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Computational biomechanics of the brain brings real benefits in the operating theatre

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SUMMARY

Neurosurgical planning is done using high-quality magnetic resonance images (MRIs) of the brain acquired before surgery. However, the brain deforms during surgery, which necessitates updating (registration) of such images to the current (i.e. intra-operative) brain geometry using either rigid body or deformable (e.g. using BSpline) image transforms. The registration process typically involves cumbersome and expensive acquisition of intra-operative MRIs to provide target images for the registration. In our previous studies, we proposed to predict the intra-operative deformation field within the brain using patient-specific non-linear biomechanical (finite element) models that require only very sparse information about the intra-operative brain geometry as an alternative to intra-operative acquisition of the entire brain MRI. In this contribution, we present our evaluation of accuracy of the registration conducted by warping the pre-operative MRIs using the predicted deformations. The results suggest that, despite requiring much less intra-operative data, the accuracy of our biomechanics-based registration is at least as high as that of non-rigid registration using BSpline and higher than the accuracy of rigid registration, which remains a method of choice in commercial image-guided surgery systems.

Key Words: *brain, Non-rigid registration, biomechanics, Hausdorff distance.*

1. INTRODUCTION

Complete (or nearly-complete) surgical removal of a tumour is desirable from the perspective of medical outcomes [1]. Such removal requires precise neuro-navigation, which is further complicated by the brain deformation (known as a brain shift) induced by craniotomy (surgical opening of the skull) [1]. The brain shift distorts the pre-operative anatomy and diminishes the utility of high-quality images acquired pre-operatively. This necessitates fusing high-resolution pre-operative imaging data with the intra-operative configuration of the patient's brain. Such fusing can be achieved by updating the pre-operative image to the current intra-operative configuration of the brain through registration [1]. The current commercial image-guided navigation systems use rigid registration. However, we are starting to see a shift towards non-rigid registration (such as those using BSpline interpolation between the pre-operative and intra-operative images [2]) that accounts for the brain tissue deformations during neurosurgery.

Vast majority of rigid and non-rigid registration methods require acquisition of the whole brain intra-operative images, which are used as the target for image registration. However, intra-operative MRI scanners are very expensive and often cumbersome. Hardware limitations of these scanners make them infeasible for frequent acquisition of the whole brain images during surgery. Therefore, recent research efforts for non-rigid neuro-image registration employ sparse information about the intra-operative brain geometry and non-linear biomechanical models to predict deformations within the brain due to craniotomy-induced brain shift [1].

In our previous studies, we developed fully non-linear finite element algorithms for real-time computation of soft tissue deformations on commodity hardware [3] and evaluated the accuracy of prediction of intra-operative brain deformations using the biomechanical brain models implemented by means of such algorithms [1]. In this contribution, we focus on comparison of the accuracy of neuro-image registration using our biomechanical models with that of non-rigid BSpline and rigid registration.

2. METHODOLOGY AND RESULTS

We analysed 33 craniotomy cases for patients with cerebral gliomas (tumours) [1].

2.1 Pre-operative to intra-operative registration using BSpline algorithm and image rigid-body transformation

We applied widely-used BSpline-based free form deformation (FFD) [2] and rigid registration algorithms implemented in 3D Slicer medical image processing software (http://www.slicer.org). These algorithms use an intra-operative image as a target image.

2.2 Registration using biomechanical modelling

In the biomechanics-based neuro-image registration, the deformation fields predicted using a numerical brain model were applied to warp the pre-operative images to the intra-operative brain configuration [3]. As explained in [3], sparse information about the intra-operative brain configuration is needed to drive the computation of brain deformations, but unlike in BSpline and rigid registrations, the process does not require acquisition of intra-operative images of the whole brain [1, 2].

Construction of patient-specific finite element meshes: As described in detail in [3], we obtained the geometry for mesh construction through segmentation of the pre-operative MRIs. In segmentation, we sub-divided the brain into healthy parenchyma, tumour and ventricles. As shown in Figure 1, we used mixed meshes consisting of hexahedral and non-locking tetrahedral elements [3]. For our cohort, accurate representation of the brain geometry necessitated meshes consisting of an order of 30000 elements and 20000 nodes .

Loading and boundary conditions: We defined the loading by prescribing deformations on the exposed brain surface in the craniotomy area. A frictionless contact is defined at the brain-skull interface to prevent the brain surface from penetrating the skull and allow sliding at the interface [3].

