An LS-DYNA® Model for the Investigation of the Human Knee Joint Response to Axial Tibial Loadings

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Abstract

Automotive accidents frequently involve fracture of the knee joints which can be related to either bone or soft tissue injuries. Previous studies show that the degree of anterior-posterior constraint of the femur bone along its longitudinal axis plays a crucial role in determining the knee-joint-fracture mechanism and internal tibial-femoral load distribution. Also, the anatomical tilt of the tibial plateau, tibial-femoral joint compression results in anterior displacement of the tibia, which has important implications in the prediction of knee injury and might lead to anterior cruciate ligament rupture.

This study aimed at validating an existing finite element LS-DYNA® human knee joint model for replication of these complex failure mechanisms when the joint is subjected to tibial axial compression loads. Simulations were run with the joint at 90˚ flexion to investigate the effects of anterior-posterior joint constraint on the injury patterns. Comparisons between simulations findings and test outcomes from literature were compared in terms of anterior-posterior and medial displacements of the femur, proximal rotation of the tibia and tibial-femoral load distribution. The finite element model predicted similar injury patterns and internal loads resulted with cadaveric specimen testing. The validated numerical model can be integrated in a complete replication of the human lower extremity and employed in simulations of knee-bolster impacts with the human leg during car crashes. It would be used to predict leg injury patterns with the knee joint subjected to simultaneously axial loading of the femur and the tibia bones.

Introduction

During a frontal car crash, the most common knee-thigh-hip (KTH) injury occurs when the knee strikes the dashboard or the steering column. In the latter case, the load can be very concentrated, with the knee striking a small area: this can cause fracture of the patella bone, which is generally comminuted and stellate as a shape. In the case of a dashboard, in high energy crashes, the knee may be significantly injured and fracture of the knee joint can be related to either bone or soft tissue injuries.

There are different scenarios to be considered when studying injury mechanism in the lower limbs as consequence of a frontal car crashes (Teresinski, 2005). A considerable parameter to be taken into account is the exact geometry of the dashboard and car interior. In fact, according to the different heights of the knee-bolster, the area of impact between the interior of the car and the lower limb can vary: the impact can affect mainly the condyle region of the knee, or it can be directed to the tibia bone. There can be also the case in which the impact is mainly coming from the pedal region and this could lead to a compression of the tibia between the pedal itself and the dashboard (Fig. 1).

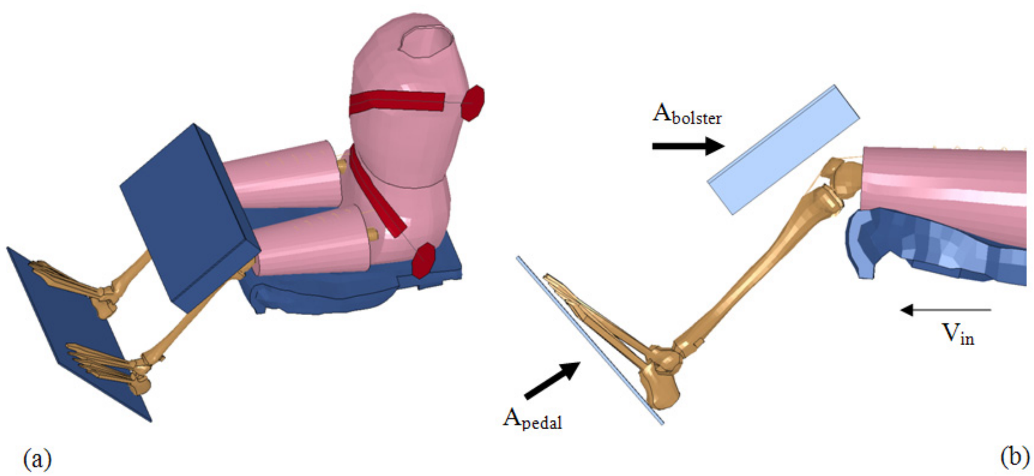

Figure 1. Prospective (a) and lateral (b) views of a simplified frontal car crash scenario with the occupant having an initial velocity V_{in} and the interior parts of the car having a deceleration A due to the impact.

