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BIOMECHANICAL ANALYSIS OF LANDING TECHNIQUES AND ASSOCIATED INJURY RISK IN LONG JUMP

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Abstract

Long jump is an athletic sport which is high impact by its nature and is characterized by approach run that accelerates with great intensity followed by dynamic take off. Such conditions often expose the lower extremities to increased biomechanical stress during landing. The force exerted on the body during landing can greatly predispose individuals to various types of musculoskeletal injuries, particularly in the region of the femur. This paper highlights an effort to study different landing techniques heel first, flat foot and forefoot in terms of their effect on stress distribution and injury possibility employing a technique that combines inverse dynamics with finite element analysis. Simulations to replicate the terminal phase of the jump were carried out based on a trained male long jumper's anthropometric and performance data. The inverse dynamics model captured joint reaction forces and moments, which were subsequently applied as boundary conditions in the finite element analysis of a three dimensional femur model derived from imaging data. Results indicated that the heel-first landing technique produced peak ground reaction forces of highest magnitude with stress concentrations localized at the medial region and lateral condyle of the femur. The maximum total displacement and equivalent stress recorded were 0.00077 mm and 191.79 MPa respectively. On the contrary, forefoot landings showed better load attenuation characteristics next to reducing stress magnitudes and distributing forces more equally across the joint. These results underscore a major contribution of landing mechanics to injury prevention and therefore may indicate forefoot landings a biomechanical way of femoral stress mitigation. In addition, the study proves that inverse dynamics integration with FEA can depict the internal loading mechanisms during athletic moves effectively, thus providing a handy platform for injury risk evaluation and technique enhancement for long jump sportsmen.

Keywords**:** Landing Techniques, Femoral Stress Distribution, Inverse Dynamics, Finite Element Analysis (FEA).

1. Introduction

Long jump is a dynamic, high stakes sport that pushes athletes to blend high speed with precise technique. It requires remarkable horizontal velocity during a rigorous run-up, execute a powerful take off soaring with controlled grace and achieve a safe high impact landing. All steps from the accelerating sprint to the critical moment of landing is not only demanding but exceptional in terms of physical strength and acquiring an extraordinary capability to absorb forces. A lot of these forces, in turn impacts the knee joints several times greater than the whole body weight. To endure this, just like beams which withstand the massive structure in high strength buildings, femur (thigh bone) in the human body plays that role. The body contains the strongest and longest bone known as the femur which connects between the hip and knee joints. Its unique anatomy supports various muscular and ligamentous attachments while enabling full limb extension during movement. However, long-term cumulative load on the femur can result in damage and degeneration of the cartilage and meniscus[1]. It is important to control this load progressively to maximize functionality during high stakes sports specifically.

Biomechanics while it addresses the major concerns of the body kinetics and kinematics, some structures in the human body come with great trade of for load balancing and the balancing tool is biomechanics. Knee joint represents the most complicated structure in the human body because it functions as a hinge joint that connects patella with femur and tibia through fibula and meniscus cartilage and associated ligaments and muscles while bearing greater weight than the athlete's body weight [2]. For the sports like long jump, knee plays a critical role. The landing phase is particularly critical as inadequate training methods risk damaging lower limb joints because they cause excessive impact forces that increases the possibility of injuries to the musculoskeletal system such as anterior cruciate ligament (ACL) tears, meniscus damage and stress fractures [3]. In terms of biomechanics, the take off leg faces intense pressure from braking after performing a 40-60 meter or longer accelerated run up. The ground provides 36.7% of total force to the human body through vertical transmission which can exceed the body weight by 12 to 20 times during take off. The knee joint injuries suffered by long jumpers reach an alarming rate of 98% [4]. This is magnificent and there is a need to study biomechanics of long jump so that the athletes can execute all movements at high horizontal velocity to achieve optimal performance. This forms the foundation of this paper. Knee joint endures substantial and rapidly varying impact forces upon ground contact making it highly susceptible to injuries [5]. Moreover, a pilot study[6] mentions knee extension moments along with knee flexion angles and lower limb force generation play essential roles in reducing ACL injury risks according to biomechanical principles in long jump events [7].

