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Numerical Investigation of Injury Mechanism on the Human Knee of Long-jumpers

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Abstract

Long-jump is a vigorous athletic event with high speed. Due to so fast run-up and take-off velocities in horizontal and vertical directions, significantly large and varying impact loads often appear in the knee joint region so that the long-jumpers are often badly injured. Based on the physical conditions of an ordinary Chinese man long-jumper, a combination of finite element analysis (FEA) and multi-body dynamics analysis (MDA) approach was tried analyzing the real and detailed long-jump process. Research results show that the maximum resultant force does appear the second phase of the long-jump and that the most notable deformation, displacement and the maximum stresses are all located at the medial sides, especially at the lateral condyle of the articular cartilage. Our results show the feasibility and effectiveness of performing MDA as a preliminary step to FEA, and provide an insight into the injury mechanism on the Human Knee of Long-jumpers.

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Keywords: Injury mechanism; Human knee joint; multi-body dynamics analysis (MDA); finite element analysis (FEA); long-jump

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1. Introduction

The knee joint with the most complex functions and constructions is the hinge of the lower limb movement. It consists of patella, femur, tibia, fibula, meniscus cartilage, and surrounding ligaments and muscles, and always endures larger load than the body weight of an athlete. Consequently, long-term cumulative load of the knee joints would lead to the wear and degeneration on the cartilage and meniscus [1].

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Long-jump includes four steps of run-up, take-off, rising and landing. The knee joints bear the impact force several times more than the body weight due to the fact that all the behaviors should be performed at high horizontal speed for the great contest achievements. Thus, it requires extremely well function of the knee joints for the athletes. In terms of biomechanics, from contacting the pedal to the knee flexion, the take-off leg endures great pressure during braking stage after accelerated run-up for 40-60 m or even longer. It is reported that the vertical force from the ground to the human body accounts for 36.7% of the total force, and it can reach 12-20 times of the body weight. The incidence of knee joint injury of the long-jumpers is as high as 98%[2].Long-jump is required that all the behaviors should be performed at high horizontal speed for the great contest achievements. Consequently, the knee joint of the athlete requires tolerating extremely large and greatly varying impact/impulsive forces in the leg contacting the ground loads and hence it is always being badly injured [3].

Currently, the cartilage injury of the knee joint is demonstrated to be one of the most serious injuries for all track-and-field events [1]. Figure 1 schematically shows the anatomy of the knee joint. As such, it is of great importance to determine the maximum stress and strain on the cartilage. For this purpose, FEA is being widely used for the injury prediction. However, due to the direct application of loads on the biological structure by using FEA, some essential factors for simulations, e.g. reaction forces in-between the structures are often ignored. As a result, there exist big differences between the numerical and the practical scenarios.

Fig.1. Anatomy of the knee.

For the disadvantages of FEA, a combination of finite element analysis (FEA) and multi-body dynamic analysis (MDA) approach, commonly used in mechanical engineering, is being tried using for the functional prediction in sport science. This may primarily be due to the following facts: 1) some key factors for all simulations, e.g. reaction forces are not ignored; 2) forces acting upon the biological structure can be estimated by using MDA firstly and then are applied to its corresponding model to further predict stain and stress across the complex and specific structure by using FEA; and 3) what is the most important is that the experimental data from electromyogram (EMG) studies are available and thus these can be incorporated into MDA models to improve the estimation of loading scenarios [3]. To the best knowledge of the authors, however, there exists no current literature on long-jump by using the combined MDA and FEA so far. This investigation is therefore concerned with the dynamics process of the entire long-jump and subsequently predicts the stress and strain patterns and distributions across the knee joint region under the varying impact loads.

2. Materials and Methods

2.1. Knee joint geometry

Due to the addressed relation between stress distribution and wear on the cartilage of the knee joint in this study and due to saving the calculation time, the three-dimensional model of the knee joint is only presented in this study. The related modeling processes are presented below.

