Journal of Biomechanics 46 (2013) 2795–2801

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

A comprehensive experimental study on material properties of human brain tissue

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ARTICLE INFO

Article history:
Accepted 2 September 2013

Keywords:
Human brain tissue
Material properties
Tension
Compression
Shear

ABSTRACT

A comprehensive study on the biomechanical response of human brain tissue is necessary to investigate traumatic brain injury mechanisms. Published brain material property studies have been mostly performed under a specific type of loading, which is insufficient to develop accurate brain tissue constitutive equations. In addition, inconsistent or contradictory data in the literature made it impossible for computational model developers to create a single brain material model that can fit most, if not all, experimental results.

In the current study, a total of 240 brain tissue specimens were tested under tension ($n=72$), compression ($n=72$), and shear ($n=96$) loading modes at varying strain rates. Gray–white matter difference, regional difference, and directional difference within white matter were also investigated.

Stress–strain relationships of human brain tissue were obtained up to 50% of engineering strain. Strain rate dependency was observed under all three loading modes. White matter was stiffer than gray matter in compression and shear. Corona radiata was found to be stiffer than cortex, thalamus, and corpus callosum in tension and compression. Directional dependency of white matter was observed under shear loading.

1. Introduction

In the United States, approximately 1.7 million people sustain a traumatic brain injury (TBI) annually (CDC, 2011). TBI also contributes to one-third of all motor vehicle related deaths (CDC, 2011) and presents a major social, economic, and health problem. In order to investigate TBI mechanisms, computational modeling has been widely applied to provide insight into the local deformation field during traumatic loading. For this purpose, understanding the biomechanical response of brain tissue is necessary to provide accurate experimental data to allow for development of constitutive equations in numerical simulations.

The mechanical response of brain tissue is complex. Current knowledge shows that brain tissue is anisotropic, non-linear, and viscoelastic (for example, Prange et al., 2000; Miller and Chinzei, 1997; Donnelly and Medige, 1997). Moreover, the constitutive equations derived under one loading condition do not necessarily predict the material response under another loading mode (Miller and Chinzei, 1997, 2002). During the past fifty years, numerous experimental studies have been published on brain tissue material properties. They have been mostly performed under a single mode of loading, e.g., compression (for example, Galford and McElhaney, 1970; Estes and McElhaney, 1970; Miller and Chinzei, 1997; Cheng and Bilston, 2007), tension (Miller and Chinzei, 2002; Velardi et al., 2006), and shear (for example, Fallenstein et al., 1969; Donnelly and Medige, 1997; Prange et al., 2000; Bilston et al., 2001; Takhounts et al., 2003; Hrapko et al., 2006). These individual studies are valuable for a better understanding of brain tissue material properties but are still insufficient to comprehensively describe the brain tissue behavior for numerical modeling purposes. Moreover, a large degree of variance observed among the published results made it impossible for computational model developers to create a single brain material model that can fit most, if not all, experimental results. There could be several different causes for this variance, such as different species, testing methods, loading conditions, temperature, post mortem time, etc.

Brain tissue is heterogeneous and anisotropic due to its neuroarchitecture. Published results indicated that material properties vary between gray and white matter (e.g., Prange et al., 2000; Manduca et al., 2001). Moreover, the material properties of a given matter may also change with the different regions from where the specimens were dissected. For example, among white matters, corpus callosum is less compliant than brain stem (Arbogast and Margulies, 1997) and corona radiata (Prange et al., 2000) under large deformation. The anisotropy of brain tissue, which could be associated with the highly oriented axon fibers, was reported in some studies (Arbogast and Margulies, 1998; Prange et al., 2000). The regional and directional dependency

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http://dx.doi.org/10.1016/j.jbiomech.2013.09.001

of brain tissue material properties during traumatic loading is important to investigate injury mechanisms at specific anatomical regions and needs to be studied carefully.

In summary, the lack of experimental studies with comprehensive loading types and well-controlled testing conditions is the major limitation on the study of brain tissue biomechanical properties, especially for human brain tissue. The purpose of this study was to experimentally investigate the material properties of human brain tissue under tension, compression, and shear at varying strain rates. In addition, the gray–white matter difference, regional difference, and directional difference within white matter were also investigated. These findings will help us to better understand brain tissue biomechanics and to develop a comprehensive and accurate constitutive model of brain tissue.

2. Material and methods

2.1. Specimen preparation

Brain tissue from post mortem human subjects (PMHS) was used in this study. To avoid tissue degeneration, PHMSs were kept intact at 4 °C until craniotomy was performed prior to testing, with an average post mortem time for testing of four days. Table 1 shows the information of PMHSs tested in this study.

Rectangular brain specimens of 14 mm × 14 mm × 5 mm were cut from the cadaveric head using two similar constructs, each consisting of a pair of paralleled scalpel blades (Fig. 1). The first pair of blades (Fig. 1a) was used to dissect a thin strip of brain tissue out of the whole brain at a thickness of 5 mm and the second pair (Fig. 1b) was then used to cut the brain strip into 14 mm × 14 mm square blocks. These constructs helped to obtain test samples fairly close to a rectangular block with uniform dimensions for tension and shear testing. The dissected brain samples were stored in artificial cerebral spinal fluid (aCSF) solution until testing.

