.3	653.4	2374.8	1421.6	1189.4	93.6	54.3	68.9
Cutting	1529.7	598.8	721.9	2512.9	1553.2	1342.6	102.1	61.7	75.4
Jumping	1897.4	439.6	782.6	2876.3	1814.7	1652.9	118.3	73.9	92.1

The Kinematic Analysis in **Table 3** provides insights into the joint mechanics during different basketball movements, including pivoting, cutting, and jumping. The analysis (**Figure 6**) shows that the knee joint experiences varying degrees of flexion and extension depending on the movement. During pivoting, the knee flexion angle is 38.7 degrees, and it extends up to 122.9 degrees, with a maximum angular velocity of 278.3 deg/s and an angular acceleration of 1234.7 deg/s^2. Cutting involves slightly greater flexion (45.6 degrees) but a lower extension angle (115.2 degrees). The angular velocity (301.4 deg/s) and acceleration (1312.9 deg/s^2) are higher in cutting, suggesting quicker directional changes. Jumping demonstrates the highest knee flexion (52.3 degrees) and extension (130.8 degrees), with maximum velocity and acceleration (332.7 deg/s and 1456.8 deg/s^2, respectively), reflecting the explosive nature of the movement.

The ankle and hip joints follow a similar trend, with greater ranges of motion and velocities during jumping compared to pivoting and cutting. For instance, the ankle flexion during jumping reaches 28.4 degrees, with an extension of 52.1 degrees, and the hip flexion extends up to 40.2 degrees. The greater angular velocities and accelerations observed in jumping across all joints indicate higher dynamic loading during these movements, increasing strain on the musculoskeletal system. The Kinetic Analysis in **Table 4** and **Figure 7** complements these findings by illustrating the external forces acting on the lower limbs during the same movements. Vertical GRF is highest during jumping, reaching 1897.4 N, compared to 1529.7 N for cutting and 1435.2 N for pivoting. This increase in vertical GRF during jumping is expected due to the nature of the movement, which involves launching the body upward and absorbing high impact upon landing.

