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Abstract

Objective To investigate the stress and strain distribution characteristics of the anterior cruciate ligament (ACL) of the left leg in volleyball players at the instant of landing after a spike, using a musculoskeletal-finite element (MS-FE) model.

Methods A finite element model (FEM) of the knee joint of a volleyball player was constructed based on MRI and CT data. Marker points and ground reaction forces were synchronously collected from the volleyball player (male, 23 years old, 88 kg, 1.95 m, dominant side: right) using a motion capture system and a three-dimensional force platform. Knee joint moments were calculated using a musculoskeletal model in OpenSim, which served as input to the finite element model to output ACL stress and strain.

Results The simulation analysis results demonstrated that at the instant when the volleyball player completed the spiking motion and landed, the equivalent stress on the ACL reached 27.7 MPa. From the perspective of stress distribution directionality, the maximum principal stress on the ACL at this time was 8.2 MPa. In terms of strain response, the equivalent strain on the ACL reached 5.4%, reflecting a relatively large comprehensive deformation amplitude in all directions. The maximum principal strain value was 5.0%, further confirming that the ligament experienced significant elongation along the fiber direction. The maximum shear strain was 7.6%, indicating that the ACL also underwent substantial lateral deformation during the landing phase.

Conclusion The validated finite element model established in this study can be used to better calculate ACL injury risk and prevention strategies during single-leg landing after spiking in volleyball players. It can also be widely applied to cartilage degeneration etiology, rehabilitation training optimization, knee joint surgery simulation, and other aspects, providing effective methods to assist athletes and ACL-injured patients in clinical treatment.

Full Text

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Investigation of ACL Stress Distribution in Volleyball Players Based on the MS-FE Model

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Abstract: Objective Based on a muscular skeletal–finite element (MS-FE) model, the stress and strain distribution characteristics of the anterior cruciate ligament (ACL) in volleyball players during the instant of landing after a dunk were investigated. **Methods** Based on MRI and CT, a knee-joint FEM of a volleyball player was established. Through a motion-capture system and a three-dimensional force platform, marker points and ground reaction forces were synchronously collected from a volleyball player (male, 23 years old, 88 kg, 1.95 m, dominant side: right side). The knee-joint moments were calculated using the musculoskeletal model in OpenSim, and the joint moments were used as inputs to the finite element model to output ACL stress and strain. **Results** The simulation analysis showed that, at the instant when the volleyball player completed the dunking action and landed, the equivalent stress borne by the ACL reached 27.7 MPa. From the perspective of stress directionality, the maximum principal stress of the ACL at this moment was 8.2 MPa. In terms of strain response, the equivalent strain of the ACL reached 5.4%, reflecting a relatively large overall deformation amplitude in all directions; the maximum principal strain was 5.0%, further confirming that the ligament exhibited an obvious elongation effect along the fiber direction; the maximum shear strain was 7.6%, indicating that the ACL also experienced relatively large transverse deformation during the landing phase. **Conclusion** The experimentally validated finite element model established in this study can be used to better calculate the risk of ACL injury and prevention strategies when volleyball players land on one leg after dunking. It can also be widely applied to studies of cartilage-degeneration etiology, optimization of rehabilitation training, and simulation of knee-joint surgery, providing effective methods for the clinical treatment of athletes and patients with ACL injuries.

Keywords: knee joint; finite element model; musculoskeletal model; OpenSim; joint moment; ACL; volleyball dunking

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Prevention of ACL injuries in volleyball players based on the MS-FE model

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Abstract: Objective Based on the muscular skeletal-finite element (MS-FE) model, we investigated the stress and strain distribution characteristics of anterior cruciate ligament (ACL) in the left leg at the moment of the volleyball player' s dunking and landing. **Methods** The knee FEM of the volleyball player

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was established based on MRI and CT, and the marker point and ground reaction force of the volleyball player (male, 23 years old, 88 kg, 1.95 m, dominant side: right side) were synchronously collected by the motion trapping system and the 3D force measuring table. The knee joint moments were calculated by the musculoskeletal model in OpenSim, and the joint moments were used as inputs to the finite element model to output ACL stresses and strains. **Results** The results of simulation analysis showed that at the moment when the volleyball player completed the dunking action and landed on the ground, the equivalent stress endured by the ACL reached 27.7 MPa, and from the viewpoint of stress distribution directionality, the maximum principal stress of the ACL was 8.2 MPa at this time; in terms of strain response, the equivalent strain of the ACL reached 5.4%, which reflected that it had a larger integrated deformation in all directions; the maximum principal strain was 5.0%, which further confirms that the ligament produced a significant elongation effect along the fibre direction; and the maximum shear strain was 7.6%, indicating that the ACL also experienced a large lateral deformation during the landing stage. **Conclusion** The validated finite element model developed in this study can be used to better calculate the risk and prevention strategies of ACL injury in volleyball players landing on one leg after dunking the ball. This study can also be widely used in cartilage degradation etiology, optimization of rehabilitation training and simulation of knee surgery, which can provide effective methods for the clinical treatment of athletes and patients with ACL injuries.

