RESPONSE OF LOWER EXTREMITY IN CAR-PEDESTRIAN IMPACT - INFLUENCE OF MUSCLE CONTRACTION

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ABSTRACT

This paper investigates the effect of muscle contraction on lower extremity injuries in car-pedestrian lateral impact. A full body pedestrian model with active muscles has been developed. FE simulations have been conducted using the full body model and front structures of a car. Two pre-impact conditions, that of a symmetrically standing pedestrian, representing a cadaver and an unaware pedestrian have been simulated. Stretch based reflexive action was included in the simulations for an unaware pedestrian. Results show that due to muscle contraction (1) peak strain in all the knee ligaments reduces (2) VonMises stresses in tibia and fibula increase to their ultimate stress limits and are predicted to fail and (3) knee joint effective stiffness increases by 67% in lateral bending.

Keywords: Muscle Contraction, Standing Posture, Car-Pedestrian Impact, Knee Injury, Finite Element Modeling

IN CAR-PEDESTRIAN CRASHES, response of human lower limb, especially the knee joint, has been studied using the passive tools such as human cadavers, mechanical surrogates and the passive lower limb FE models. The probable outcome of muscle contraction has been investigated using a lower limb FE model (single leg) with active muscles (A-LEMS) in Soni et al. (2007). More recently, Chawla et al. (2007) have performed a study using A-LEMS and reported that with muscle contraction the risk of knee ligament failure is likely to be lower than that predicted through tests on the cadavers or simulations with the passive FE models. The current study reports simulation of the loading at the knee joint in a full scale car-pedestrian impact. The A-LEMS (single leg model) has been extended to a full body model. Effects of muscle contraction on the response of lower extremity in lateral impacts, especially the knee ligaments and the bones, for a symmetrically standing pedestrian have been studied using PAM-CRASH^{TM}.

FULL BODY MODEL DEVELOPMENT

In present study, a full body pedestrian model with active muscles in both legs has been developed. For this the A-LEMS (Soni et al. 2007), which was a validated single leg model with forty two active muscles, has been adopted as the base model. In order to extend the A-LEMS (single leg model) to a full body model, an additional leg and the upper extremity was added. FE mesh of the additional leg is obtained through mirror transformation of the existing lower extremity mesh in the A-LEMS about the sagittal plane in HYPER-MESH^{TM}. Material properties of each mirrored segment and the contact definitions between them are kept similar as in the A-LEMS. As a result, a two legs FE model (legs positioned side by side) with 42 muscles in each leg has been obtained. Though the focus in the current study is to investigate the response of lower extremity, addition of the upper extremity is to include the effects of mass and mass moment of inertia of individual upper extremity segment in the simulations. The upper extremity in standard H-III dummy model available with PAM-CRASH^{TM} has been separated and integrated with the two legs FE model.

Assembled full body model thus obtained is then aligned in a symmetric standing posture of a pedestrian whose legs are in side by side stance. Relative positions of the body segments required to define the alignment of the symmetric standing posture are as reported in Woodhull et al. (1985). Series of FE simulations have been performed with the assembled model to acquire a kinestatically competent alignment between its segments. We will refer to the aligned full body pedestrian model as Pedestrian Model with Active Lower Extremity (PMALE). Fig. 1 compares the alignment (left) and

the positions of partial center of gravity (right) of the PMALE segments with the corresponding positions given in Woodhull et al. (1985).

