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Pedestrian Knee Joint Modeling and Viscoelastic Material Parameters Identification for Ligaments

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Abstract: In order to study the injury mechanisms and injury criterion, a FE model of pedestrian knee joint was modeled by human anatomical structure with ligaments MCL, LCL, ACL and PCL, capsules, meniscus and articular cartilage included. To reflect the viscoelastic characteristic of knee ligaments, linear viscoelasticity was chosen as the material model for knee ligaments. The viscoelastic material parameters such as long-term and short-term shear modulus were identificated by biomechanical experiments of knee ligaments. The comparison between the results of simulation and experiment under different strain rates indicated that the knee ligaments models with viscoelastic material could accurately simulate the biomechanical response of knee ligaments.

Keywords: Pedestrian protection; Knee joint model; Ligaments; Viscoelastic material

1 Introduction

Knee joints are the biggest and most complicated joint in human bodies. Also, it is vulnerable in vehicle-pedestrian collisions due to the fact that the initial impact between the vehicle front and the pedestrian generally occurs at the lower limb region. The injury types of pedestrian knee joint include fracture of femoral condylar, tibial plateau and patella, tear of knee ligaments and soft tissue injuries of meniscus or articular cartilage. In traffic accidents, knee injuries are always combined injuries, such as soft tissue combined injuries and multiple comminuted fractures even dislocation of knee joint. Therefore, knee injury is a high disability rate injury type in vehicle-pedestrian collisions.

In view of the severity of pedestrian knee injury in traffic accident, biomechanical study of pedestrian knee joint has caught many scholars' attention. Kajzer et al. studied biomechanical response and injury mechanism of pedestrian knee joint under side impact condition through PMHS tests, and found that bend and shear were the major injury mechanism.[1-2] Bose et al. conducted tests on isolated knee joints from PMHS in dynamic lateral-medial loading which replicated a vehicle- pedestrian impact at 40 km/h. The experimental results showed that the medial collateral ligament (MCL) was the only major load bearing knee structure that was injured in the experiments.[3] Van Dommelen et al. investigated the structural properties of the four major human knee ligaments at different loading rates and found that structural properties of knee ligaments depended on the deformation rate.[4]

As the costs and ethical restriction on biomechanical experiments, researchers turned to develop biomechanical models of pedestrian to study the biomechanical response and injury mechanism in vehicle-pedestrian accidents. Untaroiu et al.(2005) developed a knee joint model with ligaments, capsules and meniscus included. The ligament model was assumed as a quasi-linear viscoelastic (QLV) model with transversely isotropic material symmetry. However, the material parameters of the four major human knee ligaments were the same and only the MCL model was validated.[5] Takahashi et al.(2003) developed a knee joint model based on MRI scan data.[6] The ligaments were simulated by an elasto-plastic material and arbitrary strain rate dependency can be defined(*MAT PIECEWISE LINEAR PLASTICITY). The four major human knee ligaments were respectively validated according to experimental results from Bose[7] and Kerrigan[8].

In order to study on the injury mechanism and threshold of pedestrian knee joint in vehicle-pedestrian collisions, a knee joint FE model was modeled with high precision depended on human anatomical structure. To simulate the viscoelastic character of knee ligaments, linear viscoelastic material model was chosen for knee ligaments and the material parameters of each ligament were confirmed based on related biomechanical experiments. The comparison between simulation and experiment results under different strain rates indicated that the knee ligaments models with viscoelastic material could accurately simulated the biomechanical response of knee ligaments.

2 Pedestrian Knee Joint Modeling

2.1 Human Anatomical Structure of Knee Joint

As the biggest bearing joints in human body, knee joint has a complex anatomical structure. The anatomical structure of knee joint is shown in figure 1. The knee is made up primarily of femoral condyle, tibial plateau, patella and soft tissues. The soft tissues of knee joint include ligaments, capsules, articular cartilage and meniscus. Ligament is a important part of knee joint, which contribute to joint kinematics and stability. The major ligaments of knee contain medial collateral ligament (MCL), lateral collateral ligament (LCL), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) as well as patellar tendon. Between the condyle of femur and tibia, there is a crescent-shaped fibrocartilage structure named meniscus, which can provide structural integrity to the knee when it undergoes tension and torsion. The joint capsules is an envelope that entirely surrounds knee joint.

