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Crash Injury Analysis of Knee Joint Considering Pedestrian Safety

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ABSTRACT

Background: Lower extremity injuries are frequently observed in car-to-pedestrian accidents and due to the bumper height of most cars, knee joint is one of the most damaged body parts in car-to-pedestrian collisions.

Objective: The aim of this paper is first to provide an accurate Finite Element model of the knee joint and second to investigate lower limb impact biomechanics in car-to-pedestrian accidents and to predict the effect of parameters such as collision speed and height due to the car speed and bumper height on knee joint injuries, especially in soft tissues such as ligaments, cartilages and menisci.

Materials and Methods: In this analytical study, a 3D finite element (FE) model of human body knee joint is developed based on human anatomy. The model consists of femur, tibia, menisci, articular cartilages and ligaments. Material properties of bones and soft tissues were assumed to be elastic, homogenous and isotropic.

Results: FE model is used to perform injury reconstructions and predict the damages by using physical parameters such as Von-Mises stress and equivalent elastic strain of tissues.

Conclusion: The results of simulations first show that the most vulnerable part of the knee is MCL ligament and second the effect of speed and height of the impact on knee joint. In the critical member, MCL, the damage increased in higher speeds but as an exception, smaller damages took place in menisci due to the increased distance of two bones in the higher speed.

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Keywords

Pedestrians; Knee Injuries; Finite Element Analysis

Introduction

Pedestrian safety is a well-attended topic due to the statistics of car accidents all over the world. Pedestrians are one of the most vulnerable road users due to the lack of protective equipment. As a result, pedestrian accident injury risk has been widely investigated since the 1960s, when it was found that almost 95 percent of all pedestrian accidents occurred at an impact velocity less than 50 km/h and that half occurred at an impact velocity lower than 30 km/h [1-3]. Accident data from different countries were analyzed in order to study the severity of injuries in pedestrian impacts [4-11]. The results from these studies indicated that vehicle impact velocity has a significant effect on the injury severity among pedestrians.

Statistics show that one of the most body regions injured in car-to-

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pedestrian collisions is the lower extremities which are frequently injured due to the initial impact against the front bumper of a car [1]. As the bumper height is low in passenger cars, the impact mostly takes place in the knee joint or just below the knee joint [2]. Although lower extremity injuries are not fatal, they cause long term physical disability and impairment. So, studying the effect of height of car bumpers in injury severity could be useful to design safer vehicles.

The knee joint is one of the most complex joints in human body because of its complex geometry and articulations. The joint stability and compliance during functional activities are provided through anatomical structures such as ligaments, menisci and articular cartilage [3]. As a result of this complexity, the exact mechanical behavior of the knee joint is not completely known yet [12-17]. Based on this fact, a method which proved to be able to provide deep insights into the mechanical properties and performance of biological tissues is the Finite Element method.

The objectives of this article are first to generate an appropriate knee-joint FE model for predicting injury and trauma in human knee joint affected by crash via calculation of stress and strain in knee joint. On the other hand, in order to investigate the effect of velocity and height of the car bumpers on pedestrian collisions and its injury, a related parametric study is conducted.

Material and Methods

Knee Joint Geometry

In this analytical study, due to the fast development of technology, more sophisticated FE lower limb models have been developed. These models have accurate geometry mostly obtained from CT and MRI scans from human volunteers. Figure 1 shows the detailed anatomy of a knee joint.

The geometry used in this article is generated from magnetic resonance images (MRIs) of a 70 year old female donor with 77.1kg weight and 1.68m height whose reason of death was cancer [4]. The model consists of bony structures (i.e. distal femur and proximal tibia), articular cartilages (femoral, medial tibial and lateral tibial) menisci (medial and lateral) and ligaments (anterior cruciate (ACL), posterior cruciate (PCL), medial collateral (MCL) and lateral collateral (LCL)) of the right leg.

MRI scans were taken with the knee specimen in the full extension position using a 1.0 Tesla extremity MRI scanner (Orthone, ONI

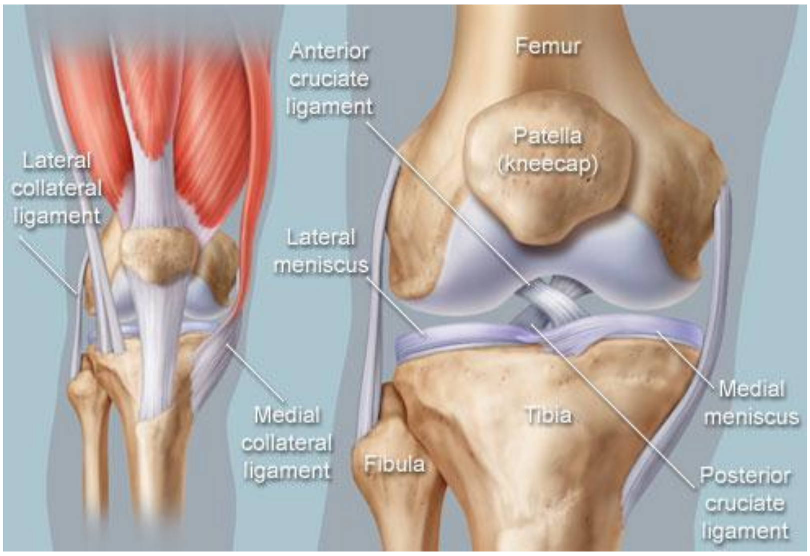

Figure 1: Knee Joint Anatomy [3]

Medical Systems Inc., Wilmington, MA), with 1.5 millimeter slices in three anatomical planes (axial, sagittal and coronal), at the Biomechanics Laboratory of the Cleveland Clinic [4].

