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A machine learning approach for real-time modelling of tissue deformation in image-guided neurosurgery

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ABSTRACT

Objectives: Accurate reconstruction and visualisation of soft tissue deformation in real time is crucial in image-guided surgery, particularly in augmented reality (AR) applications. Current deformation models are characterised by a trade-off between accuracy and computational speed. We propose an approach to derive a patient-specific deformation model for brain pathologies by combining the results of pre-computed finite element method (FEM) simulations with machine learning algorithms. The models can be computed instantaneously and offer an accuracy comparable to FEM models.
Method: A brain tumour is used as the subject of the deformation model. Load-driven FEM simulations are performed on a tetrahedral brain mesh afflicted by a tumour. Forces of varying magnitudes, positions, and inclination angles are applied onto the brain's surface. Two machine learning algorithms—artificial neural networks (ANNs) and support vector regression (SVR)—are employed to derive a model that can predict the resulting deformation for each node in the tumour's mesh.
Results: The tumour deformation can be predicted in real time given relevant information about the geometry of the anatomy and the load, all of which can be measured instantly during a surgical operation. The models can predict the position of the nodes with errors below 0.3 mm, beyond the general threshold of surgical accuracy and suitable for high fidelity AR systems. The SVR models perform better than the ANN's, with positional errors for SVR models reaching under 0.2 mm.
Conclusions: The results represent an improvement over existing deformation models for real time applications, providing smaller errors and high patient-specificity. The proposed approach addresses the current needs of image-guided surgical systems and has the potential to be employed to model the deformation of any type of soft tissue.

1. Introduction

Neurosurgery is technically challenging, requiring a high level dexterity from the surgeon. Exposed brain matter is extremely delicate: easily susceptible to injuries and with a limited capacity for regeneration, the risk of permanently damaging or rupturing critical anatomical structures is much higher than in other surgical procedures [1,2]. Recent developments in image-guidance technology have been able to provide crucial assistance to the surgeon, combining pre-operative scans with live imaging and tool tracking to offer intuitive navigation on digital displays. Optimal paths and entry points can be more easily visualised and followed during the intervention, thus minimising tissue damage, reducing operative times, and limiting the risk of complications. In particular, augmented reality (ar) has been gaining increasing attention from the clinical community. The term ar refers to an "image-enhanced operating environment" [3] generated by integrating a video feed from the operative space with a virtual rendering of subsurface anatomy and critical structures, which can be generated from pre-operative scans of the patient. AR is appealing as it allows surgeons to understand and judge the position of a hidden target, to follow predefined access routes without looking away from the screen, or to obtain visual force feedback [4,5]. The potential benefits of AR systems have been proven to be substantial, especially for complex procedures and for less-experienced surgeons [6].

Computing and displaying tissue deformation accurately and in real time during AR is key to maintaining a sense of realism and depth perception, and thus ensure optimal surgical precision. The virtual overlays must displace accordingly when a load is applied to positions in the proximity of their displayed location. Indeed, the inclusion of realistic deformation models have been shown to be crucial in many technical areas of image-guided surgery, such as registration and multimodal fusion imaging [7–11]. Failing to

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Table 1
Comparison of the main categories of deformation models.

	Accuracy	Real time	Adaptability
Finite element	++	−−	−
Mass-spring	−	+	++
Meshless	+	−	−
Boundary element	+	−	−
Geometry-based	−−	++	−

address this issue can lead to losses in performance quality and potentially fatal errors [6,10,12–15].

However, correctly predicting the deformation of an anatomical target in real time is particularly challenging. While numerous methods exist to compute the deformation of soft tissue, they are generally characterised by a compromise between speed and accuracy, due to the complex mechanical behaviour of biological tissue [16]. In fact, the high processing time required for the computation of non-linear biomechanical models is thought to be one of the main factors currently preventing accurate real-time prediction of organ deformation in image-guided surgery [17]. Furthermore, patient-specificity is an additional requirement that must be taken into account: models developed for surgical applications need to be specific to the anatomical geometry of the patient's brain and pathology, which can be extremely variable in size, location, and tissue composition [18].