A male long-jumper of the Chinese national standard (age: 20 years; mass: 70 kg; height: 1.85 m; best performance: 6.5 m) was selected from my track team of Anhui Agricultural University in China. In order to achieve the accurate geometric data on bone tissue and soft tissue, we applied the combination of computer tomography (CT) with magnetic resonance imaging (MRI) scanning technique to mid-upper tibiofibular portion and mid-lower thighbone portion of the knee joint region. The relevant measurement procedures are briefly depicted as follows:

firstly, there were no injuries with the knee joint region of the selected athlete; then, the knee joint region was necessitated not to be immovable and to locate at the center of the scanning field during the entire test; finally, the CT and MRI blocks consisted of parallel digital images separated at intervals of 0.5mm in the sagittal, coronal and axial planes with 512×512 pixels. Consequently, a total of 218 image sequences were then obtained (Fig.2).

Based on the obtained geometric data, the modeling of the knee joint was further performed: firstly, the geometric data on the knee joint were stored into a computer as a DICOM format; next, these data were imported into Mimics (Materialise's Interactive Medical Image Control Sytem, Belgium), a medical image processing code, for the construction of the 3D knee joint model; finally, the model was imported to SolidWoks, a commercial 3D modeling program in mechanical engineering, for the modification with a combined feature-based modeling and reverse engineering approach(Fig.3).

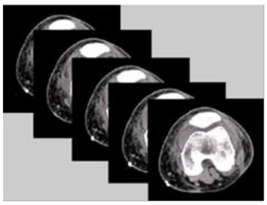


Fig.2. Part of the measured image sequences of the knee joint region

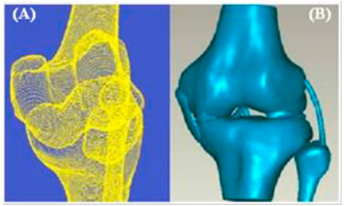


Fig.3. the 3D models of the knee joint in (A) Mimics and (B) SolidWorks

2.2. Multi-body dynamics analysis

In this work, the previously constructed 3D models of the knee joint were imported into MSC ADAMS motion simulation software for the investigation of a multi-body kinetic characteristic. Mass properties were assigned to the moving parts (i.e. articular cartilage and tibia) and soft tissue structures (i.e. muscles and ligaments). The ligaments were modeled as tension-only springs (i.e.no compressive resistance) and the muscles associated with long-jump were defined with Hill-type muscle properties as described by Van Ruijven and Weijs [4]. According to(Wen, 2010) [5], the elastic modulus and Poisson ratio for all ligaments were set to be as 430 MPa and 0.45, respectively.

Although the entire long-jump includes four steps, i.e. run-up, take-off, rising and landing, this study is primarily concerned with the second and fourth phases after the dynamics analysis of the whole procedure. This is dominantly because the run-up and landing of the aforementioned four phases generally produce the more violent loads than the other two phases (Fig.4). The contact phases were chosen for the external reaction forces, i.e. the ground reaction forces. The take-off phase started after the approach run till the jumper touched the take-off board with the takeoff leg, then covered the whole subsequent contact. The landing phase was associated with the transition from the hop to the step and then loaded the sandy pool.

