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Research Paper

Material characterization of liver parenchyma using specimen-specific finite element models

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ABSTRACT

The liver is one of the most frequently injured abdominal organs during motor vehicle crashes. Realistic car crash simulations require incorporating strain-rate dependent mechanical properties of soft tissue in finite element (FE) material models. This study presents a total of 30 tension tests performed on fresh bovine liver parenchyma at various loading rates in order to characterize the biomechanical and failure properties of liver parenchyma. Each specimen, cut in a standard dog-bone shape, was tested until failure at one of three loading rates ($0.01\ s^{-1}$, $0.1\ s^{-1}$, $1\ s^{-1}$) using a tensile testing setup. Load and acceleration recorded from each specimen grip were employed to calculate the time history of force at specimen ends. The shapes of all specimens were reconstructed from laser scans recorded prior to each test and then used to develop specimen-specific FE models. A first-order Ogden material model and the time histories of specimen end displacement were assigned to each specimen FE model. The failure Green-Lagrangian strain showed averages around 50% and no significant dependence on loading rates, but the failure 2nd Piola—Kirchhoff stress showed rate-dependence with average values ranging from 33 kPa to 94 kPa. The FE models with material model parameters identified using a simulation-based optimization replicated well the time history of load recorded during the test. The FE simulations with model parameters identified using an analytical approach or based on the displacement of optical markers showed a significantly stiffer response and lower failure stress/strain than the FE specimen-specific models. This study provides novel biomechanical and failure data which can be easily implemented in FE models and used to assess injury risk in automobile collisions.

1. Introduction

The improvements in automotive occupant safety have reduced the frontal fatality rate per mile of travel in USA about 2.6 times from 1979 to 2007 (Bean et al., 2009). The novel designs of airbags and seat belt have largely contributed to the safety improvement. However, recent statistical studies of fatal injuries (Lamielle et al., 2006) showed increases in the ratios of abdominal injuries to head and thorax injuries of 9.6 and 5 times, respectively in newer cars relative to older cars. Therefore, the protection of abdomen in frontal crashes has recently attracted increased attention in the automotive safety community.

The liver is one of the most frequently injured abdominal organs in frontal vehicle crashes (Elhagediab and Rouhana, 1998).

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The right lower rib cage covers the greater portion of the liver in the anterior region, but its downward displacement during the inhalation reduces its protection (Melvin et al., 1973). The liver is essential to life by regulating most chemical levels in the blood, so its injuries due to blunt trauma have higher morbidity and mortality rates than other abdominal organs (Nahum and Melvin, 2001). Capsule laceration and parenchyma damage are common liver injuries and can be severe (Oniscu et al., 2006). Therefore, accurate material and failure properties of the liver may help in designing advanced restraint systems based on computer simulations (Adam and Untaroiu, 2011).

Liver parenchyma data have been reported from unconfined compression tests performed on animal tissues (Umale et al., 2013; Tamura et al., 2002; Pervin et al., 2011; Roan and Vemaganti, 2003; Rosen et al., 2008) or human tissues (Rosen et al., 2008; Kemper et al., 2011). To characterize the tissue viscoelasticity under a large frequency range, oscillatory shear tests (Liu and Bilston, 2000; Valtorta and Mazza, 2005; Klatt et al., 2010; Nicolle et al., 2010), impact hammer tests (Ocal et al., 2010; Umut Ozcan et al., 2011), and indentation tests (Ottensmeyer, 2001, Samur et al., 2007, Lu and Untaroiu, 2013) have been performed on liver tissues as well. Numerous tensile studies have been performed at low level strains on specimens of liver parenchyma for surgical robot control systems and surgeon training systems based on the virtual reality techniques (Chui et al., 2007, Sakuma et al., 2003, Yeh et al., 2002, Gao et al., 2010, Gao and Desai, 2010). Several studies have also investigated the failure properties of liver parenchyma in uniaxial tension (Yamada, 1970, Uehara, 1995, Santago et al., 2009a, 2009b). An average stress—strain curve and failure data obtained on rabbit livers have been reported (Yamada, 1970), but no loading rate information was provided. The failure data recorded on porcine specimens at four different strain rates have also been reported (Uehara, 1995). The effects of environmental temperature during testing (Santago et al., 2009a) and freezing storage (Santago et al., 2009b) on liver parenchyma were investigated using bovine specimens tested in tension until failure. They found no statistically significant changes in failure stress or strain for specimens tested at normal room temperature (24 °C) and body temperature (37 °C) (Santago et al., 2009a). However, the freezing storage of tissues was shown to significantly reduce the failure strain in low strain rate tensile testing (Santago et al., 2009b). Recently, an extensive study presented the results of a total of 51 tension tests performed on human liver parenchyma at four loading rates (Kemper et al., 2010). The stress—strain curves until failure were obtained using high-speed video and optical markers placed on the specimens. Although these tests provide considerable insight into the factors that affect the tensile response of liver parenchyma, usually only stress—strain curves obtained locally from the marker displacements were reported, which was less accurate to represent the global responses of the tissue tensile properties. In addition, an implementation of test data into a FE material model and a verification of data in terms of global properties were not performed.