The most severe femur bone injury in long jump athletes is a femoral shaft fracture and knee joint cartilage injury. This type of injury is rare but extremely serious due to the high forces involved in landing. Figure 1 illustrates the anatomy of the femur bone. The evaluation of cartilage stress and strain at their peak values represents a critical matter. Biomechanical studies have shown that different landing strategies influence force distribution across the lower extremities while existing research has explored landing mechanics in various athletic populations, limited studies have directly analysed their implications in long jump athletes. This study aims to evaluate how different landing techniques affect injury risk by assessing key biomechanical parameters such as ground reaction forces, joint kinematics and stress distribution as depicted in figure 2. The findings will provide insights into safer landing strategies contributing to injury prevention frameworks in sports biomechanics.

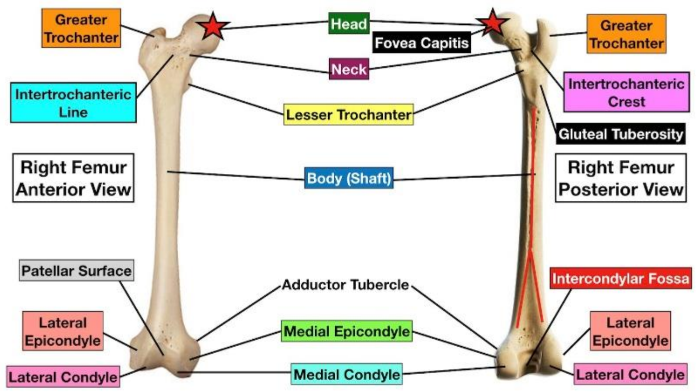


Figure 1: Anatomy of the Femur Bone

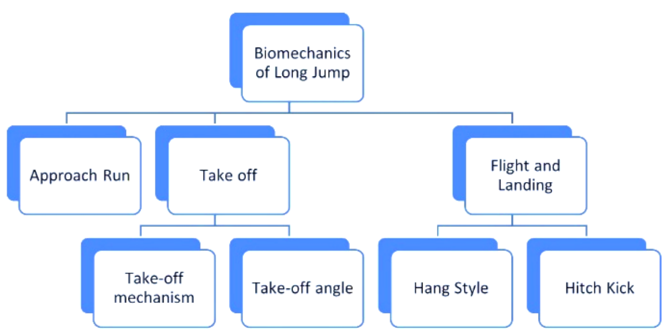
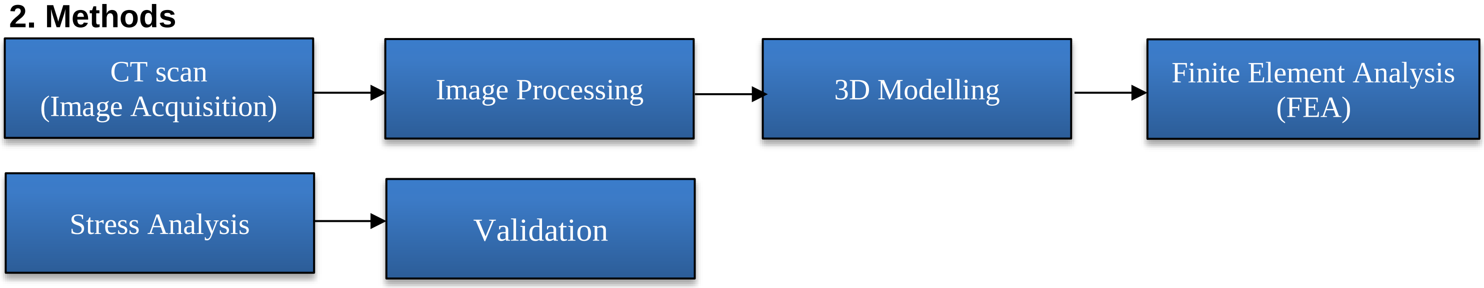


Figure 2:Biomechanics of Long Jump

2. Methods



2.1. Model Construction

This study focuses on the three dimensional modelling of the femur bone to optimize computational efficiency. A male long jumper was selected based on the possible available literature meeting all international standards. To obtain precise geometric data of the femur, computed tomography (CT) scans were acquired was employed focusing on the mid lower femur and upper tibiofibular region. The athlete had no prior femoral injuries and the imaging process ensured error free process. Based on the obtained geometric data, modelling of the femur bone was performed, acquired data was stored in DICOM format and processed using advanced image processing suite for 3D reconstruction. The resulting model was then refined in Computer Solver through feature based modelling and reverse engineering techniques. This detailed femur model enables an accurate biomechanical assessment of stress distribution; impact forces and injury risks associated with different landing techniques in long jump athletes [8].

