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Registration of Deformed Tissue with a Geometry-Contrastive Transformer Approach

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INTRODUCTION

Breast cancer affects over 2.3 million people worldwide each year. In its early stages, the disease is typically treated surgically through either mastectomy, involving complete removal of the breast, or lumpectomy, a breast-conserving procedure in which only the tumour and adjacent tissue are excised. Lumpectomy is often preferred because it preserves breast tissue and is associated with lower morbidity, including reduced pain, fewer infections, and less impact on quality of life.

Despite these advantages, a major challenge in lumpectomy is achieving accurate tumour localization, as intraoperative tissue deformation can compromise surgical precision. Current localization methods, both wire and non-wire based, have proven clinically effective but remain invasive, frequently resulting in patient discomfort [1].

Computational approaches such as Finite Element Methods (FEMs) and neural networks have been investigated as non-invasive alternatives for tumour localization. While FEMs provide biomechanically accurate modeling of tissue deformation, their high computational cost limits real-time applicability. Neural networks, by contrast, offer faster performance but often struggle to generalize across patients with different breast geometries [2].

To address these challenges, we introduce the Geometry-Contrastive (GC) Transformer, a novel deep learning framework specifically designed to deliver accurate, generalizable, and real-time tracking of deformable tumours in dynamic breast tissue [3].

MATERIALS AND METHODS

The GC-Transformer was developed using finite element meshes derived from 10 anatomically realistic breast models that differed in node density and mechanical properties to promote generalization. To simulate realistic tissue behavior, forces of varying magnitudes were applied at multiple surface points, producing 1,000 deformation cases per model and yielding a dataset of 10,000 meshes. This dataset was divided into 8,000 training, 1,000 validation, and 1,000 testing samples to enable reliable evaluation and minimize overfitting.

Model training proceeded in three stages: first, learning FEM-based deformations; second, employing Central Geodesic Contrastive (CGC) loss to enhance geometric fidelity; and third, incorporating Latent Isometric Regularization (LIR) to ensure consistent pose transfer.

RESULTS AND DISCUSSION

In contrast to conventional models that require patient-specific retraining, the GC-Transformer demonstrates strong generalization across different breast anatomies, enabling accurate tumour tracking without customization. It achieves low localization errors of 0.22 mm in training and 0.27 mm in testing, while preserving geometric consistency and reducing computational demands. As shown in Fig. 1, the model effectively transfers shape details between identity (simulation) and pose (ground truth) meshes.

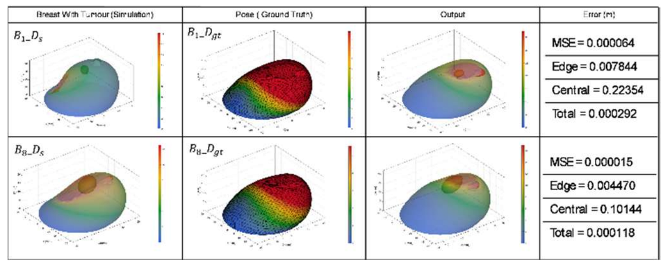

Fig1 Combining identity and pose meshes to apply the pose's shape details to the identity mesh.

CONCLUSIONS

This study introduces the GC-Transformer, trained on FEM based simulations, to enable precise tracking of deformable breast tumours in the context of simulated lumpectomy. By leveraging geometric contrastive learning, the model demonstrates strong capability in capturing complex tissue deformations, thereby offering high potential for accurate and reliable tumour localization during surgery.

Future work will focus on integrating real-time 3D scanning and augmented reality platforms to provide surgeons with enhanced intraoperative guidance and translate the proposed approach into clinical practice.

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