Several studies have been conducted in the past to develop a more complete understanding of the distribution of lower extremity injuries after impact and to relate these fracture modes with posture (Lewis et al., 1996; Sochor, 2003; Yoganandan et al., 2001; Monma and Sugita, 2001). Tests have also been conducted also to verify the consequences of frontal impacts on soft tissue, such as ligaments. As an example, Pike concluded that the location of the impact can play a significant role for fracture of knee ligaments: if the impact load is directed to the anterosuperior tibial area rather than the knee joint, the tibia is displaced posteriorly with respect to the knee. This causes straining of the posterior cruciate ligament and eventually leads to its failure (Pike, 1990). Jayaraman et. al, (2001) showed that the amount of anterior-posterior (AP) constraint provided to the knee affects the injury mechanism and associated load required to cause injury. Jayaraman et. al. theorized that because of the sloped interface α (~15 degrees) between the tibia and the femur bones, the tibia translates anteriorly relative to the femur during compressive loading of the tibia bone, as it happens when the lower extremity experiences deceleration from the pedal during the impact event (Fig. 2).

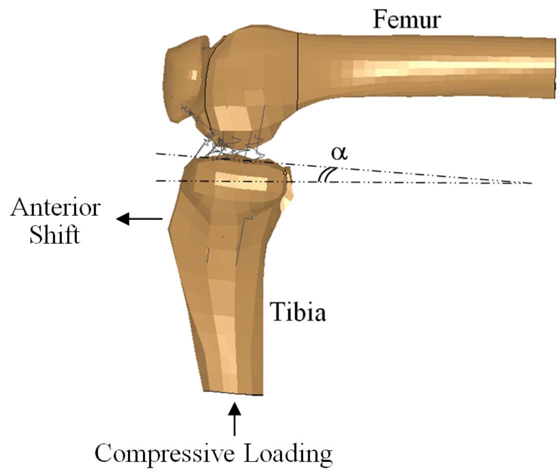

Figure 2. Anterior-Posterior (AP) motion of tibia-femur during tibia compressive loading.

To study this phenomenon, Jayaraman et. al. (2001) developed a testing device in which the tibiofemoral joint and sections of the tibia and femur were placed, and then impacted the tibia with a compressive load. The load through the tibia and femur was able to be measured, as were relevant displacements. The researchers carried out tests on six pairs of joints. For each pair of joints, the joint from one leg was tested with AP motion of the tibia relative to the femur constrained, and one joint was tested with AP motion unconstrained. The joint was loaded repeatedly to failure, with each successive load being greater than the previous one. It was found that in the unconstrained tests, failure occurred at a load 5.8 kN and the primary failure mode was rupture of the anterior cruciate ligament (ACL). A displacement between the tibia and femur of 18 mm was recorded. In the constrained tests, failure occurred at a load of 9.2 kN and the primary failure mode was fracture of the femoral condyles. This shows that the amount of load that can be carried by the knee joint without causing injury can be increased by providing adequate AP constraint. Jayaraman et. al. suggest that in an actual crash event, this constraint could be provided by the knee bolster.

Meyer et. al. (2004) presents the results of a study similar to the one conducted by Jayaraman (2001). In this study, the researchers theorized that impacting the knee with a blunt interface causes posterior translation of the tibia relative to the femur. They hypothesized that introducing an axial force through the tibia during the knee impact would counter the posterior translation by causing anterior translation, as described in the Jayaraman study. Meyer et. al. found that in joints with the axial load through the tibia, AP translation between the tibia and femur was reduced, and the load required to cause injury was increased (2004).

This study aimed at validating an existing finite element (FE) LS-DYNA human knee joint model (Silvestri et al., 2009; Silvestri et al., 2010) for replication of these complex failure mechanisms when the joint is subjected to tibial axial compression loads and the femur bone is either constrained in AP displacements and is free to displace.

