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The influence of gait stance on pedestrian lower limb injury risk

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ABSTRACT

The effect of pedestrian gait on lower limb kinematics and injuries has not been analyzed. The purpose of this paper was therefore to investigate the effect of pedestrian gait on kinematics and injury risk to the lower limbs using the Total Human Model for Safety adult male pedestrian model together with FE models of vehicle front structures. The modeling results indicate that the tibia and femur cortical bone von-Mises stress and the lateral knee bending angle of an adult pedestrian are strongly dependent on the gait stance when struck by both a sedan car and an SUV at 40 km/h. The gait analysis shows that generally the leg of an adult pedestrian has lower injury risk when the knee is flexed and linear regressions show high negative correlation between knee flexion angle during impact and knee lateral bending angle and also high negative correlation between lower leg axial rotation during impact and knee lateral bending angle. Furthermore, in some gait stances a self-contact between the legs occurs, and the peak bones stresses and knee shearing displacement in the leg are then increased. Assessment of pedestrian lower limb injury should take account of these gait stance effects.

1. Introduction

The lower limbs are generally the first body region impacted by the vehicle front-end in vehicle-to-pedestrian collisions. Not surprisingly therefore, accident studies indicate that the leg is one of the most vulnerable parts of the human body when struck by vehicles (Chen et al., 2009; Chidester and Isenberg, 2001; Otte and Haasper, 2005). Typical lower limb injuries include fractures of the long bones (femur, tibia, and fibula), injuries to the knee joint (especially ligament avulsion and condyle fractures), ankle dislocation and foot bone fractures (Otte and Haasper, 2005, 2007; Yang, 2005). Accident data has indicated that 55% of struck pedestrians were walking (Chidester and Isenberg, 2001). Previous analyses of causation of pedestrian injuries using accident data (Matsui, 2005; Otte and Haasper, 2007), mathematical models (Han et al., 2012; Liu et al., 2002; Mo et al., 2014), and cadaver tests (Kerrigan et al., 2008; Masson et al., 2007) have shown that vehicle front shape and impact velocity have a strong influence on lower limb injuries. Meanwhile, some studies (Elliott et al., 2012; Peng et al., 2012; Untaroiu et al., 2009) have shown that the pedestrian gait phase influences overall pedestrian kinematics and head injury mechanisms. However, the effect of pedestrian gait stance on lower limb kinematics and injuries has surprisingly not been analyzed. Understanding this is important since real accidents occur over the full range of gait stances, and therefore pedestrian protection requires knowledge of the influence of these gait positions in real-world accidents.

The purpose of this paper is therefore to investigate the effect of pedestrian gait on kinematics and injury risk to the lower limbs. The Total Human Model for Safety (THUMS) Version 4.0 50th percentile adult male (AM50) pedestrian model was used to simulate impact responses and injury biomechanics of pedestrians in vehicle collisions. The FE models of vehicle front structures were developed based on available FE models of a sedan and an SUV used in previous studies (Chen and Yang, 2012; Han et al., 2012). A parameter study was implemented via a set of simulations of vehicle front to pedestrian model impacts to investigate the effect of pedestrian gait stance on lower limb injury risk.

2. Methods and materials

2.1. FE human body model

The Total Human Model for Safety (THUMS) Version 4.0 AM50 pedestrian model was jointly developed by Toyota Central R&D Labs, Inc. and Toyota Motor Corporation (see Fig. 1). The THUMS

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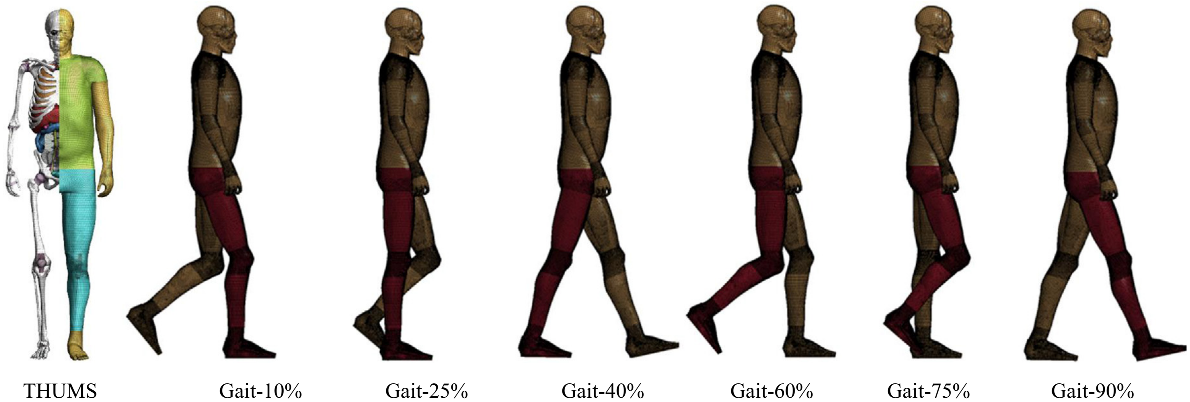

Fig. 1. THUMS Version 4 AM50 pedestrian model and gait stances (the pedestrian was struck on the right leg).