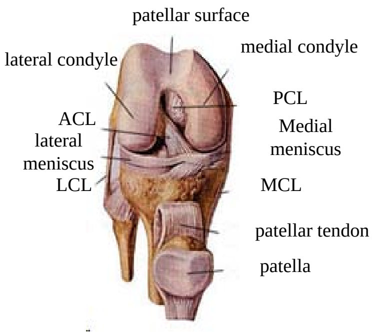


Figure 1: anatomical structure of knee joint

2.2 FE Model of Knee Joint

The FE model of pedestrian knee joint is shown in Figure 2. The models of lower extremity bones such as femur, tibia, fibula and patella were developed based on CT scan data from a volunteer close to 50th percentile Chinese male. As the three-dimensional data of all the bones were obtained from one coordinate system, therefore the bone structure in this knee joint model has correct relationship of mutual position. The bone models were modeled with hexahedral solid elements with high quality of meshes, include cortical and trabecular layers.

Soft tissues models of knee joint were developed based on human anatomical structure, with ligaments, capsules, articular cartilage and meniscus included. Knee ligaments models such as MCL, LCL, ACL and PCL were meshed with hexahedral solid elements. The position of each ligament model was confirmed by literature of anatomy, and the thickness of each ligament model was assumed to be 3-5mm[9]. Knee capsule was modeled with quadrilateral or triangular shell elements. Since no reliable data could be found in the literature, the thickness of knee capsule was assumed to be 0.5mm according to Untaroiu et al.[5] Articular cartilages were meshed with one-layer solid elements on the articular surfaces of femur, tibia and patellar. The thickness of articular cartilage was assumed to be 2-3mm base on MRI data.[10] Meniscus was also meshed with one-layer hexahedral solid elements, located between the condyle of femur and tibia. Ligaments, capsule and articular cartilages connected to bones by shared nodes.

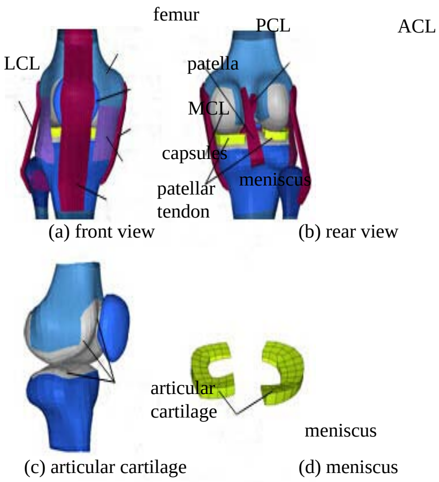


Figure 2: FE model of knee joint

3 Viscoelastic Material Parameters Identification of Ligaments

Ligaments play an important part in kinematic response of knee joint. Ligaments injuries can lead to knee joint instability. Biological tissues such as ligaments present complicated mechanical behavior of anisotropic, viscoelastic and creep. In previous biomechanical study, ligaments are usually assumed to be linear elastic material, elastic-plastic material or non-linear strain rate dependent plastic material. Compared to the former two, the latter considers ligaments strain rate dependency in order to simulate their dynamic response. However, the material models above can not accurately describe the viscoelastic characteristics of knee ligaments. Therefore, material type 6 (*MAT VISCOELASTIC) was chosen from existing LS-DYNA material library for knee ligaments in this study. This material type has the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. The constitutive model is described by the following equation:

$$\sigma_{ij} = 2\int_0^t G(t-\tau)\left[\frac{\partial \varepsilon'_{ij}(\tau)}{\partial \tau}\right]d_z \tag{1}$$

The shear relaxation behavior is given by:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t} \tag{2}$$

Where, G_∞ and G_0 are long-term and short-term shear modulus which govern the viscoelastic respone; β is the decay factor. In this study, we review the relevant literatures and set the density of each knee ligament model at 1100kg/m3, the decay factor at 100s-1, and the bulk modulus at 504Mpa according to some similar biological tissues like tendon in literatures.[11] The long-term and short-term shear modulus were subsequently optimized based on the experiment data.