Key words: knee joint; finite element modelling; musculoskeletal modelling; OpenSim; joint moment; ACL; volleyball snapping

The knee joint bears extremely high biomechanical loads during movement;

therefore, its injury incidence is relatively high. Among various knee-joint injuries, injury to the anterior cruciate ligament (ACL) is the most common. This ligament plays a key role in maintaining anteroposterior stability of the knee joint. Once injured, the knee joint often develops laxity, functional impairment, and long-term instability due to ACL injury and other problems [1]. Studies have shown that ACL injuries in volleyball players most often occur during the single-leg landing phase after spiking, accounting for as much as 84.6%, and the injured side is usually the non-dominant leg [2]. To gain an in-depth understanding of the mechanical characteristics of ACL loading, many biomechanical studies have used cadaveric specimens as the basis for analysis. Although this research approach is intuitive and clear [3-5], it has limitations for in-depth exploration [6-8], such as difficulty in obtaining specimens, high cost [6], and the complexity and susceptibility to degeneration of ACL tissue, which affect research accuracy [7], together with the difficulty of simulating complex real joint motion [8].

In recent years, with the development of digital medical technology and the progress of computational software, finite element analysis has gradually become an effective tool for studying the biomechanical behavior of the ACL [9]. This method can evaluate the mechanical response of tissues without invasive operation, can simulate experimental scenarios that are difficult to achieve in reality, and has the advantages of relatively low cost and lower risk [10]. In addition, finite element models support repeated testing and can be combined with visualization methods to improve the intuitiveness and comprehensibility of research results [11]. The construction of finite element models of the knee joint for specific individuals is usually based on CT and MRI imaging data [12]. Corresponding material properties are then assigned to different tissues, loads, boundary conditions, and mutual contact relationships are set, and the overall model construction and analysis process is completed [13]. With respect to the application of loads, current research still has certain limitations. Most studies apply loads hypothetically [14-16], which cannot simulate the load conditions of subjects in their actual environment, thereby causing relatively large errors in the results. Musculoskeletal models address this problem well [17-18]. The MS model calculates knee-joint moments by obtaining kinematic and kinetic data from volleyball players during spiking in a real environment. To date, relevant researchers have used muscular skeletal–finite element (MS-FE) models to evaluate knee-joint loads and stress distributions [19-20]. Therefore, the use of an MS-FE model as a replacement method to understand the characteristics of ACL stress distribution when volleyball players land after spiking is highly feasible.

This study will use an MS-FE model to investigate the stress and strain distribution characteristics of the ACL in the left leg of volleyball players at the instant of landing after spiking, thereby helping to provide effective methods for clinical treatment of athletes and patients with ACL injuries.

1 Objects and Methods

1.1 Objects and Data Collection

1) Kinematic and kinetic data: Figure 1 shows the data-collection process of this study. One healthy elite volleyball player from Harbin Sport University (male, 23 years old, 88 kg, 1.95 m, dominant side: right side) participated in the study.

Experimental data collection. Five spike tests were conducted in the Biomechanics Laboratory of Harbin Sport University. Data were collected synchronously using an 8-camera Qualisys motion-capture system (sampling frequency: 300 Hz; marker placement scheme: whole-body markers (Fig. 1a)) and a Kistler three-dimensional force platform (1,000 Hz, two force plates)[21-22].

Fig. 1(a) Marker placement positions

Figure 1: Fig. 1(a) Marker placement positions

(a) Marker placement positions

Fig. 1(b) Static acquisition

Figure 2: Fig. 1(b) Static acquisition

(b) Static acquisition

Fig. 1(c) Dynamic acquisition

Figure 3: Fig. 1(c) Dynamic acquisition

(c) Dynamic acquisition

Fig. 1 Diagram of data collection process

2) CT and MRI data: The left knee-joint data of volleyball players were collected using Light Speed VCT (GE, USA) and MRI Signa 3.0 T (GE, USA)[21-22].

In this study, the standard OpenSense_Subject model in OpenSim 4.3 software was used to calculate knee-joint angles and moments.

