Fiducial Marker-Based 3D Freehand Ultrasound for *in vivo* Muscle Morphology Quantification

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Summary

This study proposes the integration of a fiducial marker-based tracking method and a linear regression model for 3D freehand ultrasound (3DfUS) probe tracking. A 3D-printed dodecahedron with fiducial markers was tracked using an RGB camera, and its pose was mapped to global coordinates using a linear regression model trained with ground truth data from a motion capture system (Mocap). The proposed method demonstrated reliable tracking performance, achieving low errors in positional predictions. Future work will focus on the integration of the tracking method with an established 3D muscle reconstruction pipeline. This approach holds promises for enabling 3DfUS reconstruction while maintaining portability and cost-efficiency.

Introduction

3DfUS combines traditional B-mode ultrasound with a Mocap system to reconstruct 2D ultrasound frames into a 3D volume, allowing for accurate quantification of muscle morphology [1]. Reliable probe tracking is crucial for achieving high-quality reconstructions. While traditional optical tracking methods provide high precision, they require a specialized laboratory setup, limiting the feasibility in clinical settings. This study explores an alternative approach using an RGB camera and fiducial markers to develop a more portable solution for 3DfUS applications. Furthermore, we applied a linear regression model trained on Mocap data to correct fiducial tracking errors.

Methods

A fiducial marker-based system was designed, inspired by [2]. A dodecahedron with 22.5 mm edge length was designed in CAD and 3D printed. Twelve fiducial markers from the AprilTag family, each with 20 mm edge, were printed using a laser printer and glued to the faces of the dodecahedron. Video streams were captured using an RGB camera (LUCID PHX-CS016, 60 Hz), and marker detection and pose estimation algorithms were applied to determine the dodecahedron's translation and rotation vectors relative to the camera. Simultaneously, ground truth data was collected using a Mocap system (Vicon V16, 100 Hz), tracking a cluster of four reflective markers attached to the dodecahedron. As a pilot evaluation, we recorded seven repeated linear movements, each approximately 20 cm in length (Fig 1). A linear regression model was trained to map the fiducial marker-derived pose estimation to the global coordinate system, enabling trajectory prediction of the dodecahedron. A leave-one-out cross-validation approach was used, where six trials were used for training and the remaining trial for testing, iterating through all trials. The root mean squared error (RMSE) between the ground truth and both the raw and predicted fiducial marker-based trajectories were computed.

Results and Discussion

Compared to the raw fiducial marker, the regression model demonstrated improved performance, with an RMSE of 0.68 ± 0.25 cm, 0.42 ± 0.16 cm, and 0.11 ± 0.04 cm for the x, y, and z components, respectively. The greatest improvement was observed in the direction of the movement in y component (raw fiducial RMSE: 2.34 ± 0.87 cm), while the largest error occurred in the x-component, which corresponds to the camera's depth axis.

Several factors can influence the tracking accuracy of fiducial markers, including insufficient lighting, motion blur, camera resolution constraints. To improve accuracy and robustness, we plan to integrate advanced machine learning methods (e.g., CNNs and RNNs) for a better trajectory estimation. Future work will focus on optimizing marker arrangement, expanding the dataset to include various probe movement scenarios, and further refining the regression model.

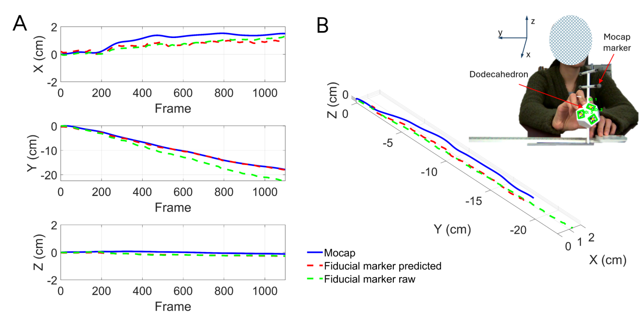

Figure 1: A) Trajectory along each axis; B) 3D trajectory.

Conclusions

This study demonstrates a pilot study evaluating the feasibility of using a fiducial marker-based system combined with machine learning for 3DfUS probe tracking. By training a linear regression model, the system effectively predicted the position of the dodecahedron, achieving small errors in most components. Further integrating advanced techniques, such as CNN and RNN, could enhance marker detection, pose estimation, and trajectory analysis, improving overall robustness and precision.

References

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