In the condition of low strain rate, the viscosity characteristic of linear viscoelastic materials can be ignored. With this understanding, viscoelastic material can be regarded as linear elastic material. As the t is long, the shear relaxation modulus becomes:

$$G = G_\infty \tag{3}$$

For linear elastic material, shear modulus *G* and bulk modulus are given by:

$$G = \frac{E}{2(1+v)} \tag{4}$$

$$K = \frac{E}{3(1-2v)} \tag{5}$$

Where, *E* is Young's modulus, *v* is Poisson ratio. According to the equations (3~5), Young's modulus *E* and Poisson ratio *v* have the following equations:

$$E = \frac{9KG_\infty}{3K + G_\infty} \tag{6}$$

$$v \approx 0.5 \tag{7}$$

As $K >> G_\infty$, *E* and G_∞ have the following approximate relationship:

$$E \approx 3G_\infty \tag{8}$$

According to the equation (8), the viscoelastic parameter G_∞ of ligaments can be obtained from Young's modulus *E* in the condition of low strain rate. Therefore, ligaments were assumed as linear elastic material previously. In order to determine the value of Young's modulus *E*, tensile tests of knee ligaments under low strain rate were simulated. After Young's modulus was determined, long-term shear modulus G_∞ could be obtained by the equation $E \approx 3G_\infty$. Then, viscoelastic model was used for ligaments. Using long-term shear modulus G_∞ determined above, short-term shear modulus G_0 could be obtained by simulating tensile tests of knee ligaments under high strain rate which was performed by Van Dommelen et al.

Takahashi et al. summarized the relationship between Young's modulus and strain rate of major knee ligaments, as is shown in the Figure 3.[12] When the strain rate is less than $0.1s^{-1}$, the Young's modulus of knee ligament is about 75MPa. As the strain rate is increased, the Young's modulus gets bigger. When the strain rate is $1s^{-1}$, the Young's modulus of knee ligament gets to 210MPa. Therefore, the values range of Young's modulus in this paper sets at 60-210MPa. According to the approximate relationship between *E* and G_∞ described above, the long-term shear modulus G_∞ values range from 20 to 70MPa.

The injuries of ligament models were modeled by element failure. According to the experiment performed by Chawla et al., knee ligaments have higher ultimate stress under high strain rate loading and higher ultimate strain under low strain rate loading.[13] Therefore, the ultimate stress and ultimate strain were both defined in this study to simulate ligament injuries under high and low strain rate loading, respectively. Butler et al. studied mechanical properties of knee major ligament and gained the ultimate stress of each ligament, as is shown in the Figure 4.[14] The ultimate stress of knee ligaments range from 10Mpa to 60Mpa.

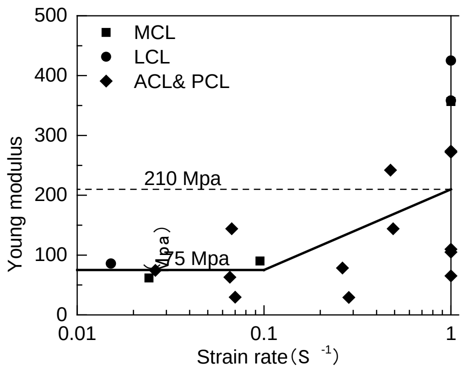


Figure 3: the relationship between Young's modulus and strain rate of knee ligaments

