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Towards measuring neuroimage misalignment

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ABSTRACT

To enhance neuro-navigation, high quality pre-operative images must be registered onto intra-operative configuration of the brain. Therefore evaluation of the degree to which structures may remain misaligned after registration is critically important. We consider two Hausdorff Distance (HD)-based evaluation approaches: the edge-based HD (EBHD) metric and the Robust HD (RHD) metric as well as various commonly used intensity-based similarity metrics such as Mutual Information (MI), Normalised Mutual Information (NMI), Entropy Correlation Coefficient (ECC), Kullback–Leibler Distance (KLD) and Correlation Ratio (CR). We conducted the evaluation by applying known deformations to simple sample images and real cases of brain shift. We conclude that the intensity-based similarity metrics such as MI, NMI, ECC, KLD and CR do not correlate well with actual alignment errors, and hence are not useful for assessing misalignment. On the contrary, the EBHD and the RHD metrics correlated well with actual alignment errors; however, they have been found to underestimate the actual misalignment. We also note that it is beneficial to present HD results as a percentile-HD curve rather than a single number such as the 95-percentile HD. Percentile-HD curves present the full range of alignment errors and also facilitate the comparison of results obtained using different approaches. Furthermore, the qualities that should be possessed by an ideal evaluation metric were highlighted. Future studies could focus on developing such an evaluation metric.

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1. Introduction

Our overall objective is to bring the well-proven benefits of image-guided neurosurgery for brain tumours to sufferers throughout the world [1]. Rather than using very expensive and often cumbersome intra-operative Magnetic Resonance (MR) scanners, we plan to include realistic computation of brain deformations, based on a fully non-linear biomechanical model, in a system to improve intra-operative visualisation, navigation and monitoring. The system will create an augmented reality visualisation of the intra-operative configuration of the patient's brain merged with high resolution pre-operative imaging data, including diffusion tensor imaging (DTI) and functional MR imaging (fMRI), in order to better localise the tumour and critical healthy tissues. We accomplish this by registering high quality pre-operative neuroimages onto the current, intra-operative configuration of the patient's brain; however, we do not use an intra-operative image as a target [2,3](Fig. 1).

We compute the deformation fields within the entire brain volume and use them to warp high-quality pre-operative MR images so that they correspond to the current, intra-operative configuration, thus compensating for the brain shift [4]. The ability to objectively evaluate the accuracy of such biomechanics-based registration against a gold standard – an intra-operative MRI – is of immense importance for the acceptance of biomechanics-based approaches by medical image analysis community and ultimately the clinicians. Moreover, as it is now recognised that precise localisation of the target is the first principle of modern neurosurgery – the measurement of the accuracy of intra-operative image registration (whether biomechanics-based or purely image analysis-based) is of primary significance [5].

There is no satisfactory gold standard for evaluating the accuracy of non-rigid registration, even though a number of widely used methods have been developed for a simpler task of rigid registration

Abbreviations: HD, Hausdorff Distance; EBHD, edge-based HD; RHD, Robust HD; MI, Mutual Information; NMI, Normalised Mutual Information; ECC, Entropy Correlation Coefficient; KLD, Kullback–Leibler Distance; CR, Correlation Ratio

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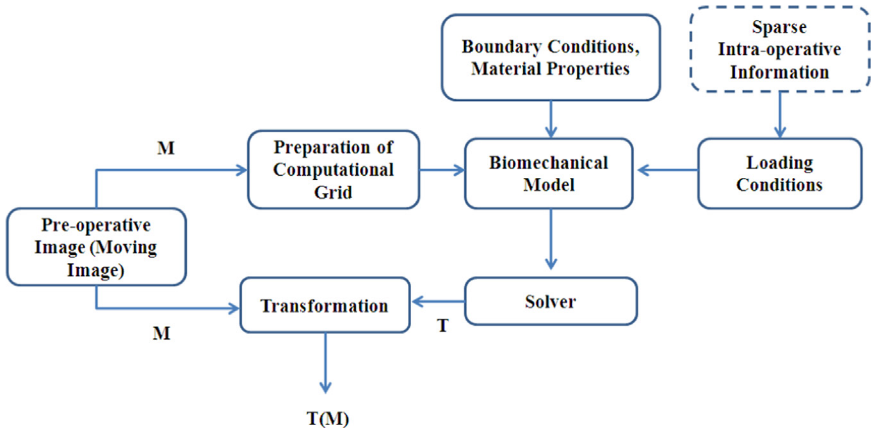

