LATERAL BENDING MOMENT THRESHOLD OF THE KNEE JOINT – EFFECTS OF ACTIVE MUSCLES

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ABSTRACT

Three cadaver test studies with varying loading conditions form the basis for current estimation of knee lateral bending moment threshold in dynamic valgus bending. There is a significant difference in the reported values. This paper verifies some of the results using an HBM and determines the knee bending moment threshold for passive loading conditions using explicit simulations. Subsequently, effects of muscle activation on the knee bending moment threshold have been investigated.

Keywords: Knee bending moment threshold, Car-Pedestrian Impact, Finite Element Modeling, Muscle Contraction

KNEE BENDING MOMENT THRESHOLD in dynamic lateral-medial valgus bending has been estimated using cadaver tests (Kajzer et al. (1997), Kerrigan et al. (2003) and Bose et al. (2004)). Kajzer et al. conducted impact tests on the lower limb of full body cadavers laid supine on the table. Femur of the impacted leg was fully constrained at two locations (i) at the greater trochanter and (ii) at the femoral supracondylar region near the knee joint. The leg was impacted near the ankle to load the knee joint in bending. Load cells mounted at the femur supports were used to measure support reactions in the tests. The reaction forces and their corresponding distances from the knee joint were then used to calculate knee bending moment. Later, Kerrigan et al. and Bose et al. conducted displacement controlled dynamic tests and loaded the isolated cadaver knee joints in pure bending in lateral-medial direction. In both the studies, knee bending moment was directly measured using six-axis load cells mounted near the knee joint.

It was found that knee bending moment threshold computed by Kajzer et al. (388 Nm, SD 89) was significantly higher than the values reported in other two studies (134 Nm, SD 7 and range 90-110 Nm in Kerrigan et al. and Bose et al., respectively). Konosu et al. (2005) explained that higher values of knee bending moment reported by Kajzer et al. could be due to an error in calculation. It was argued that instead of subtracting the femur support moments, Kajzer et al. might have added them. However, further verification of this argument was not possible because reaction force at the trochanter support was not published. Thus, the first objective of this study is to verify Konosu et al. hypothesis and subsequently determine the knee bending moment for passive loading conditions. Simulations for Kajzer's bending test and Kerrigan's 4-point bending test conditions have been performed. Knee bending moment has been estimated by integrating the moments across a section plane passing through the knee joint. Additionally, in the simulation for Kajzer's test, reaction forces at both the femur supports have been recorded and then utilized to calculate knee bending moment as suggested by Konosu et al. Bending moment values obtained through different methods have then been compared.

Furthermore, the current estimates of knee bending moment threshold do not account for effects of muscle activation since they are based on cadaver tests. Thus, the second objective of this study is to estimate the effects of muscle activation on the knee bending moment threshold. Full scale car pedestrian impact has been simulated using PMALE (having 42 active muscles in each leg) (Soni et al. 2008) and a front structure of validated car FE model. Two sets of simulations, i.e. with deactivated muscles and with activated muscles have been performed. Bending moment at the knee section plane of the impacted leg for two levels of muscle activation has then been compared to assess the effects of active muscles.

METHODS

SIMULATIONS FOR PASSIVE LOADING CASES: Simulations have been performed for Kajzer's bending test and Kerrigan's 4-point bending test conditions using passive version of lower limb model in the PMALE (Soni et al. 2008). The lower limb model contains the major passive structures such as the cortical (modeled with shell elements) and the spongy parts (modeled with solid elements) of the bones (femur, tibia, fibula, and the patella), muscle (solid elements) and skin (membrane elements). The model also includes four major knee ligaments ACL, PCL, LCL (modeled with sold elements) and MCL (modeled with shell elements considering its smaller thickness to width ratio). The "knee capsule", which encloses the knee joint and maintains joint integrity, has also been included in this model. The lower limb model has been validated against available experimental data. These validation results have been presented in detail in Soni et al. (2007).

