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Kinetic and kinematic responses of post mortem human surrogates and the Hybrid III ATD in high-speed frontal sled tests

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ABSTRACT

Despite improvements in vehicle design and safety technologies, frontal automotive collisions continue to result in a substantial number of injuries and fatalities each year. Although a considerable amount of research has been performed on PMHSs and ATDs, matched dynamic whole-body frontal testing with PMHSs and the current ATD aimed at quantifying both kinetic and kinematic data in a single controlled study is lacking in the literature. Therefore, a total of 4 dynamic matched frontal sled tests were performed with three male PMHSs and a Hybrid III 50th percentile male ATD (28.6 g, $\Delta v = 40$ kph). Each subject was restrained using a 4 kN load limiting, driver-side, 3-point seatbelt. Belt force was measured for the lap belt and shoulder belt. Reaction forces were measured at the seat pan, seat back, independent foot plates, and steering column. Linear head acceleration, angular head acceleration, and pelvic acceleration were measured for all subjects. Acceleration of C7, T7, T12, both femurs, and both tibias were also measured for the PMHSs. A Vicon motion analysis system, consisting of 12 MX-T20 2 megapixel cameras, was used to quantify subject 3D motion (±1 mm) at a rate of 1 kHz. Excursions of select anatomical regions were normalized to their respective initial positions and compared by test condition and between subject types. Notable discrepancies were observed in the responses of the PMHSs and the ATD. The reaction forces and belt loading for the ATD, particularly foot plate, seat back, steering column, and lap belt forces, were not in agreement with those of the PMHSs. The forward excursions of the ATD were consistently within those of the PMHSs with the exception of the left upper extremity. This could potentially be due to the known limitations of the Hybrid III ATD shoulder and chest. The results presented herein demonstrate that there are some limitations to the current Hybrid III ATD under the loading conditions evaluated in the current study. Overall, this study presents a comprehensive data set of belt forces, reaction forces, accelerations, and bilateral displacement data that can be used to evaluate the performance of ATDs and validate computational models.

1. Introduction

Fatalities as a result of frontal automotive collisions continue to present a major issue in the United States. Over 50% of the 25,000 passenger car and light truck occupant fatalities that occur annually are due to frontal collisions (Nhtsa, 2009). In addition, motor vehicle collisions were responsible for a total economic cost of $230.6 billion in 2000 with each fatality or critically injured survivor amounting to around $1 million (Blincoe et al., 2002). Advancing vehicle design and the integration of additional safety devices have helped curb occupant fatalities; however, the toll of frontal automobile collisions necessitates further research and improvements.

Due to the complexity of human responses in automobile collisions, it is critical to perform laboratory tests and computer simulations to fully understand the mechanisms leading to mortality and morbidity in automotive collisions. Anthropomorphic test devices (ATDs) and computational models are often used to predict the responses of human occupants. These research tools require validation using actual human occupant responses within the loading environment for which they are designed. Human volunteers are ideal for validating ATDs and computational models and assessing biofidelity (Hendler et al., 1974; Begeman et al., 1980; Siegmund et al., 2001; Törnvall et al., 2007; Seacrist et al., 2010; Beeman et al., 2012). However, the study's methodology must not introduce any appreciable risk to the subjects. Experiments must be performed under non-injurious loading conditions or utilize a pre-existing high-risk population (Ewing et al., 1969; Mertz and Patrick, 1971; Hendler et al., 1974; Begeman et al., 1980; Wismans et al., 1987; Thunnissen et al., 1995; Szabo and Welcher, 1996; Van Der

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Horst et al., 1997; Siegmund et al., 2001; Duma et al., 2005; Kumar et al., 2005; Ejima et al., 2007, 2008, 2009; Rowson et al., 2008, 2009; Arbogast et al., 2009; Seacrist et al., 2010; Beeman et al., 2011, 2012; Crandall et al., 2011; Duma and Rowson, 2011; Funk et al., 2011; Rowson and Duma, 2011). Given the ethical constraints associated with human volunteer testing, post mortem human surrogates (PMHSs) are widely used to validate and assess the biofidelity of ATDs and finite element models (FEMs).

Considerable efforts have been taken to obtain PMHS data for regional and component level validation of ATDs and computational models. Studies have evaluated the face, head–neck complex, thorax, upper extremity, and lower extremity responses independently as a result of acceleration events and impact loading consistent with automotive collisions (Mertz and Patrick, 1971; Kroell et al., 1974; Neathery, 1974; Yoganandan et al., 1996; Funk et al., 2002; Duma et al., 2003; Rupp et al., 2003; Jernigan et al., 2005; Cormier and Duma, 2009; Crowley et al., 2009; Kemper et al., 2009, 2011). These studies have been critical for developing response corridors for each particular body region. However, when the whole body is subjected to an event such as an automotive collision, body regions interact to produce the overall global response. Consequently, whole-body experimental tests are essential to fully understand how each region of the body contributes to the overall response.