Fig.4. The calculated four phases of the long-jump

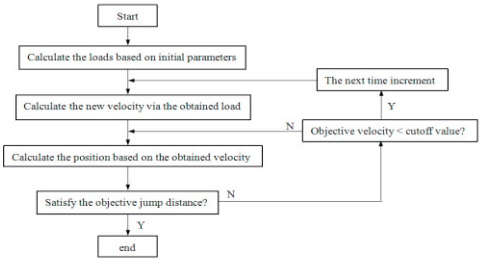


Fig.5. The flow chart of MDA of the long-jump process

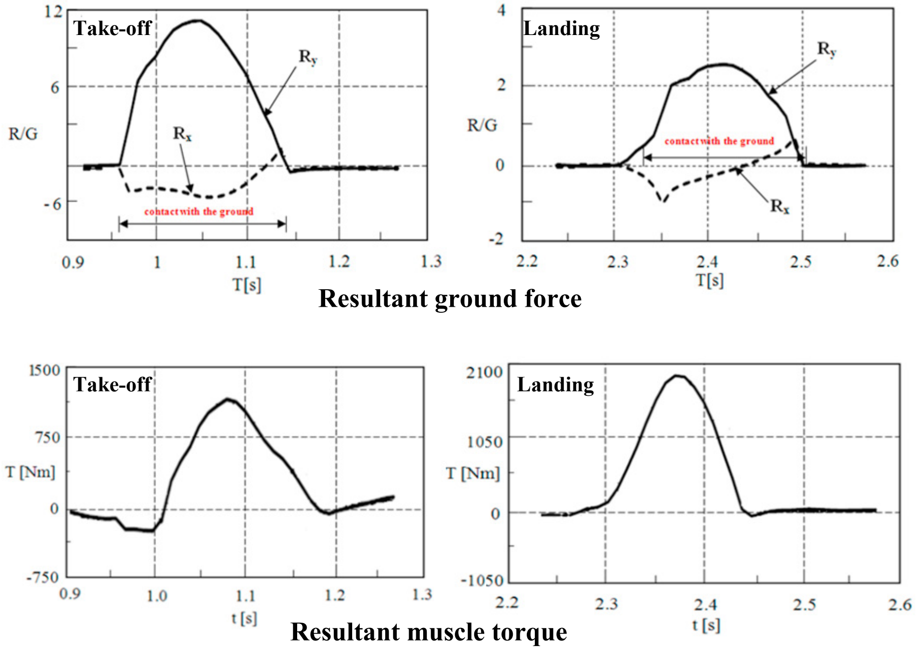


Fig.6. MDA simulation results of the take-off and landing phases during long-time

The key initial parameters for all simulations were presented as follows: an approach running speed of 8.7m/s as phase 1 was initiated, a 20-year-old competitor of mass 70kg and height 1.85 m, and the best performance of 6.5 m. The multi-body kinematic analysis for the long-jump were performed over time with a main time step of 0.0028s, where Newton-Raphson iteration algorithm was used and absolute and relative error tolerances were set as 10^{-6} and 10^{-7} respectively. Figure 5 shows flow chart of MDA of the long-jump process. The detailed MDA predictions of the long-jump are shown in Figs. 6. The obtained muscle forces and ground reaction forces were further applied to the long-jump simulations and provided joint and ligament forces for the cartilage of the knee joint.

Figure 6 shows the MDA-based predictions of the resultant ground force and muscle torques in the take-off and landing phases. As observed, both of the resultant force and muscle torque appeared in the middle of the contact phases. The maximum resultant force was almost 12 times of the bodyweight (G=686N), and the highest muscle torque almost reached 2100Nm.

2.3. Finite element analysis

In this section, the three-dimensional model of the total knee joint, previously used for the MDA, was firstly transformed into a meshed solid geometry using AMIRA image segmentation software (Mercury Computer Systems Inc, Chelmsford, USA) ,and subsequently was imported into ANSYS 11Mechanical (ANSYS, Inc, Canonsburg, PA, USA) in preparation for FEA (Finite Element Analysis). Hexahedral block-structure meshes of the bones and soft issues were constructed in ANSYS, and the element type of ligaments was defined with ‘brick’. Thus, a total of 18668 nodes and 14889 eight-node brick elements were used for the knee FE model. It should be noted that the bone models can be formed with an isotropic assumption although it is anisotropic [1]. For this reason, the bones used for FE simulation were assumed to be a linear and isotropic material in this study.

Boundary conditions, i.e. the loads in take-off and landing phases were imported directly from the MDA solutions obtained in this study, which were further divided into 1200 load steps for each cycle in accordance with the jump processes. The detailed loading data from MDA are presented in Figs.6. The boundary conditions used for FE simulation were applied to such the model as shown in Fig.7, where tibia and fibula were kept fixed. The muscle forces and ground reaction forces were applied in the FEA at one node, which was chosen by finding the closest coordinate in the FE model to the muscle force application in the MDA model. It should be noted that as the loading data come directly from the MDA models of the knee joint, the involved muscle forces and reaction forces are in equilibrium. Thus, negligible stress values can subsequently be recorded at the constraints. This is one of the most important advantages of a combined MDA and FEA approach—that is, the element stress values can be automatically written into an element table for each of the loading conditions for post processing [6].