Figure 2 illustrates geometries of tissue structures were imported into ANSYS Design Modeller for some modifications due to objectives of the present study.

As the current project aim is simulating car-to-pedestrian impact, the bony structures had been extruded to define the fixed supports and loading points of action at the end points of femur and tibia. A simple model of an impactor was designed to represent the car bumper as it can be seen in Figure 3.

Mesh Generation

Two types of surface-to-surface contact were defined between parts of the knee joint. The contact between bony structures and ligaments and also bony structures and cartilages were defined as bonded contact and the contacts between cartilages and menisci were defined as

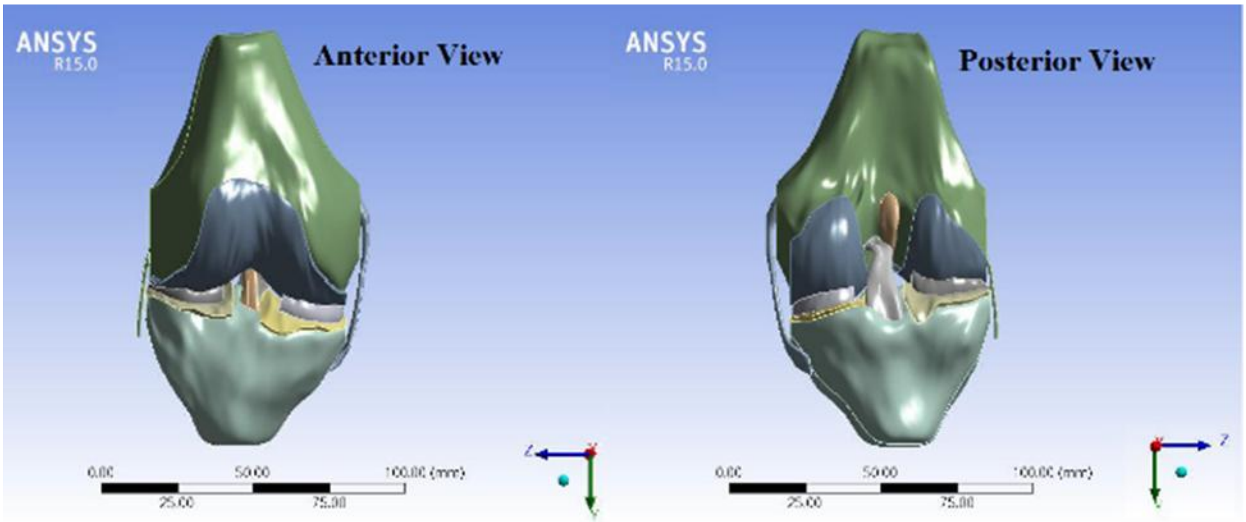

Figure 2: Knee Joint Geometry Model

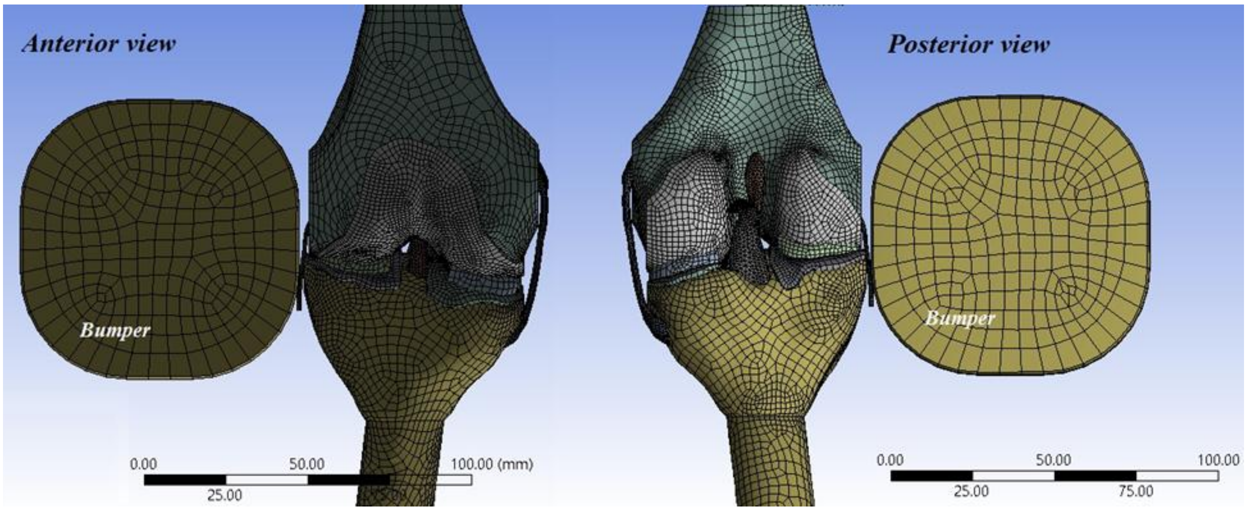

Figure 3: Mesh Development - Anterior View (Left) and Posterior View (Right)