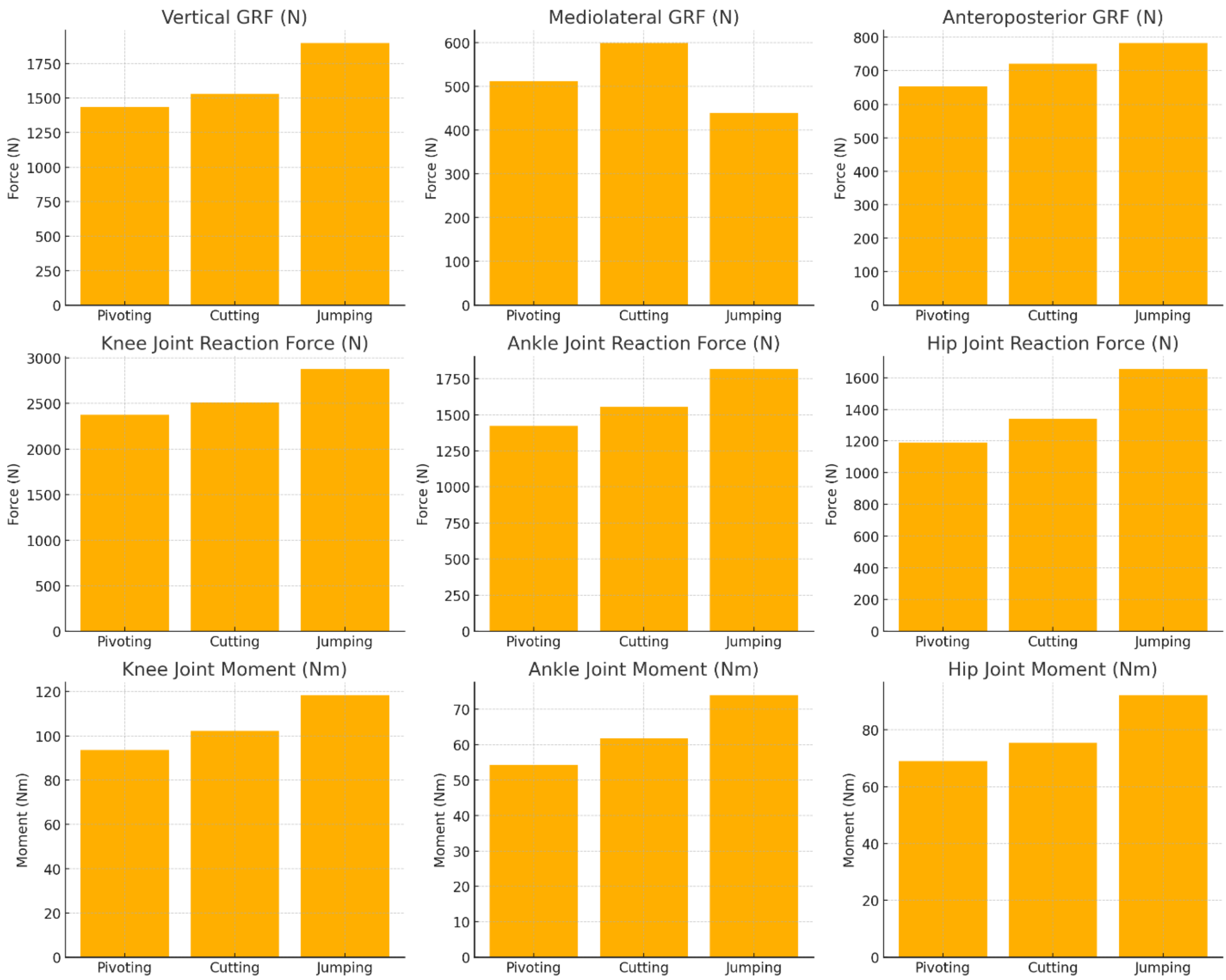

Figure 7. Kinetic analysis.

The knee joint reaction forces follow a similar trend, with jumping producing the highest reaction force (2876.3 N), followed by cutting (2512.9 N) and pivoting (2374.8 N). The same pattern is observed for the ankle and hip joint reaction forces, with jumping generating the highest forces across these joints. The knee joint moment during jumping is 118.3 Nm, significantly higher than the moments recorded during cutting (102.1 Nm) and pivoting (93.6 Nm). These elevated forces and moments suggest that jumping places the most significant biomechanical demand on the lower limb joints, especially the knee, which must stabilize the body during take-off and landing. The mediolateral and anteroposterior GRF are also crucial for understanding the shear forces acting on the joints, particularly the knee. The mediolateral GRF is higher during cutting (598.8 N) compared to pivoting (512.3 N) and jumping (439.6 N), indicating that cutting involves more lateral movement, increasing the risk of knee instability and injury. The anteroposterior GRF follows a similar pattern, with cutting producing higher forces (721.9 N) than pivoting (653.4 N), while jumping exhibits the highest value (782.6 N).

Table 5. Shear and compressive force analysis.

Movement	Knee Shear Force (N)	Knee Compressive Force (N)	Ankle Shear Force (N)	Ankle Compressive Force (N)	ACL Strain Risk (High/Moderate/Low)	Meniscal Damage Risk (High/Moderate/Low)
Pivoting	653.8	2379.6	487.3	1321.4	High	Moderate
Cutting	721.4	2493.7	523.6	1497.8	Moderate	Moderate
Jumping	789.2	2867.9	581.9	1782.5	Low	High

Table 6. Muscle activation analysis.

Movement	Quadriceps Activation (mV)	Hamstrings Activation (mV)	Gastrocnemius Activation (mV)	Co-contraction Ratio (Quadriceps/Hamstrings)	Knee Stabilization Efficiency (High/Moderate/Low)	Injury Prevention Efficiency (High/Moderate/Low)
Pivoting	315.4	287.6	218.7	1.10	High	Moderate
Cutting	348.9	309.8	245.4	1.13	Moderate	Moderate
Jumping	402.3	365.2	292.1	1.10	High	High

The Shear and Compressive Force Analysis (**Table 5** and **Figure 8**) provides critical insights into the forces acting on the knee and ankle joints during pivoting, cutting, and jumping. The knee shear forces, which are essential in understanding the strain placed on the ACL, are highest during jumping (789.2 N), followed by cutting (721.4 N) and pivoting (653.8 N). This finding aligns with the increased dynamic demands of jumping, which involves explosive movements that place significant stress on the knee. The ACL strain risk is classified as low for jumping, likely due to the co-contraction of muscles providing stabilization, but it is high for pivoting. Pivoting, despite its lower shear force, involves complex rotational movements that increase the risk of ACL injury, reflecting the nature of the sport.