Constitutive properties for the brain models: As in our previous studies [3], we employed a nearly incompressible (Poisson' ratio of 0.49) neo-Hookean hyper-elastic model for the brain tissues. For the brain parenchyma, we used the Young's modulus of 3000 Pa, and for the tumour — the Young's modulus of 3000 Pa. The ventricles were assigned properties of a very soft compressible elastic solid with a Young's modulus of 10 Pa and Poisson's ratio of 0.1[3].

Solution algorithm: We used the previously developed fully non-linear finite element procedures that utilises Total Lagrangian formulation with explicit time-stepping and dynamic relaxation [3]. To achieve the real-time computation on commodity hardware (a desktop PC), these procedures were implemented on Graphics Processing Unit (GPU) [3].

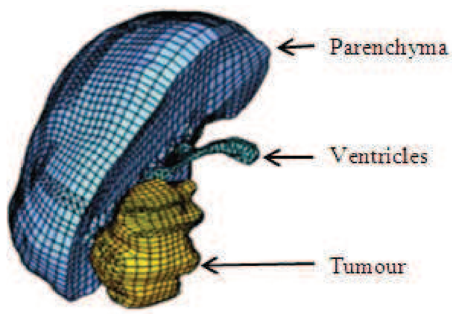

Figure 1: An example of patient-specific brain mesh used in this study. The mesh shown in this figure consists of 30574 elements and 15433 nodes. It takes less than 60 s of computation on a standard personal computer (Intel E6850 dual-core 3.00 GHz processor, 4 GB of internal memory, Windows XP operating system) to predict the brain deformations using our specialised finite element algorithms [3].

2.3 Results

To evaluate the registration accuracy, we determined an edge-based Hausdorff distance (HD) [1] between registered images (i.e. warped pre-operative MRIs) and whole brain images acquired during surgery. HD is a commonly used measure of the differences between two images [1]. As shown in Figure 2, the biomechanics-based registration is at least as accurate as that using BSpline despite the fact that it requires only very sparse intra-operative information (about deformation of the brain surface exposed during the craniotomy).

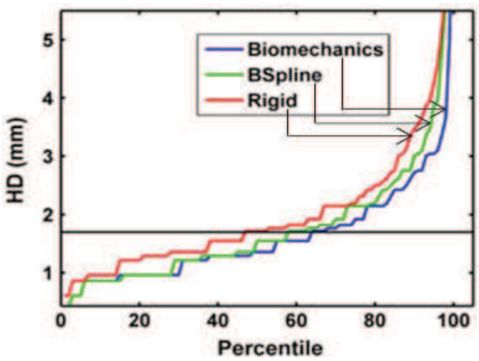

Figure 2: Typical plot of percentile edge-based Hausdorff distance between registered pre-operative and intra-operative images against the corresponding percentile of edges obtained showing relative accuracy of biomechanical, BSpline and rigid registration. At almost all percentiles, the registration error for biomechanics-based method is lower than that of BSpline and rigid registration.

For large brain deformations (exceeding 10 mm), the biomechanics-based registration is more accurate than the rigid registration [1]. This observation is further confirmed by the results of a statistical test for difference in proportions conducted to evaluate the null hypothesis that the proportion of patients for whom improved neuro-navigation can be achieved, is the same for rigid and biomechanics-based registration [1]. The null hypothesis was confidently rejected (p-value$<10^{-4}$) [1]. Even the modified hypothesis that less than 25% of patients would benefit from the use of biomechanics-based registration was rejected at a significance level of 5% (p-value = 0.02). The biomechanics-based method proved particularly effective for cases experiencing large craniotomy-induced brain deformations [1].

3. CONCLUSIONS

The results presented in this study suggest that neuro-image registration relying on sparse information about the intra-operative brain geometry and non-linear biomechanical models for predicting the intra-operative deformations within the brain is at least as accurate as the widely used non-rigid BSpline registration that requires intra-operative acquisition of the whole brain MRI. The results also indicate that biomechanical registration provides improved neuro-navigation data for a larger proportion of patients, compared to the rigid registration methods that are traditionally used in commercial neuro-navigation systems. This allows us to state that the use of comprehensive biomechanical computations for predicting the intra-operative organ deformations in the operating theatre may present a viable and economical alternative to intra-operative MRI.

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