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FEM- AND XFEM-BASED BIOMECHANICAL MODELS FOR ADVANCED IMAGE-GUIDED NEUROSURGERY

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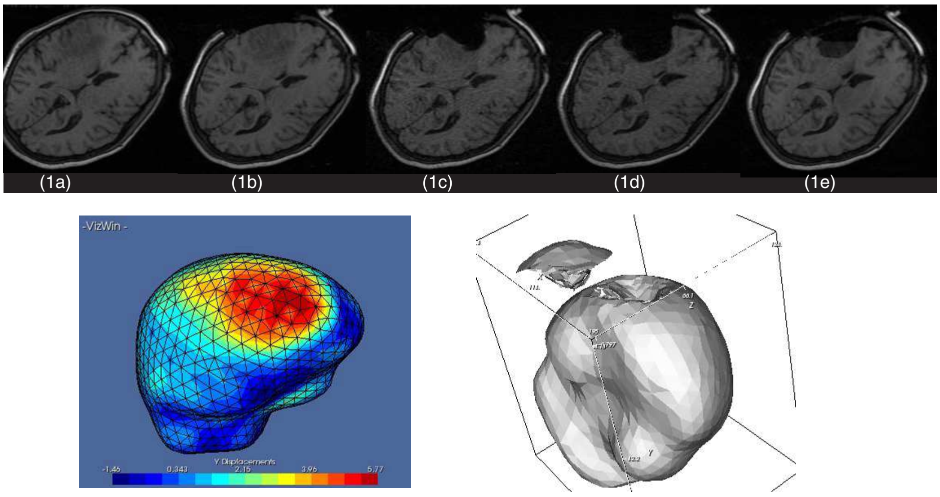
ABSTRACT

The main goal of brain surgery is to remove as much as possible of lesional tissues, while avoiding contacts with eloquent areas and white matter fiber tracts. Surgery is planned on the basis of preoperative images of multiple modalities, such as CT, sMRI, fMRI, PET, and DTI. It is generally performed using an image-guided navigation system that relates the 3D preoperative images to patient coordinates. However, throughout surgery, the brain deforms, mostly as a result of the leakage of the cerebrospinal fluid out of the skull cavity, modifications in cerebral perfusion, pharmacological modulation of the extracellular fluid, and of surgical acts, such as retraction and resection. As surgery progresses, preoperative images become progressively less representative of the brain, and navigation accuracy decreases. One solution is to evaluate brain deformations from reduced-quality intraoperative images acquired at several critical points during surgery, and to update, i.e. to deform, all high-quality preoperative images using a nonrigid registration technique.

One category of such techniques uses biomechanical models based on the Finite Element Method (FEM). Prior to surgery, a biomechanical brain model specific to the patient is built from preoperative images: the model consists of a volume mesh of finite elements, and of one or more mechanical behavior laws assigned to them. During surgery, a number of key anatomical landmarks are extracted and tracked through successive intraoperative images. The estimated displacements of these landmarks are applied to the biomechanical model and drive its deformation. The resulting displacement field of the biomechanical model is used to deform the preoperative images.

Most studies of brain deformation based on biomechanical models have focused on the early stages of surgery, i.e. prior to any significant deformation and any cut [1]. The reported accuracy for deformation prediction is about 1 voxel. The situation becomes more complex when local connectivity is altered, e.g. due to a cut, a retraction, or a resection, which implies model discontinuities. Because discontinuities do not necessarily lie on element boundaries, the use of FEM implies remeshing or mesh adaptation. However, other methods have been developed in the field of fracture mechanics that avoid remeshing or mesh adaptation. One example is the eXtended Finite Element Method (XFEM) [2]. This method allows the object to be modeled by finite elements without explicitly meshing the discontinuities, which can then be located arbitrarily with respect to the underlying finite-element mesh. In addition, no remeshing is required when the discontinuity changes shape.

We propose a 3D FEM- and XFEM-based end-to-end system capable of updating preoperative images in the presence of brain shift followed by successive resections (Fig. 1) [3].



(2) (3)

Figure 1: **(1st row)** Sequence of five intraoperative MR (iMR) images. **(1a)** 1^{st} iMR image, acquired before the opening of the skull. **(1b)** 2^{nd} iMR image, acquired after the opening of the skull and dura, and, thus, after some brain shift. **(1c)** 3^{rd} iMR image, acquired after a 1^{st} resection. **(1d)** 4^{th} iMR image, acquired after a 2^{nd} resection. **(1e)** 5^{th} iMR image, acquired after a 3^{rd} resection and some postoperative brain shift. **(2)** FEM-modeling of brain shift with color levels corresponding to the displacements. The location of brain shift resulting of the opening of the skull and dura is clearly visible. **(3)** XFEM-modeling of 2^{nd} resection. FEM and XFEM results are computed with Metafor (http://garfield.ltas.ulg.ac.be/oo_meta/.)

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