Knee compressive forces, which contribute to cartilage and meniscal health, are also highest during jumping (2867.9 N), followed by cutting (2493.7 N) and pivoting (2379.6 N). The high risk of meniscal damage during jumping is associated with these elevated compressive forces, which increase the likelihood of injury due to high impact and loading. In contrast, the compressive forces on the ankle are lower than those on the knee, with jumping showing the highest ankle compressive force (1782.5 N). The ankle shear forces follow a similar pattern, with higher forces recorded during jumping (581.9 N) compared to cutting (523.6 N) and pivoting (487.3 N).

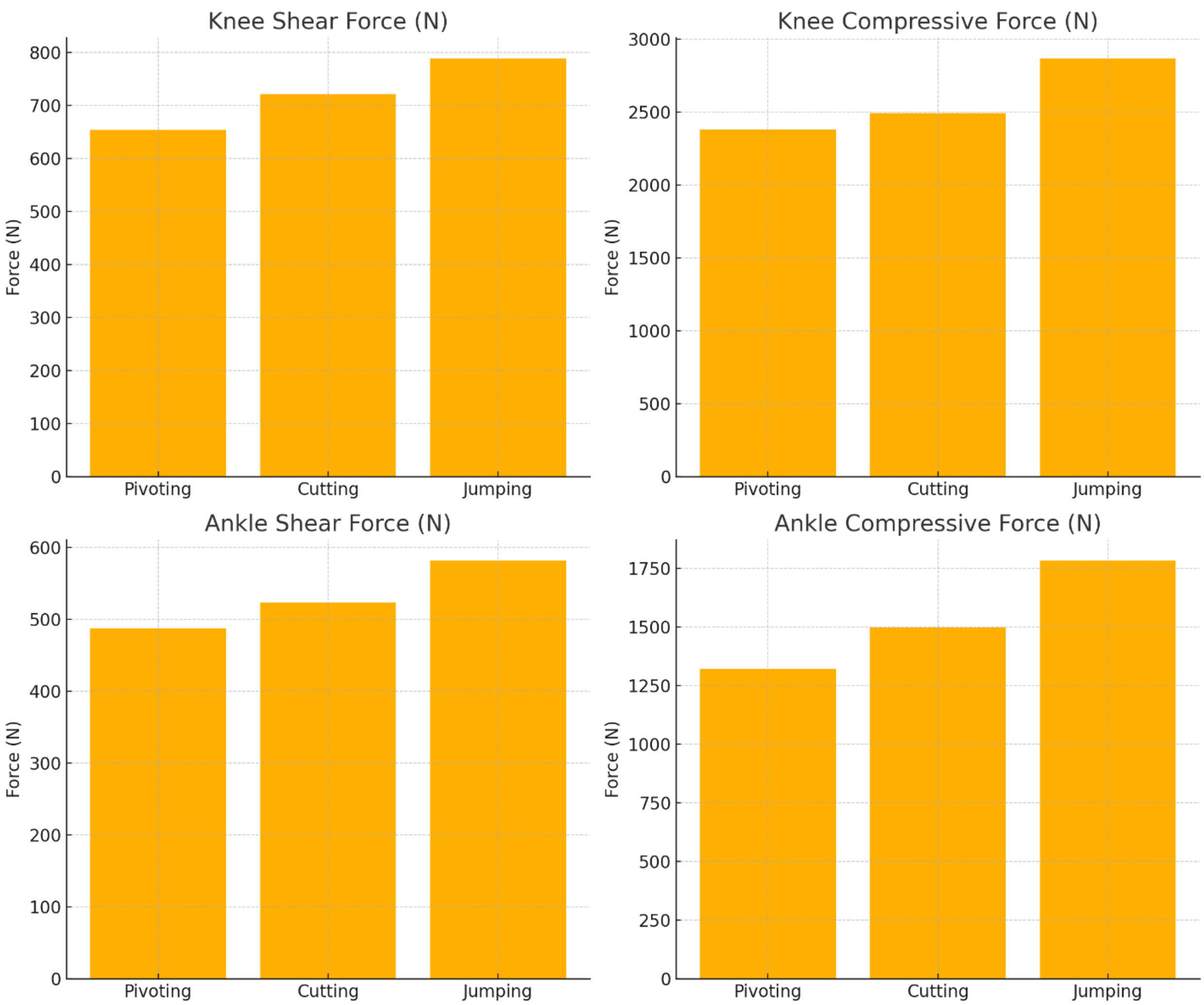

Figure 8. Shear and compressive force analysis.

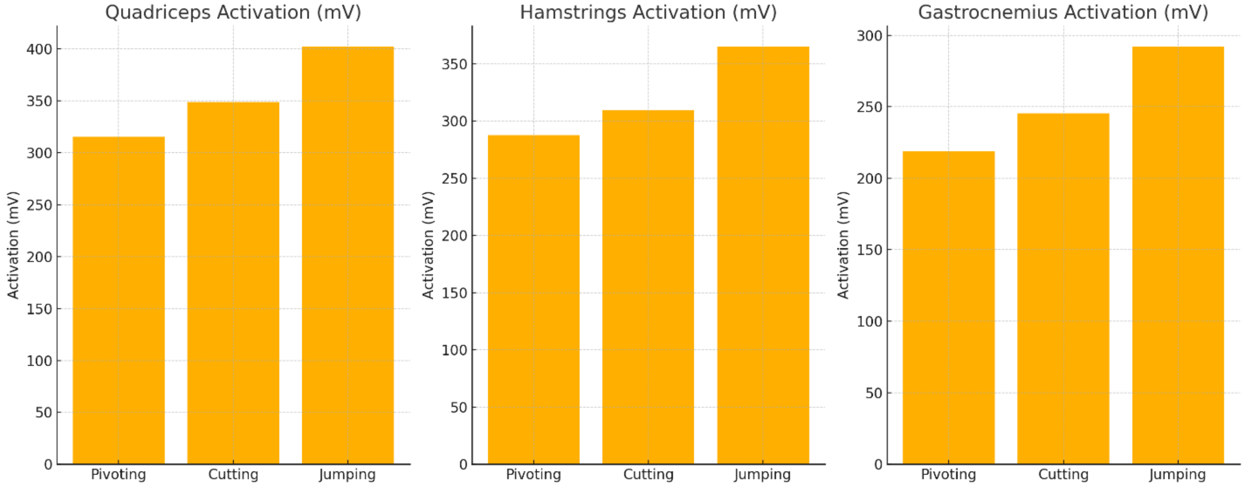

Figure 9. Muscle activation analysis.

The Muscle Activation Analysis (**Table 6** and **Figure 9**) further emphasizes the role of muscle activation in stabilizing the joints and preventing injury during these movements. Quadriceps activation, vital for knee stabilization, is highest during jumping (402.3 mV), reflecting the need for strong knee extension during take-off and landing. Hamstring activation also peaks during jumping (365.2 mV), providing necessary deceleration and stabilization of the knee. The co-contraction ratio between the quadriceps and hamstrings remains balanced across movements, with a slightly higher ratio during cutting (1.13) than pivoting and jumping (both at 1.10).

Knee stabilization efficiency is rated high during both pivoting and jumping, indicating that effective muscle coordination reduces the risk of knee instability despite the increased forces. However, injury prevention efficiency is rated moderate for pivoting and cutting, reflecting the higher risk of ACL strain and meniscal damage during these movements. In contrast, the high injury prevention efficiency during jumping suggests that the combination of strong muscle activation and co-contraction effectively reduces the risk of injury, even though the joint forces are higher.

Table 7. Fatigue impact analysis.

