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Finite element comparison of human and Hybrid III responses in a frontal impact

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ABSTRACT

The improvement of finite element (FE) Human Body Models (HBMs) has made them valuable tools for investigating restraint interactions compared to anthropomorphic test devices (ATDs). The objective of this study was to evaluate the effect of various combinations of safety restraint systems on the sensitivity of thoracic injury criteria using matched ATD and Human Body Model (HBM) simulations at two crash severities. A total of seven (7) variables were investigated: 3-point belt with two (2) load limits, frontal airbag, knee bolster airbag, a buckle pretensioner, and two (2) delta-v's – 40 kph and 50 kph. Twenty four (24) simulations were conducted for the Hybrid III ATD FE model and repeated with a validated HBM for 48 total simulations. Metrics tested in these conditions included sternum deflection, chest acceleration, chest excursion, Viscous Criteria (V*C) criteria, pelvis acceleration, pelvis excursion, and femur forces. Additionally, chest band deflection and rib strain distribution were measured in the HBM for additional restraint condition discrimination. The addition of a frontal airbag had the largest effect on the occupant chest metrics with an increase in chest compression and acceleration but a decrease in excursion. While the THUMS and Hybrid III occupants demonstrated the same trend in the chest compression measurements, there were conflicting results in the V*C, acceleration, and displacement metrics. Similarly, the knee bolster airbag had the largest effect on the pelvis with a decrease in acceleration and excursion. With a knee bolster airbag the simulated occupants gave conflicting results, the THUMS had a decrease in femur force and the ATD had an increase. Preferential use of dummies or HBM's is not debated; however, this study highlights the ability of HBM metrics to capture additional chest response metrics.

1. Introduction

In the United States (US), there were an estimated 32,367 vehicle occupant fatalities in 2011, with passenger car and light truck occupants comprising 21,253 of these fatalities (NHTSA, 2011). In addition, over 60% of passenger car and light truck vehicle accidents are frontal collisions. The total number of injuries greatly exceeds the number of fatalities, as approximately 2.0 million vehicle occupants are injured in passenger car and light truck frontal collisions annually (NHTSA, 2011). Injuries sustained in motor vehicle collisions range from non-life threatening eye and upper extremity injuries to more serious head and chest injuries (Brumbelow and Zuby, 2009; Chen and Gabler, 2014; Cormier and Duma, 2009; Duma et al., 2003; Elhagediab and Rouhana, 1998; Gabler et al., 2005; Samaha and Elliott, 2003). The chest most frequently sustains an AIS 3+ injury, when compared to other body regions, for vehicle occupants that are involved in a frontal collision, wearing a seat belt, and in a vehicle with a good IIHS offset frontal crash protection rating (Brumbelow and Zuby, 2009). In addition, previous cadaveric studies have reported that rib fractures are the most common skeletal injury in frontal belted sled tests (Cromack and Zipperman, 1975; Crandall et al., 1997; Kalleris, 1998; Patrick, 1976; Ramet and Cesari, 1979).

Finite element models (FEMs) and anthropomorphic test devices (ATDs) are frequently used to predict the risk of thoracic injuries in motor vehicle collisions. These tools rely on biomechanically based thoracic criteria to assess thoracic injury risk in automotive collisions and evaluate the effectiveness of new and existing safety restraint systems. The literature regarding thoracic

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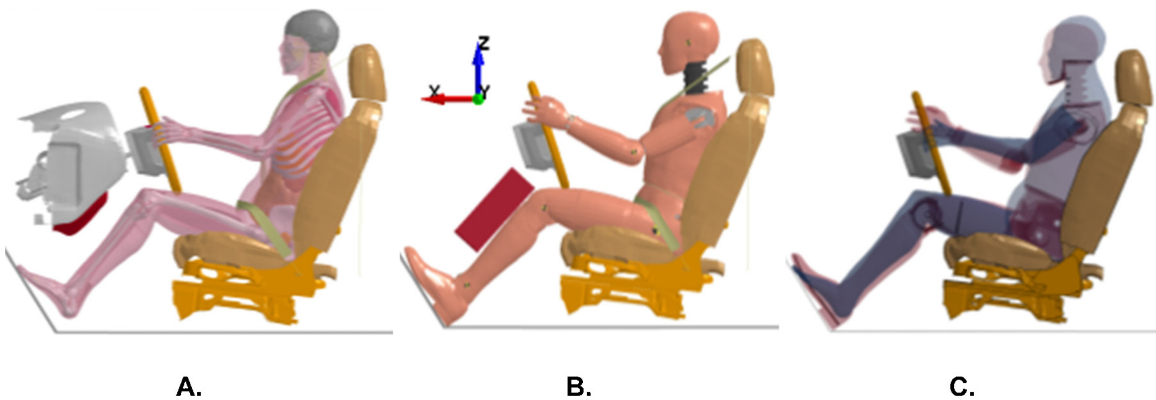

