A Computational Framework to Optimize Fiducial Marker Layout for Tracking Tumor Deformation

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For the purpose of minimally invasive surgery, it is often desired to create an accurate geometric model of an anatomical region of interest (ROI), such as a tumor or an organ. While it is quite expensive and technically difficult to reconstruct the ROI in real time when the patient is on the operation table, fiducial markers (FM) tracing can facilitate such a reconstruction process, combined with prior knowledge of the tumor shape, the FM relative location, and the application of finite element simulations. This concept has been demonstrated recently for the case of head-and-neck cancer, using prior CT scanning and plausible tumor deformation between prescanning and surgical operation. The current study proposes a computational framework for searching the optimal number and layout of FM, thereby minimizing the cost of operation. The current investigation advances in three main steps: (i) creation of virtual benchmarks, (ii) prediction of deformation between scanning and operation, and (iii) FM layout optimization. Virtual benchmarks are created by applying random smooth forcefields on the tumor surface. These random forcefields are obtained from the eigendecomposition of the discretized Laplace-Beltrami operator. Deformation prediction is carried out by applying the smooth force fields, given the locations of the FMs and practical constraints. Finally, simulated annealing (SA) is used to search for the FM layout that yields the best prediction accuracy. Starting from a random FM layout, our approach is capable of finding a FM layout that outperforms FM layouts that are empirically chosen, such as FM placements at axis-aligned extrema, high curvature points and metric k-centers. Given 10 mm as the maximum induced displacement on the tumor surface, the maximum surface offset error between the benchmarks and our FM-optimized predictions is around 1.3 mm. This represents a 40% decrease in prediction error compared to the empirically chosen FM layouts. This study further demonstrates that FMs in certain regions other than empirical selections can capture the subtlety in deformations, and thus improve the prediction accuracy. Our framework can be applied to the general problem of FM-based deformation prediction that can account for a wide range of external load configurations.