Methodology

An existing FE LS-DYNA model of the knee joint from Silvestri et al. (2009) was considered (Fig. 3). The joint consisted of femur, tibia and patella bones, with the tibia flexed at 90 degrees. Femur and tibia bones were sectioned approximately 15 cm proximal and distal to the center of the knee condyles, to reproduce the same geometry of knee joint used by Jayaraman (2001). The femur was replaced by an enhanced FE representation of the bone from Silvestri et al. (2010). Ls-PrePost software was used for remeshing the tibia bone (LSTC, 2007a). The patella bone was constrained in its position by use of discrete spring elements. All bones are modeled with solid elements and no flesh tissue was included to replicate the conditions in the Jayaraman tests (2001). The menisci is modeled was plastic kinematic material properties. Both femur and tibia bones were represented with orthotropic material properties (MAT_59 in LS-DYNA) reported in Table 1, applied according longitudinal coordinate reference systems with longitudinal direction parallel to the main axis of the bone (LSTC, 2007b).

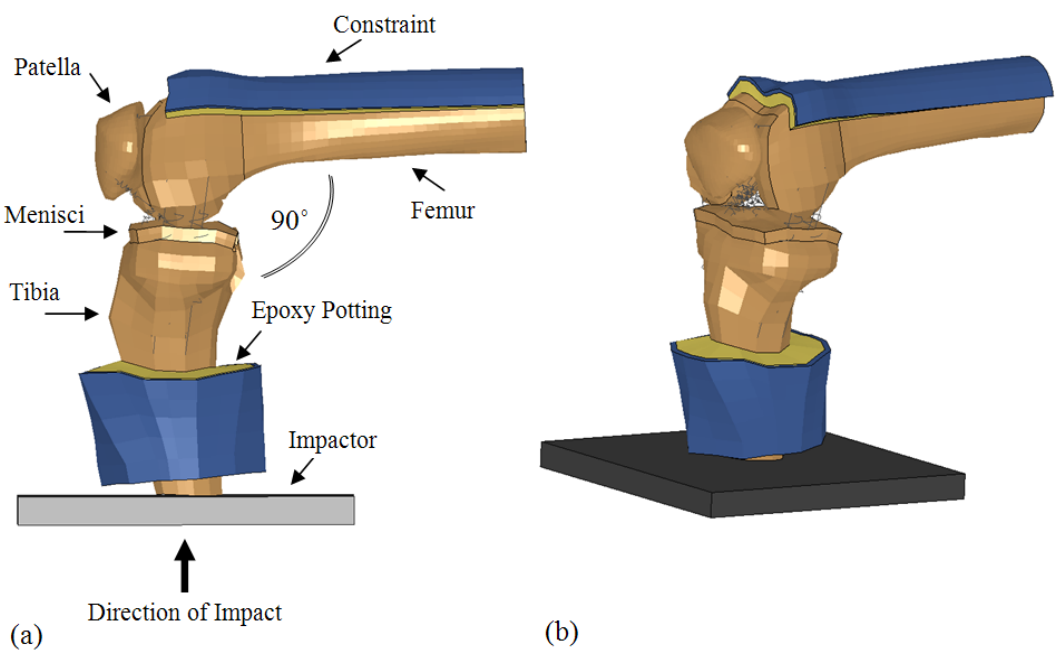

Figure 3. Lateral (a) and prospective (b) views of the FE LS-DYNA model of the knee joint used in this study.

The tibia bone was potted in an aluminum sleeve, while the femur bone was tied to epoxy bedding (Fig. 4). Elastic properties were given to the epoxy material. A rigid steel plate was modeled to compressively load the tibia, in the direction of the main axis of the bone.

