*Proceedings of the 11th International Forum of Automotive Traffic Safety, 2014, pp 343-351*
*No. ATS.2014.316*

# Development of a FE Model of Lower Extremity for Chinese Pedestrians

**Lan Fengchong, Huang Wei, Chen Jiqing, Wu Kai**
*South China University of Technology, Guang Zhou, China, 510640*
*E-mail: scuthuangwei0504@163.com*

**Abstract:**

Pedestrian protection is a research focus in the field of automotive safety. In order to improve the study of injure biomechanics and pedestrian protection, many investigators both at home and abroad have developed FE models for pedestrians according to foreign data. But most of them are not suitable to Chinese pedestrians because of the difference between Chinese and foreigners. Based on the CT scans of 50th percentile Chinese male volunteer, this paper developed a finite element model of lower extremity with good biomechanical properties. The FE model contained major anatomical structures of human lower limb, such as femur, tibia, fibula, patella, hip and knee-joint. Especially, the knee-joint model included important soft tissues such as ligaments, meniscus and capsule. The bones were modeled with hexahedral solid elements, included cortical and trabecular layers; the ligaments were modeled with quadrilateral shell elements. Both the bone models and ligament models were defined failure to model the fracture of bones and the tear of ligaments. The model developed in this study was compared with other models developed by Untaroiu(2004), Takahashi(2000), etc. As with other models, this model has high biofidelity. The FE Model of lower extremity can be used in the research of injure biomechanics for Chinese pedestrians in traffic accidents.

**Keywords:** Car crash safety; Pedestrian Protection; Injury Biomechanics; Finite Element Method of Lower Extremity

## 1 Introduction

China is one of the countries with the largest number of casualties in traffic accident. According to official data, in 2009 the automobile population of China only accounts for 3% of the world, but the road deaths account for 16%. Compared with passengers, pedestrians are the vulnerable group of road users. Statistically, Pedestrian deaths as a percentage of total traffic fatalities approach 26% in China, however, it's only 11% in the US and 14% in Germany. [1-2] In the field of pedestrian protection, China drops behind developed countries.

In road accidents, head and lower extremity are the most common injury parts of pedestrians, accounts for 31.3% and 32.4% respectively of casualties in traffic accidents. Head injuries are the major cause of pedestrian deaths. Though lower extremity injuries are generally not fatal, it is the major factor that makes pedestrians disability. The finite element model of human lower extremity is developed to study the injury mechanisms and predict the risk of injury of pedestrians' lower extremity in road accidents. It can provide technical basis for safety design of vehicles, which has vast importance to pedestrian protection.

Many investigators both at home and abroad have developed FE models of lower extremity. For instance, Yang J K et al. developed a FE model of the human lower extremity skeleton in 1996, which was highly simplified in structures.[3] In the model reported by Costin Untaroiu et al.(2005), major anatomical structures were included and the model was validate against several PMHS tests.[4] Most of the models were developed according to foreign data, such as Visible Human Male Project(VHMP) developed by The National Library of Medicine. Obviously, there are many differences between Chinese and foreigners in human body size. For example, the average heights of Chinese and American males are 168mm and 177mm respectively. Therefore those models are not suitable to Chinese pedestrians. This Paper aims to develop a FE model of lower extremity of 50th percentile Chinese male. The model is developed to understand the injury mechanisms of lower extremity during car to pedestrian impacts.

## 2 Development of lower extremity model

According to the anatomical structures, human lower extremity includes thigh, knee joint, leg and foot. During vehicle-pedestrian collision Accident, bone fracture and ligament tear are the most severe injuries of lower extremity with an Abbreviated Injury Scale (AIS) rating about 3.[5] In view of this, the study has an emphasis on the development of skeleton models and ligament models in knee joint, especially long bones of lower extremity such as femur, tibia and fibula.

### 2.1 Modeling method

The modeling flow diagram of lower extremity is shown in Figure 1. The geometry model was based on the CT scans collected from a volunteer close to the 50th percentile Chinese male. To reconstruct the geometry of lower extremity, points cloud was derived from the CT scans using medical software Mimics. The figure 2 shows the points cloud extraction of hard bones in lower extremity. The geometric models of lower extremity bones were reconstructed based on the points cloud through reverse modeling method. Appropriate geometric simplification was taken for finite element pre-processing. The FE mesh was generated using special pre-processor software ICEM, which has special function of plotting hexahedron gridding through mapping technology. Soft tissues such as ligaments can't be extracted from CT scans, therefore they were built according to anatomical structures using hypermesh without geometry models. The material properties were selected from references published before. The geometry of the bones in this study is shown in Figure 3.

