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Identifying the properties of ultra-soft materials using a new methodology of combined specimen-specific finite element model and optimization techniques

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ABSTRACT

Development of novel protective helmets requires a better understanding of the mechanical properties of brain tissues. In this paper, a new methodology was developed using a reverse engineering (RE) based approach to identify the material properties for ultra-soft materials, such as human brain tissues, that are very difficult to cut into an accurate geometric shape necessary for engineering measurements. The basic idea behind this method is to include geometric effects by using a sample-specific finite element model in conjunction with a set of optimization procedures that allows systematic adjustments of material parameters until the calculated responses matched the measured ones. The experimental component consists of conducting simple uniaxial compression tests at two different loading rates to obtain force–displacement relationships, instead of the less accurate stress–strain curves, that could be used directly to minimize an objective function. The Shepard-k-Nearest method was employed to establish an approximated model (i.e. a response surface) and a genetic algorithm was used to search the optimal design variables (i.e. material parameters) in the design space. The optimized parameters were then used to describe the material behavior in a third sample-specific FE model and the model-predicted force–deflection data were compared with experimental data at a third loading rate that were not used for optimizing material parameters. This new approach makes it possible to identify material constants of ultra-soft biological tissues and engineering materials (e.g. silicone gels and rubbers) without using a large number of test samples.

1. Introduction

Traumatic brain injury (TBI) due to vehicular crashes and sporting activities causes millions of death and hospitalization every year around the world [1]. A large number of experiments have been conducted using volunteers, human cadavers, animals, and crash dummies to advance our understanding of TBI associated injury biomechanics. Unfortunately, many of these tests tended to investigate the association between external impact force and injury outcome to derive global injury mechanism and threshold rather than tissue-level injury mechanisms and thresholds needed for designing more effective personal protective equipments to mitigate TBI severity or eliminate the injury altogether.

Since the 1990s, increasing efforts have been made to develop numerical models, largely based on the finite element (FE) method, to depict intracranial responses in order to identify injury mechanisms and to propose tissue-level injury thresholds [2–7]. The FE method is noted for its superb capability to model structures with an irregular geometry, inhomogeneous and nonlinear material properties, and complex boundary and loading conditions. It can also compute responses that cannot be easily measured experimentally, such as wave propagation, tissue level strain contours, and energy dissipation. To ensure the validity of FE simulations of various TBI scenarios, reliable mechanical properties of the brain and cranial bone tissues under impact loading conditions are essential. In recent years, numerical simulations have been increasingly applied in the development of novel protective helmets design, where FE helmet models are coupled with FE human head models with simplified or detailed anatomical features [8–12]. Accurate prediction of intracranial responses (e.g. pressure, shear strain, and stress within the cranium) during impact also requires a better understanding of the mechanical properties of brain tissue at varying strain rates.

Conventional brain tissue testing methods include shear [13–18], compression [16,19–21], and tension tests [22,23]. In these tests, brain samples were cut into cylindrical or cubic shapes. Because brain tissues are very compliant, it is extremely difficult to dissect a cylindrical or cubic shaped sample from the entire brain. It has been reported that the dimensions of the samples could differ from the intended size by 10–20% [20]. Therefore, assuming a constant cross-sectional area could yield erroneous engineering

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strain values unless a large number of tests were performed under the same protocol to average out the sample-to-sample differences. Unfortunately, testing a lot of samples is very time consuming and costly. Additionally, human brain tissues are very difficult to obtain, even if time and money is not a major hindrance. Thus, new ways to acquire accurate brain material properties are desirable.

The purpose of this study was to develop a methodology in which a set of reverse engineering (RE) based optimization procedures was used to identify the material parameters of ultra-soft biological tissues or engineering materials, e.g. human gray and white matters, silicone gels or rubbers directly from uniaxial tests, such as compression or shear. The basic idea of this approach was to combine sample-specific numerical simulations with a set of optimization procedures to systematically adjust various material parameters until calculated mechanical responses optimally matched those measured experimentally. The advantage of this approach relies on the fact that geometric variations are eliminated due to the use of sample-specific FE models. Consequently, optimizations are focused on matching the easily obtainable force–deflection data instead of the more difficult to determine stress–strain relationship, which depended greatly on an accurate assessment of changing cross-sectional properties. To date, this approach has been applied in material processing [24–27] and structural analyses [28,29] of elasto-plastic media. To the best of our knowledge, no such studies have been reported on determining the properties of the very compliant materials, particularly human brain tissue.