1.2 Modeling Tools

This study used a Windows 11 personal computer configured with a 12th-generation Intel Core i5-12450H processor, 16 GB memory, a 1 TB hard drive, and an NVIDIA 4060 discrete graphics card, in combination with multiple professional software tools, to perform finite-element modeling of the knee joint. The software used for modeling included: medical image processing software

Mimics 21.0 (Materialise, Belgium), preprocessing mesh-generation software HyperMesh, and the finite-element analysis platform ANSYS[21-22].

1.3 Modeling Process

The finite-element modeling was divided into three steps.

Step 1: Mimics software was used to process the medical images, obtain the three-dimensional structural model of the knee joint, export it in STL format, and perform optimization processing[23].

Step 2: Import the optimized three-dimensional model into HyperMesh for meshing. In HyperMesh, use the surface tool in the geom module, and convert the mesh into a geometric model through the "from FE" command; then export it as a general STP-format file for subsequent finite-element analysis.

Step 3: Import the STP into ANSYS Workbench, assign material parameters according to tissue type[^24]. Then set boundary conditions and apply loads: the starting and ending points of the cruciate ligaments and the medial and lateral collateral ligaments are fixedly connected to the femur and tibia; the tibia and fibula are kept in a fixed state; the medial collateral ligament is set to sliding contact with the bone surface; the proximal and middle regions of the femur are set as fully fixed[^25]; finally, knee-joint moment loads are added according to experimental data. A longitudinal load of 750 N and an internal rotation torque of 10 Nm are applied at the top of the femur to simulate tibial internal rotation, and the equivalent stresses and maximum shear stresses of the meniscus, femoral cartilage, and tibial cartilage are observed[^25].

1.4 Model validation

Strain and stress tests were performed on the model to verify its validity. The specific methods were as follows: Method 1, the femur was completely fixed, the knee joint was established in an upright position, and a 134 N anterior pushing force was applied to the upper end of the tibia[^23] to observe the magnitude of tibial plateau displacement; Method 2, by applying a longitudinal load of 750 N and an internal rotation torque of 10 Nm at the top of the femur to simulate tibial internal rotation, the equivalent stresses and maximum shear stresses of the meniscus, femoral cartilage, and tibial cartilage were observed[^25].

1.5 Data statistics

The obtained data are expressed as mean ± standard deviation. Joint moments were standardized using the subjects' own body mass[^26–27].

2 Results

2.1 Model validation results

Method 1: Tibial plateau translation analysis

Under the same physiological loading conditions, quantitative analysis of tibial plateau translation was performed using the knee-joint finite-element model established in this study. The results showed that the translation was 4.75 mm (Fig. 2), which was highly consistent with the result obtained from the knee-joint model previously constructed by the research group for this project (4.30 mm)[^23], verifying the stability and accuracy of the model construction.

Model validation results

Figure 4: Model validation results

(a) Method 1

Meniscus equivalent stress

Femoral cartilage equivalent stress

Tibial cartilage equivalent stress

Meniscus shear stress

Femoral cartilage shear stress

Tibial cartilage shear stress

(b) Method 2

Fig. 2 Model validation results

Further comparison with literature data showed that the output results of the model in this study were similar to those of PEÑA et al. (4.75 mm)[^28], Liu Xiaomin et al. (4.83 mm)[^29], GABRIEL et al. (5.0 mm)[^30], and SONG et al. (4.6 mm)[^31], indicating that the knee-joint finite-element model established in this study has good reliability and repeatability in terms of biomechanical response.

Method 2: Stress Distribution in Cartilage and Meniscus During Knee Valgus Simulation

During the simulation of knee valgus deformation, the model further output the distributions of equivalent stress and maximum shear stress in the meniscus, femoral cartilage, and tibial cartilage. The specific equivalent stresses were 14.93, 2.22, and 2.50 MPa, respectively; the corresponding maximum shear stresses were 7.75, 1.18, and 1.41 MPa, respectively (Fig. 3). These stress levels show a high degree of consistency with the results obtained from the finite element model established by Yang Junliang et al. [24], further verifying the applicability and reliability of the model in this study for simulating complex knee-joint conditions.

(a) Equivalent stress

Fig. 3 Stress-strain analysis results of ACL

Figure 5: Fig. 3 Stress-strain analysis results of ACL

(b) Maximum principal stress

(c) Maximum shear stress

(d) Equivalent strain

(e) Maximum principal strain

(f) Maximum shear strain

Fig. 3 Stress-strain analysis results of ACL

Taken together, the results of the above two validation methods indicate that the finite element model constructed in this study has relatively high accuracy and stability in predicting structural response and mechanical behavior, and can provide a solid theoretical basis for further biomechanical research and clinical application.

