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Development of structural and material clavicle response corridors under axial compression and three point bending loading for clavicle finite element model validation

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ABSTRACT

Clavicle injuries were frequently observed in automotive side and frontal crashes. Finite element (FE) models have been developed to understand the injury mechanism, although no clavicle loading response corridors yet exist in the literature to ensure the model response biofidelity. Moreover, the typically developed structural level (e.g., force–deflection) response corridors were shown to be insufficient for verifying the injury prediction capacity of FE model, which usually is based on strain related injury criteria. Therefore, the purpose of this study is to develop both the structural (force vs deflection) and material level (strain vs force) clavicle response corridors for validating FE models for injury risk modeling. 20 Clavicles were loaded to failure under loading conditions representative of side and frontal crashes respectively, half of which in axial compression, and the other half in three point bending. Both structural and material response corridors were developed for each loading condition. FE model that can accurately predict structural response and strain level provides a more useful tool in injury risk modeling and prediction. The corridor development method in this study could also be extended to develop corridors for other components of the human body.

1. Introduction

Clavicle injuries are fairly common during automotive accidents. Over 9700 occupants restrained by a three-point-belt sustain clavicle fractures every year (Kemper et al., 2009). It was also reported that 66% of shoulder injuries during car lateral impacts are clavicle fractures (Frampton et al., 1997).

A number of FE models have been developed by researchers to study clavicle and shoulder injuries (Arregui-Dalmases et al., 2010; Duprey et al., 2008; Duprey et al., 2010; Li et al., 2013). Although the biomechanical response of the clavicle has been characterized separately under both axial compression loading (Arregui-Dalmases et al., 2008; Duprey et al., 2008) and three point bending (Kemper et al., 2009; Bolte et al., 2000), no clavicle response corridor exists in the literature for these FE model validations.

In addition, most of the corridors that exist in the literature were reported in terms of structural behavior, e.g., force–deflection (Lobdell et al., 1973; Kerrigan et al., 2003; Ivarsson et al., 2005). However, such a structural description has been shown to be often insufficient for the development of models which could accurately predict fracture timing. Untaroiu et al. (2006) showed that, for example, it is possible to tune a FE model of the femur to match an experimental force–deflection response well with both an elastic–plastic and elastic-transversely isotropic material model; however, neither of these models were capable of predicting experimental bone surface strains, and the choice of material model can substantially affect the strain response prediction. Since strain threshold are often used to predict fracture in FE models, structural response validation is insufficient for fracture prediction. Thus, an FE model that can accurately predict both structural response and surface strain in experiments provides for a much more useful tool in injury risk modeling.

In this study, the clavicles were loaded to failure in axial compression and three point bending components level tests with boundary conditions representative of clavicle loading under side impact and frontal impact crashes respectively. Both structural level (force vs deflection) and material level (force vs peak strain) response corridors were developed for each loading condition to assist in FE model development and response validation.

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2. Methods

2.1. Sled test and clavicle loading condition identification

Side and frontal sled tests in this study were conducted to justify loading conditions for clavicle component level tests: (1) loading directions (the neutral axis orientation) and (2) loading rate (strain rate). To characterize these loading conditions, a methodology based on bone surface strain measurement and linear beam theory was used (Untaroiu et al., 2007). Four uni-axial strain gages were installed around the perimeter of the clavicle cross-section at the location of maximum posterior concavity of the clavicle (Fig. 1a). This location was chosen because it is easily identifiable on the clavicle and failures most often occur in the middle third of the clavicle. A clavicle local coordinate system (CS) was defined in this study for convenience of expressing the clavicle neutral axis orientation under loading (Fig. 1a). However, it should be noted that the anterior/posterior direction in the clavicle local CS does not necessarily correspond to the human body anterior/posterior direction.

The side impact sled test was conducted at lateral impact speed of 4.3 m/s using a rigid wall mounted to a massive 1700 kg rail-mounted sled with a 50th percentile male post-mortem human surrogate (PMHS). The strain gages were installed on the clavicle of the impact side (Fig. 1b). The frontal impact sled test was conducted at an impact speed of 11.1 m/s with a 50th percentile PMHS. The strain gages were installed on the clavicle which was loaded by three point seat belt (Fig. 1c). The general methodology for the side and frontal impact tests closely followed the methods utilized in previous experiments conducted at the University of Virginia (Lessley et al., 2010; López-valdés et al., 2010).

The location of the neutral axis was determined at each time point by assuming a linear strain profile across the cross-section, assuming a linear beam approximation of the clavicle (Untaroiu et al., 2007) (Fig. 2). The CT scans of the clavicle with strain gauge attached were used to identify the strain gage locations. The neutral axis was then calculated with the strain gage time history data using the same method as in Untaroiu et al. (2007). The neutral axis orientation time history during the tests was then calculated by the slope of the neutral axis line (Fig. 2d). The neutral axis angle was then reported as average angle during the major loading periods in the tests (in this case it is from 23 ms to 30 ms) relative to the clavicle local anterior–posterior direction (local *z*-axis).

