ISSN 1746-7659, England, UK
Journal of Information and Computing Science
Vol. 13, No. 1, 2018, *pp*.044-048

Modeling of human knee joint and finite element analysis of landing impact motion

Bao Chunyu[1,3], Meng Qinghua[2,3] Guo Baochuan[3]
[1] College Sports Training Science,Tianjin University of Sport,tianjin 300381,China
[2] School of education and psychology,Tianjin University of Sport,Tianjin 300381,China
[3] Tianjin Key Laboratory of Exercise Physiology and Sports Medicine,Tianjin University of Sport,Tianjin 300381,China
(Received October 12, 2017, accepted December 20, 2017)

Abstract. objective:Three dimensional digital modeling of human knee joint is carried out, and the mechanical behavior of knee joint in landing impact motion is analyzed by finite element method, which provides a reasonable basis for prevention of knee joint sports injury.Methods: three dimensional geometric model of knee joint was reconstructed by software Mimics;Transforming 3D geometric model into 3D finite element model by 3-matic software;The finite element software ANSYS was used to analyze the stress and strain of the cruciate ligament, tibial cartilage and meniscus in different impact motions.Results and conclusion:1. jumping and landing impact moment, knee cartilage, ligament, meniscus stress increases with the increase of the height of jumping, the tibia, the average distribution of the lateral platform landing impact load, the stress is greater than the anterior cruciate ligament posterior cruciate ligament, jumping height is 66cm, should be the force of posterior cruciate ligament in very close to the maximum, suggesting jumping height greater than 66cm in normal life or race training is easy to damage the posterior cruciate ligament.2, the posterior cruciate ligament with limited internal rotation of the femur in knee function, under the situation that internal rotation of the femur or tibia external rotation may damage the posterior cruciate ligament.

Keywords: landing impact; knee joint; finite element analysis; modeling

1. Introduction

The finite element method has been widely used in machinery manufacturing, transportation, civil engineering and other fields as a method of mathematical physics. At present, more and more scholars tried to solve some problems in sports with this method, and obtained results. The knee joint as the largest and most complex joint plays an important role to move and maintain body posture, at same time it is the easiest to damage. In sports, such as basketball, football, badminton and other sports, athletes often urgently stop, change direction, start and brake and other compound action mode, especially the impact load of knee joint is very large at the moment of landing, so in this process, it is extremely easy to cause the knee injury. The main purpose in the paper is to establish a three-dimensional finite element model of the knee joint, including bone, cartilage, ligament, meniscus and other main mechanical bearing parts, to analysis mechanical characteristics of the knee joint with the finite element method, in order to provide bio-mechanical basis for the prevention of knee joint injury.

2. Materials and methods

2.1 The main equipment and software

Professional medical image processing software(Materialise's Interactive Medical Image Control System, Materialise Corporation, Belgium). 3-matic software, as the subsidiary software of Mimics, Geomagic Studio2014（Raindrop Corporation, U.S.A）,ANSYS/Workbench14.0（ANSYS Corporation, U.S.A）

2.2Estalishment of three-dimensional finite element model of knee joint

A male volunteer, aged 26, 170cm, 70kg, the function and structure of knee joint is normal, without history of trauma, the X examination to exclude the rheumatoid arthritis and osteoarthritis. CT scanning from the end of the femur to foot at anatomical position, the slice thickness is 0.5mm.The scanned image is inserted into the optical disk in DICOM format.

The CT data was imported into the Mimics software, the original image was cut segmentation, for convenient operation, each mechanical component of knee was generally created a mask, and named automatically and marked in different colors. The three-dimensional model of each component of knee was established, which was composed of femur, tibia, fibula, patella, lateral collateral ligament, cruciate ligament, meniscus and cartilage after threshold segmentation, clipping mask, regional growth, morphological operations and mask editing and a series of operations, which can be enlarged, reduced, rotated, observed from any angle. The three-dimensional model of knee joint was completed through reducing the shell, smoothing and wrapping the model.

