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The influence of pre-existing rib fractures on Global Human Body Models Consortium thorax response in frontal and oblique impact

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ABSTRACT

Many post-mortem human subjects (PMHS) considered for use in biomechanical impact tests have pre-existing rib fractures (PERFs), usually resulting from cardiopulmonary resuscitation. These specimens are typically excluded from impact studies with the assumption that the fractures will alter the thoracic response to loading. We previously used the Global Human Body Models Consortium 50th percentile whole-body finite element model (GHBMC M50-O) to demonstrate that up to three lateral or bilateral PERFs do not meaningfully influence the response of the GHBMC thorax to lateral loading. This current study used the GHBMC M50-O to explore the influence of PERFs on thorax response in frontal and oblique loading. Up to six PERFs were simulated on the anterior or lateral rib regions, and the model was subjected to frontal or oblique cylindrical impactor, frontal seatbelt, or frontal seatbelt + airbag loading. Changes in thorax force-compression responses due to PERFs were generally minor, with the greatest alterations seen in models with six PERFs on one side of the ribcage. The observed changes, however, were small relative to mid-size male corridors for the loading conditions simulated. PERFs altered rib strain patterns, but the changes did not translate to changes in global thoracic response. Within the limits of model fidelity, the results suggest that PMHS with up to six PERFs may be appropriate for use in frontal or oblique impact testing.

1. Introduction

Tests with post-mortem human subjects (PMHS) are frequently used to estimate the biomechanical response and injury tolerance of humans to impact. For use in biomechanical impact testing, PMHS must meet inclusion criteria that can include restrictions on height, weight, age, and the structural integrity of the skeleton. As a result, many PMHS that are initially considered for impact testing are ultimately excluded, limiting the pool of suitable specimens and increasing the time and expense required to obtain an adequate number of subjects for a test series.

The presence of pre-existing rib fractures (PERFs) on potential PMHS is an important factor affecting suitability for impact studies. The majority of PMHS that are initially considered are elderly persons, with a significant proportion of them having multiple PERFs resulting from cardiopulmonary resuscitation (CPR) (Hoke, and Chamberlain, 2004; Pinto et al., 2013). For testing involving the thorax, PMHS that meet the inclusion criteria without identifiable existing fractures are typically used for a single impact test, with the concern that any rib fractures resulting from the test will influence the thoracic response of subsequent tests. Given the scarcity of suitable PMHS, multiple tests are sometimes conducted on a single subject with the impacts designed to be substantially below the threshold for skeletal injury (e.g., Kent, 2008; Kent et al., 2004; Shaw et al., 2006; Shaw et al., 2007). Since the influence of the first test on the PMHS response is unknown, even if no injuries are identified, any results from subsequent tests are usually interpreted with caution.

Physical testing with PMHS cannot precisely determine the influence of PERFs on thorax response as no two PMHS are identical and comparisons of subjects with and without PERFs are confounded with both variability among subjects and variations in test input conditions. By using a validated whole body finite element model, the influence of PERFs on global thorax response, along with comparisons of rib-level stress and strain responses, can be predicted deterministically. We previously showed that

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up to six PERFs has a minimal influence on global thoracic response in the Global Human Body Models Consortium 50th percentile male (GHBMC M50-O) (Gayzik et al., 2011) whole body finite element (FE) model in lateral impact (Zaseck et al., 2016). The aim of the current investigation was to provide an initial look at the influence of PERFs on thorax response to frontal and oblique loading conditions. Full-thickness PERFs were therefore simulated in the GHBMC model to provide a 'worst-case' scenario to examine how various quantities and locations of PERFs change the GHBMC response.

2. Methods

2.1. GHBMC finite element model

Thorax response to frontal and oblique loading was simulated with the GHBMC M50-O FE model, which has skeletal geometry determined from medical images of a 26-year-old man (Gayzik et al., 2011). Rib material properties and failure criteria were the default GHBMC values. Specifically, ribs were modeled as an elastic-plastic material with plastic failure defined at 1.8% and 13% plastic strain for the cortical and trabecular components, respectively, which is representative of a 50-year-old occupant (Golman et al., 2014). Elements were deleted once they reached failure strain so that more realistic rib behavior and ribcage movement could be determined.

2.2. Modeling of pre-existing rib fractures

PERFs were modeled as non-displaced, transverse fractures by detaching elements through the cross-section of both the 3D solid (cancellous bone) and 2D shell (cortical bone) elements in the rib. Contacts between the detached surfaces were added using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE in LS-DYNA. Friction at the fracture interface was set at 0.3, which was chosen to approximate bone-on-bone friction of a smooth interface (Shockey et al., 1985). PERFs were simulated on either the most lateral rib region, approximately 50–60% along the length of the rib as measured from the costovertebral joint (CVJ), or on the anterior region of the rib, approximately 20 mm lateral to the costochondral joint (CCJ). These locations correspond to rib regions most commonly fractured during CPR (Pinto et al., 2013) (Fig. 1).

