SHORT COMMUNICATION: STAPP CAR CRASH CONFERENCE

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Evaluating Pedestrian Injury Risk in SUV Impacts Using a Validated Human Body and Vehicle Model

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ABSTRACT – Pedestrian fatalities have surged recently, with SUVs disproportionately causing severe injuries than sedans. This study aimed to enhance the biofidelity of the THUMS AM50 pedestrian model by validating it against recent cadaver-SUV impact tests and to explore how body orientation and gait influence injury outcomes. The THUMS model was improved to better match PMHS kinematics, particularly in the torso. Injury thresholds for bones and ligaments were updated to reflect age-related variations, improving prediction accuracy. Subsequent simulations with a validated SUV model revealed that body orientation significantly affects injury outcomes. Forward-facing and oblique orientations had the highest risk of knee ligament ruptures, while lateral impacts led to more pelvic and rib fractures. Gait stance had a lesser effect on injury severity, though lateral impacts showed larger deviations in head, sacrum, and knee trajectories. The study highlights the role of body orientation in determining injury severity and informing future pedestrian safety measures.

INTRODUCTION

Pedestrian fatalities in vehicle crashes have surged by 80% since 2009, now representing 17% of total crash deaths (IIHS, 2023). Light trucks, especially Sports Utility Vehicles (SUVs), are frequently involved in pedestrian impacts. SUVs account for 91% of front-end impacts among light trucks and are disproportionately responsible for pedestrian fatalities, striking 14.7% of pedestrians but causing 25.4% of deaths (Edwards & Leonard, 2022). Compared to passenger cars, SUVs are more likely to cause severe injuries, particularly to the thorax (Monfort & Mueller, 2020).

Finite element (FE) human body models (HBMs) are valuable tools for studying the biomechanics of pedestrian injuries under various impact conditions. To ensure accurate predictions of pedestrian responses and injuries, HBMs must be validated against post-mortem human surrogate (PMHS) tests. While the Total HUman Model for Safety (THUMS) has been validated using PMHS tests, these validations primarily involved impacts with small or mid-size sedans (Forman et al., 2015; Kerrigan et al., 2008). However, validation for SUV impacts has not yet been performed. The validation studies have shown that the THUMS model exhibits reduced lateral bending of the thoracic spine and delayed head/neck motion compared to PMHS data. Other studies reported that the THUMS model overestimated tibia fractures and knee ligament ruptures while underestimating pelvic and rib fractures (Chen et al., 2018; Wu et al., 2017). Further validation, particularly against PMHS-SUV tests, along with refinement of the model and injury thresholds is necessary to improve model's biofidelity, capability, and injury prediction accuracy.

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Several studies have explored the effects of impact velocity, location, gait, and posture on pedestrian injuries using HBMs (Chen et al., 2015; Pak et al., 2021). Most focused on sedan impact, with some using simplified SUV models. However, these SUV models were often validated against crashworthiness tests not pedestrian-vehicle test, which involve different energy levels and may lead to inaccurate HBM responses.

This study aimed to 1) enhance the biofidelity of the THUMS AM50 pedestrian model by validating it against the latest PMHS-SUV generic buck tests, and 2) investigate the effects of gait stance and orientation on kinematics and injuries across different body regions using the validated THUMS pedestrian model and a validated Nissan Rogue SUV model.

METHODS

Model Validation against PMHS SUV Buck Impact

Model Setup. The THUMS AM50 v4.02 (TOYOTA, 2021) was used to simulate a PMHS pedestrian impact with a SUV generic buck at 40 km/h (Song. et al., 2017). The FE SUV buck was modeled based on the geometry and material properties described by Song et al. (2018). The HBM impacted the buck at a mid-gait stance laterally (Figure 1).

Kinematics and Kinetics Response Output. Nodes corresponding to the target locations used in the PMHS tests were defined at the head, shoulder, T1, T4, T12, upper and lower sacrum, knee, and ankle to monitor kinematics. The kinematics and impact forces between the HBM and the bumper leading edge

(BLE), bumper, and spoiler were compared with test data. The model's biofidelity was evaluated using the CORA rating (Gehre & Stahlschmidt, 2011).

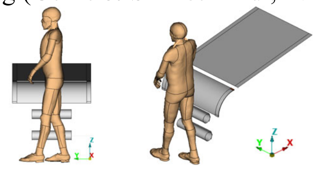

Figure 1. THUMS pre-impact position with SUV buck

Updated THUMS Model. Using the current THUMS model, a significant overprediction of upper body kinematics, particularly in the Z direction, was observed compared to PMHS tests. To address this, the material properties for the flesh in the thorax, shoulder, and pelvis were modified. The bulk modulus was adjusted from 4.59 MPa to either 60 or 100 MPa. These updated parameters are consistent with published data and those used in the GHBMC HBM (Schwartz et al., 2015).