The current study employs specimen-specific finite element (FE) models, as a few recent studies (Untaroiu, 2005, Untaroiu et al., 2005; Untaroiu, 2010, Hu et al., 2009, Hu et al., 2011, Gras et al., 2012), to identify material parameters of liver parenchyma by a FE simulation-based optimization approach. Because this approach is still computationally time consuming, an analytical model was also employed to identify the material and failure parameters of 30 specimens tested in uniaxial tension. The average stress—strain curves and test corridors developed based on specimen-specific models, analytical models, and marker data were compared. In the future, we believe this data could be used to define deterministic and stochastic material models (Hu et al., 2011) for liver parenchyma based on a tabulated formulation of hyper-elasticity with rate effects (Kolling et al., 2007), which may improve the accuracy of human FE models.

2. Methods

2.1. *Specimen preparation and testing procedure*

Uniaxial tensile tests were performed on the parenchyma of 10 fresh bovine livers obtained from Animal Technologies (Animal Technologies, Inc. Tyler, TX) within 36 h after slaughter. In order to preserve the tissue between the time of procurement and specimen preparation, the livers were immersed in a bath of Dulbecco's Modified Eagle Medium (DMEM) to maintain specimen hydration, and cooled (without freezing) with wet ice.

Cubic blocks of parenchyma (Fig. 1a) were first cut and securely held in a slicing jig, an aluminum fixture with vertical slots spaced 5 mm apart (Kemper 2010; Kemper 2011). Then, the slicing was performed smoothly, to avoid tissue damage and deformation, using a blade assembly consisting of five long skinner blades (R-203506MOD, American Cutting Edge, Centerville, OH) (Fig. 1b). A custom stamp and stamping base were used to obtain the “dog-bone” shape

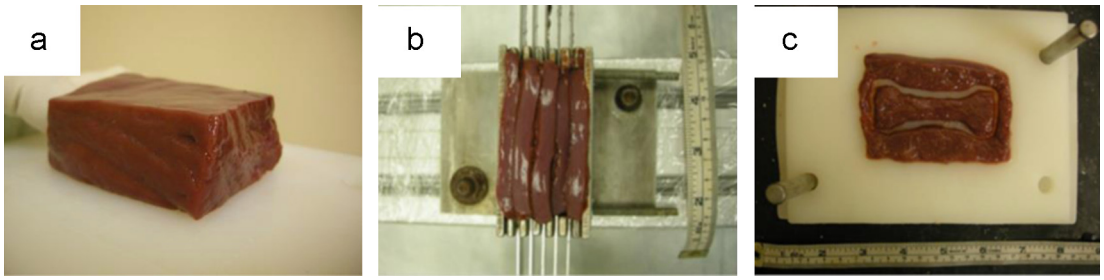

Fig. 1 – Specimen preparation. (a) cubic block of tissue, (b) tissue slicing and (c) tissue stamping.