A Computational Framework to Optimize Fiducial Marker Placement to Account for Intraoperative Tissue Deformation

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Introduction: For the purpose of minimally invasive surgery, imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound (US) are utilized for procedure preplanning and intraoperative monitoring. In the preplanning phase, the geometry of the region of interest (ROI) is reconstructed, and is later registered with the observed ROI shape during surgery. Unfortunately, a notable difficulty with this two-phase approach is the potential mismatch of the ROI between these two phases, which diminishes the impact of preplanning.

The current study aims at bridging the gap between the two imaging stages by optimizing the fiducial marker (FM) layout. While it is technically difficult and computationally expensive to reconstruct the ROI in real time, using an intraoperative imaging modality, FM tracing can be used for predicting the treated and potentially deformed ROI. Recent study[1] has demonstrated the feasibility of reconstructing ROI in real time by tracking FM positions, in combination with the prior knowledge of the ROI geometry and physically based simulation. In this study, a computational framework is proposed for optimizing the number and layout of FM, thereby improving the outcome out of the clinical operation.

Materials and Methods: The current study uses a head-and-neck tumor model constructed from CT scanning to demonstrate the computational framework. The proposed framework consists of three main steps: (i) creation of ground truth deformations by applying random and smooth force fields on the tumor surface using a physically based deformation model, (ii) reconstruction of the deformed shapes by tracing FMs, and (iii) optimization of FM layout using the so-called simulated annealing (SA) approach.

Results and Discussion: In order to evaluate framework performance, the optimized FM layouts are compared with empirically selected FM layouts such as FM placements at high curvature points, metric k-centers, and axis-aligned extrema. Given the tumor size of $19.9 \times 36.3 \times 67.9 mm^3$, a maximum displacement of 20 mm on tumor surface is chosen for the ground truth deformations to reflect the typical range of deformation. Starting from an arbitrary FM layout, our SA algorithm is able to find a FM layout that outperforms empirical selections. The maximum surface offset between the ground truth and our FM-optimized reconstruction is 3.21 mm on average. This equals to a 50% decrease in the reconstruction error when compared with the reconstructed shapes from empirically selected FM layouts. The presented framework can be applied to the general problem of FM-based deformation prediction that can account for a wide range of external force configurations.

Conclusions: A proof of concept for a computational framework to optimize FM layout for tracking tissue deformation has been developed. The reconstruction accuracy using the optimized FM layout is superior to those using empirical selections by 50%. Applications of FMs and the presented SA algorithm can bridge the gap between preplanning and intraoperative US imaging for the purpose of tumor destruction.

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