2.2 Mechanical Response Analysis of the ACL in Volleyball Players

By establishing a three-dimensional dynamic model of volleyball players at the instant of landing after a spike and combining it with finite element simulation analysis, this study successfully obtained the stress and strain distribution characteristics of the anterior cruciate ligament at this critical moment, providing important mechanical evidence for understanding its injury mechanism.

According to the simulation results shown in Fig. 3, the equivalent stress sustained by the ACL at landing reached 27.7 MPa, the maximum value in this movement cycle, suggesting that it faces a relatively large structural load under landing impact. This stress peak not only indicates that the ACL is in a critical mechanical state, but may also be closely related to the high-incidence moment of injury, especially when there is insufficient muscle protection or an unreasonable landing posture, which makes acute injury more likely to be induced.

Further analysis shows that the maximum principal stress of the ACL was 8.2 MPa, indicating that at this stage the ligament underwent significant tensile deformation along its fiber principal-axis direction. The maximum shear stress reached 14.7 MPa, reflecting that the ligament structure not only bears axial tension but is also accompanied by strong shearing action. This combined stress state may be closely associated with complex movement patterns generated in the knee joint at the instant of landing, such as internal rotation, external valgus, or excessive knee external-rotation angle, demonstrating the multidirectional and nonlinear characteristics of the load borne by the ACL. The strain analysis results are also worthy of attention. The equivalent strain of the ACL reached 5.4%, the maximum principal strain was 5.0%, and the maximum shear strain was as high as 7.6%. Such high-level strain responses indicate that during the landing phase, the ACL not only undergoes significant deformation, but also has complex deformation directions, with obvious multiaxial load-coupling phenomena. It can therefore be seen that, during movement, the ACL does not merely bear tension in a single direction, but encounters the superposition of multiple forces in a three-dimensional mechanical environment, significantly increasing its risk of injury. Identifying the moments of high mechanical risk for the ACL during landing can help formulate more targeted training strategies, such as strengthening knee-joint stability training and optimizing landing techniques, thereby reducing the incidence of non-contact ACL injury. By analyzing the load path and stress changes of the knee joint during movement execution, athletes can be guided to optimize the airborne and landing actions after a spike, such as controlling the knee-joint internal-rotation angle and avoiding knee valgus. Based on the force direction and deformation pattern of the ACL at key moments, a more scientific basis can be provided for knee-protection devices in sports.

3 Discussion

This study aimed to construct and validate a knee-joint finite element model specifically for volleyball players, in order to evaluate the loading and deformation of the anterior cruciate ligament during the completion of a spiking technical movement, thereby providing a theoretical basis and technical support for the prevention of ACL injury. In the research process, a musculoskeletal system model was first established based on individual CT and MRI imaging data. Through this model, the multidirectional moments of the knee joint during the landing phase after spiking were calculated; subsequently, the obtained data were introduced into the finite element model as boundary conditions, enabling prediction of the mechanical response of the ACL under dynamic impact, including equivalent stress, maximum principal stress, maximum shear stress, and corresponding strain indices.

The finite element simulation results obtained in this study showed good consistency with experimental data reported in the relevant literature[^23,^25,^28^-^33]. For example, cadaveric double-leg landing impact experiments observed ACL strain peaks between 2.9% and 5.4%[^34], while in vivo experiments showed that the maximum ACL strain induced by single-leg jump landing could reach 6.4%-7%[^35]. In this study, the peak ACL strain during the simulated volleyball spiking and single-leg landing was close to the above values, further validating the accuracy of the model. It is worth noting that the strain recorded in this study was slightly higher than that during conventional jumping movements, mainly because the movement intensity during a volleyball spike is greater and the ground reaction force caused by single-leg landing is higher; this also indirectly indicates the applicability and sensitivity of the model in dealing with complex sport scenarios.

In terms of stress, the study results showed clear differences. Compared with Ren Shuang et al.[^25], who observed maximum principal stress (8.77 MPa), equivalent stress (8.88 MPa), and shear stress (3.44 MPa) under a 134 N anterior load, the ACL maximum principal stress (8.2 MPa), equivalent stress (27.7 MPa), and maximum shear stress (14.7 MPa) measured in this study were all significantly higher. This difference mainly arose from differences in model input conditions: this study was based on ground reaction force and knee-joint moment data during the real spiking-landing process of volleyball players, which were much higher than the unidirectional force input used in static loading experiments and could better reflect injury risk in real sport environments.

In addition, compared with the experimental design of Yang Junliang et al.[^24], who simulated knee valgus and internal rotation by applying fixed forces and moments at the proximal tibia, this study used a motion-capture system and a three-dimensional force-measurement platform to synchronously acquire load data during athletes' actual movement process, greatly improving the authenticity of the loading conditions and the accuracy of the model prediction results.

