Pedestrian Knee Kinematics and Injuries upon Vehicle Collision Considering Realistic Pre-impact Avoidance Maneuvers

Wenxuan Shen, Qing Zhou, Jisi Tang *

I. INTRODUCTION

Vehicle accident-induced pedestrian fatalities remain a significant global health issue. Field data report a diverse range of pre-impact poses for pedestrians. However, in existing laboratory tests and simulation investigations, researchers tend to manually prescribe standard subject setup, i.e., standing, or representative gaits. It is therefore necessary to find out a way to study pedestrian biomechanics under "in situ" conditions. In this study, we propose to incorporate realistic pedestrian avoidance maneuvers into car-to-pedestrian impact simulation, and explore knee kinematics and injuries therein. Results reveal that knee injuries are sensitive to pedestrian avoidance mode. An in-depth case study advocates that the response significantly varies even with a slight change in the initial pose.

II. METHODS

Virtual Reality and Active Avoidance Modes

A virtual reality (VR) based experimental platform was established [1] to study the active avoidance behavior of pedestrian against imminent car-to-pedestrian conflict. Motion Captor captures real-time posture and converts to joint parameters. The observed maneuvers from 34 experiments (involving 19 subjects) are categorized into three modes [2]: (1) forward avoidance (FA), the subject accelerates ahead to avoid collision; (2) oblique stepping (OS), the subject raises hands and steps sideward by instinct; and (3) backward avoidance (BA), the subject decelerates and steps backward.

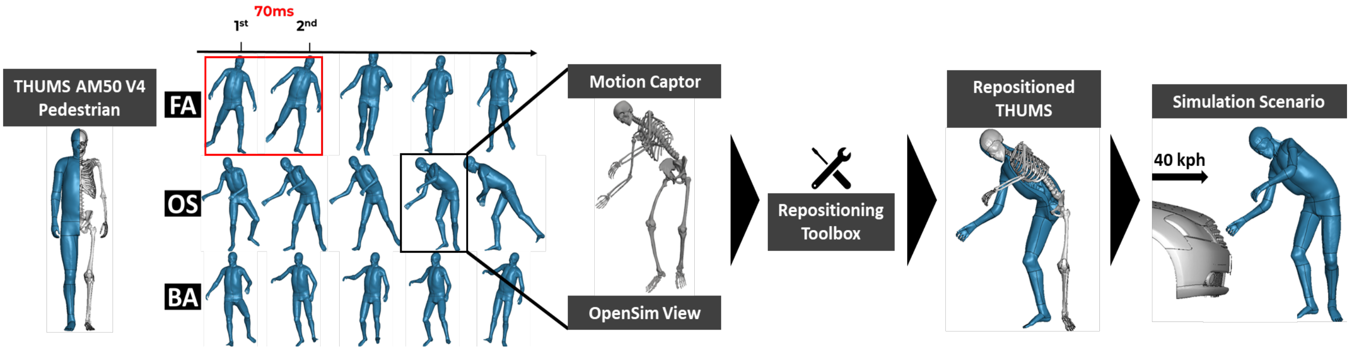

Fig. 1. The overall dataflow of the current study. The baseline THUMS model is repositioned to 15 avoidance postures captured in the VR tests, respectively, and subsequent car-to-pedestrian impacts are simulated thereafter.

HBM Repositioning Toolbox and Simulation Setup

We had developed a fast and biofidelic toolbox to reposition finite-element human body models (FE-HBMs) [3]. In this study, the THUMS AM50 V4 pedestrian model is repositioned into posture-specific models based on the captured joint parameters with comparable mesh quality as the baseline. Three VR tests are chosen to represent the typical avoidance modes, and five postures are selected in real-world chronological order in each mode ($5\times 3=15$ models, Fig. 1.). A validated sedan model provided by OEM partner is recruited. The car centre runs into the repositioned pedestrians at 40 km/h from the direction defined in the experiments. All simulations are conducted in LS-DYNA (LSTC, US). As a preliminary work, we are interested in MCL force, which evaluates the risk of MCL rupture, a typical injury pattern with high occurrence frequency in field data. On the kinematical level, the overall impact-induced arthrokinematics of knee joint is decomposed into translational and rotational degrees of freedom (DOFs) following method proposed in [4], to provide quantitative insight into the move. The MCL force responses are statistically analyzed to examine inter-mode variance. Additionally, we conducted a comprehensive investigation on two cases with a very short real-world time difference (70 ms) in FA mode (emphasized in Fig. 1), to highlight how active maneuvers drastically affect knee arthrokinematics and ligament biomechanics.

J. Tang (e-mail: drjisitang@gmail.com) is a Research Associate, W. Shen is a PhD student and Q. Zhou is a Professor of Mechanical Engineering, all in the School of Vehicle and Mobility at Tsinghua University, Beijing, China.