Figure 3: 3D Model of Femur Bone

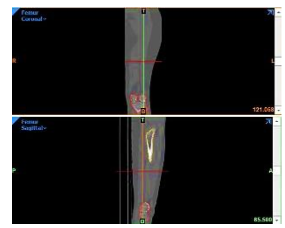


Figure 4: CT scan of Femur Bone

2.2. Inverse Dynamics Analysis

To further assess the biomechanical response of different landing techniques, an inverse dynamics approach was conducted to evaluate joint moments, reaction forces and muscular contributions during impact. An inverse dynamics analysis was performed on the femur to quantify internal forces and moments during various landing techniques. Using mathematical computations instead of motion capture data, joint reaction forces and torques were calculated via Newton-Euler equations and Lagrangian mechanics. This method integrated segmental mass properties, joint kinematics and external forces to determine the ground reaction force acting on the femur, providing critical insights into biomechanical stress during impact [9]. The material properties of all the ligaments used in the model were derived from Table 1 with elastic modulus set at 430 MPa and Poisson ratio set at 0.45.

Table 1: Key Findings of Inverse Dynamics Analysis

S. No	Details	Description
1.	Mass of Athlete	70 Kg
2.	Body Weight of Long Jump Athlete	686 N
3.	Maximum Resultant Force	12x (8232 N)
4.	Approach Running Speed	8.7 m/s
5.	Torque	2100 N/m
6.	Height	1.85 m
7.	Young’s Modulus	2.13 GPa
8.	Density	2 g/cm^3
9.	Poisson’s Ratio	0.45

Table 1 depicts all vital simulation parameters which include an initiation speed of 8.7m/s in phase 1 and a 70 kg 1.85 m tall 20 years old athlete with a best jump distance of 6.5 m. Analysis revealed that the contact phases contained the maximum points of both resultant force and muscle torque. The simulated muscle torque reached nearly 2100 Nm while the maximum resultant force reached near 12 times bodyweight [10]. A comparative evaluation of landing techniques revealed that improper force attenuation leads to higher femoral loading, increasing the risk of stress fractures and cartilage degeneration.

2.3. Finite Element Analysis

FEA represents a computational method which analyses stress distribution together with structural behaviour when structures experience dynamic loading conditions. In long jump landings, the femur experiences high impact forces increasing the risk of stress fractures particularly in the distal metaphysis and femoral condyles[11]. The stress behaviours of vertebrate long bones are typically analysed through classic beam theory in biomechanics models especially for intra-specific scaling models [12].

The compressive force applied at the cross-section centroid produces normal stress which can be calculated:

$$\sigma_{comp} = \frac{F}{A_{cort}} \qquad \textbf{(1)}$$

The bending stress changes throughout symmetric beams according to:

$$\sigma_{bending}(y) = \frac{M_x y}{I_x} \qquad \textbf{(2)}$$

Biological research describes the relationship between axial compression forces and bending stress $\sigma_{combined} = \frac{M_x y sin\theta}{I_x} + \frac{F cos\theta}{A_{cort}}$ **(3)**

Where,

$\sigma_{combined} = Sum\ of\ Compressive\ and\ Bending\ Stresses$

$\theta = Angle\ between\ loading\ direction\ and\ principal\ axis$

So,

$\theta = 0^o$, $\sigma_{combined}$ is equal to σ_{comp}

$\theta = 90^o$, $\sigma_{combined}$ is equal to $\sigma_{bending}$

Due to the established link between stress distribution and cartilage wear and to conserve computational resources, only the 3D knee joint model is presented. The previously used total knee joint model was first converted into a meshed solid geometry using Materialise Magics and then imported into ANSYS Mechanical for finite element analysis. In ANSYS, hexahedral block structure meshes were generated for the bones and soft tissues with ligaments modelled using brick elements. The model comprised approximately 400,000 nodes and 250,000 elements with increased mesh density in high stress areas such as the distal femur, femoral condyles and patellofemoral joint. The femur bone was meshed using SOLID186 elements, which is well suited for capturing stress distribution. Considering that bone is highly anisotropic, it is still reasonable to model the bone under isotropic assumption [13] .Therefore, current study assumes bone linear and isotropic material for FE simulation.