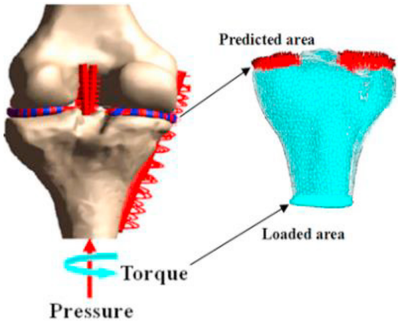


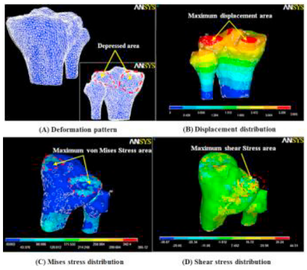
Fig.7. loaded knee joint

3.Results and Discussion

As depicted above, during the long-jump the wear and degeneration of the cartilage is the most serious in the knee joint area. For this reason, this section focused on the deformation pattern, displacement and stress distributions of the articular cartilage based on the obtained MDA solutions of the knee joint. The related numerical simulation results are presented below.

Figure 8(a) shows the FE simulations on the mechanical properties of the articular cartilage of the knee joint region during the long-jump. As observed, the most notable deformation and displacement areas and the maximum Von Mises and shear stresses all appeared at the medial sides, especially at the lateral condyle of the articular cartilage. The calculated maximum displacement, Von Mises stress and shear stress were 1155.36 MPa and 133.53 MPa, respectively.

In order to validate the effectiveness of our numerical simulations, we qualitatively compared the obtained calculations with the corresponding medical measurements using the magnetic resonance imaging (MRI) scanning technique. This measured evidence was achieved with the MRI system (MAGNETOM Spectra 3.0T, Siemens, Germany) at the first affiliated hospital of Anhui Medical University in China. It should be noted that the examiner, an athlete engaging long-jump contest, has the same height and weight as the athlete. And what is the most importance is that this measured evidence was obtained at the time when the examiner was injured due to the long-jump. Figure 9 shows a high-solution and sharp image of the injured knee joint for visualization. As observed, at the articular cartilage zone of the knee joint there are the most severe worn lands (see the red arrows). These locations are right where our numerical simulations in Fig.8 predicted. It is inferred that there is good qualitative agreement between the calculated with the measured.



(A) Deformation pattern (B) Displacement distribution (C) Mises stress distribution (D) Shear stress distribution

Fig.8. FEA-based predictions on the articular cartilage

Fig.9. MRI measurements of the injured knee

From the mechanics viewpoints, for a mechanical component, a greater load is generally prone to incur a more severe worn land. As depicted previously, the human bodies are similar to mechanical systems. For this reason, the articular cartilage is completely considered as a mechanical component. During the violent exercises, e.g. long-jump, the foregoing section is the primary loaded area of the knee joint, whose main functions are to absorb and alleviate the stress and strain due to the ground reaction. Consequently, the maximum stress and strain generally appear on this section. The current clinical data do demonstrate that the greatest wear contours during the long-jump appear on the articular cartilage of the knee joint because of the extremely large and greatly varying impact/impulsive forces. This result eventually causes the knee joint to be badly injured [8].

4. Conclusions

This study was primarily to apply the generated MDA load data during long-jump to a finite element model of the human knee joint for deformation, displacement, and stress analyses. The obtained results demonstrates that the maximum resultant force both occurred in the take-off phase of the long-jump and that the most notable deformation, displacement and the maximum stresses all appeared at the medial sides, especially at the lateral condyle of the articular cartilage. From the viewpoint of mechanics, these greater stresses may eventually contribute to the more wear contours.

Although there exit some limitations, this work shows the importance of considering different loading scenarios combined MDA simulation with FEA, as the variation in stress across the knee joint varies with different loading conditions. The numerical results obtained qualitatively agree with the measured evidences in the hospital, in turn providing insights into a better understanding of injury mechanisms of the jumpers.

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