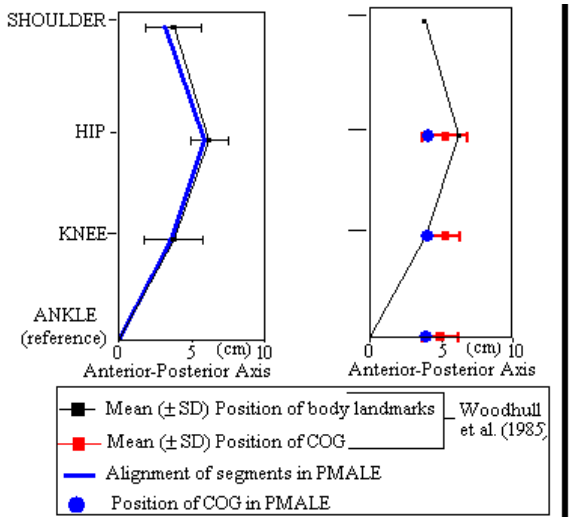

Fig. 1 – Alignment (left) and positions of partial COG (right) of the PMALE segments plotted against the positions given in Woodhull et al. (1985)

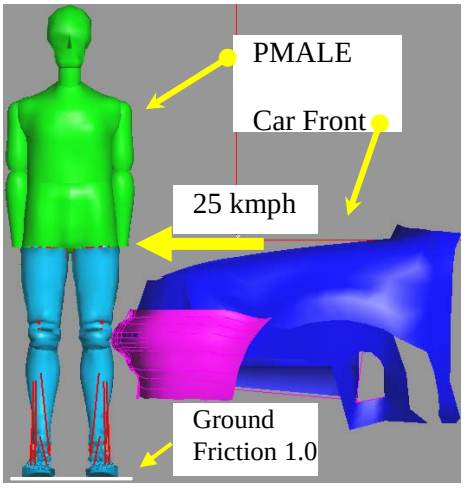

Fig. 2 – Simulation set up used in the present study showing the PMALE and FE model of the car front

SIMULATIONS FOR STANDING POSTURE

SIMULATION SETUP Fig. 2 shows the simulation setup used in the present study. Here, the real world car-pedestrian impact has been reproduced using the PMALE and front structures of a validated car FE model. PMALE is configured as standing freely with legs in a side by side stance on a rigid plate in a gravity field. Friction coefficient between the shoes and the plate has been set to 1.0. In the present study, we intend to investigate effects of active muscles in low velocity lateral impacts. A car front with a total mass of 1158 kg (mass of the front structures is. 355 kg and 803 kg is modeled as added mass to account for the remaining car structures) is propelled with a speed of 25 kmph towards the PMALE to impact its left leg laterally. In simulations, the car front is positioned at a height above the rigid plate corresponding to that when the car is rolling on its tyres. The use of the car model removes the ambiguity that earlier investigations have encountered regarding the specifications of the impactor and if the conditions simulated correspond to an actual crash.

PEDESTRIAN PRE-IMPACT CONDITIONS Two pre-impact pedestrian conditions i.e. the cadaveric and the reflex conditions have been simulated in the present study. These conditions have been modeled in the simulations as described in Chawla et al. (2007).

Strain time history of each knee ligament and VonMises stress contours in bones of the impacted leg i.e. left leg of the PMALE have been calculated in the simulations. Response of cadaveric and reflex conditions has been then compared to determine the role of muscle loading.

RESULTS

In both cadaveric and reflex conditions, the car front impacts on the knee joint of the left leg in the lateral side. As a result, both tibia and femur are forced to move in the medial direction. In the initial phase (4-10 ms), the axial compression on the left leg along with the friction at the foot resists the moving car front. By 30 ms, left leg establishes contact with the medial side of the right leg and the contact force peaks around 38 to 40 ms. During this interaction (30 to 40 ms), the right leg along with the friction at the right foot inhibits the movement of the left leg and works as a supporting structure. In the remaining portion of the simulations both the legs move together.