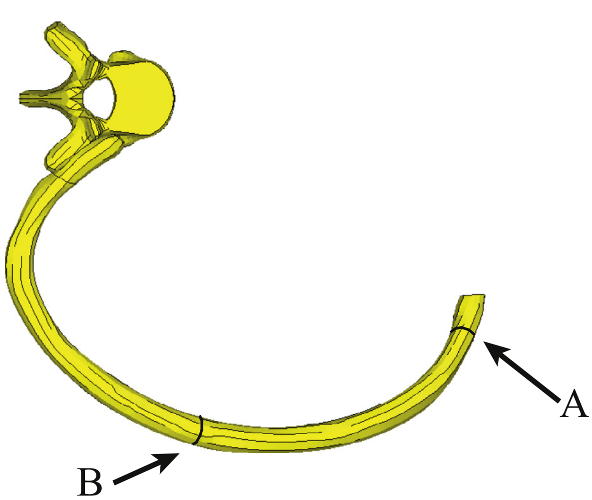

Fig. 1. Superior view of rib and vertebral body showing the location of simulated pre-existing rib fractures on the anterior rib (A), and lateral rib (B) regions.

2.3. Simulation setups and matrices

Four PMHS test series were simulated (Fig. 2). The set-ups included two cylindrical impactor tests, one frontal (Kroell et al., 1971; 1974) and one oblique (Viano, 1989), one frontal seatbelt loading scenario (Shaw et al., 2009), and one frontal seatbelt + air bag loading scenario based on NCAP Test #7147 (NHTSA, 2012). The impactor in both the Kroell frontal and Viano oblique loading scenarios struck the model with an initial speed of 6.7 m/s. In the Shaw frontal loading scenario, the model was restrained in the passenger-side configuration, and subjected to a frontal deceleration (total ΔV = 11.1 m/s). In the NCAP loading condition the model was restrained in the drivers-side configuration, and subjected to airbag loading and a frontal deceleration (ΔV = 18.5 m/s). All simulations were run using LS-DYNA MMP810 R681.0 (Livermore Software Technology Corporation, Livermore, CA) with 16 processors on the University of Michigan's Advanced Research Computing cluster.

The conditions simulated are shown in Table 1. The simulations with PERFs included fractures on one, three, or six ribs, which spans the range of fractures typically sustained during CPR (Hoke and Chamberlain, 2004; Pinto et al., 2013). Twenty-three simulations total were run for each of the Viano oblique impactor, Shaw frontal seatbelt, and the FNCAP frontal seatbelt + airbag loading conditions. The models include 12 with a single PERF, four models with three PERFs, and six models with six PERFs on either the anterior or lateral rib regions. Thirteen models total were simulated in the Kroell frontal impactor loading condition due to the symmetric nature of the loading. All simulations were compared with a baseline model with no PERFs.

Simulations are designated by their simulation set-up, fracture location, and fracture region (i.e., Shaw_Lat_R4 refers to the model in the Shaw frontal seatbelt loading condition with a PERF on the lateral region of right rib four). Baseline models with no PERFs are designated by their loading condition and BL (i.e., Kroell_BL).

2.4. Data processing

All simulation data were extracted using LS-PrePost 4.3 (Livermore Software Technology Corporation, Livermore, CA). Applied force data were extracted and filtered with SAE Class 180 filtering. For the pure frontal loading conditions, chest compression was calculated by measuring the change in distance between a sternum node and a T8 vertebral body node (nodes 4187668 and 4131458, respectively; Fig. 3). For the Viano oblique loading condition, the location and magnitude of maximum chest compression were determined using the built-in GHBMC middle chestband, which passes over the sternum at the level of rib 7, following the method of Yoganandan et al. (2008). A chestband reference line was defined between the most posterior chestband node and the chestband node passing over the sternum. The distance between the center of this line and each node along the chestband on the impacted side was determined, and the change in length of this line was calculated throughout the simulation. Maximum external half-thorax compressions were calculated as the maximum percent change of length in this line during the simulation. Principal strains at maximum chest compression were extracted from elements lying along the outer abscissa of ribs one through 10 for all models (Leport et al., 2011).

2.5. Comparison to published corridors

The force-deflection simulation data from the Kroell loading condition were compared to an experimental corridor developed by Lebarbe and Petit (2012), which was derived using normalized force data from a number of similar PMHS frontal thoracic impact