Loading and boundary conditions of both the tests have been reproduced in the simulations (Fig. 1(a) and Fig. 1(b)). A section plane (shown as plane PP in Fig. 1) has been defined through the knee joint to directly compute knee bending moment (referred as M_{pp}) in these simulations. Additionally, in the simulation of Kajzer's test, reaction forces (KSR and TSR) have been recorded at two femur support locations (i.e. at KS and TS, respectively). These support reaction forces and their corresponding distances from the knee level (i.e. A and B, respectively) have then been used to calculate the knee bending moment. Two formulas (referred as M_{KAJ} and M_{KON} corresponding to Kajzer's and Konosu's calculations respectively), shown in Fig. 1, have been used. Here, the femur support distances from the knee joint i.e. A (118 mm) and B (338 mm) corresponds to Kajzer's bending test #15B. This specific test has been selected because of the similarity in the height and weight characteristics of the PMHS with the model.

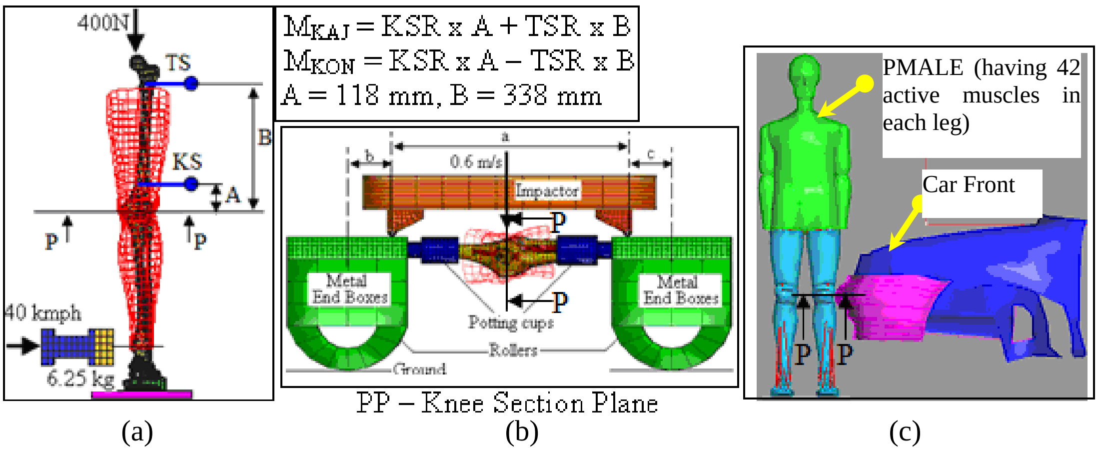

Fig. 1 Simulation setups for (a) Kajzer's test, (b) Kerrigan's test and (c) active muscle effects - full scale car pedestrian impact

EFFECTS OF MUSCLE ACTIVATION: To estimate effects of muscle activation, full scale car-pedestrian impact simulations have been performed using PMALE (having 42 active muscles in each leg) and front structures of a car FE model. Here, PMALE is configured as standing freely on a rigid surface in a gravity field (Fig. 1(c)). Car front is propelled with a speed of 25 kmph towards PMALE in lateral direction. Two sets of simulations, viz, 1) with deactivated muscles 2) with activated muscles (including reflex action) for an unaware pedestrian have been performed. Activation levels in the muscles have been assigned so as to maintain the standing posture. Detail description on modeling active muscles is presented in

Soni (2009). Knee bending moments at the section plane (i.e. plane PP in Fig. 1(c)) for different levels of muscle activation have been recorded and then compared.

RESULTS

KNEE BENDING MOMENT THRESHOLD IN PASSIVE LOADING: Fig. 2 (a) compares the support reaction forces obtained in the simulation with the test results published in Kajzer et al. (2007). It is observed (Fig. 2(a)) that both peak value of KSR and its occurrence time in the simulation (2150 N at 21.5 ms) lies within the range reported in the tests (1600 N(600 SD) and 17.20 ms (6 SD)). It is also noticeable that the TSR remains lower that the KSR during the entire simulation.

