Hierarchical 3D Registration of the Hand and Wrist from Sequential 3DCT

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INTRODUCTION: Accurate data on *in vivo* skeletal joint and implant kinematics can be insightful in addressing a wide range of questions in musculoskeletal research and health care. Projective imaging modalities such as BVR are ill suited to anatomy with multiple occlusions or bony overlap, as in the hand, wrist or foot. Sequential 3D CT and 4DCT are utilized in these research domains with increasing frequency. Tracking these smaller, low contrast, individual bones can be extremely challenging. In this work, we present Hierarchical 3D Registration (3DH), a 3DSlicer module for efficient, semi-automated registration of multiple bones imaged with sequential 3DCT or 4DCT.

METHODS: The Hierarchical 3D Registration module in 3D Slicer is designed for skeletal motion tracking in volumetric image modalities: static or dynamic computed tomography (3DCT and 4DCT, respectively). The module facilitates semi-automatic registration via a bone hierarchy, intelligent sub volume extraction, boundary-tests and forward propagation of successful registration to subsequent data frames. As input, 3DH requires 1) previously segmented bones loaded as STL models, arranged by the user in a drag and droppable hierarchy, 2) the source volume from which the bones were segmented and, 3) the target volume sequence. To generate the target volume sequence, the Slicer DICOM module can be used to seamlessly import 4DCT directly as a sequence node into the scene, while the Sequences module can be used to construct a sequence node from a series of 3D CT scans. The use of bone surface models provides 3D visual interaction, fast initial alignment input and provides qualitatively verified registration. The underlying sub-volume region of interest (ROI) of a given bone model is extracted from the source volume and from the target volume in each frame. Using ITKElastix (https://elastix.dev/), the optimal volumetric registration is resolved between target and source sub volumes and is applied to the bone model for visual confirmation. Arranging bone models in a hierarchy in 3DH is intended to reflect the anatomical relationships between parent and child bones, and is inspired by our previous approach.[1] Starting with the root bone, the entire hierarchy is registered in each frame, traversed in a breadth-first manner. Once the optimal transformation for a bone is found, it is propagated to all child bones in the hierarchy, adjusting the starting position for each subsequent bone in the current frame. This hierarchical approach enhances the optimization process by accounting for motion constraints and thereby improving the alignment accuracy throughout the sequence. To validate the method, hand and wrist of 9 volunteer subjects without thumb carpometacarpal pathology, pain or radiographic disease were CT scanned in wrist neutral and 10 thumb range-of-motion or task poses. The radius, trapezium (TPM) and first metacarpal (MC1), previously segmented from the neutral scan (resolution 0.39 x 0.39 x 0.625mm^3), were registered using 3DH for all frames and volunteers. The same data were previously registered using Markerless Registration (MR), via tissue-classified distance fields.[1] Transformation matrices from neutral to pose for each bone were exported. Relative MC1 motion, resolved in TPM articular coordinate system (CS) was express as helical axis of motion rotation (phi) and translation (mm). Bland-Altman analysis was used to quantify the bias, the standard deviation (SD) of the bias, and the 95% limits of agreement (LOA) between paired MR and 3DH registered helical axis of motion parameters.

RESULTS: Across all subjects and tasks, the bias (SD) of the rotation of the MC1 in TPM CS between MR and 3DH was -0.05° (0.69°). The 95% LOA of the rotations were -1.4° and 1.3°. When comparing the translation of the MC1, the bias (SD) was -0.05 mm (0.32 mm). The lower and upper 95% LOA for translation were -0.68 mm and 0.57 mm. One outlier result with a difference of 5.3° and 2.6 mm was computed. On further investigation, a previously unrecognized error in MR MC1 registration was revealed, while the MC1 was successfully registered using 3DH (Figure 1., arrows Figure 2.).

DISCUSSION: Hierarchical 3D Registration enables the semi-automatic tracking of multiple bones in 3DCT or 4DCT. Herein, we reanalyzed data of 9 subjects performing 10 thumb tasks, which were previously registered via our markerless registration method.[1] The accuracy of our MR method was previously established as less than 0.3 mm in translation and less than 0.4° in rotation, on average, for multiple carpal bones in 3DCT volume images with a voxel resolution of 0.31 x 0.31 x 1mm^3. The agreement between parameters calculated using MR and the 3DH was less than 1/10 of these values, substantiating the accuracy of our newly implemented 3DH registration module. The qualitative analysis of the outlier of agreement showing an unrecognized error from our previous method, which was successfully registered using 3DH, highlights 3DH's improved accuracy.

SIGNIFICANCE: We have developed and deployed a free, open-source software solution for musculoskeletal registration from 3D and 4D CT datasets. Our solution is especially useful for tracking small bones, such as those in the wrist/hand and ankle/foot. Our overarching goal of developing open-source solutions for image-based kinematic analysis is to increase access to high-quality standardized tools, ultimately providing a dynamic platform for the sharing of novel analysis algorithms, methodologies, and data. This should promote collaboration, simplify the harmonization of methods for large multi-center research studies, lower the bar of entry for early-stage investigators, and facilitate translation towards clinical use.

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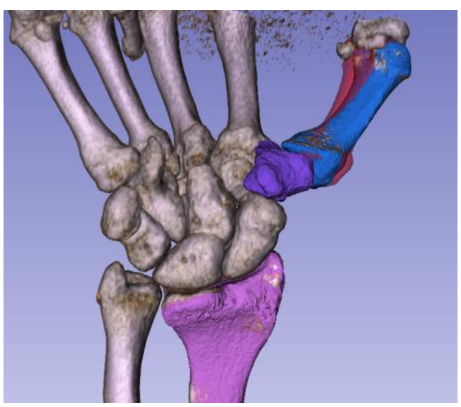

Figure 1. Volume rendering of the source volume CT (off-white) overlaid with 3DH-registered radius (pink), TPM (purple) and MC1 (blue). Prior Markerless Registered MC1 (red) reveals visible registration error.

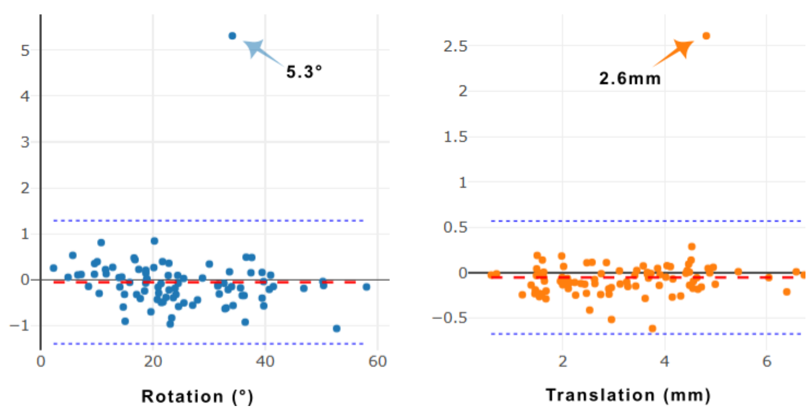

Figure 2. Bland-Altman analysis across all subjects and tasks for Hierarchical 3D Registration against established markerless registration. The kinematic variables analyzed were the relative helical rotation angle and MC1translation from neutral to pose, as though the TPM were fixed. Outliers in agreement highlighted by arrows and values annotated.

REFERENCES: 1. Marai GE, Laidlaw DH, Crisco JJ. Super-resolution registration using tissue-classified distance fields. IEEE Trans Med Imaging. 2006 Feb;25(2):177–187. PMID: 16468452.