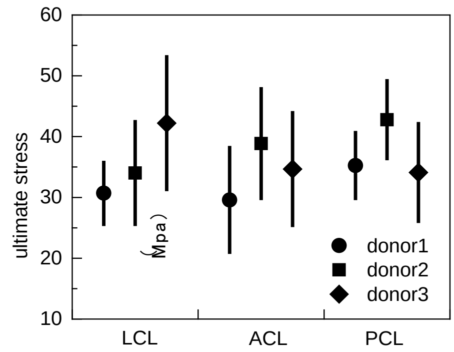


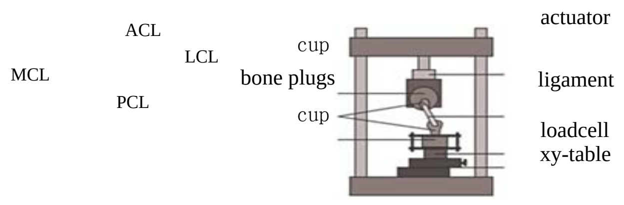
Figure 4: ultimate stress of knee ligament

Mo et al. established the strain failure parameters of the knee ligaments based on the ultimate strain from the previous tensile tests, as shown in the table 1.[15] The values of ligament failure parameters in this study were optimized within the range mentioned above.

Table 1: ultimate strain of knee ligament

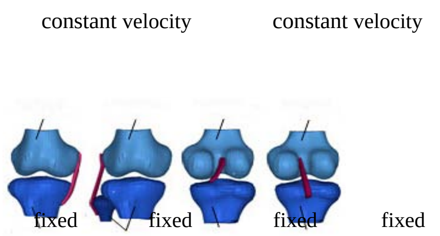
literature	MCL	LCL	ACL	PCL
Arnoux et al.	25-38%	25-38%	18-24%	18-24
Kerrigan et al.	11-20%	7-11%	-	-
Van Dommelen et al.	39(8.6)%	18(1.8)%	aACL18(3)% / pACL22(3)%	aPCL18(2)% / pPCL14(1)%
Mo et al.	30%	34%	31%	28%

The schematic illustration of ligament test setup performed by Van Dommelen et al. is shown in figure 5. Bone-ligament-bone specimens such as MCL, LCL, ACL and PCL were tested to failure in tension with the knee in full extension. The rate dependence of the structural response of the knee ligaments was investigated by applying different loading rates. The simulation setup in this study is shown in figure 6. The viscoelastic parameters of knee ligaments obtained in this study based on ligament tensile tests are list in table 2.



（a）schematic illustration （b）experimental installation

Figure 5: schematic illustration of ligament test setup



(a)MCL (b)LCL (c)ACL (d)PCL

Figure 6: schematic illustration of simulation setup

Table 2: viscoelastic parameters of knee ligament

ligament	density (kg/m^3)	bulk modulus (Gpa)	short-term shear modulus (Gpa)	long-term shear modulus (Gpa)	decay factor (s^{-1})	ultimate strain (%)	ultimate stress (Gpa)
MCL	1100	0.504	0.045	0.031	100	0.35	0.034
LCL	1100	0.504	0.059	0.036	100	0.16	0.024
ACL/PCL	1100	0.504	0.068	0.045	100	0.32/0.27	0.052/0.040

4 Comparison Between Simulations and Experiments

Figure 7~8 compare the MCL model predicted force-deflection curve to those obtained experimentally by Van Dommelen et al. at different loading rates. The simulation results showed good agreement with the associated experimental data. The injury thresholds of MCL model were 1.45KN and 1.27KN respectively at high strain rate loading(1600mm/s) and low strain rate loading(1.6 mm/s), which were consistent with the test results.

