Nonrigid Registration of Medical Images Using Finite Element Modeling

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The Problem: To measure the non-rigid deformation of the brain during surgery. We have a sequence of MRI data sets taken of patients undergoing brain surgery. We are investigating the tissue motion of these patient's brains in order to develop a model of motion during surgery. Our ultimate goal is to have a predictive model of brain tissue motion based on pre-operative data and minimal real-time information. However, our immediate concern is simply to measure the motions in the data sets we have.

Motivation: Surgical navigation systems present pre-operative three dimensional data to a surgeon, augmenting the surface information visible to the surgeon's eye. The additional information below the surface can better guide a surgeon to his target while helping him avoid regions that should not be damaged. Navigation systems typically assume that the brain is rigid during surgery. However motions of the brain, for example, can easily reach 2 cm during an operation. These motions are sufficient that the rigidity assumption leads to inaccuracies in the location and sizes of objects in the brain. We would like to model the motion of components of the brain so that accurate descriptions of their location and shape can be predicted during surgery.

Previous Work: Until recently, most work for measuring deformation fields in medical images was based on local image structure. For example, Hata et. al used local image gradients to attempt to register images with limited success [4]. Similarly, Gaens et. al used a multi-resolution method in conjunction with mutual information based techniques [2]. More recently, Hagemann et. al used a biomechanical model of the brain, in conjunction with a user matching landmarks on each image [3]. Ferrant et. al used a combination of image gradients forces and elastic forces to align 3D images [1]. Our methods resemble those of Ferrant.

Approach: We are interested not only in measuring deformations but in predicting them. Therefore, we have chosen a biomechanical based method for measuring motions that will allow us to generate biomechanical models of the brain. We represent the brain as a linearly elastic body. Because deformations during surgery generally happen slowly, a linear elastic approximation may be a good one.

We created an algorithm to quickly divide the brain into a finite element model (FEM) using tetrahedra as our finite elements. If the brain has been segmented, we cut tetrahedra in order to accurately represent surfaces within the brain. We then balance elastic and image based forces in order to deform one three dimensional image into the next.

A fast numerical implementation of the elastic FEM algorithm is critical to the success of this project. Because consecutive images during surgery are separated by hours, large deformations occur between images. To account for the large motions accurately requires an iterative algorithm to deform an FEM model small distances in each iteration. Each iteration requires the formation and solution of a sparse matrix equation. The formation step takes as long, and sometimes longer, than the solve step. Therefore, we are working on methods to create the memory structure for the sparse matrix only once and only update entries of the matrix due to finite elements that have moved significantly.

Difficulty: There are several causes of deformation and shift of the brain. These causes include redistribution of pressure which leads to tissue motion. Loss of cerebrospinal fluid and volume changes in venous blood also cause deformation. Gravity draws the brain downward causing a shift of the brain and some deformation. These causes of deformation can be accounted for in a straight forward manner. However, it is difficult to determine how a model of the brain should be altered to represent a surgeon removing tissue. Similarly, it is difficult to represent the topology change of the system. The brain starts surgery with an outer surface and an inner surface around the tumor. During surgery, those two surfaces are connected by cutting.

Because it is not possible to predict the actions of the surgeon, we expect that no model of tissue motion will be sufficiently predictive to be useful. We expect that additional data gathered during surgery will be necessary to make a model useful.

Impact: This work will allow us to characterize where motions do and do not occur in order to model the brain during surgery. This work should tell us how much and what type of additional information will be necessary in order to predict motions of the brain during surgery.

Future Work: After the deformation fields are measured accurately, we will approach the difficult problem of predicting motion.

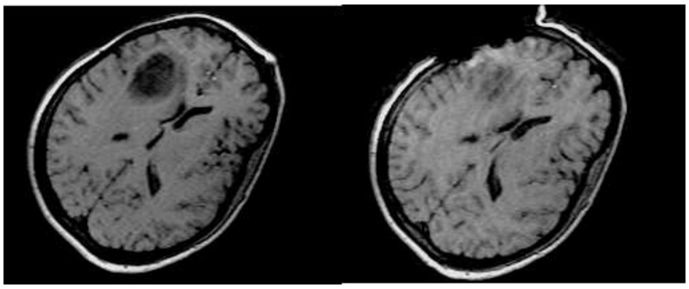

Figure 1: MRI image of a patient before and after the start of surgery.

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