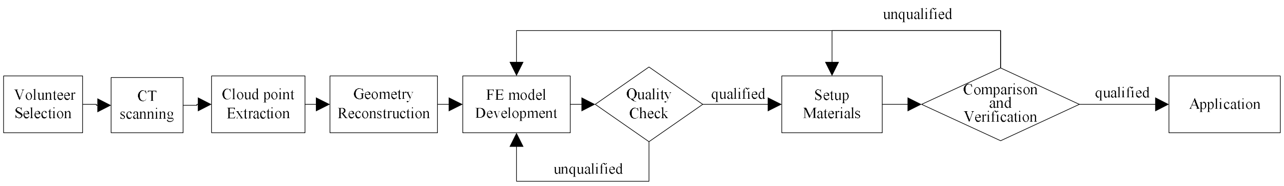
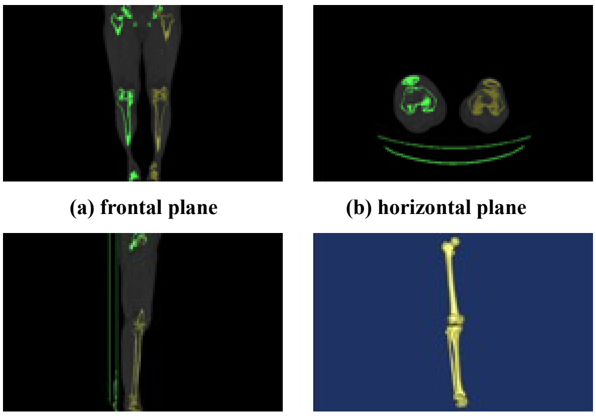



**Figure 1. The modeling flow diagram of lower extremity**



**(a) frontal plane** **(b) horizontal plane**

**(c) sagittal plane** **(d) point cloud**

**Figure 2. Point cloud extraction of hard bones in lower extremity**

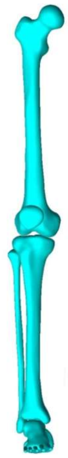


**Figure 3. Geometry of bones in lower extremity**

The comparison of physical characteristics is shown in table 1. The subject in this study is very close to the 50th percentile Chinese male(GB 10000-88) in physical characteristics. Besides, the difference between 50th percentile Chinese male and VHMP subject is obvious enough. Therefore, compared to those models which were based on VHMP subject, the model developed in this study is more suitable for Chinese pedestrians.

**Table 1. The comparison of physical characteristics**

| | Height (mm) | Weight (Kg) | Length(mm) | |
|---|---|---|---|---|
| | | | thigh | leg |
| subject in this study | 1680 | 59 | 470 | 366 |
| 50th percentile Chinese male | 1678 | 59 | 465 | 369 |
| VHMP subject | 1800 | 90.5 | - | - |
| Hybrid III (50th percentile) | 1755 | 77.7 | - | - |

## 2.2 Model introduction

The FE model of lower extremity is constituted by bones and soft tissues. Bone models include hip, femur, tibia, fibula, patella and foot bone. Soft tissues concentrate in knee joint, contains ligaments, meniscus and capsule. The bones and meniscus were modeled with hexahedral solid elements. Cortical and trabecular bones were distinguished by different material properties. Soft tissues such as ligaments and capsule were meshed with quadrilateral shell elements. The interface between ligament and bone was modeled using shared nodes. The FE model of lower extremity is shown Figure 4.

Femur, tibia and fibula are all long tubular bones with marrow cavity inside. The diaphyseal of femur and tibia were modeled with three-layer hexahedral solid elements, all the three layers were considered as cortical bone. The thickness of the cavity wall was controlled in a range of 3-6 mm according to statistics. The epiphyseal cortical bone was modeled with only one outer layer solid elements, because compact bone in epiphyseal is much thinner than it in diaphyseal. To avoid the element size to be too small, the marrow cavity of fibula was ignored. Just like femur and tibia, the diaphyseal region of fibula model was considered as cortical bone. And the epiphyseal cortical bone was modeled with only the outer layer of epiphyseal solid elements, where the interior region is filled with trabecular bone elements. The FE models of hip, patella and foot bone were also meshed with hexahedral solid elements, and cortical and trabecular layers were included. Bone models were connected by ligaments with nodes shared. The Figure 5 shows the FE model of tibia.