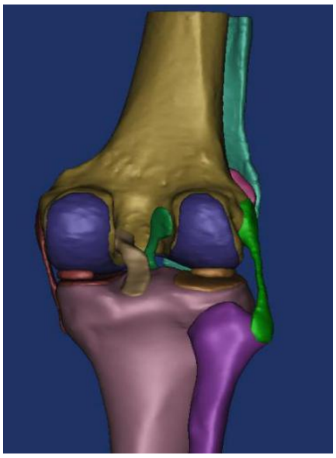
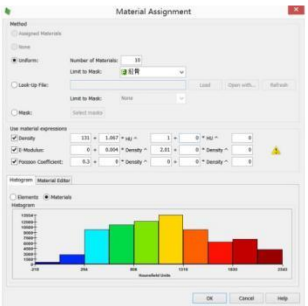


Fig1. The three-dimensional model of knee joint

There is a model's view window in the Remesh module of the 3-matic software, the quality of the triangular mesh can be examined through the window. The triangular mesh which was optimized is created as a finite element volume mesh. The element attribute of finite element is defined as solid185 element, which is defined by 10 nodes, each node has 3 degrees of freedom in XYZ direction. It has the ability of super elasticity, creep and large deformation[1], Finally, the CDB format files that can run in ANSYS are exported.

3.3 Setting of material properties of finite element model

There is a correlation between bone density and elastic modulus, although there is not a formula which can accurately calculate the relationship between bone density and elastic modulus. But under different experimental conditions, many empirical formulas have been proposed, the bone density can be calculated by the CT value of bone tissue ,so the elastic modulus can be calculated by CT value.



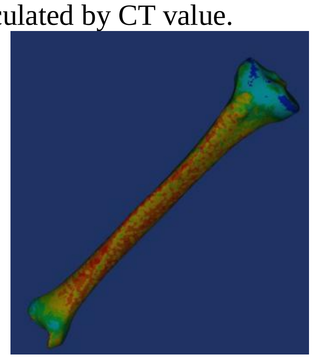


Fig.2 The window of evaluation Fig.3 The model of tibia after evaluation

The material properties of biological tissue is anisotropic[2-4], the elastic modulus of bone can be obtained according to the CT value, the material properties of ligament, cartilage, meniscus came from the literature, as isotropic linear elastic materials. The material properties of ligaments are very special, which have hyperelastic properties. Many scholars[5] have studied on ligaments,In this paper, the material properties of ligaments are defined as linear elasticity.

Tab.1 Material parameters of knee joint

Structure	Type of element	elastic modulus(MPa)	Poisson's ratio
meniscus	Solid185	59	0.49
cartilage	Solid185	5	0.46
ligament	Solid185	215.3	0.40

There were set into no separation contacts between the upper surface of the meniscus and the lower surface of the femur cartilage, between the lower surface of the femur cartilage and the upper surface of the tibial cartilage, and the rest of the model were set as binding contacts without relative motion. The whole model of knee joint were made up of 22 pairs of contacts, the friction is small because of the synovial fluid in articulatory antrum, so the coefficient of friction is zero between the meniscus and cartilage.

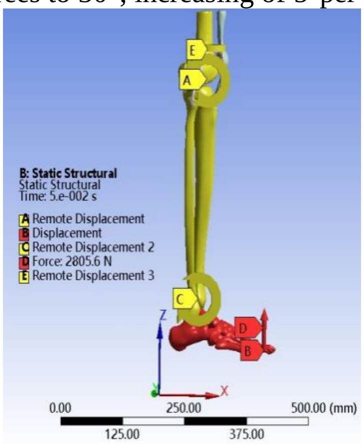
2.4 Simulation analysis

Experiments were carried out before the motion simulation, 12 male athletes as volunteers, age: 24 years old, height: 174cm, body weight: 68kg, they were asked to vertically jumped on the force platform with your feet from different height of 22cm, 44cm and 66cm, the parameters of kinematics and kinetic were calculated at the moment of maximum value in the vertical direction(Tab.2).

Tab.2 Biomechanical parameters of lower limbs at the moment of maximum value in the vertical direction

Height(cm)	contact time(s)	flexion angle of knee(°)	angle between tibia and horizontal plane(°)	Force in Z(N)
22	0.05	30.75±1.92	71.63±2.22	2529.75±280.75
44	0.05	49.00±4.74	57.26±2.31	3044.42±811.43
66	0.05	51.75±5.11	55.42±2.50	5611.25±672.00

Firstly, Motion simulation was carried out under three different vertical height of falling, adding boundary conditions and loads to the model, the load is the biomechanical parameter obtained in the experiment. Secondly, motion simulation was carried out under different angle of rotation of femoral at vertical drop height of 66cm, applying a load of the femoral rotation during flexion landing process, internal and external rotation angle from 5°degrees to 30°, increasing of 5°per time(Fig.4,5).