2. Methods

Fig. 1 shows the five-step process of the proposed optimization schemes. In Step 1, rectangularly shaped brain tissues were dissected from whole brain in preparation for testing. A laser scanner was employed to obtain the three-dimensional (3-D) profiles of the specimens in Step 2. In Step 3, compression tests were conducted at three different strain rates while force–displacement curves were recorded. In Step 4, the sample-specific geometry obtained from laser scanning was meshed into a sample-specific FE model, using the experimental loading and boundary conditions. Additionally, each parameter needed for the constitutive model was assigned a range of values selected from literature and subjected to optimization. Finally, an optimization tool was used in Step 5 to assign each and every material parameter with a constant value within the range specified and then the FE solver was executed to calculate the corresponding force–displacement curves. The optimization algorithms further adjusted the material parameters automatically and then repeated these procedures until the objective function of minimizing the total difference between experimental data and model predicted result was achieved. These five steps are detailed below.

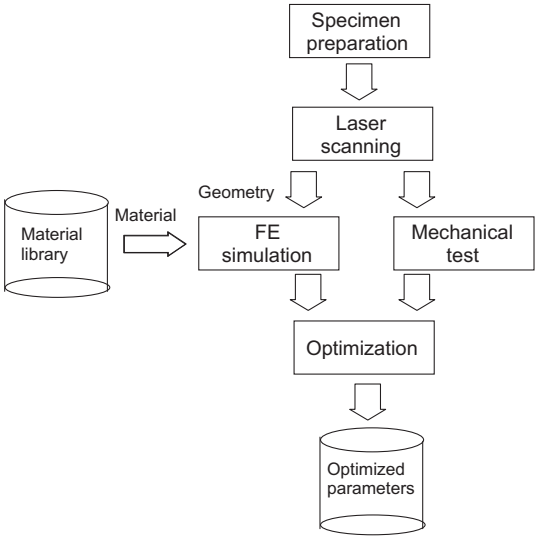

Fig. 1. Work flow of the material parameters identification procedure for brain tissue.

2.1. Specimen preparation

A 45-year-old male human cadaveric head (1 week after death) was obtained through the Willed Body Program at Wayne State University. A motorized Stryker saw (Model 8208-210, Stryker Co., Kalamazoo, MI) was used to open the skull just superior to the Frankfort horizontal plane before the brain was carefully removed. Six brain tissue specimens were taken from two locations, with one located at the thalamus (gray matter) and the other at the corona radiata (white matter) along the fiber orientation (Fig. 2) to determine if there was a difference in gray and white matter properties. A surgical scalpel was used to dissect three rectangular specimens of approximately 15 mm × 15 mm × 8 mm from each region for testing at three different strain rates. Because fresh brain tissue was too soft to cut into a perfect rectangular shape, thickness variations were as high as 2.5 mm.

2.2. Laser scanning to obtain the sample profiles

The 3-D geometry of each sample was captured using a laser scanning system (E-scan 3363, 3-D Digital Corp., Sandy Hook, CT) equipped with a modified lens to enable close range scanning of small samples with a resolution of 0.05 mm (Fig. 3). Before scanning, brain sample was positioned on a dark-colored plate fasten to a rotary table and the distance between the sample and scanner adjusted to ensure that the entire sample was within the field of view for all angles to be scanned. The laser device automatically scanned the specimen surface exposed to the laser beam and recorded the reflection data points. In order to cover all sides of the specimen, repeated scans were performed by rotating the table approximately 45° after each scan. Each brain sample required a minimum of eight scans to ensure that all sides were covered with some overlap. Finally, all scanned images were co-registered and a 3-D reconstruction algorithm, built into the software of the scanner, was used to rebuild the 3-D surface profile of the specimen in STL format, a file format used for stereolithography computer aided design (CAD) software created by 3-D Systems (3D Systems Co., Rock Hill, SC). This format generates a surface composed of very small triangles describes only the surface geometry of a 3-D object without any representation of color, texture or other common CAD model attributes.

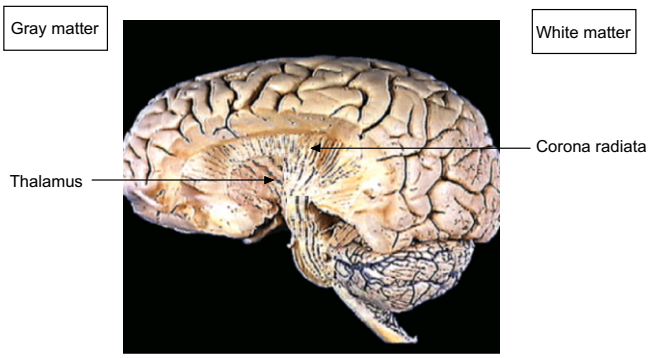

Fig. 2. Locations of the brain tissue samples studied: thalamus in gray matter and corona radiata in white matter.