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Research Paper

Modeling the biomechanical and injury response of human liver parenchyma under tensile loading

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ABSTRACT

The rapid advancement in computational power has made human finite element (FE) models one of the most efficient tools for assessing the risk of abdominal injuries in a crash event. In this study, specimen-specific FE models were employed to quantify material and failure properties of human liver parenchyma using a FE optimization approach. Uniaxial tensile tests were performed on 34 parenchyma coupon specimens prepared from two fresh human livers. Each specimen was tested to failure at one of four loading rates ($0.01\,s^{-1}$, $0.1\,s^{-1}$, $1\,s^{-1}$, and $10\,s^{-1}$) to investigate the effects of rate dependency on the biomechanical and failure response of liver parenchyma. Each test was simulated by prescribing the end displacements of specimen-specific FE models based on the corresponding test data. The parameters of a first-order Ogden material model were identified for each specimen by a FE optimization approach while simulating the pre-tear loading region. The mean material model parameters were then determined for each loading rate from the characteristic averages of the stress–strain curves, and a stochastic optimization approach was utilized to determine the standard deviations of the material model parameters. A hyperelastic material model using a tabulated formulation for rate effects showed good predictions in terms of tensile material properties of human liver parenchyma. Furthermore, the tissue tearing was numerically simulated using a cohesive zone modeling (CZM) approach. A layer of cohesive elements was added at the failure location, and the CZM parameters were identified by fitting the post-tear force–time history recorded in each test. The results show that the proposed approach is able to capture both the biomechanical and failure response, and accurately model the overall force–deflection response of liver parenchyma over a large range of tensile loadings rates.

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1. Introduction

Liver injuries frequently caused by both frontal and side impact motor vehicle collisions are associated with high morbidity and mortality rates (Nahum and Melvin, 2002). Capsule lacerations and parenchyma damage are common liver injuries and could be severe (Harbrecht et al., 2001). Injury mechanisms of blunt liver trauma, such as deceleration injury and crush injury, have been proposed in the literature (Jin et al., 2013; Ahmed and Beckingham, 2007). However, these injury mechanisms are primarily dependent on the injury location observed in medical images, and the assumed direction and location of applied force during the crash. Recent experimental studies (Howes et al., 2012) have investigated the relative kinematics of the thoraco–abdominal organs during dynamic blunt loading using high-speed biplane x-ray technology. While the results were promising, the limited field of view and simplified loading conditions make a complete understanding of liver injuries challenging. Human finite element (FE) models have the capability to simulate each time step during an impact event and calculate the stress/strain field within human organs that could be correlated with injuries. However, the FE predictions are highly dependent on the model geometries, the connections of its parts, and especially the assigned material properties. Therefore, to numerically investigate liver injuries, biofidelic material properties are needed over a large range of loading rates.

Several studies have investigated the failure properties of liver parenchyma in uniaxial tension using animal specimens: bovine (Santago et al., 2009a, 2009b; Lu et al., 2014) porcine (Hollenstein et al., 2006; Chui et al., 2007; Brunon et al., 2010) and rabbit (Yamada, 1970). Recently, an extensive study presented the results of a total of 51 tensile tests performed on human liver parenchyma at four loading rates (Kemper et al., 2010). The stress–strain curves until failure were obtained using load cells, pre-test pictures, high-speed video, and optical markers placed on the specimens. Although these previous studies provide considerable insight into the factors that affect the tensile response of liver parenchyma, the strain time histories were usually obtained from the local marker displacements. Additionally, FE material models, with verification in terms of global properties of entire specimens, were not developed based on the experimental test data.

The primary goal of this study was to accurately model both the biomechanical and failure responses of human liver parenchyma under tensile loading. To identify the parameters of a non-linear material model assigned to liver parenchyma, specimen-specific FE models and a simulation-based optimization approach were employed as in other recent studies (Hu et al., 2009, 2011; Untaroiu, 2013; Untaroiu and Lu, 2013; Lu et al., 2013). Then, the average stress–strain curves and failure properties developed based on specimen-specific FE models were compared to local marker data. To model the tear of the liver parenchyma, the Cohesive Zone Modeling (CZM) approach, implemented recently in most FE software packages, was utilized to model the pre- and post-failure behavior of parenchyma coupon specimens. The data reported in the current study could be easily implemented in current human liver models (Behr et al., 2003; Vavalle et al., 2013). Then, a better understanding of liver injury mechanisms could be obtained using biofidelic human models in numerical impact simulations.

2. Methods

2.1. Experimental testing

Uniaxial tensile tests were performed on the parenchyma of two fresh human livers. Thirty-four “dog-bone shape” specimens were prepared using the custom blade assembly, slicing jig, and stamp described in previous studies (Kemper et al., 2010; Lu et al., 2013, 2014; Untaroiu and Lu, 2013). The length, width, and thickness of the gage length were approximately 55.5 mm, 10 mm, and 5 mm respectively. The liver parenchyma specimens did not contain any visible defects, vasculature, or the capsule. The longitudinal direction (or “loading direction”) of the specimens was parallel to the surface of the liver. Prior to testing, specimens were immersed in a bath of Dulbecco’s Modified Eagle Medium (DMEM) to maintain specimen hydration. It should be mentioned that one previous study (Santago et al., 2009b) found no statistically significant changes in failure tensile stress or strain between specimens tested at normal room temperature (24 °C) and body temperature (37 °C). Therefore, the human liver parenchyma was tested at a normal room temperature (24 °C), and within 48 h of death to minimize the effects of tissue degradation (Lu and Untaroiu, 2013).

The testing system consisted of two motor driven linear stages (Parker Daedal MX80S, Irwin, PA) mounted to a vertically oriented aluminum plate (Fig. 1). The specimen

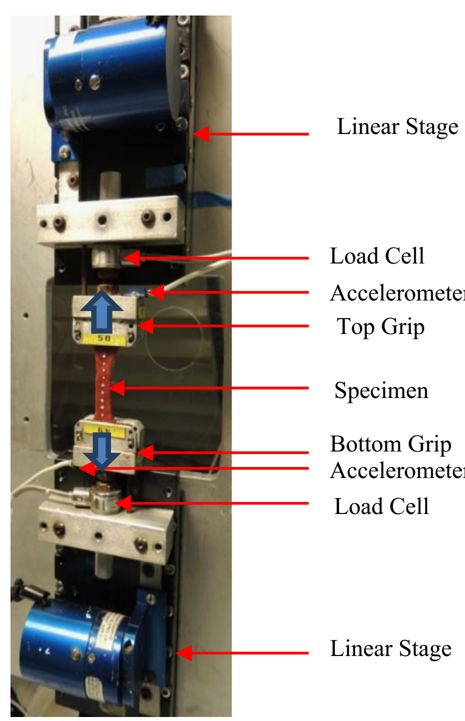

Fig. 1 – Experimental setup.

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