frictional contacts. Bones were assumed to be rigid in this model, so they can be represented only by their surface. Quadrilateral dominant meshing method was used to mesh the bones, menisci and cartilages and ligaments. In all cases, both quadrilateral and triangular elements have been used for increasing the mesh efficiency. Figure 3 shows the whole knee and impactor meshed model.

The quality of the meshed model for computational reliability was verified by checking the distribution of multiple element geometric parameters such as element quality and aspect ratio. The average element quality of the model was 0.8 and the average aspect ratio is 1.43 which represents a reliable FE model quality.

Material Properties

Numerous FE studies have considered bones to be rigid bodies due to their high stiffness compared to other soft tissue [18-19]. In this study, we considered bones as elastic materials to optimize the accuracy and calculation time of the simulation. The density, Young modulus, Poisson's ratio and yield stress of bony structures are shown in Table 1.

The Menisci and cartilages are hydrated tissues. However, in crash cases which exhibit short loading times compared to the viscoelastic time constant of nearly 1500 seconds for articular cartilage [5, 19-22], articular cartilage should be described by its instantaneous elastic modulus [23-25]. For that reason, all articular cartilage structures (femoral and tibial) were assumed to act as linear elastic, homogenous and isotropic materials with the material properties shown in Table 1. For the same reason, menisci were also assumed to be linear elastic and isotropic with the average properties in Table 1.

Anatomically, ligaments are composed of bundled collagen fibers which run mostly in parallel along the ligament length which made them anisotropic from mechanical characteristics point of view [26-27]. In some studies, to simplify the material properties of ligaments, they were assumed to act as linear elastic isotropic materials [1]. We followed this assumption without loss of generality in analysis and the material properties of ligaments as seen in Table 1.

Boundary Conditions and Loadings

In order to validate the model, firstly a lateral static force of 200N was applied to the knee. On the next step, to simulate car-to-pedestrian impacts in which the bumper of a car impacts the lower leg laterally, the dynamic simulation which presents a better understanding of impact is applied. In both simulations, the pedestrian has been configured as standing on the ground with a friction coefficient of 1.0 by fixing the bottom surface of tibia in all 6 directions [13]. A load of 350 N corresponding to half the body weight of a normal weighted person has been applied at the top surface of

Table 1: Material Properties of Knee Joint Tissue

Structure	ρ (kg/m^3)	Young's Modulus E (Mpa)	Poisson's Rations	Yield Stress σ_y (Mpa)
Femur	2000	13500	0.3	6.6
Tibia	1800	20000	0.315	5.3
Articular Cartilages	1500	5	0.46	-
Menisci	1500	250	0.3	-
Ligaments (ACL, PCL, MCL, LCL)	1100	345	0.22	29.8

femur.

In dynamic simulations, two impact points of action on the knee joint are assumed. One would present On-Knee impact orientation and other Below-Knee impact orientation. These locations have been selected to account for variation of height of impact on pedestrian lower extremity due to the varying bumper height in different vehicles.

In below-knee impact orientation, the impactor hits the lower leg laterally at 6cm below the tibia plateau and compels it to translate in medial direction relative to femur.

The impactor (i.e. car bumper) with the weight of 20 kg and structural steel material properties with a modified density of 1.13E5 kg/m3 was propelled in the horizontal direction with an initial velocity to the lower leg in each height [13]. This initial velocity is chosen to be once about 25 km per hour and once about 32 km per hour to compare the speed effect on the impact. The explicit dynamic method was chosen to analyse the impact simulation implemented in ANSYS Explicit Dynamics system.

Results

Contour plots of effective (Von-Mises) stress, maximum principal stress, Equivalent elastic strain and maximum principal elastic strain were studied to gain a better understanding of the results. The results are discussed in three sub-sections in this article. The first one is an overlook of the contours in 25kmph impact. Sub-section 2 represents a comparison between 25kmph and 32kmph simulation contours both in on-knee orientation and sub-section 3 includes the lower-knee impact contours in comparison with the same impact velocity of 25kmph on-knee simulation contours. In the second and third sub-sections, the results are shown in strain contours.