Fig. 1. The initial configuration of the reduced vehicle interior with (A) THUMS model, knee bolster, frontal airbag (prior to deployment) and belt; (B) Hybrid III ATD with knee bolster airbag, frontal airbag and belt; and (C) overlay of the THUMS (red) and Hybrid III (blue) positions. Rigid parts are shown in light gray with the other components deformable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

loading in full scale post mortem human surrogate (PMHS) testing has focused predominately on the understanding of thoracic injury mechanisms and the development of global criteria that can be used to assess thoracic injury risk using ATDs (Eppinger, 1976; Kuppa and Eppinger, 1998; Laituri et al., 2003, 2005; Mertz et al., 1991, 1997; Morgan et al., 1986, 1994; Pintar et al., 1997; Viano and Lau, 1986; Viano, 1989). These studies have yielded a number of different thoracic injury criteria including: belt tension, peak sternum deflection, maximum chest deflection, rate of chest compression, chest acceleration, as well as various combinations of these parameters. The current thoracic criteria used in the National Highway Traffic Safety Administration (NHTSA) FMVSS 208 frontal compliance test indicates that 63 mm of center sternum deflection corresponds to 50% risk of sustaining an AIS3+ thoracic injury for a 50th percentile male. In addition, thoracic acceleration cannot exceed 60 g's for more than 3 ms. However, regulatory agencies outside the US, such as the EURO New Car Assessment Program (NCAP), use other thoracic injury criteria, such as the Viscous Criterion (V*C), in addition to peak sternum deflection.

Ultimately, a given thoracic injury criterion should ideally be able to accurately discriminate loading and risk for both PMHS and ATD loading events regardless of the safety restraint conditions. However, previous research has reported that the threshold corresponding to 50% risk of an AIS3+ thoracic injury is higher for blunt loading compared to belt loading for certain thoracic injury criteria (Mertz et al., 1991; Morgan et al., 1994). In addition, it has been shown that fracture patterns can vary considerably with respect to different safety restraint conditions such as belt only, airbag only, and combined belt and airbag loading (Kalleris et al., 1998; Kent et al., 2001). Furthermore, Kent et al. (2003) performed matched PMHS and Hybrid-III ATD tests over a range of crash severities and restraint system combinations and reported that the relationship between the ATD response and AIS 3+ thoracic injury risk was highly sensitive to the experimental conditions.

The effect of safety restraint conditions on the sensitivity of thoracic injury criterion poses a unique challenge as continued advancements in automotive safety yield new safety restraint technologies such as lap belt pretensioners, shoulder belt pretensioners, load limiters, and knee bolster airbags. Incorporating these new systems in conjunction with 3-point belts and frontal airbags can alter occupant interaction with vehicle components and subsequent injury patterns. Weaver et al. (2013) demonstrated that knee bolster airbags changed injury distribution with an increase in tibia and fibula injury but a decrease in head and pelvis injuries. Since the evaluation of current thoracic injury criteria has focused primarily on belt only, airbag only, and combined belt and airbag loading, it is unclear if these criteria are sensitive to the potential benefits that new technologies, such as knee bolster airbags, can provide with respect to the mitigation of thoracic injury risk. Therefore, the purpose of the current study was to evaluate the effect of various combinations of safety restraint systems on the sensitivity of thoracic injury criteria using matched ATD and Human Body Model (HBM) simulations at two crash severities.

2. Methods

Simulations of a frontal impact were conducted with two velocities, 40 and 50 km/h, and various combinations of a seatbelt, frontal airbag, seatbelt load limiters, knee bolster airbags, and seatbelt pretension. The occupant was placed in a reduced vehicle configuration developed from the 2001 Ford Taurus model available on the National Crash Analysis Center (NCAC) website (Kan and Marzougui, 2012, Fig. 1). The intent of the reduced vehicle model was to provide a standard platform, similar to an experimental test buck, so the effect of different restraint configurations could be isolated. The seat frame, seat cushions, and knee bolster (KB) geometry and material properties from the Taurus model were used. The floor pan was modeled in a simplified condition using two flat plates. The steering wheel and frontal airbag were obtained separately from the NCAC steering wheel and airbag model. The floor pan, dash panel and steering column were converted to rigid parts and constrained to move together. The input acceleration pulse was applied to these components. There were no seatbelt or knee bolster airbag models in the NCAC repository; therefore, proprietary seatbelt and knee bolster airbag material properties were obtained from a restraint and vehicle manufacturer, respectively.

The Toyota Total Human Model for Safety (THUMS) version 4 was selected as the HBM. This model has been validated over a wide range of frontal impact scenarios (Iwamoto et al., 2003; Shigeta et al., 2009). The Humanetics H350 Adult ATD FEM version 7.1.8 was used as the ATD FEM (Humanetics, Plymouth, MI). The Hybrid III FEM was also validated over a range of impact conditions at various levels of the model, from materials to full body sled tests (Moss et al., 1997). The seat position was adjusted until the anterior aspects of the occupant's knees were 10 cm from the KB (in simulations with no knee bolster airbag present) along an axis perpendicular to the KB front surface (Fig. 1A).

The seatbelt was fitted once the occupant was in the final position. Three load limits were defined for the belt: 4 kN, 6 kN, and no load limit. The belt load limit and pull-out response was