Although this study achieved certain results in terms of simulation accuracy and biomechanical fidelity, some limitations should still be noted: the sample size was limited, and the modeling data came from only one national-level volleyball player, lacking representativeness for groups with different competitive levels; the research content focused on the spiking action and did not cover other key technical movements in volleyball, such as blocking, take-off, and directional movement; the stress–strain calculations used transient finite element analysis, but rigid-body dynamics or advanced explicit dynamics software such as LS-DYNA was not introduced for coupled simulation of the dynamic process; the further influence of different landing strategies and muscle activation levels on the ACL response was not considered.

In summary, the knee-joint finite element model constructed in this study performed well in terms of structural accuracy, data-driven characteristics, and dynamic adaptability, and was able to effectively simulate the stress–strain behavior of the ACL in volleyball players under high-impact technical movements. Application of the model can help identify high-risk segments of sports injury and provide important quantitative support for formulating scientific training plans and rehabilitation-prevention strategies.

4 Conclusion

The validated finite element model established in this study can be used to better calculate the risk of ACL injury and prevention strategies when volleyball players land on one leg after spiking. At the same time, this study can also be widely applied to cartilage-degeneration pathology, optimization of rehabilitation training, and knee-joint surgical simulation, helping to provide effective methods for the clinical treatment of athletes and patients with ACL injuries.

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Figures

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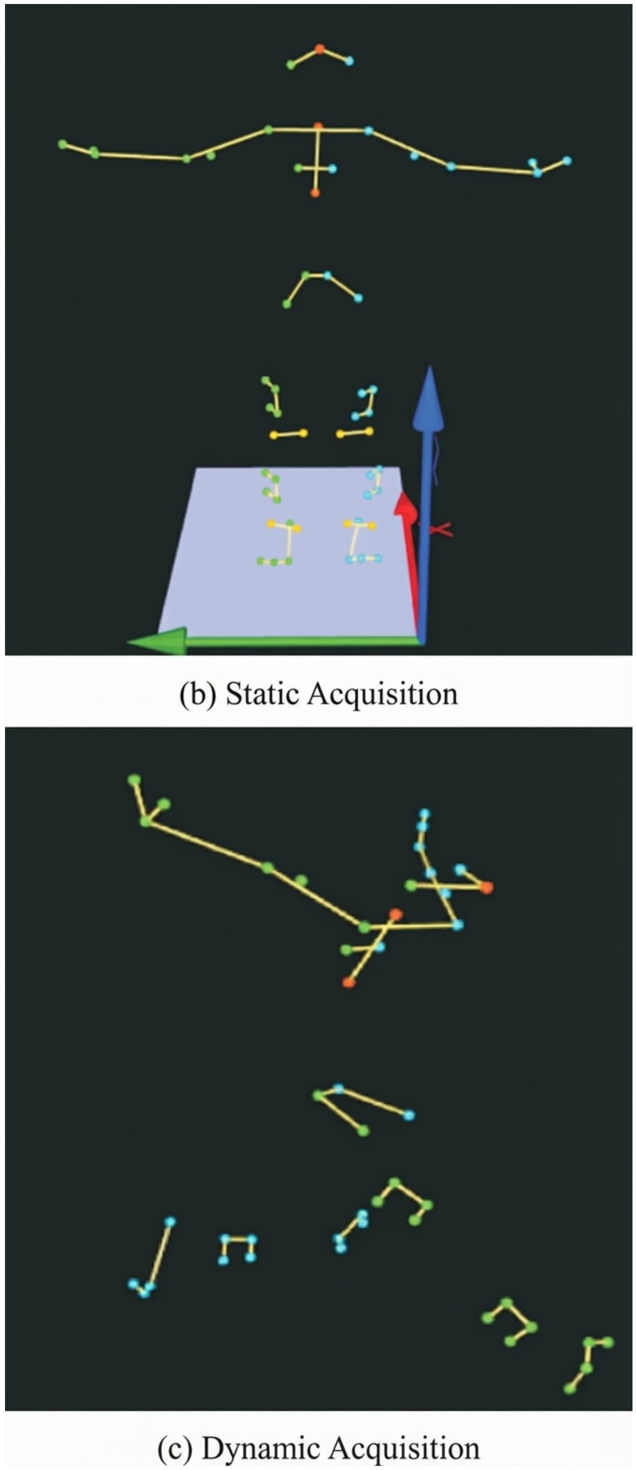

(b) Static Acquisition

(c) Dynamic Acquisition

Figure 6: Figure 1