In this work, two different types of tibial impact simulations were performed. With the first one (Fig. 4(a)), the femur bedding was constrained in y and z direction, allowing the femur to displace for anterior-posterior (AP) motion only (Fig. 5(a)). With the second simulation (Fig. 4(b)), boundary conditions applied to the femur bedding allowed the femur bone for both AP and medial-lateral (ML) motions (Fig. 5 (a) and (b)).

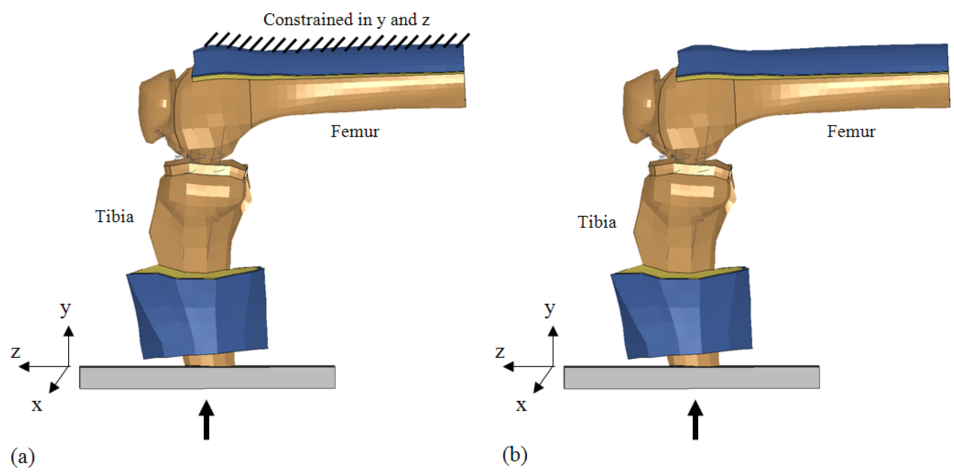

Figure 4. Constrained (a) and unconstrained (b) femoral Anterior-Posterior motion cases considered in this study.

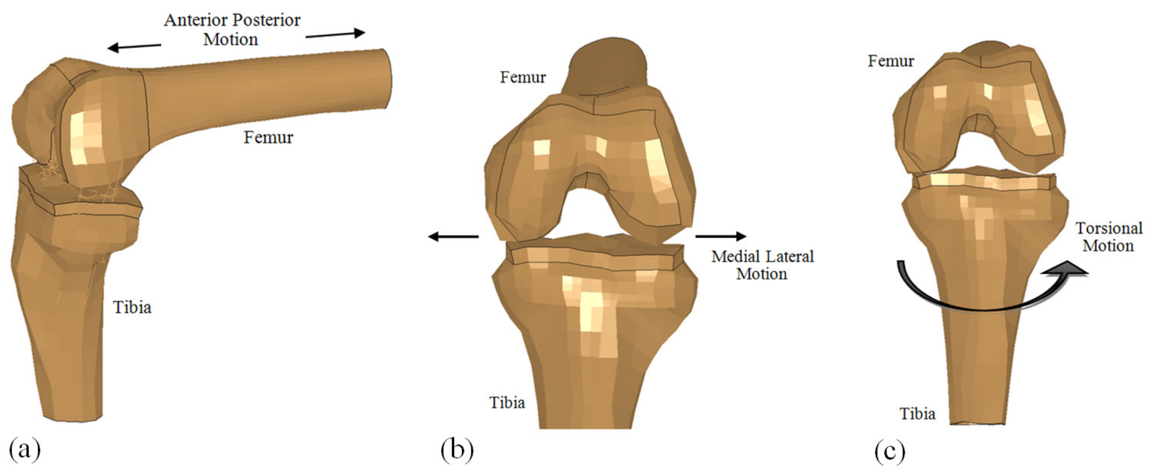

Figure 5. Femoral Anterior-Posterior (a), femoral Medial-Lateral (b) and tibial Torsional (c) motions of the knee joint.