Figures 4 to 6 show all four contour types of each member of a knee joint. As it is shown

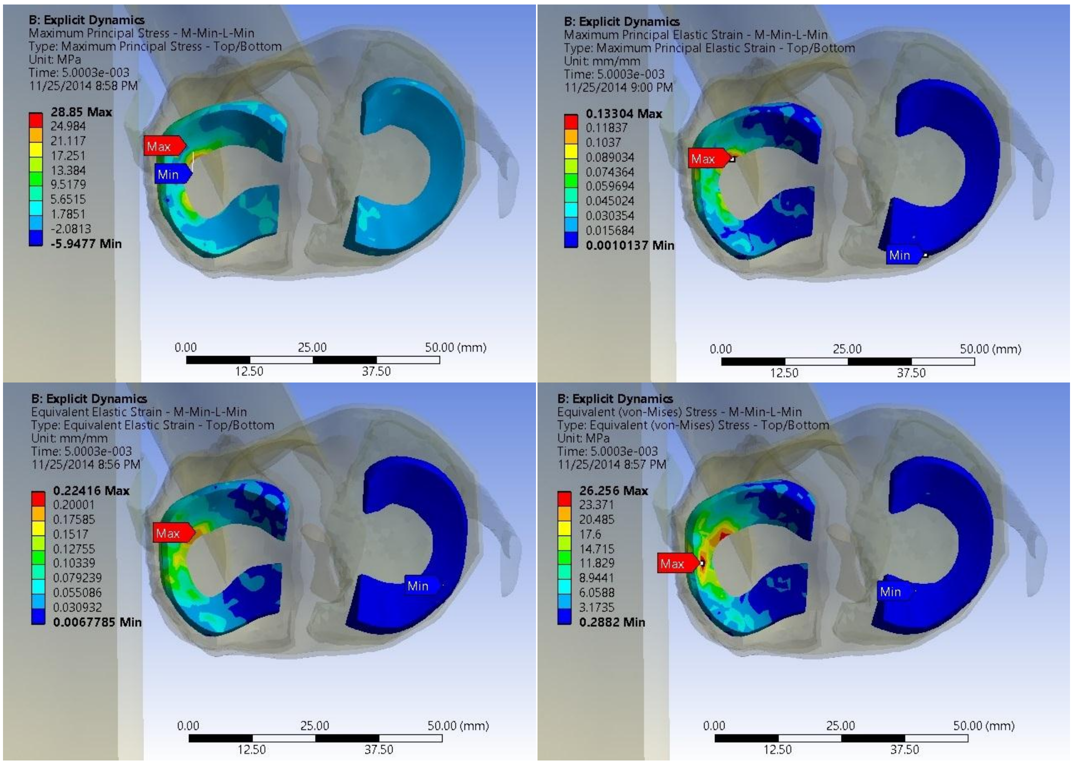

Figure 4: Equivalent (Von-Mises) Stress, Maximum Principal Stress, Equivalent Elastic Strain and Maximum Principal Elastic Strain in Menisci - 25kmph On-Knee Impact