The peak strain along the strain gauge cross-section was also calculated to determine the clavicle loading strain rate. To calculate peak strain, the point that was farthest from the neutral axis line was identified and the peak longitudinal strain on the strain gauge cross section were then calculated (Untaroiu et al., 2007). The clavicle loading strain rate in the sled tests was then calculated as the slope of the linear curve fitted in the peak strain time history data between the onset of loading and the time of maximum loading. These clavicle loading conditions in the sled tests (both the loading direction and rate) were then considered and achieved during the design of the loading condition for clavicle component level tests.

2.2. Clavicle component level tests

2.2.1. Specimen preparation

Twenty clavicle specimens extracted from 12 PMHS were tested for the component level tests (Table 1). The PMHS were obtained and treated in accordance with the ethical guidelines established by the Human Usage Review Panel of the National Highway Traffic Safety Administration. The test protocol was also reviewed and approved by any internal oversight committee from the University of Virginia. All soft tissues were cleaned and removed from the clavicles. Each clavicle was then measured to determine the length of the clavicle in the medial–lateral direction (*x* direction in clavicle CS) (Table 1). Each clavicle extremity was also potted in a square-shaped aluminum mold with a polyurethane resin (R1 FastCast®, Formula 891, Goldenwest Mfg., Cedar Ridge, CA). The bone was rotated until the major plane (*x*–*z* plane) of the clavicle was aligned with one face of the potting mold (to ensure that the anterior, superior, posterior, and inferior aspects of the clavicle bone were aligned with the mold edges), and the loading is then applied within the clavicle major plane(*x*–*z* plane) (Fig. 3a).

Similarly, four uni-axial strain gages were also adhered around the perimeter of the clavicle cross-section at the location of maximum posterior concavity of the clavicle as in the sled tests. One gage was positioned on each of the four anatomical aspects of the bone—anterior, superior, posterior and inferior—with the sensitive axis of the gage aligned with the longitudinal axis of the bone (Fig. 3a). Medium-resolution (~0.25 mm in-plane resolution, 0.625 mm slice thickness) CT scans were then taken of each specimen after the preparation process was completed for calculating the location of the strain gauges and therefore determine neutral axis orientation.

2.2.2. Test fixture, instrumentation, test procedure

A total of 20 tests were performed on the 20 clavicle specimens. Half of the specimens were tested to failure in axial compression and the other half of the specimens were tested to failure in 3-point bending.

The axial test fixture provided a pinned boundary condition at the medial end of the specimen and a fixed boundary condition at the lateral end (Fig. 3b). The medial resin block was attached to a metal cup which was permitted to rotate about the clavicle superior–inferior axis only. The lateral end was clamped to the

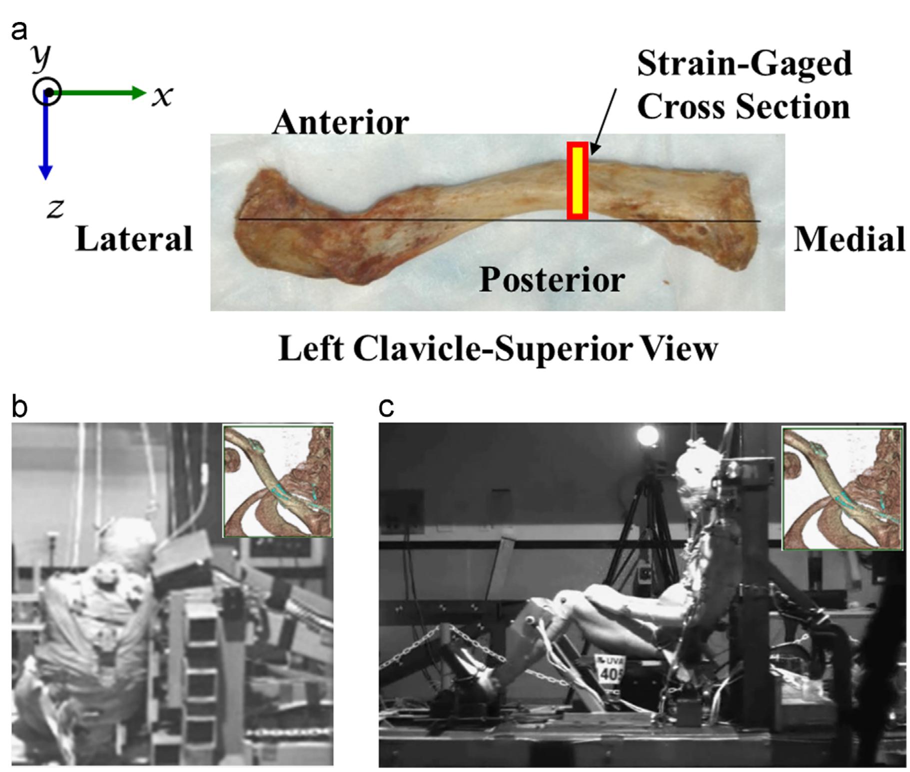

Fig. 1. (a) Clavicle local coordinate system: (1) the clavicle major plane defines the *x*-*z* plane; (2) *x*-axis pointing from clavicle lateral to medial side; (3) *z*-axis points from anterior to posterior, (4) *y*-axis points from inferior to superior. (b) Side impact sled test setup with 4 strain gage adhered in the right side (impact side) clavicle. (c) Frontal impact sled test setup with 4 strain gage adhered in the left side clavicle.