Assessment of Ankle Injury Mechanisms in Vehicle Crashes: A Comparative Simulation-Based Study Using HBMs and an ATD

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I. INTRODUCTION

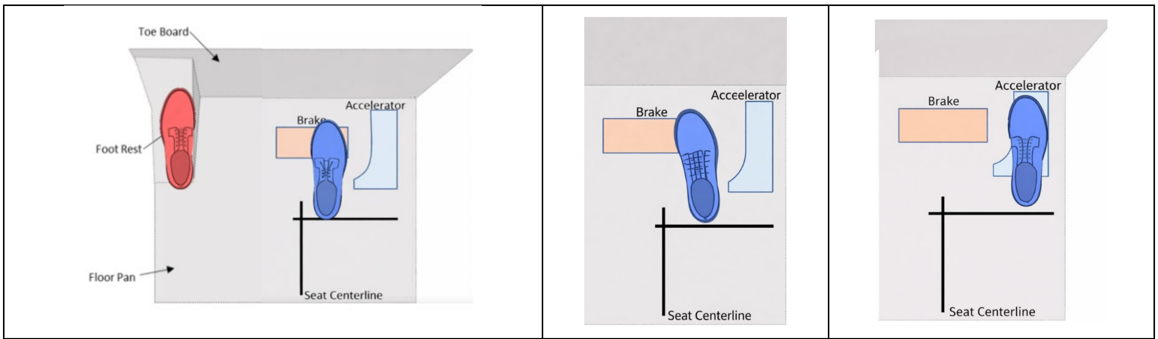
Ankle injuries represent one of the most frequently reported AIS2+ lower extremity injuries among belted occupants involved in frontal motor vehicle collisions (MVCs) [1]. Despite substantial advancements in occupant restraint systems, the underlying kinematic behaviour and load transfer mechanisms contributing to ankle injury remain insufficiently understood [2-4]. This study investigates ankle injury mechanisms using both virtual anthropomorphic test devices (ATDs) and human body models (HBMs) under controlled frontal crash conditions.

II. METHODS

An open-source finite element (FE) model of a 2014 Honda Accord was adapted into a sled test configuration, with upgraded seat-belt pretensioner and load-limiter systems, knee bolster geometry and stiffness, steering column, brake pedal assembly (with a realistic stiffness [5]), and rigid gas pedal in pre-depressed position. The 50th percentile male representations of THOR (THOR-M50), THUMS v6.1 (THUMS-M50), and GHBMC v6.0 (GHBMC-M50) were employed to assess the influence of foot posture, seat position, seat friction, crash severity (ΔV), seat-belt pretensioner force, and knee bolster position and material properties on ankle joint responses. Three different postures of the right foot were studied: on the gas pedal; pivoted between the gas and the brake; and squarely on the brake pedal (Fig. 1).

III. INITIAL FINDINGS

Foot posture, ΔV, and seat track position consistently showed the greatest influence on ankle loading among the parameters investigated. Foot-on-gas configurations produced eversion-dominated ankle loading; pivot-brake postures generated higher inversion moments with complex transitions in dorsiflexion moments; and foot-on-brake conditions resulted in dorsiflexion-dominated responses.



(a) (b) (c)

Fig. 1. The driver's foot positions. Left foot on dead pedal (Red), (a) Right foot (blue) on brake nominal, (b) Right foot partially on brake pivot, and (c) right foot on gas.

Overall, the three occupant models tended to exhibit similar overall effects of the study parameters, though the magnitude of lower extremity loading differed. As can be seen in Fig. 2, some differences were observed in the ankle loading kinematics of the three models, affected by the subtle details of the geometric interaction with the pedals and footwell. For example, all three models exhibited substantial right foot eversion with the foot on the gas. The corresponding peak eversion moments were 110 Nm for THOR-M50, 60 Nm for THUMS-M50, and 90 Nm for GHBMC-M50. In contrast, with the foot on the brake both the THOR and the THUMS moved directly forward into the brake, and the ankle was loaded primarily in dorsiflexion. The GHBMC, however, experienced sufficient off-axis loading of the ankle to cause ankle eversion. As can be seen in Fig. 2, these differences in kinematics are at least partially attributable to subtle differences in the geometric interaction between the lower extremities and the environment. With the foot pivoted over to the brake, the foot of the THOR and THUMS tended to bridge between the toepan contour near the gas pedal (engaging with the heel) and the brake pedal (engaging with the

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toes). This resulted in relatively stable loading that did not result in substantial ankle rotation. In contrast, the GHBMC did exhibit substantial ankle rotation, either from subtle differences in the foot–toepan interaction, differences in the stability of the ankle joint, or differences in the line of action of the force vector of the tibia.