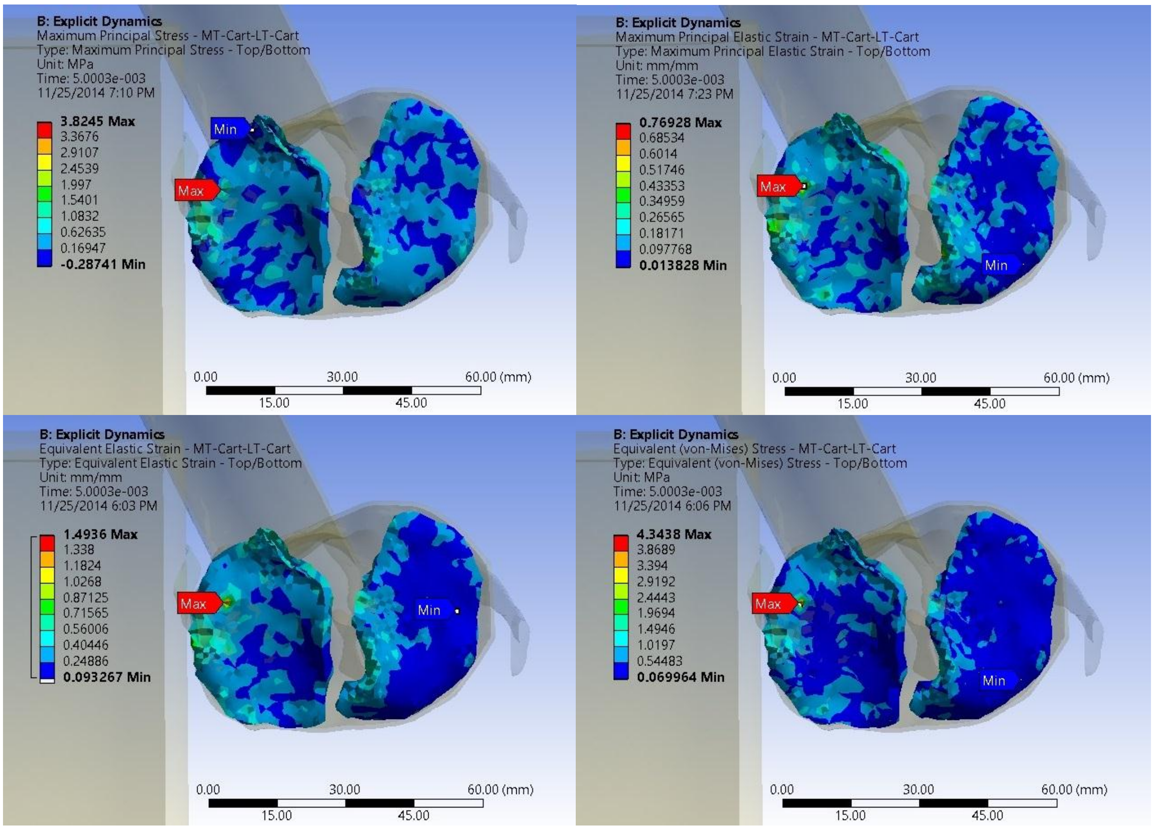

Figure 5: Equivalent (Von-Mises) Stress, Maximum Principal Stress, Equivalent Elastic Strain and Maximum Principal Elastic Strain in Tibial Cartilages - 25kmph On-Knee Impact

in Figure 4, the highest equivalent (Von-Mises) stress and the highest maximum principal stress in menisci took place respectively at the superior and inferior regions of the lateral meniscus with the values of 26.256 and 28.85 Mpa. Moreover, the highest equivalent elastic strain and the highest maximum principal elastic strain in menisci took place respectively at the inferior region and the internal edge of the lateral meniscus with the values of about 0.22 and 0.13.

Figure 5 shows the contours in femoral and tibial cartilages in 25kmph simulation. As shown in these contours, stress and strain are higher at the exterior regions of the femoral cartilage and at the central region of the tibial cartilage.

Simulation demonstrates the critical points in ligaments take place in the middle region of MCL as it is shown in Figure 7 and based on stress and strain amounts in all members and also the material properties of them, it can be presumed that MCL would be the first member to fail. The highest Von-Mises stress and maximum principal stress in the MCL ligament are 71.055 and 71.93 Mpa which are much bigger than the yield stress in Table 1, 29.8 Mpa.

Discussion

Considering that the damages in menisci and ligaments mainly cause more serious impairments in comparison with cartilages injuries, in this section and the next section of this article, the numerical results will be discussed only in menisci and ligaments. The peak amounts of equivalent elastic strain and maximum principal plastic strain increased about 29 and 25 pecent, respectively in MCL. In menisci, these