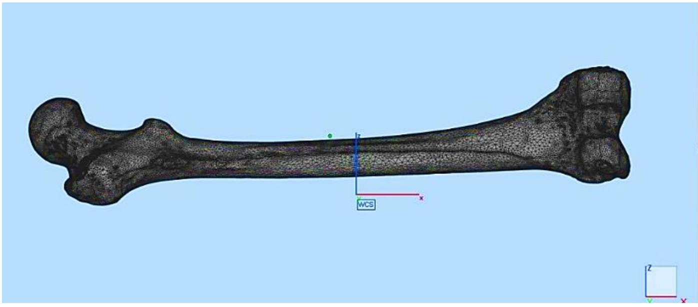


Figure 5: Meshed Profile of Femur Bone CAD Model

Table 2: Mechanical Properties of Femur Bone

S. No	Material Properties	Value
1	Young's Modulus	2.13 GPa
2	Density	2 g/cm^3
3	Poisson's Ratio	0.45
4	Tensile Strength	200 MPa

The research evaluated a single leg stance under test conditions that ranged from a minimum force of 1000N to a maximum of 3000N. The load application started from normal femoral head position toward its axis at a force level equivalent to twelve times body weight [14]. The study analyzed the femur condyle region using fixed support constraints while following experimental and numerical methods reported in literature based studies. Various studies employed fixed support by restricting the movement of condyle sections at approximately 25%.

3. Results and Discussion

During long jump landings, the femur and its articular cartilage are subjected to significant stress and wear. Focusing on deformation, displacement and stress distribution especially under flat footed landing conditions. Numerical simulations indicate that high compressive forces result in substantial cartilage deformation and displacement, potentially accelerating wear and deterioration. The related numerical simulation results are presented below.