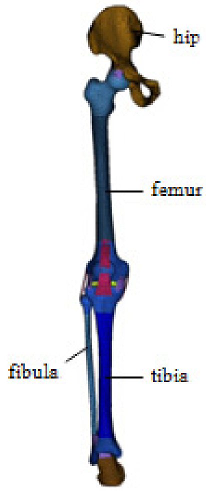



**Figure 4. The FE model of lower extremity**

Knee joint is not only the biggest but also the most complicated joint in the human body. It plays an important role in biomechanical responses of lower extremity in pedestrian-vehicle collision. Besides, knee joint injury is a common injury type for pedestrians in road accidents. Therefore the knee joint model was an emphasis object in this study. The knee joint model contained major soft tissues such as ligaments, meniscus and capsule, which contribute to joint kinematics and stability. Ligament models included medial collateral ligament (MCL), lateral collateral ligament (LCL), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) as well as patellar tendon. They were meshed with quadrilateral shell elements. To avoid hourglass deformation, the ligaments were modeled with fully integrated shell element. Since lack of reliable data in related literatures, the thicknesses of ligament models were assumed to be the same, with constant shell thickness of 3.5mm. Knee capsule was also modeled with shell elements with thickness of 0.5 mm, which covered the knee joint and connected the distal femur to the proximal tibia. Meniscus was a major anatomical component in knee joint between distal femur and proximal tibia. It was meshed with hexahedral solid elements. Ligaments and capsule connected bones by using shared nodes. The interface between menisci and tibial plateau was modeled by tied contact. Figure 6 shows the FE model of the knee joint.

The whole model consists of 51897 hexahedral solid elements and 2783 quadrilateral shell elements. The quality of the FE mesh was verified, such as jacobian. The minimum jacobian of the solid elements was 0.31. Only 2 % of the total solid elements were less than 0.55. Besides, the jacobian of shell elements were above 0.7. The quality of the entire model is acceptable.

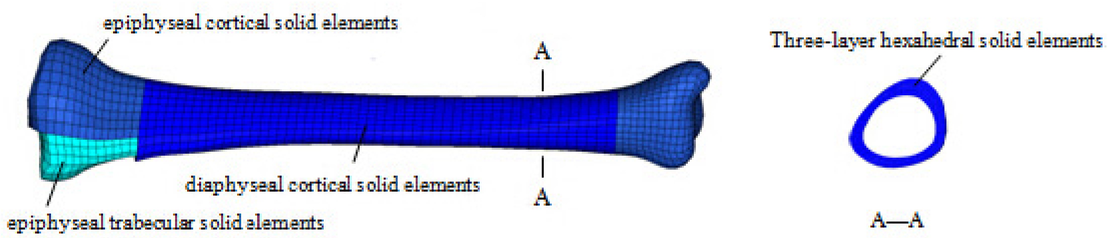
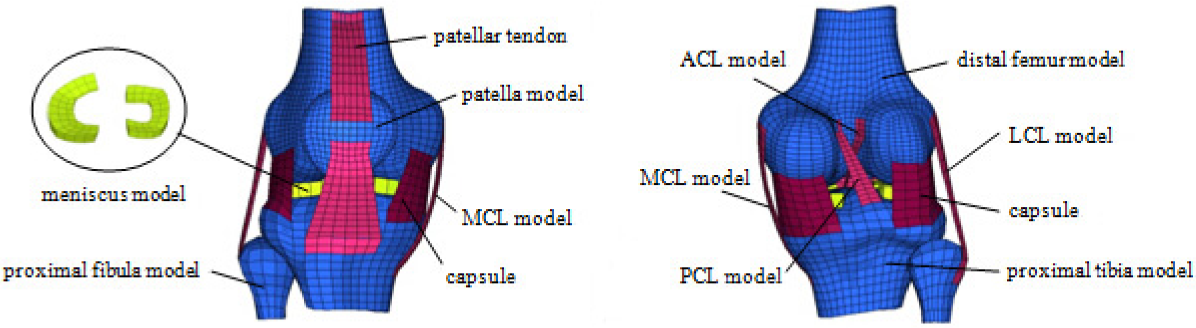



**Figure 5. The FE model of tibia**




(a) front view (b) rear view

**Figure 6. The FE model of knee joint**

## 2.3 Material for the FE model

LS-DYNA was chosen as the FE solver in this paper. All the material models were selected from the existing LS-DYNA material library. Material properties of biological tissues such as bones and ligaments are always nonlinear and viscoelastic. In this study, as the limitation of the material library and the lack of correlative studies, isotropic elastic-plastic material was chosen for bones and ligaments models(*MAT_PLASTIC_KINEMATIC). The failure can be defined in the material model to simulate bone fracture and the ligament tear. The other tissues such as meniscus, capsule and patellar tendon were considered as elastic materials(*MAT_ELASTIC). The damages of them were ignored in this study. Material parameters were selected according to the researches from Untaroiu, Takahashi, Zhang, etc. The difference between Chinese and foreigners in material parameter was neglected .The material parameters used in this model are summarized in Table 2 and Table 3.