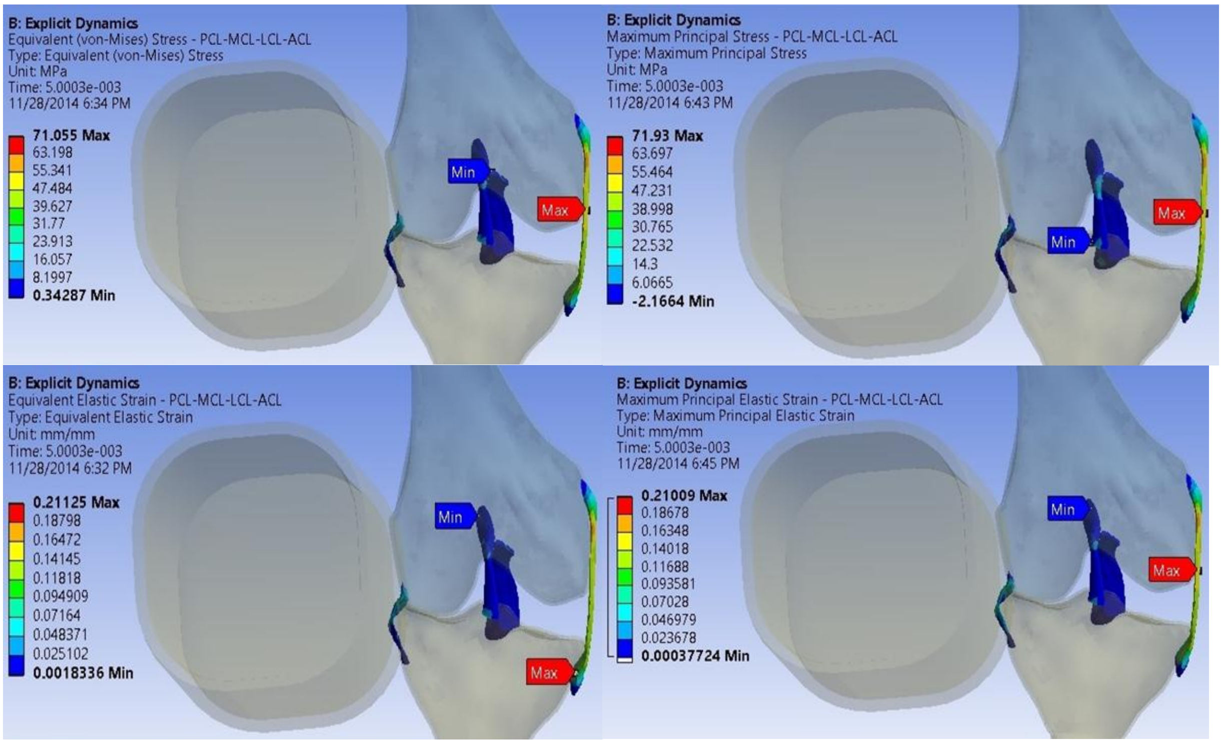

Figure 6: Equivalent (Von-Mises) Stress, Maximum Principal Stress, Equivalent Elastic Strain and Maximum Principal Elastic Strain in Ligaments - 25kmph On-Knee Impact (In the right side of the figure, Contours of MCL is shown for better demonstraition)

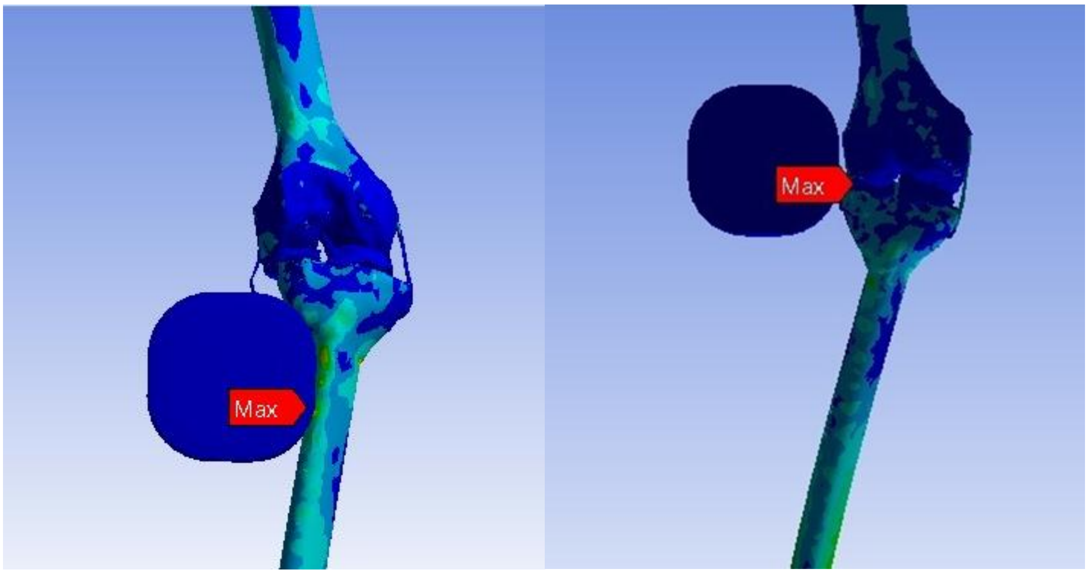

Figure 7: Comparison between On-Knee and Below-Knee Orientations both with the velocity of 25kmph – Equivalent Stress - Overview

amounts decreased 13 and 29 percents.

As the results show, the injuries in all bony and soft tissues increase in higher speeds except for menisci. Higher speeds cause higher impact energy and for sure cause more and bigger injuries. In meisci, the injuries were lowered which could be a result of increasing distance between femur and tibia at higher speeds due to separation tendency of the joint in collisions.

Figures 7 and 8 show the equivalent (Von-Mises) stress contour of the whole knee joint in order to study the bumper height effect. As it shows, the risk of tibia injuries increases in below-knee impacts due to impact orientation which is on tibia bone. It has been observed in soft tissue results that the injuries in all connective tissues are bigger in on-knee impact due to the straight impact on the joint except for ligaments. In below-knee impacts, the separation tendency of the two bony structures seems to put the MCL ligament in more tension.

By lowering the impact height, the percentage of increase of peak amounts of equivalent elastic strain and maximum principal plastic strain in MCL is about 81 and 86. In menisci, these amounts decreased about 36 and 47 percents.

Conclusion

In this study, a detailed three-dimensional FE model was prepared and a series of finite element simulations was implemented to analyze the influence of vehicle impact velocity and the height of the vehicle bumper on injury in the knee joint members during collision. The conclusions can be summarized as follows.

The most vulnerable member of knee joint in all simulations was the MCL ligament which means the failure will first take place in MCL in lateral impacts in car-to-pedestrian accidents.