The knee bending moments (M_{KAJ}, M_{KON} and M_{PP}) calculated using three different methods in the simulation are compared with the test results in Fig. 2(b). It is observed that in the simulation, peak values of knee bending moment at the knee section plane i.e. M_{PP} (115 Nm at 10.40 ms) and the M_{KON} formula (97 Nm at 21.5 ms) are fairly close. On the other hand, peak bending moment calculated using the M_{KAJ} formula (424 Nm at 23.3 ms) are significantly higher and lies within the range (388 Nm (89 SD), 16.80 ms (6.30 SD)) reported in the tests. This would suggest that Kajzer et al. added the two support moments instead of subtracting them.

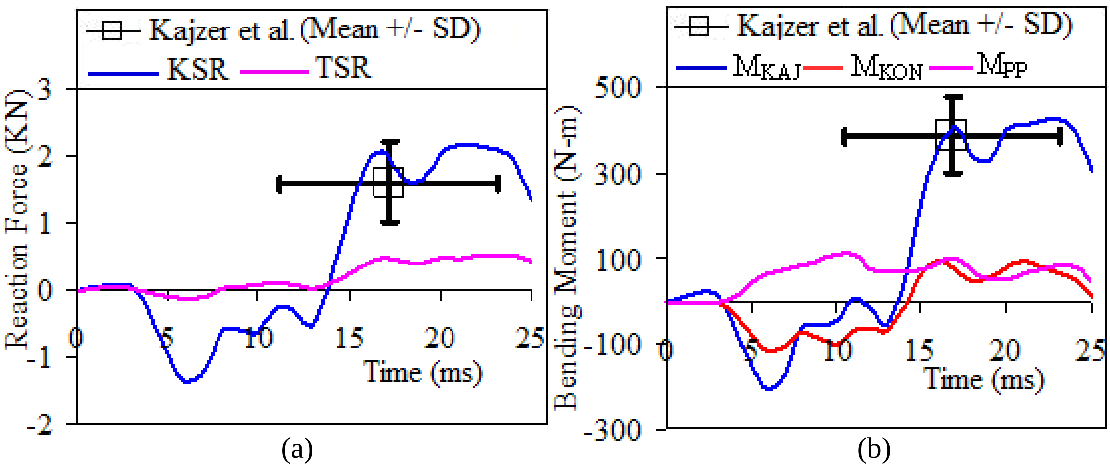

Fig. 2 Comparison between simulation results and Kajzer et al. test resutls (a) support reaction forces (note: Only KSR values were published in the paper) and (b) bending moments calculated using different methods

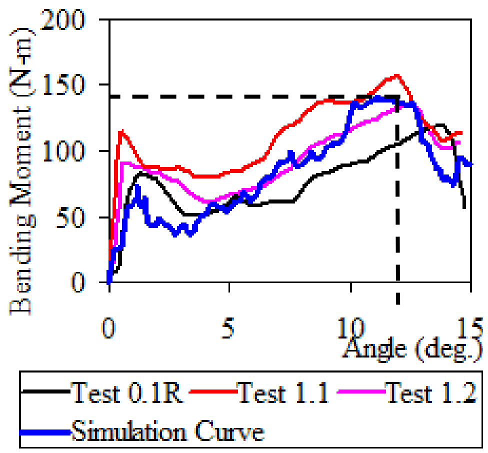

Fig. 3 Comparison of bending moment-angle response between simulation and Kerrigan et al. tests