**Table 2. Mechanical Properties of Bones used in the Model[4,6-7]**

| Bones | | Density（kg/m$^3$） | Elastic Modulus (GPa) | Poisson's Ratio | Yield Stress(MPa) | Failure Strain(%) |
|---|---|---|---|---|---|---|
| Femur | diaphyseal cortical bone | 1850 | 13.5 | 0.315 | 129 | 3.7 |
| | epiphyseal cortical bone | 1850 | 14.1 | 0.315 | 120 | 2.0 |
| | epiphyseal trabecular bone | 1100 | 0.295 | 0.315 | 9.3 | 13.4 |
| Tibia | diaphyseal cortical bone | 1850 | 17.1 | 0.315 | 125 | 1.8 |
| | epiphyseal cortical bone | 1850 | 17.5 | 0.315 | 129 | 2.8 |
| | epiphyseal trabecular bone | 1100 | 0.30 | 0.315 | 5.3 | 13.4 |
| Fibula | diaphyseal cortical bone | 1850 | 17.5 | 0.315 | 105 | 1.0 |
| | epiphyseal cortical bone | 1850 | 17.9 | 0.315 | 120 | 3 |
| | epiphyseal trabecular bone | 1100 | 0.445 | 0.315 | 7.2 | 13.4 |
| Hip Patella | cortical bone | 2000 | 17.3 | 0.315 | 100 | - |
| | trabecular bone | 1000 | 0.25 | 0.315 | 10 | - |

**Table 3. Mechanical Properties of Soft tissues used in the Model[8]**

| Soft tissues | Density（kg/m$^3$） | Elastic Modulus (GPa) | Poisson's Ratio | Yield Stress(MPa) | Failure Strain(%) |
|---|---|---|---|---|---|
| MCL | 1100 | 0.190 | 0.40 | 36 | 2 |
| LCL | 1100 | 0.170 | 0.40 | 29 | 1 |
| ACL | 1100 | 0.200 | 0.40 | 58 | 4 |
| PCL | 1100 | 0.160 | 0.40 | 35 | 2 |
| Patellar tendon | 1000 | 0.225 | 0.40 | - | - |
| Capsule | 1000 | 0.100 | 0.40 | - | - |
| Meniscus | 1000 | 0.250 | 0.40 | - | - |

## 3 Comparisons

As the FE model of lower extremity developed in this study was based on 50th percentile Chinese male, it was different from other models developed by foreign researchers. Typical models developed by Takahashi, Untaroiu and Kikuchi respectively were selected to compare with the model developed in this study.

Long bongs such as femur, tibia, and fibula are the most important structures in lower extremity. Long bong models developed in this study were compared with other models by modeling the quasi-static 3-point bending test, which was conducted in 1970 by Yamada[9], etc. The simulation process of femur model is shown in figure 7. The femur model was positioned horizontally on its posterior sides. Friction coefficient was defined between the femur model and the support plate to avoid the femur model slipping during loading. The femur model was loaded at the mid-shaft by a cylindrical impactor with a diameter of 25mm. The impactor was constrained to move against the femur model with a constant velocity of 0.01m/s until the fracture of femur model happened. The cylindrical impactor and support plates were meshed with solid elements, and all of them were considered as rigid. The simulation condition in this study should keep consistent with it in related literatures. Force-deflection curves were obtained and compared with the results published by Untaroiu(2004)[10] and Takahashi(2000)[6]. The simulation processes of tibia and fibula model were the same as femur.

MCL is one of the most important ligaments. It is also the most vulnerable ligaments for pedestrians in road accidents. MCL model developed in this study was compared with other models by modeling ligament tensile test, which was conducted by van Dommelen [11] in 2005. The simulation process of MCL model is shown in figure 8. The proximal tibia model was fixed. The distal femur model moved straight up in a constant velocity of 1600mm/s until the ligament was torn. In the procedure of simulation, force-deflection curve of MCL model was obtained and compared with the results published by Untaroiu(2005)[4] and Kikuchi(2006)[12].

