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BRAIN DEFORMATION UNDER MILD IMPACT: MAGNETIC RESONANCE IMAGING-BASED ASSESSMENT AND FINITE ELEMENT STUDY

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Abstract. The knowledge of in vivo human brain deformation within the skull is essential in understanding brain injury mechanisms. Such measurements have become possible only in recent years thanks to the advancement of magnetic resonance imaging (MRI) technique. In this paper, we first study in vivo human brain deformation under mild impact induced by a 2-cm head drop using tagged MRI and the harmonic phase (HARP) imaging analysis technique originally developed for cardiac motion analysis. A finite element (FE) simulation of mild impact is then carried out using a patient-specific 3-D head model. A reasonably good correlation is found between the predicted deformation field from FE modelling and the results from MRI-based assessment. It is found that the maximum deformations occur within a few milliseconds following the impact, which is during the first oscillation of the brain within the skull, with the maximum displacements of 2-3 mm and the maximum strains of 5-10%. To our knowledge, this study is the first attempt where the deformation field obtained by MRI-based assessment is correlated with the prediction of a corresponding FE model, and it is also the first validation of a FE brain injury model on in vivo human brain deformation data.

Key words. brain injury; magnetic resonance imaging; image processing; finite element modelling

1. Introduction

To gain understanding of brain injury mechanisms, researchers have long been interested in brain deformation within the skull under various traumatic loading conditions. However, direct observation of human brain deformation in vivo is extremely difficult. Therefore, physical models such as animals, human cadavers, and inanimate replicas have been used in the past to study deformation patterns of the brain under either impact or impulsive loading. To track brain motion, different techniques utilized in physical experiments include high speed X-ray with embedded radioactive markers in test animals or human cadavers [7, 8, 12, 17], use of Lucite calvarium to replace a portion of the skull for direct observations of brain motion [5, 15], and use of gelatin models to simulate brain material [6, 9, 11]. The experimental studies using above techniques have contributed significantly to our understanding of brain injury mechanisms in the past several decades. However, the extent to which the experimental results may be applied to human brain in vivo is uncertain due to the discrepancies of geometry and material properties between in vivo human brain and each of these physical models. To obtain a better understanding of brain injury mechanisms, the use of in vivo human brain for experimental studies plays an irreplaceable role, and such experiments have become possible since the invention and advancement of the medical imaging technique, the magnetic resonance imaging (MRI).

MRI is known to be the most powerful tool for non-invasive assessment of biological soft tissues in vivo, which makes it suitable for brain research. In fact, in

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the field of cardiac research, a special MRI pulse sequence called tagging [1, 18] has been developed and has become a well established technique to image cardiac motion. MRI tagging is used to spatially modulate the longitudinal magnetization of the subject to create temporary features called tags in the myocardium. The tag pattern is subsequently deformed by the heart motion and can be visualized in an image sequence reconstructed from sufficient data acquired over many heartbeats in a single breath hold [14]. Various image processing techniques have also been developed to analyze the tagged cardiac MRI images to estimate the motion quantities such as displacements and strains of the myocardium. In particular, a novel image processing technique called harmonic phase (HARP) image analysis developed in [13, 14] provides a fast and automated means to estimate dense motion quantities from tagged cardiac MRI images. The tagged MRI and the HARP image processing techniques developed for cardiac motion tracking has been applied to obtain deformation fields of in vivo human brain during mild acceleration [2, 4, 16].

Our present study not only deals with kinematics of a deforming brain which is motivated by Bayly et al.'s work [2], but also includes a mechanical model that deals with the mechanics from the standpoint of Newtonian dynamics, i.e. also including momentum balances and constitutive laws. In this paper, we study the brain deformation induced in mild impact from a 2 cm vertical head drop. We carry out the head drop experiments using human volunteers, acquire tagged MRI images during the head drop, apply the HARP analysis to the tagged MRI images, and obtain the brain motion estimates. In addition, we build a mathematical model of mild impact of the human head through finite element (FE) modelling, and compare the predicted deformation fields with those from MRI-based HARP estimates. The significance of the comparison is two-fold. On one hand, to the best of our knowledge, this is the first attempt where the deformation field obtained by MRI-based assessment (i.e., tagged MRI images and HARP analysis) is correlated with predictions of a corresponding FE model. A good correlation provides a validation of the sensitivity of the tagged MRI and HARP analysis to the deformations caused by the mild impact loading. On the other hand, our work is also the first attempt to use deformations of in vivo human brain for FE head injury model validation. A good correlation serves as a validation of our proposed FE model for brain injury research.

2. Methods

The organization of this section is as follows. First, we present our head drop experiment, tagged MRI image acquisition, and the implementation of the HARP image processing technique to track brain motion induced in mild impact. Secondly, the FE modelling of mild impact is described.

2.1. MRI-based assessment of brain deformation. A healthy adult with no history of head trauma was recruited to participate in the 2-cm vertical head drop experiment. The experiment was carried out at the Biomedical Imaging Center (BIC) at the University of Illinois at Urbana-Champaign in accordance with the Institutional Review Board. All MRI data collection was performed on a Siemens Allegra 3T scanner. During the 2 cm vertical head drop, a custom-made MRI-compatible head drop device (HDD) is secured to the MRI head coil to guide the motion of head (Fig. 1), and the occipital region of the head is impacted with a rigid plate after the drop. At the start position, the HDD is raised to the elevated position and locked. As the head begins to drop after activation of a release mechanism, a fiber optic system of the HDD triggers the dynamic imaging sequence of the MRI