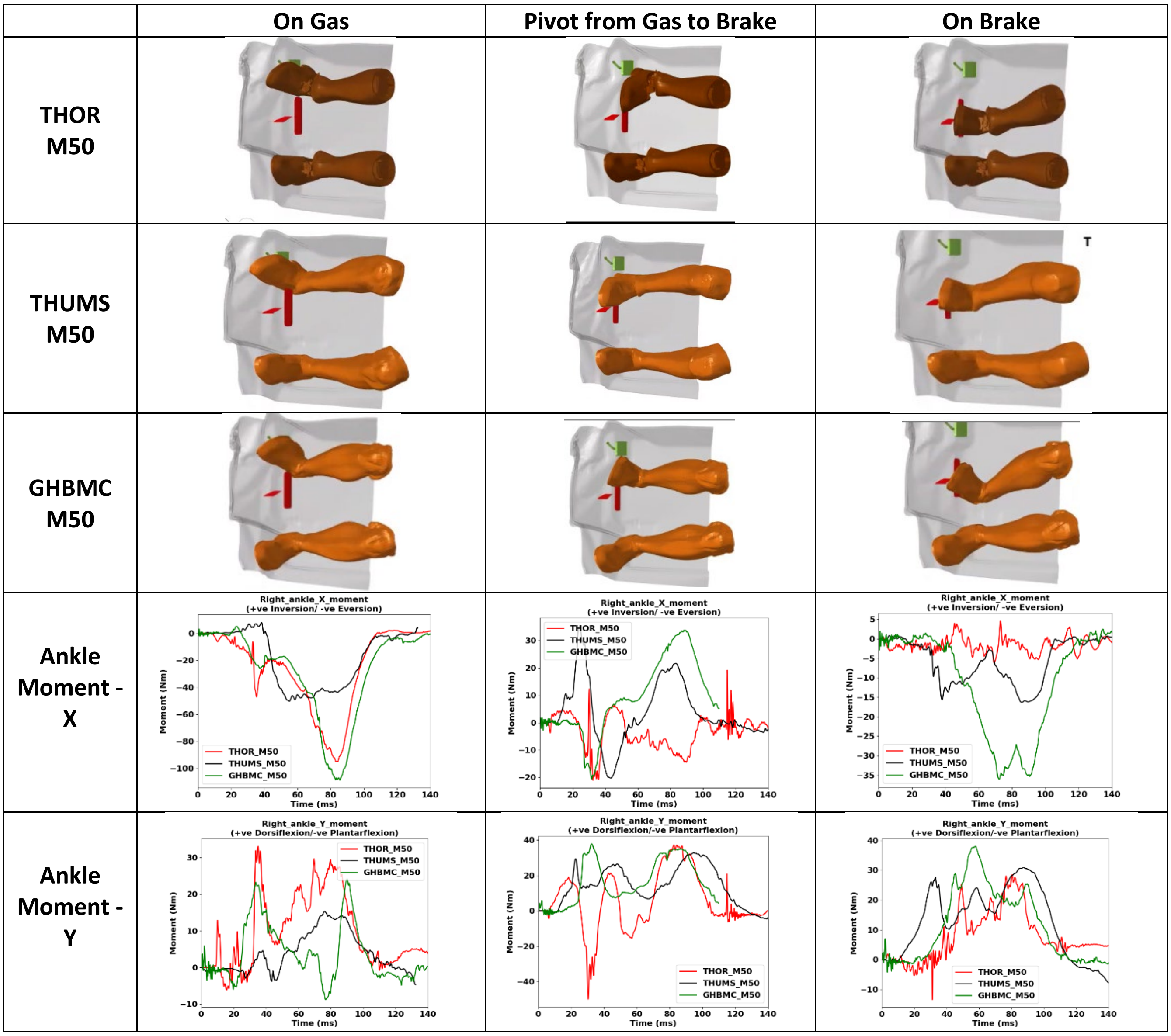

Fig. 2. Overhead still captures of the simulations, focused on the lower extremities (taken at approximately the time of peak ankle rotation) along with ankle moments – time history for various right foot posture

THOR-M50 also exhibited higher femur and tibial load magnitudes, especially in the foot-on-gas configuration, reflecting its stiffer leg construction and limited joint mobility. The peak tibial axial force was almost twice in THOR-M50 compared to the HBMs, suggesting a more abrupt and concentrated load transfer through the lower extremity.

IV. DISCUSSION

Ankle loading is chaotic, with many different potential loading mechanisms that may contribute to injury. These results demonstrate that the geometry of interaction between the feet and the pedals/toepan can have a substantial effect on inversion/eversion loading of the ankle. This can result in substantial differences in ankle loading affected by foot posture, as well as the specific geometry and ankle joint stiffness of the occupant model being used. Given the chaotic and sensitive nature of this loading, efforts to reduce the risk of ankle injury may be enhanced by addressing unstable ankle loading modes, and by reducing inertial loading from forward excursion of the pelvis and torso.

V. REFERENCES

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