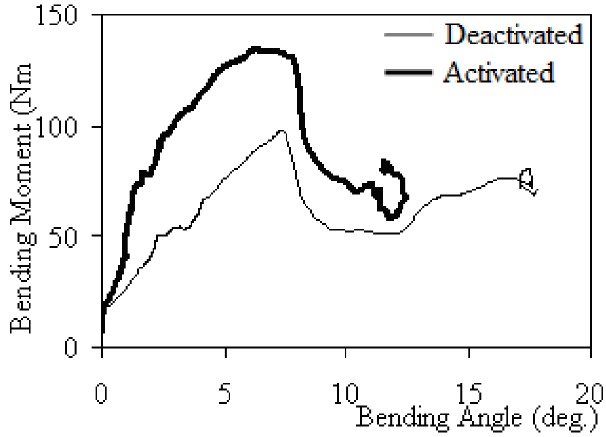

Fig. 4 Comparison of knee bending moment - angle response calculated in simulations for both activated and deactivated muscles

Furthermore, Fig. 3 compares the knee bending moment-bending angle response obtained in the simulation with that of three experiments reported in Kerrigan et al. (2003). It is seen that peak value of the knee bending moment estimated by the model (135 Nm) is in the range of peak bending moment values (115 – 155 Nm) obtained in the tests and are also close to the M_{KON} and M_{PP} values.

ACTIVE MUSCLE EFFECTS: Fig. 4 compares the knee lateral bending moment - angle response of the impacted leg for both activated and deactivated conditions. It is observed that with activated muscles; the limiting knee bending moment (135 Nm) has increased approximately 1.4 times as compared to deactivated muscles (96 Nm). Tangential bending stiffness has also been calculated using the bending moment-angle response (shown in Fig. 4) of the knee joint. It is found that lateral bending stiffness of the knee joint has significantly increased by approximately 58% with activated muscles (18.93 Nm/deg, R2 = 0.8849) as compared to the deactivated muscles (11.99 Nm/deg, R2 = 0.986).

CONCLUSIONS

Following conclusions can be drawn from the present study

1) It is observed that knee bending moment threshold calculated using the "incorrect" formula (i.e. M_{KAJ}) (424 Nm) is close to the value reported by Kajzer et al. (1997) (388 Nm). On the other hand, knee bending moment threshold calculated using the "correct" formula (i.e. M_{KON}) (97 Nm) is close to the bending moment computed through the section defined at knee joint (115 Nm) as well as to the results of cadaver test done at UVA (115-155 Nm). This confirms the observation by Konosu et al. that the bending moment calculation of Kajzer et al. was in error.

2) It can be summarized that lateral bending moment threshold of the passive knee joint lies in the range from 95 -155 Nm.

3) Muscle activation has a significant contribution to the knee bending limit. Muscle contraction can increase the bending moment threshold of the knee joint by as much as 40% and the lateral bending stiffness by 60%.

References

1. Kajzer, J., Schroeder, G., Ishikawa, H., Matsui, Y., and Bosch, U., (1997) Shearing and bending effects at the knee joint at high speed lateral loading, In proceedings of the Society of Automotive Engineers, SAE Paper 973326.

2. Kerrigan, J., Bhalla, K., Madeley, N., Funk, J., Bose, D., Crandall, J. (2003) Experiments for establishing pedestrian impact lower injury criteria. In Proceedings of the Society of Automotive Engineers World Congress, SAE Paper 2003-01-0895.

3. Konosu A., Issiki, T., and Tanahashi, M., (2005) Development of a biofidelic flexible pedestrian leg-form impactor (Flex -PLI 2004) and evaluation of its biofedility at the component level and the assembly level, Society of Automotive Engineers World Congress, SAE paper, 2005-01-1879.

4. Soni, A., Chawla, A., and Mukherjee, S., Effect of muscle contraction on knee loading for a standing pedestrian in lateral impacts, In Proceedings of 20th ESV conference 2007, Paper No. 467.

5. Soni, A., Chawla, A., Mukherjee, S. and Malhotra R., Response of lower extremity in car-pedestrian impact - influence of muscle contraction, In Proceedings of the IRCOBI conference, 2008, pp. 469-472.

6. Soni, A., A study on the effects of muscle contraction on the lower extremity response in car-pedestrian crashes, PhD Thesis, 2009, Indian Institute of Technology Delhi, India