Vehicle impact velocity has significant influ-

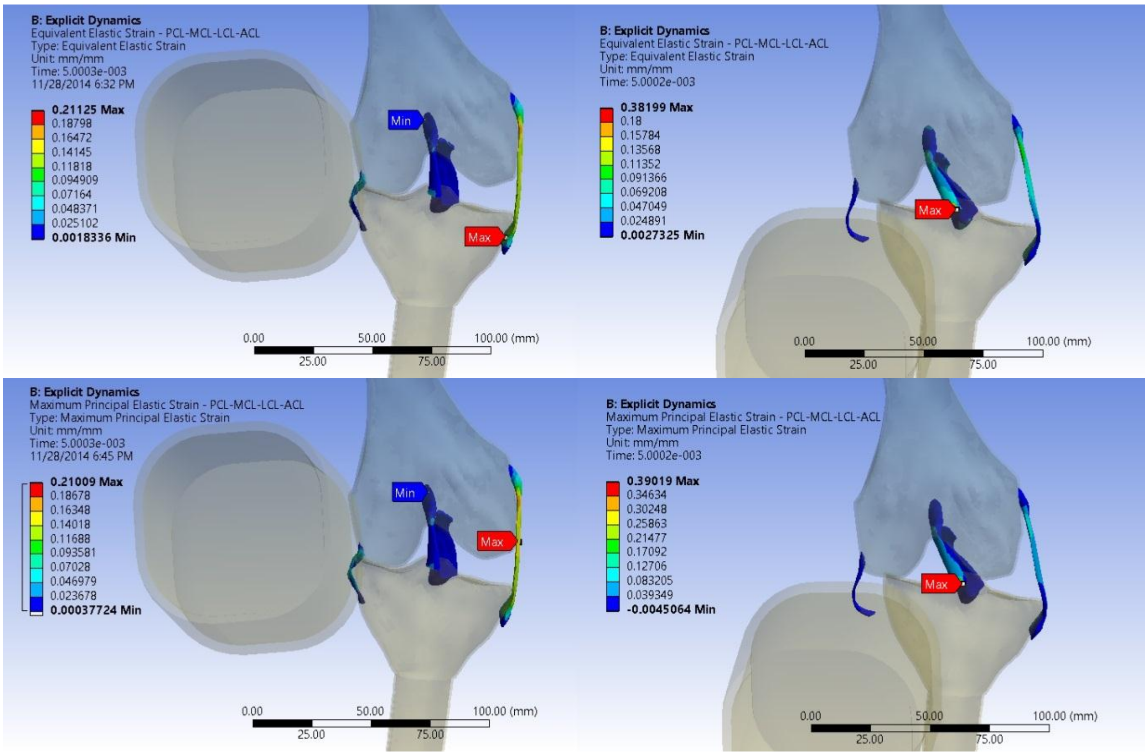

Figure 8: Comparison between On-Knee and Below-Knee Orientations - 25kmph - Equivalent Elastic Strain and Maximum Principal Strain in Menisci, respectively

ence on both bony and soft tissues of the knee joint injury. In the critical member, MCL, the damage increased at higher speeds but as an exception, lower damages took place in menisci due to the increased distance of two bones at the higher speed. Generally, it can be concluded that injury risks can be reduced if the vehicle impact velocity lessens. So, reducing impact velocity was confirmed as an effective approach to mitigate the severity of pedestrian injuries in car-to-pedestrian collisions.

The bumper height of the car affects the amount and type of damages in each member. As a general result, in below-knee impact orientation, the tibia and ligaments damage increase due to the straight impact on the tibia and higher tension in ligaments and the frictional connective soft tissues such as menisci and cartilages sustain less amounts of stress due to the lack of impact concentration in them.