Version 4.0 AM50 pedestrian model contains nearly two million elements and enables prediction of brain and internal organ injuries as well as skeletal and ligament injuries. The leg models of THUMS include all the skeletal parts and the major soft tissues. The skeletal parts were modeled by elastic–plastic material and hyperelastic material was assumed for flesh, ligaments and tendons (Shigeta et al., 2009). The biofidelity of the models of body region components and the kinematics of the whole body model were verified in previous studies by comparing their impact responses with cadaver tests (Shigeta et al., 2009; Watanabe et al., 2011). The THUMS lower limb model showed good agreement with post mortem human subjects (PMHS) test data of static bending and dynamic impact in the validations with the maximum relative errors within ±15% (Shigeta et al., 2009).

The THUMS model was configured in six gait cycle stances based on the previous study (Untaroiu et al., 2009) and these were used to assess the influence of pedestrian gait on lower limb kinematics and injuries. To set the gait stance, firstly the joints were rotated according to the angle data from the study of Untaroiu et al. (2009). The ligaments were modified if they loosened due to joint rotation, then the skin and flesh parts around the rotated joints were remeshed (Toyota Motor Corporation, 2011). Unfortunately, there are no cadaver tests in which different initial gait positions are used, so it is not possible to explicitly validate the biofidelity of the modified.

The right leg was the struck leg for all simulations. As shown in Fig. 1, the struck leg standing (10%, 25% and 40% stances) or in swing (60%, 75% and 90% stances), leading (10%, 75% and 90% stances) or lagging (25%, 40% and 60% stances), knee flexed (10%, 60% and 75% stances) or straight (20%, 40% and 90% stances), and lower legs overlapping in the sagittal plane (25% and 75% stances) or not (10%, 40%, 60% and 90% stances) were considered in the gait stance matrix. This simulation matrix also considered different knee initial positions between the struck and non-struck leg: both are flexed (10% and 60% stances), both are extended (40% and 90% stances), one is flexed and one is extended (25% and 75% stances).

2.2. *Vehicle front FE models*

FE models of a Sedan front and an SUV front were created for simulations of vehicle–pedestrian collisions based on full scale FE models of production vehicles. The frontal structures were extracted from the original models by removing the rear part of both vehicle models from the A-pillar, as shown in Fig. 2(a) and (b). The mass and inertia of the removed parts were compensated for to retain the original mass distributions.

2.2.1. *Sedan front FE model*

The sedan front FE model was established based on a medium-size production vehicle, see Fig. 2(a). The vehicle FE model includes a total of 277,095 elements and 275,277 nodes and the mass is 1370 kg. The model consists of hexahedron solid elements, shell elements, beam elements, spring elements and damping units. The sedan FE model was validated against two types of frontal impacts results, including a 100% overlap rigid barrier crash test at 50 km/h and a 40% offset deformable barrier crash test at 56 km/h and was used previously for frontal impact simulations (Chen and Yang, 2012).

2.2.2. *SUV front FE model*

The SUV front FE model (Fig. 2(b)) was based on a Toyota RAV4 FE model from NCAC (2008), which was originally generated for

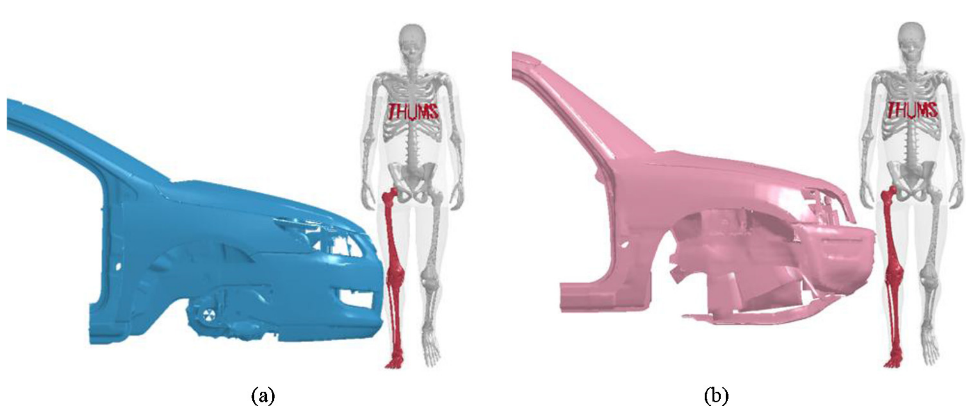

Fig. 2. Vehicle front FE models with THUMS pedestrian model: (a) sedan-to-THUMS and (b) SUV-to-THUMS.