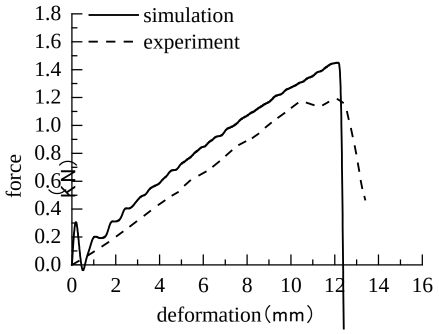


Figure 7: verification of MCL at high strain rate loading

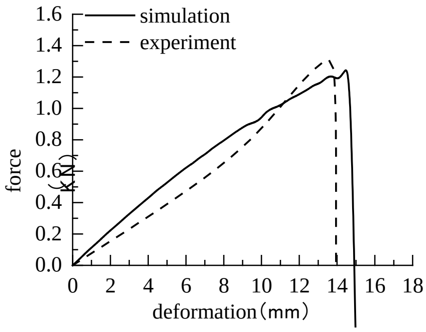


Figure 8: verification of MCL at low strain rate loading

The ultimate stress of MCL model was about 34Mpa at high strain rate loading as shown in figure 9, which was consistent with the result of 38.6±4.8Mpa reported by Quapp et al.[16] The ultimate strain of MCL model was 35%, which was in the range of 25~38% reported by Arnoux et al.[17]

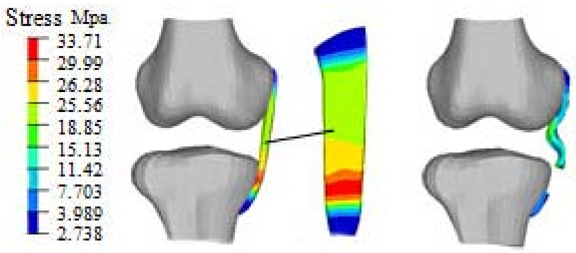


Figure 9: stress nephogram of MCL at high strain rate loading

The simulation results of the LCL tensile tests at different strain rate loading and the associated experimental results were shown in figure 10 and 11 respectively. The simulation results showed close agreement with experimental data in terms of the maximum force and maximum deformation. The injury thresholds of LCL model were 0.65KN and 0.46KN, and the maximum deformation were 8.5mm and 9.0mm at high and low strain rate loading respectively, which were within the range of the experimental data. The ultimate stress of LCL model in this study was 24Mpa and within the range of the experimental data (36±12Mpa) reported by Butler et al.[14] The ultimate strain of LCL model was 16%, which was also close to test result (20±5.5%) reported by Van Dommelen et al.