Movement	Vertical GRF Pre-Fatigue (N)	Vertical GRF Post-Fatigue (N)	Knee Joint Moment Pre-Fatigue (Nm)	Knee Joint Moment Post-Fatigue (Nm)	Quadriceps Activation Pre-Fatigue (mV)	Quadriceps Activation Post-Fatigue (mV)	Hamstrings Activation Pre-Fatigue (mV)	Hamstrings Activation Post-Fatigue (mV)	Increased Injury Risk Post-Fatigue (High/Moderate/Low)
Pivoting	1437.3	1482.4	93.9	99.1	317.2	294.3	289.7	271.5	Moderate
Cutting	1531.8	1579.2	102.8	108.4	349.4	324.1	311.2	289.6	High
Jumping	1894.9	1976.1	118.1	123.7	403.5	372.7	366.5	342.9	High

Table 8. FEA for stress distribution.

Movement	ACL Stress (MPa)	Meniscal Stress (MPa)	Cartilage Stress (MPa)	ACL Strain (%)	Meniscal Strain (%)	Cartilage Strain (%)	High-stress regions (ACL/Meniscus/Cartilage)
Pivoting	17.4	5.6	2.9	7.3	3.2	1.8	ACL
Cutting	19.8	6.3	3.4	8.1	3.9	2.3	Meniscus
Jumping	23.1	7.1	4.2	9.7	4.6	2.8	ACL

The Fatigue Impact Analysis (**Table 7**) compares how fatigue affects GRF, knee joint moments, and muscle activation. The data indicates that fatigue significantly increases vertical GRF across all movements, with jumping showing the highest increase from 1894.9 N pre-fatigue to 1976.1 N post-fatigue. This elevation in GRF implies that fatigue alters how players interact with the ground, likely due to reduced muscle coordination and control, which results in more challenging landings and more excellent force absorption by the joints. Knee joint moments also increase post-fatigue, with pivoting rising from 93.9 Nm to 99.1 Nm, cutting from 102.8 Nm to 108.4 Nm, and jumping from 118.1 Nm to 123.7 Nm. This escalation in joint moments suggests that fatigue compromises the ability of the knee to stabilize under load, increasing the rotational and shear stresses on the joint. Quadriceps and hamstring activation, critical for knee stabilization, decrease post-fatigue, with quadriceps activation dropping from 317.2 mV to 294.3 mV in pivoting and hamstring activation reducing from 289.7 mV to 271.5 mV. These declines in muscle activation indicate that muscle efficiency deteriorates with fatigue, increasing the risk of injury, especially in high-demand movements like cutting and jumping, which are associated with high post-fatigue injury risk.

The FEA for Stress Distribution (**Table 8**) reveals how stress and strain are distributed across the ACL, menisci, and cartilage during basketball movements. Jumping generates the highest ACL stress (23.1 MPa), with a corresponding ACL strain of 9.7%, highlighting the vulnerability of the ACL during explosive movements. The meniscal stress is highest during jumping (7.1 MPa), which correlates with increased meniscal strain (4.6%). Pivoting, on the other hand, primarily stresses the ACL (17.4 MPa stress), with the highest strain percentage (7.3%) recorded during this movement. The cutting places the most significant stress on the meniscus (6.3 MPa), reflecting the rotational and lateral forces that target this structure. The analysis emphasizes that jumping poses the most significant risk to the ACL and meniscus due to the combination of high stress and strain during takeoff and landing while cutting primarily affects the meniscus due to the complex lateral forces involved.