2. Background: deformable models

Out of the currently available deformable models, non-physical or geometry-based models are by far the fastest and can be computed in real time, since they are based on a mathematical representation of the object's surface [19,20]; however, they lack the accuracy required reliably for medical applications [16,21]. On the contrary, physics-based models can approximate the non-linear behaviour of soft tissue much more accurately [20], but their high computational load and storage requirements do not allow them to be computed in real time [22]. These include mass-spring models (MSM) [13,16,21,22], the boundary element method (BEM) [20,23], the meshless method [18] and the widely used finite element method (FEM) [8,24,25]. Table 1 summarises the capabilities of the aforementioned approaches in terms of accuracy, real-time computation, and adaptability to topological changes—meaning how easily the model can be updated intra-operatively when the anatomy is altered.

Because of the accuracy required for neurosurgery, FEM represents an ideal choice to predict soft tissue deformation. It is a numerical technique that computes an approximate solution to a system of partial differential equations (PDEs) by subdividing the volume of the object considered into smaller parts—finite elements. The solution to the PDE system is solved with an approximation at each node of the resulting mesh, which can be further expanded to any point in the continuum domain (*i.e.* the object being considered) through interpolation [26]. FEMs have been widely adopted in the literature for various kinds of biomechanical modelling, and particularly for medical applications, due to its high accuracy [23]. The continuum approach not only allows for internal anatomy to be modelled in detail, but also offers the possibility to include information about anisotropy of the tissue, and has been proven to correlate with clinical and animal studies [27,28].

A principal limitation of this approach is its extremely slow computational speed for complex, non-linear problems. Even with special-purpose parallel hardware and software real-time computation is not currently feasible [29]. Even the most recent efforts in this direction, which use implicit FEM formulations and graphical processing unit (GPU) (rather than central processing unit (CPU)) parallelisation, have not obtained optimal real time performances despite much faster computational times [13]. In any case, it is unrealistic to expect current surgical theatres to be widely equipped with such large-scale, expensive, and specialized computers.

An attractive alternative to obtaining rapid, high accuracy reconstruction is to represent the results of FEM simulations in a simpler format, taking advantage of the fact that a different model can be calculated for each patient, and that the range of forces applied in neurosurgery is generally limited to values below 1 N [30]. It is therefore only necessary to derive and formalise a model that deals with very specific and limited set of situations and conditions. Gillies and Bourmpos [31] have proven that it is possible to encode finite element solutions into a less computationally-expensive model. They used fuzzy logic and neural networks to deform a sphere with the output of a haptic device for surgical training. However, only a very limited number of possible deformations are included, and their models do not work well for unknown forces. Mosbech et al. [32] also proposed a data-driven method for soft tissue deformation computation, implementing principal component analysis (PCA) on data from *in vivo* measurements, yielding promising results. However, the reliance of the model on PCA may not allow the non-linearity of soft tissue behaviour to be accurately predicted; indeed, the errors obtained in the study are too large for surgical applications (>1.4 mm). The results show nonetheless the potential to improve on this method. We believe that a data-driven model that takes into account the complexity of soft tissues' biomechanical properties could achieve much lower errors with comparable instantaneous speed.

3. Aim

In this paper, we propose an approach to derive a realistic and computationally-inexpensive deformation model using machine learning on a large number of data obtained from patient-specific fem simulations. The simulations are performed in advance on a polygonal mesh generated from pre-operative magnetic resonance imaging (MRI) scans. The results are then fed to learning algorithms that perform regression in order to predict the deformation of a pathology in real time, given the knowledge of quantities measurable in a surgical theatre—namely information about the anatomical geometry and the force applied by the surgeon. A brain tumour will be used to illustrate the type of delicate structure typically encountered in neurosurgical procedures. The proposed method, illustrated in Fig. 1, is based on the assumption that at least one of the tools used in the intervention is equipped with a force sensor and an accelerometer or gyroscope, such as in force feedback systems [1,4,33–35].

4. Data acquisition method

4.1. Mesh generation

In order to simulate the process with which the model would be derived before a surgical intervention, a mesh of a brain afflicted with a tumour was generated from an MRI scan. A number of MRI images were obtained from the Repository of Molecular Brain Neoplasia Data [36], selecting one with sufficiently high contrast and resolution to guarantee high quality segmentation. BrainSuite [37] was used in order to automatically segment the brain in regions containing white matter (WM), grey matter (GM), cerebrospinal fluid (CSF), and the skull. The skull was removed, and the WM and GM were considered to have identical properties [24,38,39]. Furthermore, the CSF was not incorporated in the model. This choice was motivated by the fact that fluid-filled regions (such as ventricles and meninges) are thought to affect the deformation of the

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