Conflict of Interest

None

References

1. Yong H, Jikuang Y, Koji M. Virtual Reconstruction of Long Bone Fracture in Car-to-pedestrian Collisions Using Multi-body System and Finite Element Method. *Chinese Journal of Mechanical Engineering*. 2011;**24**:1045-55. doi.org/10.3901/CJME.2011.06.1045.
2. Chawla A, Mukherjee S, Soni A, Malhotra R. Effect of active muscle forces on knee injury risks for pedestrian standing posture at low-speed impacts. *Traffic Inj Prev*. 2008;**9**:544-51. doi.org/10.1080/15389580802338228. PubMed PMID: 19058101.
3. Kiapour A, Kiapour AM, Kaul V, Quatman CE, Wordeman SC, Hewett TE, et al. Finite element model of the knee for investigation of injury mechanisms: development and validation. *J Biomech Eng*. 2014;**136**:011002. doi.org/10.1115/1.4025692. PubMed PMID: 24763546.
4. Sibole SC, Erdemir A. Chondrocyte deformations as a function of tibiofemoral joint loading predicted by a generalized high-throughput pipeline of multi-scale simulations. *PLoS One*. 2012;**7**:e37538. doi.org/10.1371/journal.pone.0037538. PubMed PMID: 22649535. PubMed PMCID: 3359292.
5. Pena E, Calvo B, Martinez MA, Doblare M. A three-dimensional finite element analysis of the combined behavior of ligaments and menisci in the healthy human knee joint. *J Biomech*. 2006;**39**:1686-701. doi.org/10.1016/j.jbiomech.2005.04.030. PubMed PMID: 15993414.
6. Ashton S. A preliminary assessment of the potential for pedestrian injury reduction through vehicle design. *SAE Technical Paper*. 1980; 0148-7191.
7. Yaksich S. Pedestrians with Mileage; a Study of Elderly Pedestrian Accidents in St. Petersburg, Florida: American Automobile Association; 1964.
8. Eberhardt AW, Keer LM, Lewis JL, Vithoontien V. An analytical model of joint contact. *J Biomech Eng*. 1990;**112**:407-13. doi.org/10.1115/1.2891204. PubMed PMID: 2273867.
9. Mak AF, Lai WM, Mow VC. Biphasic indentation of articular cartilage--I. Theoretical analysis. *J Biomech*. 1987;**20**:703-14. doi.org/10.1016/0021-9290(87)90036-4. PubMed PMID: 3654668.
10. Armstrong CG, Lai WM, Mow VC. An analysis of the unconfined compression of articular cartilage. *J Biomech Eng*. 1984;**106**:165-73. doi.org/10.1115/1.3138475. PubMed PMID: 6738022.
11. Kong C, Yang J. Logistic regression analysis of pedestrian casualty risk in passenger vehicle collisions in China. *Accid Anal Prev*. 2010;**42**:987-93. doi.org/10.1016/j.aap.2009.11.006. PubMed PMID: 20441804.
12. Oh C, Kang YS, Kim W. Assessing the safety benefits of an advanced vehicular technology for protecting pedestrians. *Accid Anal Prev*. 2008;**40**:935-42. doi.org/10.1016/j.aap.2007.10.010. PubMed PMID: 18460361.
13. Bartel DL, Davy DT. Orthopaedic biomechanics: mechanics and design in musculoskeletal systems. New Jersey: Prentice Hall; 2006.
14. Rosen E, Sander U. Pedestrian fatality risk as a function of car impact speed. *Accid Anal Prev*. 2009;**41**:536-42. doi.org/10.1016/j.aap.2009.02.002. PubMed PMID: 19393804.
15. Waiz FH, Hoefliger M, Fehlmann W. Speed limit reduction from 60 to 50 km/h and pedestrian injuries. *SAE Technical Paper*. 1983; 0148-7191.
16. Li G, Lopez O, Rubash H. Variability of a three-dimensional finite element model constructed using magnetic resonance images of a knee for joint contact stress analysis. *J Biomech Eng*. 2001;**123**:341-6. doi.org/10.1115/1.1385841. PubMed PMID: 11563759.
17. Donahue TL, Hull ML, Rashid MM, Jacobs CR. A finite element model of the human knee joint for

the study of tibio-femoral contact. *J Biomech Eng*. 2002;**124**:273-80. doi.org/10.1115/1.1470171. PubMed PMID: 12071261.

18. Guo Y, Zhang X, Chen W. Three-dimensional finite element simulation of total knee joint in gait cycle. *Acta mechanica solida sinica*. 2009;**22**:347-51. doi.org/10.1016/S0894-9166(09)60283-4.
19. Ashton S, Pedder J, Mackay G. Pedestrian injuries and the car exterior. *SAE Technical paper*. 1977; 0148-7191.
20. Adouni M, Shirazi-Adl A. Consideration of equilibrium equations at the hip joint alongside those at the knee and ankle joints has mixed effects on knee joint response during gait. *J Biomech*. 2013;**46**:619-24. doi.org/10.1016/j.jbiomech.2012.09.035. PubMed PMID: 23123074.
21. Woo SL, Abramowitch SD, Kilger R, Liang R. Biomechanics of knee ligaments: injury, healing, and repair. *J Biomech*. 2006;**39**:1-20. doi.org/10.1016/j.jbiomech.2004.10.025. PubMed PMID: 16271583.
22. Anderson RW, McLean AJ, Farmer MJ, Lee BH, Brooks CG. Vehicle travel speeds and the incidence of fatal pedestrian crashes. *Accid Anal Prev*. 1997;**29**:667-74. doi.org/10.1016/S0001-4575(97)00036-5. PubMed PMID: 9316714.
23. Bose D, Bhalla KS, Untaroiu CD, Ivarsson BJ, Crandall JR, Hurwitz S. Injury tolerance and moment response of the knee joint to combined valgus bending and shear loading. J Biomech Eng. 2008 Jun;130(3):031008. doi: 10.1115/1.2907767. PubMed PMID: 18532857.
24. Cuerden R, Richards D, Hill J, editors. Pedestrians and their survivability at different impact speeds. 18-21 June 2007. Lyon: Proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles; 2007.
25. Hannawald L, Kauer F. Equal effectiveness study on pedestrian protection. Dresden: Technische Universität Dresden; 2004.
26. Kramer M, Burow K, Heger A. Fracture mechanism of lower legs under impact load. *SAE Technical Paper*. 1973; 0148-7191.
27. Bendjaballah MZ, Shirazi-Adl A, Zukor D. Biomechanics of the human knee joint in compression: reconstruction, mesh generation and finite element analysis. *The knee*. 1995;**2**:69-79. doi.org/10.1016/0968-0160(95)00018-K.