Table 1. Material properties used for the FE Femur and Tibia bones representation (E = Young Modulus, ν = Poisson's Ratio and G = Shear Modulus).

Property	**Femur** (Silvestri et al., 2010)	**Tibia** (Limbert et al., 1998)
Density (Kg/mm^3)	1.900e-09	1.849e-09
E_a Longitudinal (Mpa)	11500	20700
E_b Transverse (Mpa)	17000	12200
E_c Normal (Mpa)	11500	12200
ν_{ba}	0.23	0.237
ν_{ca}	0.23	0.423
ν_{cb}	0.43	0.423
G_{ab} (Mpa)	3280	5200
G_{bc} (Mpa)	3280	5200
G_{ca} (Mpa)	3600	5200

To replicate the impact event, average data results obtained by the tests were applied as input in the FE simulations in terms of load applications. For the constrained case, the compressive load applied longitudinally to the tibia axis was a linear load curve reaching 9200 N at the time of 57 ms. For the unconstrained case, the load applied to the tibia axis was a linear load curve reaching 5800 N at the time of 55 ms.

Simulations were run to investigate the effects of anterior-posterior joint constraint on the injury patterns. Results obtained from simulations and test outcomes from literature were compared in terms of anterior-posterior and medial displacements of the femur, proximal rotation of the tibia and tibial-femoral fracture mechanisms.

Results and Discussion

Sub-session: Constrained AP Motion

For this simulation, four response variables were recorded and compared to the test outcomes from Jayaraman et al. (2001): maximum displacement of the tibia, maximum medial displacement of the femur, maximum internal rotation of the tibia and anterior-posterior femur load. As it is shown in Table 2, all these FE outcomes fell in the range of the recorded experimental results, with the only exclusion of the maximum displacement of the tibia bone, which from the FE simulation resulted being 25% circa lower than the lower extremity range from the tests.

Table 2. Comparison of FE and test results for the 90 degree AP constrained knee joint impact.

Output	**Simulation**	**Test** (Jayaraman et al., 2001)
Max Displacement of Tibia (mm)	~ 6	9.5 ± 1.9
Max Medial Displacement of Femur (mm)	~ 4	2.9 ± 10
Max Internal Rotation of Tibia (Degrees)	~ 6	8.8 ± 8.8
Anterior-Posterior Femur Load (kN)	~0.75	1.2 ± 0.5
Fracture Mechanism Knee Joint	None	Femoral Condyle Fracture and/or Tibial Plateau Fracture

Figure 6 shows the Von Mises stress distribution in the FE knee joint at the moment of maximum load. From these results, it does not seem that any fracture occurs in the knee joint due to the impact event. Fracture in the femoral condyle was considered to happen when the Von Mises stresses reached the value of 190 Mpa anywhere in the condyle region (Silvestri et al., 2009). Or, fracture in the tibial plateau was supposed to occur if the Von Mises stresses reached a value of 130 Mpa, as it was found being the yield value for tibia bone, from literature. These values were not reached (if excluded a very small proximal region of the tibia shaft in contact with the steel impactor), thus the authors conclude that no hard tissue was injured during this FE simulation. Also, it was no observed any injury to the soft tissue of the knee joint (ligaments).