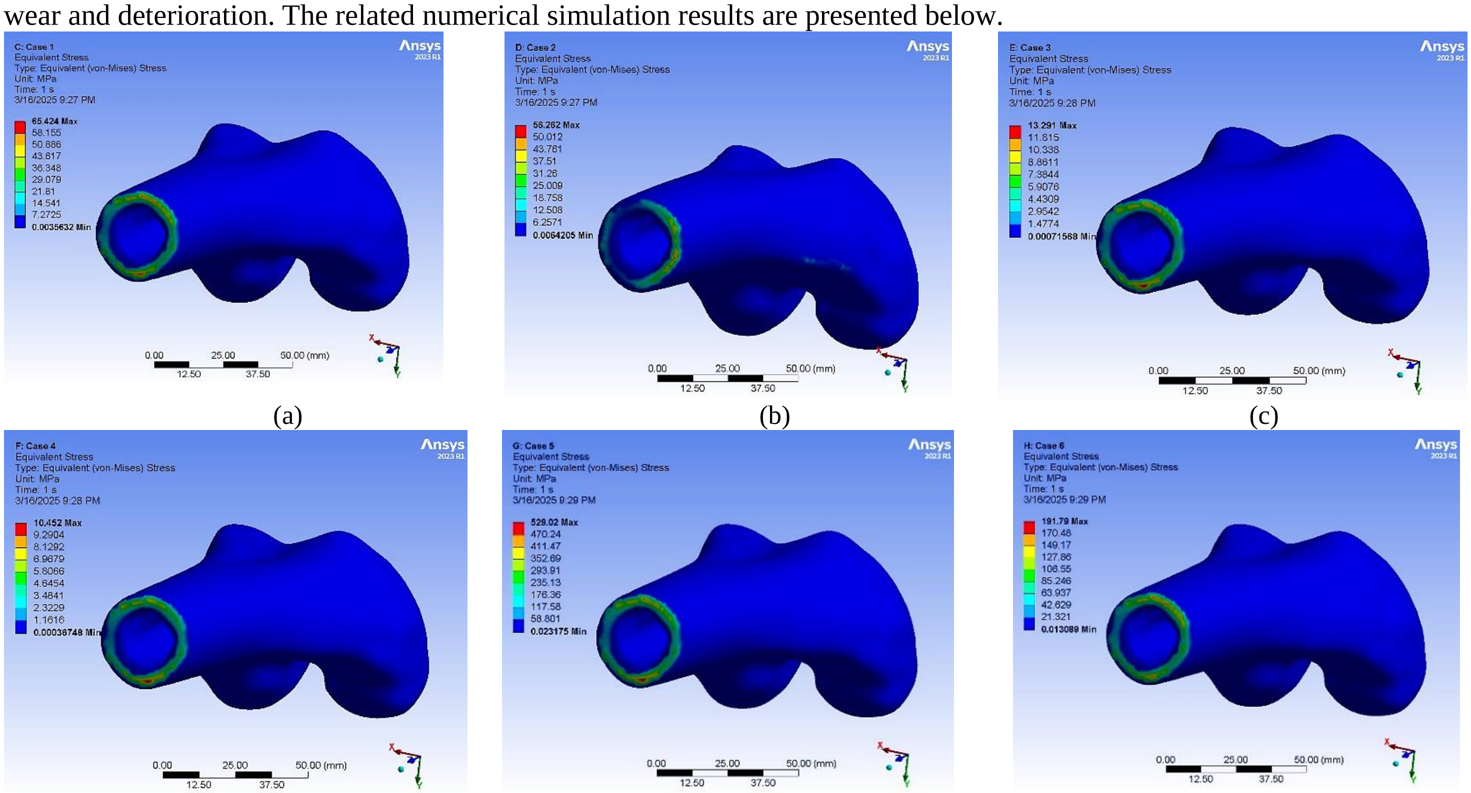
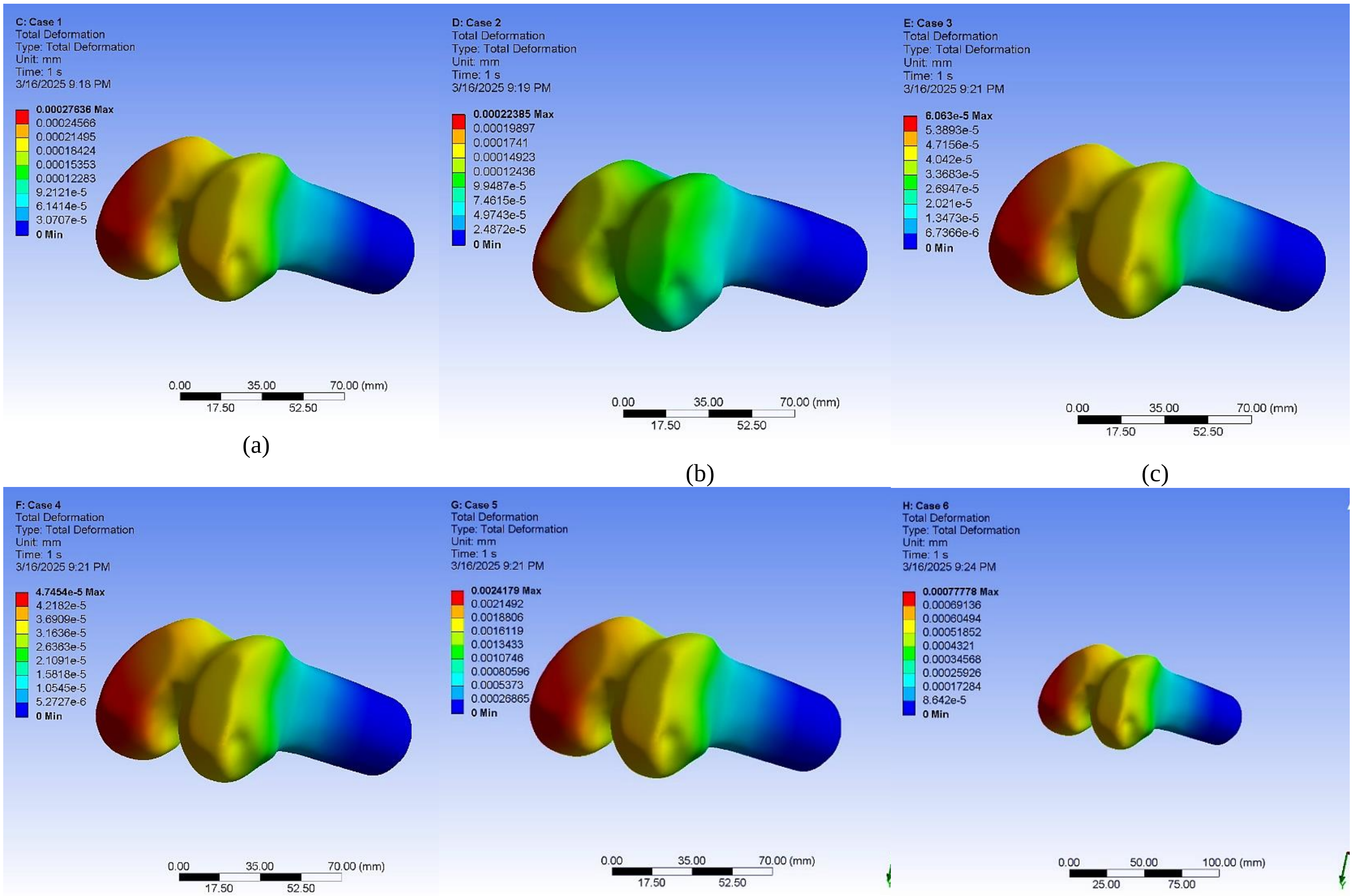