Several studies have examined whole body responses with the use of PMHSs and ATDs (Patrick and Trosien, 1971; Schmidt et al., 1974; Begeman et al., 1980; Kallieris et al., 1982; Wismans et al., 1987; Petitjean et al., 2002; Vezin et al., 2002; Forman et al., 2006; Shaw et al., 2009; Lopez-Valdes et al., 2010; Yoganandan et al., 2011; Beeman et al., 2012). These tests have varied in velocity, acceleration severity, restraint systems, as well as the type of data collected. Data in any particular study is largely limited by the specific focus of the study. Generally, studies concentrate on the collection and analysis of one type of data such as accelerations or kinematics, exclusively. When focused on kinematic data, trajectories are often presented for only one side of the body rather than bilaterally. Reaction force data has only been presented in a limited number of studies (Begeman et al., 1980; Marcus et al., 1987; Petitjean et al., 2002). Reaction load data in these studies typically focuses on specific subject-buck interfaces, rather than all interfaces, as a result of the studies objectives. Individual foot loads, seat back, seat pan, and steering column loads have not been presented for a single test series. Consequently, there is a need for dynamic whole-body testing which quantifies accelerations, reaction forces, and bilateral displacement data in one controlled study. In addition to limited data collection, there are few studies which present matched dynamic tests with both PMHSs and the current ATD used for regulatory tests. Therefore, the purpose of this study was to examine the response of PMHSs and the Hybrid III ATD in matched dynamic frontal sled tests to generate a comprehensive data set for ATD and computational model validation.

2. Materials and methods

A total of 4 dynamic matched frontal sled tests were conducted with three male PMHSs and a Hybrid III 50th percentile male ATD (Table 1). Approval for the use of cadavers in this test series was obtained from the Virginia Tech Institutional Review Board (IRB). All tests were performed on a 1.4MN ServoSled^{TM} system (Seattle Safety LLC, Kent, WA) with a custom test buck. The high severity acceleration pulse (28.6 g, Δv = 40 kph) was designed to match that of a standard FMVSS 208 frontal barrier test of a mid-size passenger sedan. The test buck x-direction acceleration–time history for each subject is shown in Fig. 1. For all data presented, the start of the acceleration pulse corresponded to t = 0.05 s.

Table 1
Subject demographic and anthropometric information.

Subject		Gender	Age (years)	Height (cm)	Seated height (cm)	Weight (kg)
Type	Number					
ATD	1	Male	–	177.8	80.5	77.7
	1	Male	51	174.0	79.8	74.3
PMHS	2	Male	63	176.0	80.5	68.6
	3	Male	79	184.0	80.8	86.4

The custom rigid test buck was comprised of a seat back, seat pan, steering column with a simulated steering wheel, and individual foot plates (Fig. 2). From the horizontal plane, the steering column was at an angle of 65°, the seat back was at an angle of 70°, the seat pan was at an angle of 10°, the right foot plate was at an angle of 58°, and the left foot plate was at an angle of 55°. Forces were measured at each of these rigid interfaces between the subject and test buck. A six-axis load cell was installed on both the seat pan and seat back (Robert A. Denton, Inc., 44 kN – Model 2513, Rochester Hills, MI). A six-axis load cell was installed on the right foot support (Robert A. Denton, Inc., 13.3 kN – Model 1794A, Rochester Hills, MI) and left foot support (Robert A. Denton, Inc., 13.3 kN – Model 1716A, Rochester Hills, MI). A five-axis load cell was installed on the steering column (Robert A. Denton, Inc., 22.2 kN – Model 1968, Rochester Hills, MI). Three single-axis accelerometers (Endevco 7264B, 2000 G, San Juan Capistrano, CA) were rigidly mounted to each reaction plate to facilitate inertial compensation. Three single-axis accelerometers (Endevco 7264B, 2000 G, San Juan Capistrano, CA) were rigidly mounted to the test buck under the seat pan to obtain sled acceleration.

Subjects were positioned in the center of the test seat (right to left), pelvis pushed backwards, with the feet centered on the foot plates (Fig. 3). The legs of the PMHSs were positioned so that ankle, knee and hip joints were in line. For each PMHS, the legs were held in position with masking tape attached to the steering column. The hands of the PMHSs were positioned on the simulated steering wheel and held in place with the use of masking tape. The cervical spine of each PMHS was aligned with the mid-sagittal plane and the head was held in an upright position with the use of masking tape. The masking tape on the legs, hands, and head was cut slightly prior to testing to ensure that it would tear free during the test. The lungs were pressurized to 13.8 kPa prior to each test with the use of a tracheostomy tube. The arterial vessels were pressurized to 13.8 kPa prior to each test with the use of a tube inserted in the left carotid artery.

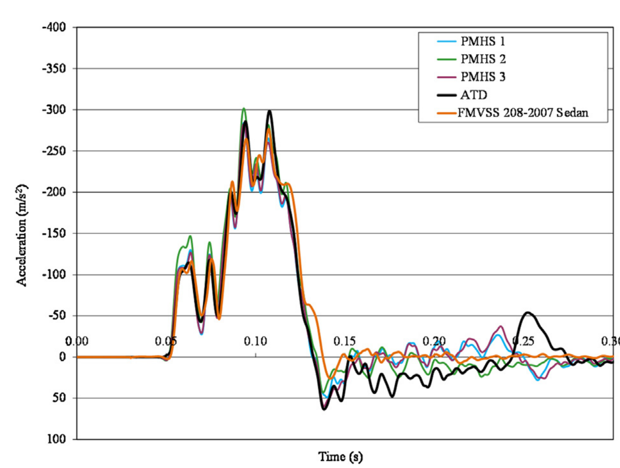

Fig. 1. Test buck x-direction acceleration-time history.