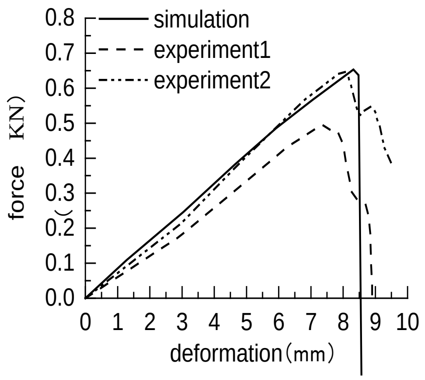


Figure 10: verification of LCL at high strain rate loading

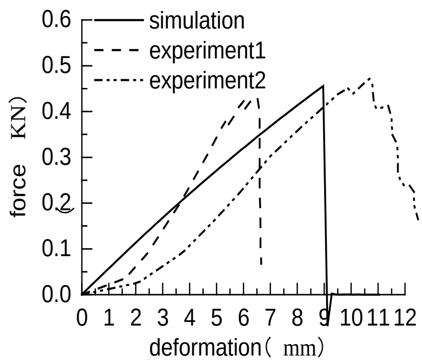


Figure 11: verification of LCL at low strain rate loading

In the experiment reported by Van Dommelen et al., the cruciate ligaments (ACL and PCL) were only tested at high strain rate loading. Therefore, the viscoelastic parameter G_∞ of cruciate ligaments cannot be obtained in the condition of low strain rate. In this case, the viscoelastic parameters of ACL and PCL were adjusted based on the parameters of MCL and LCL. The cruciate ligaments were split into two functional bundles: the antero-medial part (aACL and aPCL) and the postero-lateral part (pACL and pPCL). Tensile test were performed on both bundles of cruciate ligaments at high strain rate loading (1600mm/s). In terms of anatomical structure, the two functional bundles were not obviously split. Therefore, in this study each cruciate ligament was simplified and regard as one bundle. During the validation, the maximum tensile forces of each cruciate ligament in simulation results were demanded in the range of the sum of the associated two functional bundles' tensile forces reported in experiment and the maximum elongations of each cruciate ligament were demanded consistently with the test results. The force-deformation response predicted by the ACL and PCL model were compared with test results, as is shown in figure 12 and 13, respectively.

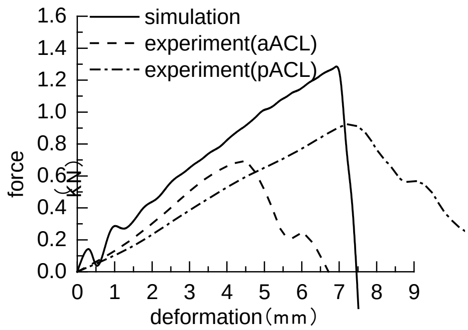


Figure 12: verification of ACL at high strain rate loading

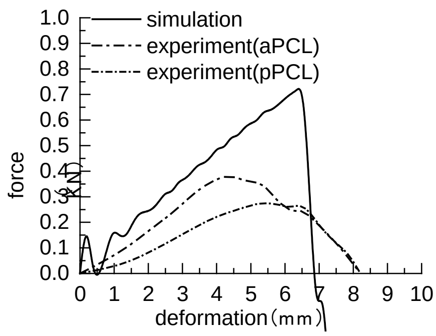


Figure 13: verification of PCL at high strain rate loading

At high strain rate loading, the injury thresholds of ACL and PCL were 1.32KN and 0.74KN, and the maximum deformation were 7.0mm and 6.5mm, respectively. The maximum tensile forces and deformations all meet the simulation requirements described above. The ultimate stress of ACL and PCL model were 52Mpa and 40Mpa, which were within the range of the experimental data reported by Butler et al.[14] As lack of experimental data at low strain rate loading, the ultimate strain of ACL and PCL model were directly set as 32% and 27% according to Mo' research.[15]

The simulation results of major knee ligaments at different strain rate loading and associated experimental data reported by Van Dommelen et al. were compared in table 3. The simulation results showed good agreement with experimental data. Thus, the major knee ligament models developed in this study using the viscoelastic parameters could accurately simulated the mechanical characteristics of knee ligaments.

Table 3: verification results of knee ligaments

	loaidng（mm/s）	maximum force /KN	
		experiment	simulation
MCL	1600	1.40±0.32	1.48
	1.6	1.40±0.22	1.27
LCL	1600	0.54±0.11	0.65
	1.6	0.44±0.08	0.46
aACL	1600	0.99±0.56	1.32
pACL		1.00±0.19	
aPCL	1600	0.65±0.29	0.74
pPCL		0.29±0.09	

5 Conclusion

1. A FE model of knee joint for pedestrians was modeled with high-precision and detailed into human anatomical structure, including ligaments such as MCL, LCL, ACL and PCL, capsules, meniscus and articular cartilage.

2. Considering the viscosity characteristic of knee ligaments, a linear viscoelastic material model was chosen for knee ligaments from existing LS-DYNA material library and the viscoelastic material parameters such as long-term and short-term shear modulus were identified based on the ligament tensile tests performed by Van Dommelen et al.

3. The comparison between the simulation and experiment indicated that the major knee ligament models with the viscoelastic parameters identificated in this study could accurately simulated the mechanical characteristics of knee ligaments. The knee joint model could be used for the study of the injury mechanisms and injury criterion of knee join in vehicle-pedestrian collisions.

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