STRAIN IN KNEE LIGAMENTS Fig. 3 illustrates the calculated strain time history in knee ligaments of the impacted leg (i.e. left leg of the PMALE) for both cadaveric and reflex condition. It is evident that strains in knee ligaments have reduced significantly in the reflex conditions as compared to the cadaveric condition. Peak strain value in ACL (Fig. 3) has dropped by a factor of 1.3

in reflex condition as compared to the cadaveric condition. Reduction in strain is seen even more prominent in PCL (Fig. 3). In reflex condition, strain in PCL remains nearly 0% for the entire duration of simulation whereas it reaches up to 4.03% in the cadaveric condition. This can be attributed to the reduced relative displacement of tibia in inferior direction in the reflex condition. Peak MCL strain (Fig. 3) in both the conditions reaches the ligament failure limit of 15% (as per Butler et al. 1986). However, in comparison to the cadaveric condition, failure is delayed by 4-5 ms in the reflex condition. It is observed that strain in LCL remains below 1% in both the conditions.

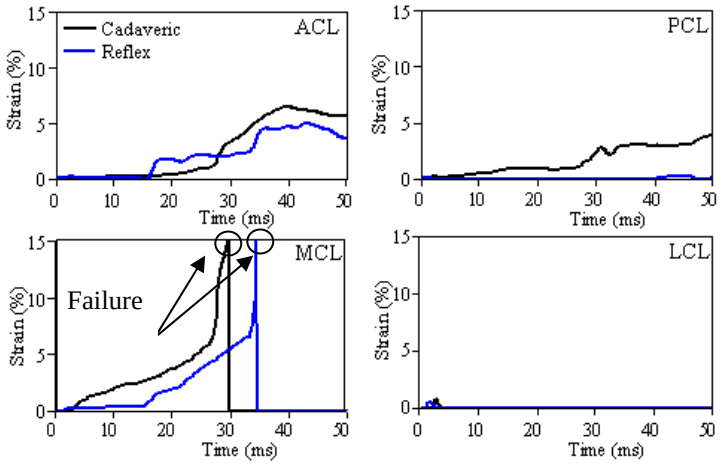

Fig. 3 - Comparison of strain in knee ligaments of the impacted leg (i.e. left leg) (ACL, PCL, MCL, and LCL) calculated in the simulations for both cadaveric and reflex conditions

VONMISES STRESSES IN BONES Fig. 4 and Fig. 5 shows the VonMises stress distribution on the bones of the impacted leg (i.e. left leg). It is apparent that stresses in bones have increased significantly in the reflex condition as compared to the cadaveric condition. Fig. 4 shows that at 40 ms in the reflex condition, stress in the lateral region of knee joint are significantly higher as compared to the cadaveric condition. This is due to the higher compressive force between the tibia plateau and the femur condyle caused by the muscle pull in the reflex condition. Later, at 48 ms in the reflex enabled situation, stresses in the medial side of mid tibia and fibula (as shown in Fig. 5) have increased to their ultimate stress limit (138.1 MPa). Whereas, in cadaveric condition stress in tibia and fibula remained below the failure limits.

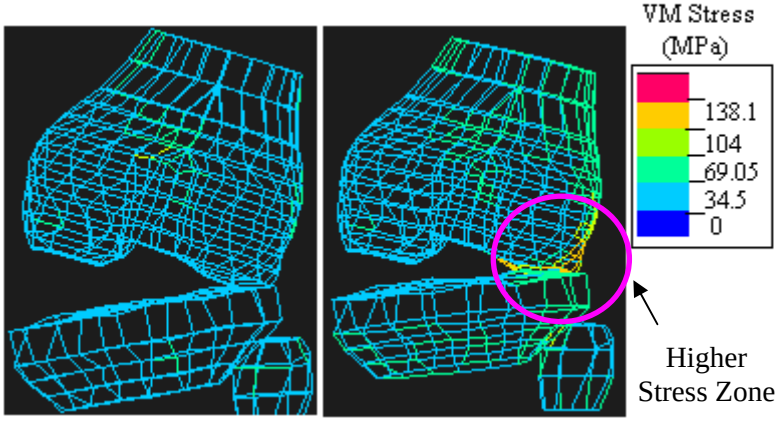

Fig. 4 – Comparison of VonMises stress distribution on bones at knee joint at 40 ms in cadaveric (left) and reflex (right) conditions