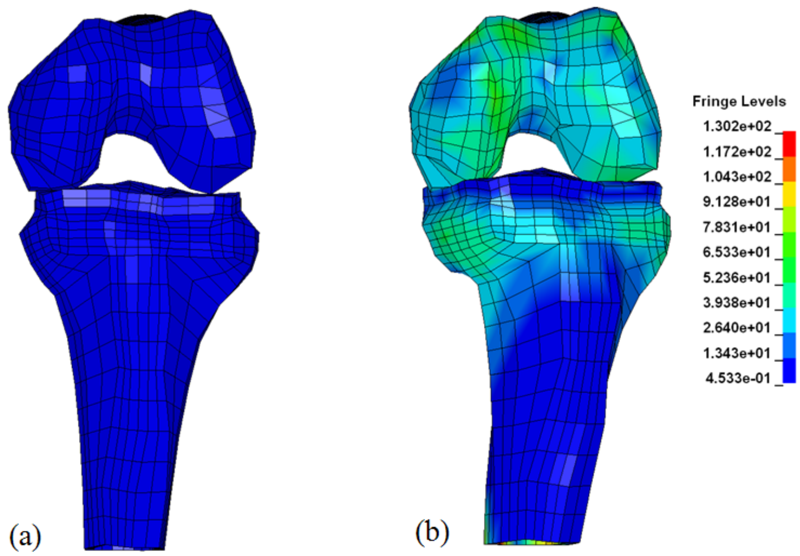

Figure 6. Initial (a) and at time of maximum load (b) configurations for the FE constrained AP motion simulation. Von Mises stress distribution (MPa) in the knee joint at the time of maximum load is reported (b).

Sub-session: Unconstrained AP Motion

For this simulation, four response variables were recorded and compared to the test outcomes from Jayaraman et al. (2001): maximum displacement of the tibia, maximum medial displacement of the femur, maximum internal rotation of the tibia and anterior-posterior femur displacement. As it is shown in Table 3, the FE outcomes nicely fit the recorded experimental results, with the only exception of the maximum medial displacement of the femur bone, which from the FE simulation resulted being significantly circa lower than the result from the tests.

Table 3. Comparison of FE and test results for the 90 degree unconstrained knee joint impact.

Output	**Simulation**	**Test** (Jayaraman et al., 2001)
Max Displacement of Tibia (mm)	~4.3	~5
Max Medial Displacement of Femur (mm)	~2.5	~8
Max Internal Rotation of Tibia (Degrees)	~13	~13
Anterior-Posterior Femur Displacement (mm)	~15	~18
Fracture Mechanism Knee Joint	ACL Rupture	ACL Rupture

Figure 7 shows the Von Mises stress distribution in the FE knee joint at the moment of maximum load. Even for this simulation, no bone fracture occurs in the knee joint due to the impact event. Fracture of the Anterior Cruciate Ligament (ACL), however, was observed considering the injury criteria for knee ligament injuries developed by Viano (1978) and Mertz (1990). Viano observed partial ligament tears occurring at 14.4 mm of relative translation between the femur and the tibia, while Mertz recommended injury threshold level of 15 mm for relative translation between the two bones in a 50th percentile male. During this FE simulation, an anterior-posterior femur displacement of slightly over 15 mm was observed. This indicates that according to the recommendation of Viano (1978) and Mertz (1990), an ACL rupture has occurred in the knee joint for the impact condition applied.