Figure 6: Simulations of Equivalent Stress

(a) Take Off (Before Push Off) (b) Take Off (Push Off Moment) (c) Flight (Early Phase)
(d) Flight (Mid Air) (e) Landing (Touchdown) (f) Landing (Shock Absorption)



(d) (e) (f)

Figure 7: Simulations of Total Deformation in Femur Bone

(a) Take Off (Before Push Off) (b) Take Off (Push Off Moment) (c) Flight (Early Phase)
(d) Flight (Mid Air) (e) Landing (Touchdown) (f) Landing (Shock Absorption)

Seeking insights from Figure 6 and Figure 7, key finding reveals significant facts into femoral stress and cartilage wear during long jump phases including take off, push off, flight and shock absorption. In take off, forces reach approximately 1400 N, straining the femur as force is generated. During push off, forces climb to 3000 N with high muscle torque elevating the risk of stress and microfractures. Whereas the flight phase experiences minimal external load, reducing stress whereas touchdown encounters peak forces that significantly compress the femoral cartilage and increase wear risk. Finally, during shock absorption, forces decrease to 5000 N mitigating stress and facilitating energy dissipation. These findings emphasize the importance of proper landing mechanics particularly during touchdown and shock absorption to minimize femoral stress and cartilage deterioration. Optimal technique reduces injury risk while preserving bone structure and joint health. To validate our numerical simulations, results were qualitatively compared to the computed results with CT scan measurements which confirmed their accuracy.

4. Recommendations for Safe Landing

An overview of biomechanical features and injury risk factors across different landing strategies is provided in Table 3. It indicates that athletes should aim for knee flexion angles between 30° and 40° at initial contact to balance ACL protection and performance while maintaining neutral hip and knee alignment in the frontal and transverse planes to reduce harmful joint moments.

Enhancing ankle dorsiflexion range and stability minimizes compensatory movements at the knee and hip, and incorporating task-specific landing drills improves neuromuscular activation patterns. Therefore, training programs that include perturbation exercises must prepare athletes for unexpected landing scenarios, further reducing ACL injury risk.

Table 3: Landing Techniques, Biomechanical Features, and Injury Risk Factors

Landing Technique	**Key Biomechanical Features**	**Injury Risk Factors**
Natural Landing	Reduced knee flexion, shorter contact time	Increased ACL injury risk due to higher knee abduction/adduction moments
Soft Landing	Greater knee flexion, longer contact time	Reduced ACL injury risk, but poorer performance due to lower jump height
Staggered Foot Landing	Higher muscle activation in gluteus maximus, iliopsoas and quadriceps femoris	Increased muscle activation may lead to overuse injuries
Simultaneous Bilateral	Higher stresses occur across the hip and knee joints and ankle complex.	Elevated risk of acute injuries such as ACL tears
Falling Technique	Knee abduction and internal rotation moments showed lower levels during the activities.	Lower ACL injury risk, particularly in perturbation scenarios

5. Conclusion

This study highlights the critical role of landing techniques in influencing biomechanical stresses on the femur and its articular cartilage during the long jump. Findings reveal that touchdown with impact forces reaching up to 12x body weight, presents the highest injury risk by causing significant cartilage compression and potential long term joint deterioration. Peak deformation, displacement and stresses are concentrated on the medial femur particularly at the lateral condyle which accelerates the wear/damage. Conversely, the shock absorption phase is marked by the increased knee flexion effectively dissipating forces, thereby reducing femoral stress and cartilage damage.

These results highlight that improper landing techniques which fail to distribute impact forces evenly, greatly increase injury risk. Athletes are advised to adopt refined landing strategies such as controlled knee bending and balanced force absorption to protect joint health, extend their careers and enhance overall performance through targeted training and advanced movement analysis.

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