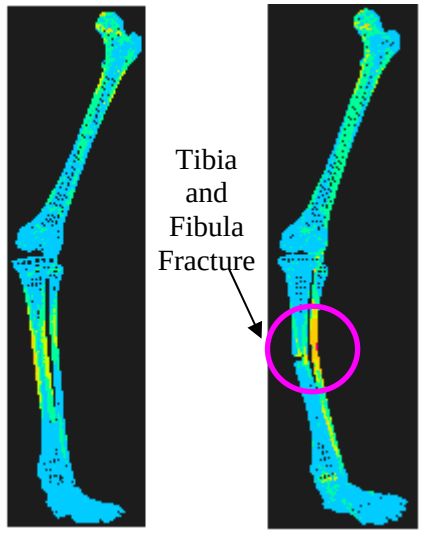

Fig. 5 – Comparison of VonMises stress distribution on femur, tibia and fibula at 48 ms in cadaveric (left) and reflex (right) conditions

KNEE LATERAL BENDING STIFFNESS Fig. 6 compares the knee lateral bending moment - angle response of the impacted leg for both cadaveric and reflex conditions. Peak bending moment is found to be significantly higher in the reflex condition (135 Nm) than in the cadaveric condition (96 Nm). Knee bending angle at the time of MCL failure has increased by 2 degrees in reflex condition (15.2 deg) as compared to the cadaveric condition (13.2 deg). Tangential bending stiffness has been calculated using the bending moment-angle response (shown in Fig. 6) of the knee joint. It is found that lateral bending stiffness of the knee joint has significantly increased by approximately 67% in reflex condition (10 Nm/deg) as compared to the cadaveric condition (6 Nm/deg).

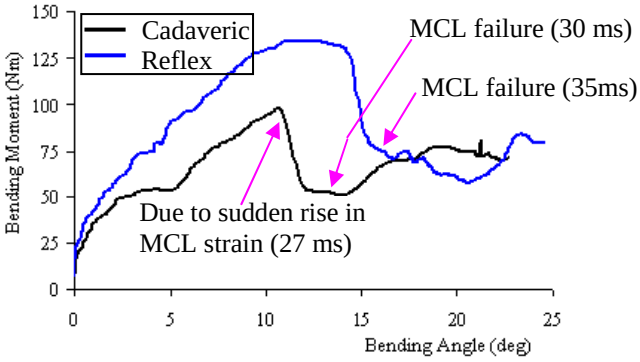

Fig. 6 – Comparison of knee bending moment - angle response calculated in simulations for both cadaveric and reflex conditions

CONCLUSIONS

In the present study, a full body pedestrian model named as PMALE has been developed. PMALE is then used to investigate the effects of active muscle forces on the response of lower extremity in a car-pedestrian lateral impact. Differences in response between a cadaver and an unaware pedestrian (with active muscles) have been studied. To assess the effect of muscle activation, strains in knee ligaments, VonMises stress in bones and knee lateral bending moment-angle response of the impacted leg (i.e. left leg of the PMALE) have been compared. Following conclusions can be drawn

1. In the present study, peak strains in all knee ligaments were found lower in the reflex condition (with active muscles). This reinforces our previous findings that the risk of ligament failure in real life crashes is likely to be lower than that predicted through cadaver tests or simulations.
2. MCL has failed, whereas, LCL remained nearly unstrained. This implies that in lateral impacts, MCL could be considered as the most vulnerable and LCL as the safest ligament.
3. Increased stresses in bones at lateral side of knee joint and failure occurred at mid tibia and fibula in the reflex condition leads to the conclusion that chances of bone fracture increases with muscle contraction.
4. Knee lateral bending stiffness has increased by 67% in the reflex condition. This suggests that due to muscle contraction knee joint becomes stiffer in lateral bending.

References

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