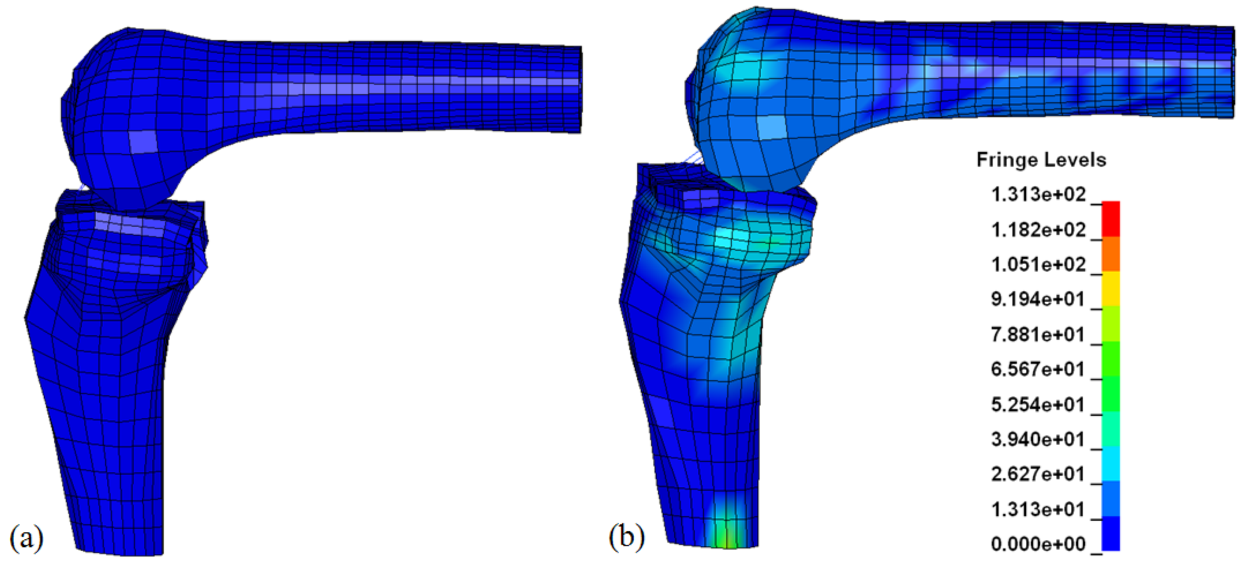

Figure 7. Initial (a) and at time of maximum load (b) configurations for the FE unconstrained AP motion simulation. Von Mises stress distribution (MPa) in the knee joint at the time of maximum load is reported (b).

A few comments should be made regarding the outcomes of the simulations. First, it must be noted that Jayaraman et al. (2001) performed repetitive impact tests on the same knee joint until fracture was occurring in the sample. With this work, only one FE impact simulation was performed to replicate each impact event (constrained and unconstrained AP motion). Consequently, in the FE simulations there were no pre-stress conditions, which very likely occurred during the experiments. It is a possibility that, during the tests, unrevealed micro-fractures occurred in the bones with the first loadings, which lead to catastrophic failure in next impacts. Applying only one impact event in the FE simulation did not permit to consider pre-stressed elements in the joint bones. Future research can be directed to the replication of similar simulations with use of the LS-DYNA *CASE card, which would allow for sequential loadings (LSTC, 2007(b)).

The resulted obtained, also, are partially in agreement with Quenneville (2010), who performed LS-DYNA impact simulations on an FE tibia model and found that non-destructive simulations occurred with a peak axial force of 10.4 kN (which is surely an higher value than the one applied in the constrained AP motion impact in this study).

Also, the anatomical tilt of the tibial plateau of the current FE model was found to be very small in comparison to the values recorded by the joints in the experiments by Jayaraman et al. (2001). This might have important implications in the prediction of knee injury and might lead to different results in terms of forces and displacements obtained in the FE simulations.

The authors recommend future research aimed at investigating geometrical and material properties of the tibia bone, and applying use of *CASE card for consideration of sequential impact loading for a more realistic representation of the tests considered.

Conclusions

This work aimed at validating an FE model of the human knee joint for tibial impact loadings. It is shown from previous studies that the degree of anterior-posterior constraint of the femur bone along its longitudinal axis plays a crucial role in determining the knee-joint-fracture mechanism and internal tibial-femoral load distribution. Two impact events were here replicated: in the first case, the FE tibia bone was impacted along its axis, with the femur bone constrained in its anterior-posterior motion. With the second case, the tibia was loaded having the femur bone free to move in any direction. The developed FE model was able to predict similar injury patterns, displacement results and internal loads resulted with cadaveric specimen testing.

Future research aims at integrating the validated FE model in a complete replication of the human lower extremity and employing it in simulations of knee-bolster impacts with the human leg during car crashes. The scope would be to analyze/predict leg fracture modes with the knee joint subjected to simultaneously axial loading of the femur and the tibia bones, such it could occurs when the human leg is trapped between the pedal and the knee bolster during a car crash event.

Acknowledgments

This project has been sponsored by the National Transportation Biomechanics Research Center of the National Highway Traffic Safety Administration (NHTSA) under contract DTNH22-04-H-01424, Analytical Crash Simulation.

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