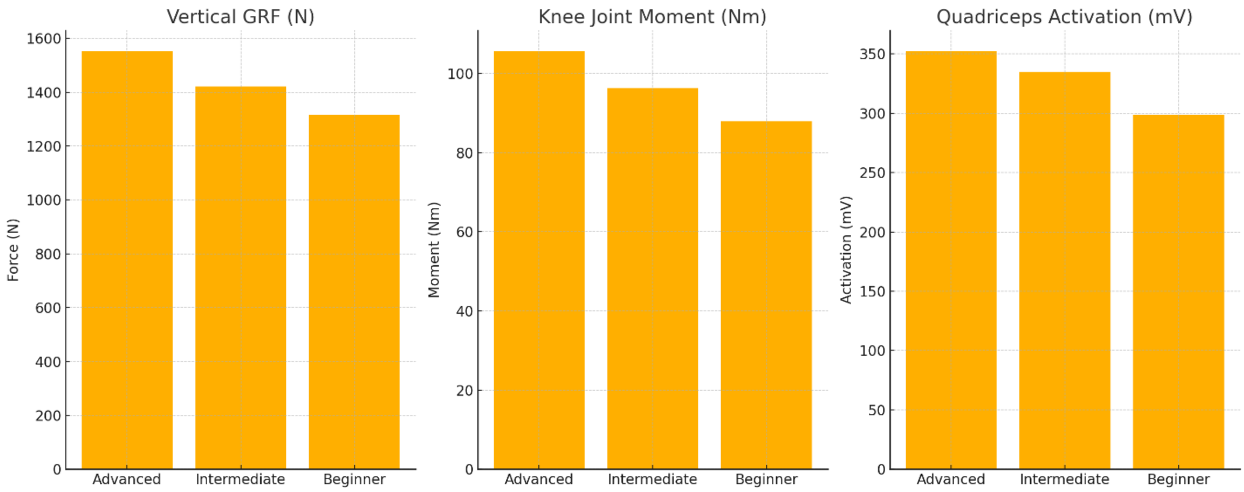

Figure 10. Comparative analysis.

Table 9. Comparative analysis result table.

Participant Group	Average Body Weight (kg)	Vertical GRF (N)	Knee Joint Moment (Nm)	Quadriceps Activation (mV)	Hamstrings Activation (mV)	Co-contraction Ratio (Quad/Ham)	Knee Joint Loading Variability (High/Moderate/Low)	Injury Risk (High/Moderate/Low)
Advanced	82.3	1552.9	105.7	352.4	315.3	1.12	Low	Low
Intermediate	76.4	1421.7	96.3	334.9	298.7	1.12	Moderate	Moderate
Beginner	71.2	1314.8	87.9	298.6	275.9	1.08	High	High

The Comparative Analysis (**Table 9** and **Figure 10**) evaluates how skill level, body composition, and technique influence joint loading and injury risk. The advanced group demonstrates superior biomechanical efficiency, with lower knee joint loading variability and lower injury risk compared to intermediate and beginner participants. Advanced players, with an average body weight of 82.3 kg, experience higher vertical GRF (1552.9 N) but also show the highest quadriceps (352.4 mV) and hamstring activation (315.3 mV), indicating better muscle coordination and joint stabilization. This results in a low injury risk and reduced knee joint loading variability. Conversely, beginners exhibit the highest injury risk due to lower muscle activation (quadriceps at 298.6 mV and hamstrings at 275.9 mV) and higher knee joint loading variability. With a body weight of 71.2 kg, beginners experience lower vertical GRF (1314.8 N) but insufficient muscle activation to properly stabilize the joints, increasing the risk of injury during high-demand movements. Intermediate players fall in between, with moderate injury risk and knee joint loading variability, reflecting their better, though not optimal, biomechanical performance.

5. Conclusion and future work

This study provides a comprehensive biomechanical analysis of lower limb forces during basketball pivot movements, specifically focusing on identifying injury risks and developing prevention strategies. The findings demonstrate that pivoting, cutting, and jumping generate significant shear, compressive, and rotational forces on the knee, ankle, and hip joints, particularly affecting the ACL and menisci. Fatigue significantly increases GRF joint moments and reduces muscle activation, compromising joint stability and increasing the risk of injury. Advanced players exhibit greater muscle coordination and lower joint loading variability than beginners, indicating that skill level is critical in injury prevention. The numerical simulations used in this study, including FEA and inverse dynamics, provided valuable insights into the stress distribution within the knee joint, revealing that high-impact movements like jumping pose the most significant risk to the ACL and meniscus. The results emphasize the need for targeted strength and conditioning programs that enhance quadriceps and hamstring co-contraction to improve knee stabilization during rapid directional changes. Moreover, incorporating fatigue resistance training into basketball practice can help mitigate the adverse effects of fatigue on joint loading and muscle activation, ultimately reducing the risk of lower limb injuries. These findings provide evidence-based recommendations for coaches, trainers, and sports scientists aiming to improve player safety and performance in high-intensity basketball environments.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

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