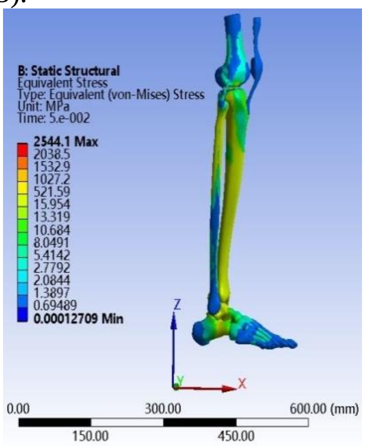


Fig.4 The boundary conditions and loads Fig.5 The contact stress contour of landing

3. Results

Tab.3 The biomechanical parameters of lower limb under different height

parameters	22	44	66
angle of knee(°)	30.75	49	51.75
angle of tibia anteversion(°)	18.37	32.74	34.58
force of foot(N)	1264.88	1522.21	2805.63
stress of interior cartilage of tibia(MPa)	11.68	19.49	20.28
stress of external cartilage of tibia(MPa)	11.36	18.94	19.73
stress of anterior cruciate ligament(MPa)	3.11	5.17	5.41
stress of posterior cruciate ligament(MPa)	9.61	16.06	17.28
stress of interior meniscus(MPa)	53.11	88.75	93.43
stress of posterior meniscus(MPa)	54.12	90.46	94.28

Tab.4 Stress of knee joint under different rotation angle(MPa)

angle of rotation （°）	interior cartilage of tibia	external cartilage of tibia	anterior cruciate ligament	posterior cruciate ligament	interior meniscus	posterior meniscus
0	21.09	18.86	4.74	17.60	91.88	95.22
+5	22.57	18.58	5.07	17.53	94.16	92.37
+10	23.56	18.46	4.88	18.40	97.40	94.39
+15	24.69	18.39	4.83	19.06	100.78	95.32
+20	25.96	18.33	4.90	19.58	103.65	95.31
+25	27.15	18.39	5.08	20.34	106.92	96.00
+30	28.88	18.39	5.16	20.75	109.90	96.32
-5	20.05	19.13	4.77	17.03	89.31	95.01
-10	19.33	19.40	5.15	15.96	86.36	92.15
-15	18.67	19.79	4.95	15.87	85.42	94.48
-20	18.23	20.21	5.24	15.00	82.97	92.22
-25	18.52	20.68	5.02	15.03	82.03	94.86
-30	18.53	21.18	5.12	14.92	80.37	94.97

Note: + shows interior rotation; - shows external rotation

4. Conclusions and future works

Jumping, knee cartilage, ligament, meniscus stress increases with the increase of the height of jumping, the tibia, the average distribution of the lateral platform landing impact load, the stress is greater than the anterior cruciate ligament posterior cruciate ligament, jumping height is 66cm, the stress of posterior cruciate ligament in very close to the maximum, suggesting jumping height greater than 66cm in normal life or race training is easy to damage the posterior cruciate ligament;The posterior cruciate ligament with limited internal rotation of the femur in knee function, under the situation that internal rotation of the femur or tibia external rotation may also damage the posterior cruciate ligament.

Acknowledge

Fund project:Project Supported by National Natural Science Foundation of China (11372223,11102135); Key ProjectS of Tianjin Natural Science Foundation of China (17JCZDJC36000)

5. References

[1] Pena E,Calvo B, Martinez M A, Doblare M.A three-dimensional finite element analysis of the combined behavior of ligaments and menisci in the healthy human knee joint.Journal of Biomechanics,2006,39(9):1686-1701

[2] Butler D L, Sheh M Y, Stouffer D C, et al. Surface strain variation in human patellar tendon and knee cruciate ligaments. Journal of Biomechanical Engineering, 1990, 112(1):38-45.

[3] Quapp K M, Weiss J A. Material characterization of human medial collateral ligament. Journal of Biomechanical

Engineering, 1999, 120(6):757-763.

[4] Rivaux G, Rubod C, Dedet B, et al. Comparative analysis of pelvic ligaments: a biomechanics study. International Urogynecology Journal, 2013, 24(1):135-139.

[5] Huang H. Biomechanical response for periodontal ligament based on hyperelastic model. Journal of Southeast University, 2013.