III. INITIAL FINDINGS

Figure 2 (a). shows MCL force corridors per mode, where mean and standard deviation (SD) of the five cases in each mode are displayed respectively. The mean peak force of BA is 27.6% higher than OS. Of note, the BA curve has a second peak, suggesting there are follow-up interactions after initial contacts. Variance in FA curve concentrates around the first peak (see the red area in Fig. 2 (a)), while the OS and BA curves globally fluctuate, with a wider high-variance band, which means the response patterns are more inconsistent in these modes.

Figure 2 (b). illustrates the MCL forces per case in FA mode, where the 1st and 2nd cases are very close in time (only 70 ms apart), but the peak MCL forces are significantly different (2493.9 versus 583.9 N). Same trend can also be found in the peak abduction angle of knee joint (23° versus near 0°). From a biomechanical point of view, the difference in initial knee configuration influences the momentum transfer during impact. A more flexed knee in the 2nd case promotes the entire upper and lower leg to rotate about the hip joint as the car front intrudes (Fig. 2 (b)), which unloads the MCL from lateral bending-induced tension. By contrast, in the 1st case the knee is more extended at the beginning of the impact, so the leg is like a slender cantilever beam. Bumper strike at the middle bends the flexible system and stretches the MCL, which significantly increases the associated injury risk.

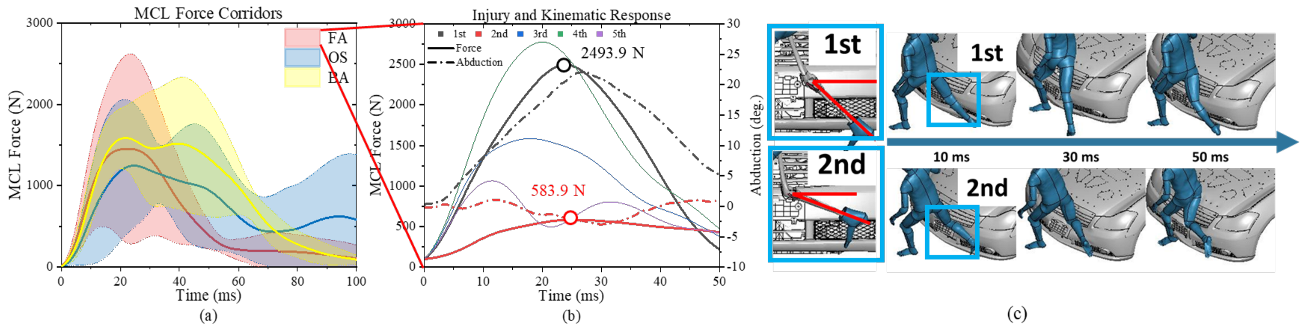

Fig. 2. (a) MCL force-time corridors; (b) MCL force and knee abduction in FA mode; (c) lower-extremity kinematics.

IV. DISCUSSION

This study is the first attempt, to the best of our knowledge, to incorporate pedestrian pre-impact avoidance maneuvers into sophisticated HBMs. Our previous study revealed that pedestrian response is sensitive to posture [5]. Avoidance mode matters partly because it globally alters pre-impact posture. However, case study demonstrates that even if initial postures are very similar on the whole-body level, the subsequent response might still be drastically apart. The mechanism behind is the dynamics might magnify the slight difference in initial posture, because of the complex knee anatomy and anisotropic structural resistance. The cases also inspire us that if the upper and lower leg can be guided to move in a "synchronized" way upon impact, it will be beneficial to reducing the injury risk of knee joint.

The overall study suggests that not only the global avoidance modes can intuitively affect the impact response, but also the subtle component-level changes in pre-impact posture. The injuries in realistic accident scenarios are therefore more complicated than expectation. Current safety design targeting only a few representative cases is far from enough in this sense. Scenario-specific protection through adaptive mechanisms based on vehicle perceptions, i.e., integrated safety, is the promising solution, such as the conceptual adaptive bumper design by our team [6]. The findings in this work provide further insight into the biomechanics of lower extremity, and inspire the design and implementation of the mechanisms in future. This study also points out that only considering the global mode of pedestrian avoidance in decision-making is not enough, the protection strategy must consider the specific posture. This brings more challenges to relevant topics, e.g., perceptions, as well.

V. ACKNOWLEDGEMENTS

This study was supported by the National Natural Science Foundation of China (52102476, 51975313).

VI. REFERENCES

[1] Li, et al., *IRCOBI Asia*, 2021.
[2] Li, et al., *Front Bioeng Biotechnol*, 2021.
[3] Tang, et al., *IRCOBI*, 2022.
[4] Grood, et al., *J. Biomech Eng*, 1983.
[5] Tang, *Traffic Inj Prev*, 2020.
[6] Shen, et al., *IRCOBI*, 2022.