Updated Tissue Level Injury Threshold. The original THUMS model represents a 35-year-old male, whereas the average cadaver age in the PMHS tests was 78 years old. Age-dependent tissue-level injury thresholds are necessary for accurate injury prediction. For lower leg bone fractures, the maximum principal strain (MPS) criterion was updated from 0.3 to 0.14 to represent a 78-year-old, based on the equation: Strain = 4.235 – 0.03625 × AGE (McCalden et al., 1993). The age-dependent rib fracture threshold was applied using $Risk = 1 - \exp(-(\frac{strain}{\exp(-3.72 - 0.0135 \cdot AGE)})^{3.36})$ reported by Forman et al. (2022). New MPS thresholds of 0.24 for cruciate ligament rupture (ACL, PCL) and 0.3 for collateral ligament rupture (MCL, LCL) were proposed based on the study by Arnoux et al. (2002).

Effect of Body Position during Pedestrian-Vehicle Impact on Injury Outcomes

The validated THUMS was used to simulate a pedestrian impacted by a 2020 Nissan Rogue V2 SUV. This FE vehicle model, developed and validated for pedestrian impact by the Center for Collision Safety and Analysis at George Mason University (CCSA, 2022), was assigned an initial velocity of 40 km/h. Various body orientations relative to the vehicle were examined, including lateral (0°), oblique backward (45°), backward-facing (90°), oblique forward (-45°), and forward-facing (-90°). Additionally, the pedestrian gaits at impact included Standing (S), Walking with the Left Leg Forward (W_LF), and with the Right Leg Forward (W_RF) (Figure *2*).

The trajectories of the head CG, T1, T12, sacrum, right knee, and right ankle in the XZ plane, defined by nodes at bony landmarks, were analyzed. Head responses, including resultant impact velocity and angle, Wrap Around Distance (WAD), time to head contact, and linear and angular acceleration, were also evaluated.

The age-dependent MPS thresholds were defined for a 35-year-old subject using the same functions. The MPS 0.0135 was set for the ribs and 0.03 for cortical bones in the lower extremities. The bending moment thresholds for femur and tibia fractures were set at 447 Nm and 312 Nm, respectively (Kerrigan et al., 2004). Criteria for AIS 4+ head/brain injuries were BrIC of 1 (Takhounts et al., 2013) and HIC_{15} of 1000.

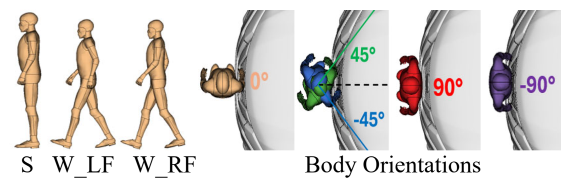

Figure 2. Gait and body orientations of THUMS and SUV

RESULTS

Generic SUV Buck Validation

The improved model achieved higher CORA scores, particularly for displacement in the lower extremity (0.75) and thorax/shoulder/head regions (0.82), compared to the current version (0.64, 0.77) and the GHBMC model (0.41, 0.66). The CORA for average force and displacement across all body regions were 0.65 and 0.78, respectively, indicating a good correlation with the test results (Figure 3).

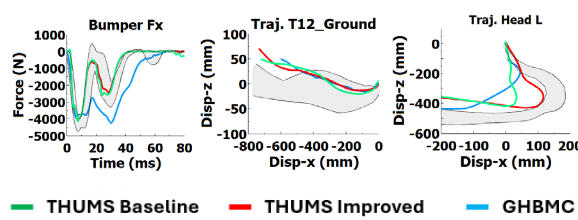

Figure 3. Bumper force, T12 and head trajectory compared

The improved THUMS model accurately predicted 80% of the injuries observed in PMHS tests (24 injuries), including MCL(R), ACL(L), tibia, femur(L), fibula, pubic rami, acetabulum, iliac wing(L), ribs, and scapulas(R), based on the updated thresholds. Additionally, the model did not predict any false injuries absent in the PMHS tests.