Brain tissues were dissected from four locations, two in the gray matter (cortex and thalamus) and the other two in the white matter (corpus callosum and corona radiata), in order to determine if there is a regional difference on mechanical properties of the brain (Fig. 2). Additionally, directional dependent properties of the white matter were investigated in two ways. Tension and compression tests were conducted along two directions and shear tests were conducted along three directions. The definition of loading with respect to the fiber orientation (direction) is illustrated in Fig. 3. During dissection, the general direction of the axon fiber was followed based on anatomical knowledge, which was lateral–medial at corpus callosum and radial at corona radiata (see Fig. 2). The directional dependency of gray matter was not investigated in this study because its neuroarchitecture did not show any clear evidence of fiber alignment and no data reported in the literature thus far indicates any directional dependency for the gray matter. A total of 240 brain tissue specimens were tested under tension ($n=72$), compression ($n=72$), and shear ($n=96$) loading modes under varying strain rates. The test matrices are shown in Tables 2 and 3.

Table 1
Basic PMHS characteristics and the test matrix.

Patient no.	Sex	Age	Tension	Compression	Shear
IIAM 0293	M	66		×	
WSU 362	F	67		×	
WSU 364	M	45		×	
WSU 501	M	85	×		×
WSU 526	F	80	×		×
UM 33,769	F	60	×	×	
WSU 590	F	94			×
WSU 603	M	64	×		
UM 33,881	M	67			×

2.2. Mechanical testing

2.2.1. Tension and compression

Tension and compression tests were performed on the brain tissue samples using a test apparatus as shown in Fig. 4. Testing was performed within an environmental chamber installed on the Instron testing table. Steam generated from an electric kettle was directed into the chamber through a pipe to humidify and heat the air inside. All tests were conducted at 37 °C monitored using a thermometer positioned next to the brain tissue samples. No pre-conditioning was performed and only one loading cycle was executed on each sample.

Prior to tension testing, the bottom surface of the brain tissue block was glued (Crazy glue, Elmer's Products, Inc., Columbus, OH) onto a polyethylene plate connected to a 22.24 N capacity load cell (MDB-5, Transducer Technology Inc, Temecula, CA). The same glue was applied on the top surface of the brain tissue sample. The top polyethylene plate, which was connected to the actuator of an Instron Machine (Model 1321 frame with a Model 8500 controller, Canton, MA), was then lowered to adhere the top plate to the brain tissue sample. The position of Instron actuator was recorded at the moment the plate surfaces contacted brain tissue specimen. A pre-compression of 1 mm was applied and maintained for one minute to allow glue set. Prior to applying tension loading, the pre-compression was released by lifting up the actuator to the pre-recorded position.

The compression test was conducted using the same setup as the tension test but glue was not applied to allow free expansion of specimens.

2.2.2. Shear test

The testing fixture for the shear test is shown in Fig. 5. The brain tissue specimen was glued on the fixed block. The micrometer head mounted on the moving block served to horizontally move the moving block to apply pre-compression to allow glue to set. Similar to the tension and compression test, the reading of the micrometer head was recorded at the initial contact between brain specimen and moving block. After the glue was set, the moving block was reversed back to release the pre-compression. The Instron actuator then lifted up to apply shear loading on the specimen. The shear test was also conducted at 37 °C and only one loading cycle was executed on each sample without pre-conditioning.

2.3. Data acquisition and analysis

Force–displacement histories were recorded from tension, compression, and shear testing at a sampling rate of 10 kHz. Engineering stress was calculated as the ratio of force and nominal area of specimen and engineering strain was calculated as the ratio of actuator displacement and nominal initial thickness of specimen.

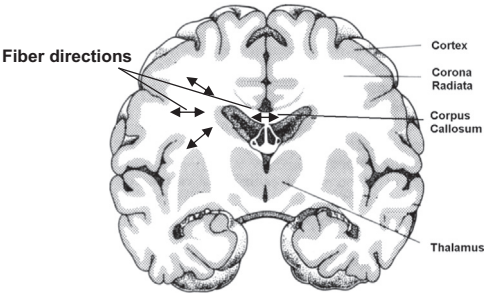

Fig. 2. Locations of the brain tissue samples tested: gray matter (cortex and thalamus) and white matter (corpus callosum and corona radiata).

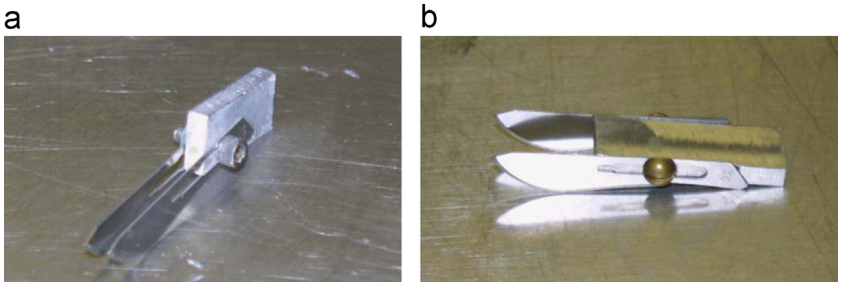

Fig. 1. Uniform dimension cutting constructs.