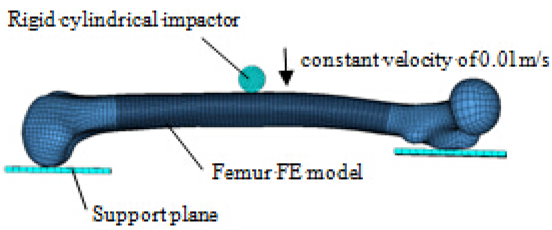



**Figure 7. Simulation process of femur model**

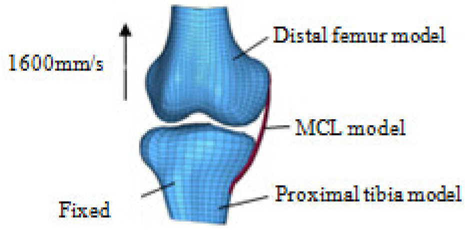



**Figure 8. Simulation process of MCL model**

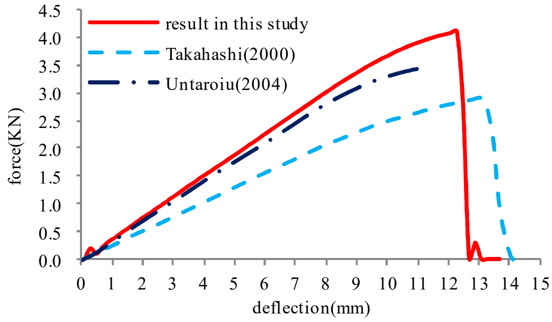



**Figure 9. Comparison of different femur models**

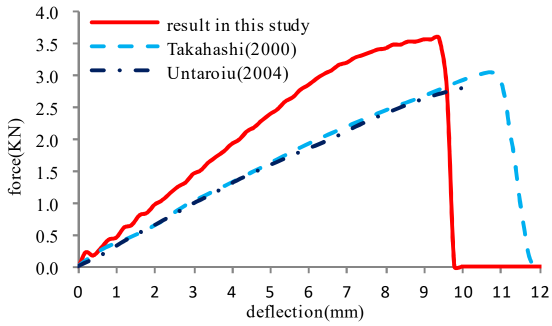



**Figure 10. Comparison of different tibia models**

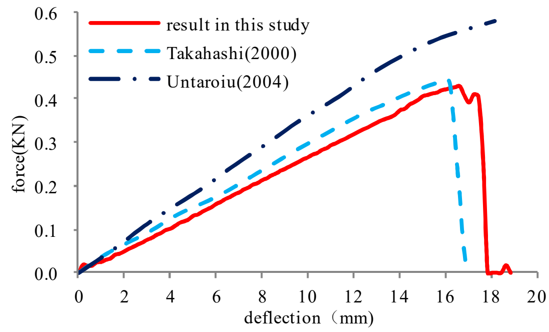



**Figure 11. Comparison of different fibula models**

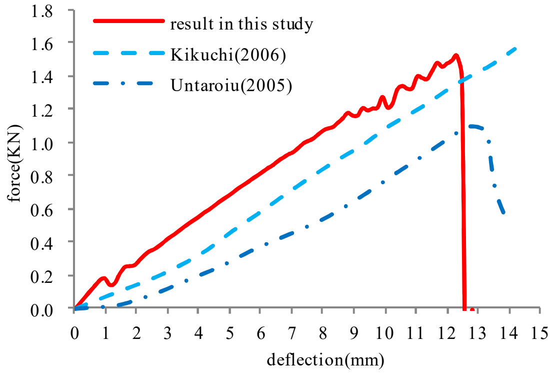



**Figure 12. Comparison of different MCL models**

The comparisons of quasi-static 3-point bending simulation results for long bone models are shown in figure 9-11. It can be found that the curvilinear trend of three different models is identical. The ultimate forces of femur, tibia, and fibula model in this study were 4.08KN, 3.58KN and 0.43KN respectively. The results of femur and tibia model were obviously higher than the results of Takahashi, but the fibula models showed good agreement. In the study of Takahashi, the diaphyseal cortical bone of femur and tibia were modeled by only one-layer solid element, in contrast, diaphyseal cortical models in this paper were meshed with three-layer solid element. The mechanical properties of which modeled by only one-layer elements should be worse than those meshed with multilayer elements. On the other hand, considering the individual difference, the difference among those three models is acceptable. In other words, the models of femur, tibia, and fibula in this study have high biofidelity just as the models developed by Untaroiu and Takahashi.