Fig. 1. Registration process based on a biomechanical model.The flow chart depicts various steps used in registering the pre-operative images onto their intra-operative configuration using biomechanical models. M is the moving image (pre-operative image). T is the transform that registers the pre-operative image onto current intra-operative configuration of the brain. T(M) is the transformed moving image (warped pre-operative image).

of neuroimages [6,7]. The registered pre-operative images are evaluated using intra-operative images as ground truth [8]. Evaluating the accuracy of non-rigid registration is inherently difficult and has attracted a lot of attention in medical image analysis literature [7,9,10]. In particular, inter-subject non-rigid registration accuracy evaluation of brain MR images has been investigated in great detail [10,11]. Unfortunately, the conclusions of these papers are rather sober: even though a number of registration approaches performed well as measured by a variety of image similarity indices, most of these evaluation metrics are unable to measure the misalignment of structures reliably [7]. However the accuracy of structure alignment is the key requirement for intra-subject, intra-operative neuroimage registration aimed at producing reliable data for neuro-navigation.

Our objective is to generate accurate data for neuro-navigation and therefore the estimation of the extent to which the warped (registered) pre-operative images are misaligned relative to the current, intra-operative configuration of patient's brain is of great importance to us. We require measures that provide the misalignment (alignment error) estimates in millimetres (mm), for the evaluation results to be of any practical use. It appears, therefore, that we need to focus on approaches allowing comparison of two sets of feature points. One such measure, often used in image analysis, is the Hausdorff Distance (HD) [12].

The choice of the "features" whose locations in images are compared appears as probably the most important practical aspect of application of HD-based approaches. For example, Ferrant et al. used 400 manually selected landmarks, and identified the misalignment (in mm) of the corresponding landmarks before and after registration [13]. A similar approach was used by Clatz et al. [14]. These approaches are labour-intensive and probably unsuitable for large amounts of image data. The practical difficulty of having an expert carry this out reproducibly needs to be highlighted, and therefore replacing that expert landmark selection with an automated process would be beneficial [15].

Another suggested approach is to conduct segmentations of small regions of the brain [10]. These regional segmentations are like landmarks, but instead of points, they are small regions. A lot of effort has been put into obtaining regional segmentations, and the best techniques are competitive with expert segmentations [16–18]. However, the precision of small regions for assessing accuracy may be limited by the region size.

We also applied HD measures to contours of structures (ventricles and tumours) segmented in warped pre-operative and intra-operative images [19,20]. The published results look very convincing, but their validity crucially depends on the accuracy and reproducibility of manual segmentation, which unfortunately is always in doubt.

HD-based approaches that do not rely on manual segmentation or (expert) identification of landmarks require automatic, repeatable identification of corresponding features in compared images. It has been demonstrated that point-sets forming edges or contours of segmented regions, may be used together with HD-based methods to estimate the misalignment of neuroimages [8,20,21]. In this paper we analyse results obtained using two such methods: Edge-based Hausdorff Distance (EBHD) [21] and Robust Hausdorff Distance (RHD) [8] metrics.

We conducted the evaluation by applying known deformations to simple artificial sample images, and MR images of real cases of brain shift. Additionally, we computed other commonly used evaluation metrics such as Mutual Information (MI), Normalised Mutual Information (NMI), Entropy Correlation Coefficient (ECC), Kullback–Leibler Distance (KLD) and Correlation Ratio (CR) to demonstrate that their utility in assessing the quality of registration, and in particular the degree of structure misalignment and accuracy of surgical target localisation, is limited, as was also suggested by Rohlfing [7].

The paper is organised as follows: in Section 2, a brief description of the evaluation metrics used for assessing registration accuracy is provided; in Section 3 we present verification results for simple sample images, and five real craniotomy-induced brain shift cases; and finally, the discussion and conclusions are given in Section 4.

2. Materials and methods

2.1. Medical imaging data

We chose the pre-operative MR images which we previously used to build biomechanical brain models [20]. These five image datasets with brain tumours (cerebral gliomas) were randomly selected from a retrospective database of 859 intracranial tumour cases available at the Harvard Medical School's clinical affiliate Brigham and Women's Hospital in Boston [22]. Images were acquired using a 0.5 T open MR system in the neurosurgical suite. The resolution of the images is 0.85 mm × 0.85 mm × 2.5 mm. Consent for the use of the anonymised retrospective image database was obtained in accordance with the Institutional Review Board of the Children's Hospital (Harvard Medical School's clinical affiliate) in Boston (whose researchers accessed the database).

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