Pedestrian Impact Mid-Size SUV Simulation

Injury prediction. Knee ligament strains were significantly affected by body orientation ($p < 0.001$, one-way ANOVA) but not by gait. ACL and PCL ruptures occurred in the -90° and -45° impact cases but were absent in 90° and 45° impacts. MCL and LCL injuries occurred in all lateral and -45° impacts during walking gaits, but not in the standing gait.

Tibia fractures were observed in 40% cases, mostly in head-on impact followed by lateral impact. There was no significant difference in tibia strain between the left and right sides ($p = 0.58$), though more tibia injuries were predicted for the right leg. Bending moments predicted in all cases were below the threshold.

Pelvic fractures occurred at the pubic ramus, acetabulum, and iliac wing, primarily due to lateral impacts. Rib fractures occurred in 73% cases and most frequently occurred in the upper thorax region (1st to 4th ribs). Multiple rib fracture (>3 ribs) occurred exclusively from backward facing (90°) impact.

HIC15 ranged from 329 to 2521, with 66% of cases exceeding 1000 in S and W_RF gait. BrIC ranged from 1.3 to 2.2, indicating a risk of AIS 4+ brain injury.

The largest deviations in dynamic trajectories among the three gaits were due to lateral impacts, with deviations in the head, sacrum, and knee at 66, 75, and 40 mm, respectively, in the X direction (Figure 4).

From body orientation -90° to 90°, the number of knee ligament ruptures was advisedly correlated while the number of rib fractures was positively correlated with the body orientations (Figure 5).

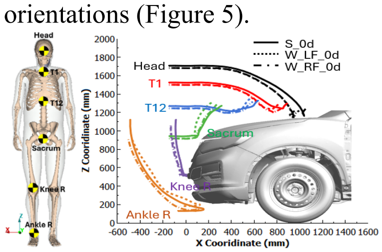

Figure 4. Trajectories from three gaits in a lateral impact

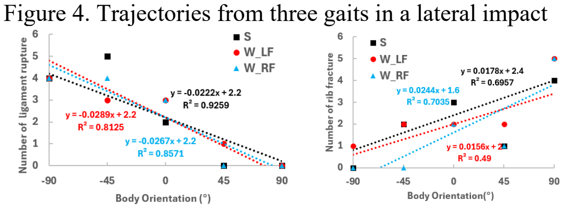

Figure 5. Relationship between the number of knee ligament rupture and rib fracture and body orientation

DISCUSSION

Age-specific criteria led to the accurate prediction of fractures in the lower extremity and rib cage which could have been missed by using the original criteria. The left-side pelvic fractures were underpredicted due to threshold was set for a 35-year-old male. Given the significantly higher incidence of pelvic fractures observed in field data (Starnes et al., 2011), incorporating age-related material properties or strain criteria would improve prediction accuracy.

The tibia moment in lateral impact ranged from 127 to 240 Nm, consistent with the results by Pak et al. (2021), who simulated various gait in lateral impacts with GHBMC M50 and a SUV-buck. Moment-based criteria failed to predict injuries, suggesting strain criteria may be more suitable. The model predicted a higher occurrence of leg bone fractures (40%) compared to the 0% by Chen et al. (2015) who used THUMS M50 and a sedan model at various gaits and orientations. This difference suggests a higher risk of leg injury from an SUV impact compared to a sedan. The high incidence of pelvic fracture highlights the need to address pelvic injuries in SUV collisions.

Limitation: the model was only validated against lateral impact at mid-gate, thus findings from other conditions should be interpreted with caution.

CONCLUSIONS

The THUMS pedestrian model's validity was enhanced by its first validation against recent PMHS pedestrian-SUV buck impact tests. Modified flesh properties in the torso region improved upper body and head kinematics. Updates to the lower extremity failure strain improved injury prediction accuracy to 93%, increasing the model's robustness and biofidelity for the simulation of pedestrian-vehicle impact.

At a 40 km/h impact speed, various injuries across different body regions were predicted for a pedestrian struck by an SUV. The severity and type of injury varied based on the pre-impact body orientation, while gait had less influence.

Forward-facing and oblique forward had the highest risk of injuries, particularly knee ligament ruptures. Pelvic injuries were most common in lateral orientation, affecting both sides. Backward facing and oblique backward showed lower risk of knee injuries and limited pelvic injuries to one side.

Rib and scapula fractures frequently occur in backward, oblique backward and lateral orientations, but less common in forward-facing orientations. AIS 4+ head/brain injuries were predicted in all body orientations, except in the left-forward walking gait where the HIC value was below 1000.

The findings underscore the role of body orientation in determining injury severity in pedestrian-SUV collisions, with implications for safety standards.

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