In addition, the simulation results show that long bones have good linear relation between deflection and loading force under static load in the middle range. The linear relation can be shown to be:

$$f=ax.$$

where $x$ is the deflection of long bones in mid-shaft and $f$ is the loading force. The parameter $a$, ultimate forces and deflections for femur, tibia and fibula model in this study are shown in the table 4. With this formula, deflection or load can be calculated when the other one is known.

**Table 4. Parameters in the linear formula**

| $f$=ax | femur | tibia | fibula |
|---|---|---|---|
| a (KN/mm) | 0.33 | 0.38 | 0.03 |
| ultimate force (KN) | 4.08 | 3.58 | 0.43 |
| ultimate deflection (mm) | 12.3 | 9.4 | 16.6 |

The comparison of simulation results for different MCL models is shown in figure 12. The ultimate force of the MCL model developed in this study was 1.61KN. The simulation result showed good agreement with the result of Kikuchi. In the study of Untaroiu, the MCL model was stretched in quasi-static condition, so the ultimate force was much smaller than the result of 1.61KN. As with the models developed by Kikuchi and Untaroiu, the MCL model developed in this study is reliable.

## 4 Conclusions

This study developed a finite element model of lower extremity with good biomechanical properties to research injure biomechanics and pedestrian protection. Specially, the model was based on $50^{th}$ percentile Chinese male. It can represent Chinese human body characteristics.

The model included major anatomical structures of human lower limb such as such as femur, tibia, fibula, patella, hip and knee-joint. The knee-joint included important soft tissues such as ligaments, meniscus and capsule. Cortical and trabecular bones were distinguished by different material properties. Both the bone models and the ligaments models were defined failure to model bone fracture and ligament tear.

The model was compared with other models developed by foreign researches. As with those models, the model developed in this study has high biofidelity. It can be used in the research of injure biomechanics for Chinese pedestrians in road accidents.

## References


[1] ERSO. Statistical Report 2006[6]. European Commission: European Road Safety Observatory, 2006.

[2] NHTSA. Traffic Safety Facts 2006[R]. USA: Department of Transportation National Highway Traffic Safety Administration, 2007.

[3] Yang J K, Wittek A, Kajzer J. Finite Element Model of the Human Lower Extremity Skeleton in a Lateral Impact, 1996.

[4] Costin Untaroiu, Kurosh Darvish and Jeff Crandall. A Finite Element Model of the Lower Limb for Simulating Pedestrian Impacts[J]. Stapp Car Crash Journal, 2005(49), 157-181.

[5] Kai-Uwe Schmitt, Peter F.Niederer, Markus H.Muser, et al. Trauma Biomechanics: Accidental injury in traffic and sports [M]. Beijing: China Machine Press, 2012, pp. 123-124.

[6] Takahashi Y, Kikuchi Y, Konosu A, et al. Development and validation of the finite element model for the human lower limb of pedestrians[J]. Stapp Car Crash J, 2000(44): 335-55

[7] Zhang Guanjun.A Study on Characteristics of Lower Extremity and Related Parameters in Vehicle-Pedestrian Crashes[D]:Hunan University, 2006.

[8] Kennedy J C, Hawkins R J, Willis R B, et al. Tension Studies of Human Knee Ligaments: Yield Point, Ultimate Failure, and Disruption of the Cruciate and Tibial Collateral Ligaments[J]. Journal of Bone and Joint Surgery, 1976,58(3): 350-355.

[9] Yamada H. Strength of biological materials: The Williams & Wilkins Company, 1970: 19-280.

[10] Costin Untaroiu, Kurosh Darvish, Jeff Crandalf, et al. Development and Validation of a Finite Element Model of the Lower Limb[C] // 2004 ASME International Mechanical Engineering Congress and Exposition, 2004 : 53-62.

[11] van Dommelen J.A.W, Ivarsson B.J, Jolandan M, et al. Characterization of the Rate-Dependent Mechanical Properties and Failure of Human Knee Ligaments [C] // SAE Technical, Paper Number 2005-01-0293, Warrendale, 2005: 1-11.

[12] Yuji Kikuchi, Yukou Takahashi and Fumie Mori. Development of a Finite Element Model for a Pedestrian Pelvis and Lower Limb[C] // 2006 SAE International, Paper Number 2006-01-0663, 2006.