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DETERMINING THUMB OPPOSITION KINEMATICS USING DYNAMIC CT: OPPERTUNITIES AND CHALLENGES FOR MUSCULOSKELETAL MODELLING

[1] Faes Kerkhof, [2] Eddy Brugman, [1]Priscilla D'Agostino, [1,2]Filip Stockmans, [3]Ilse Jonkers, [1]Evie Vereecke

[1] Department of Development and Regeneration @ Kulak, KU Leuven, Belgium
[2] AZ Groeninge, Kortijk, Belgium
[3] Department of Kinesiology, KU Leuven, Belgium
E-mail: Faes.Kerkhof@kuleuven-kulak.be

INTRODUCTION

Characterisation of in vivo -thumb kinematics allows precise biomechanical analysis of healthy and pathological joint movement. When movement characteristics and musculoskeletal structure are combined, more insight can be gained on the relation between anatomy and function in native and diseased joints. However, due to the complex 3D arrangement of the small carpal bones with multi-planar range of motion and skin movement artefacts, it is difficult to determine the in vivo movements using standard 3D motion capture techniques. Thumb kinematics have been investigated using various methods, e.g. static CT scans, fluoroscopy, high-speed video, opto-electric- and electromagnetic-based systems. However, none of these methods allows direct evaluation of 3D bone movement. The most important drawback of the various motion tracking systems are the skin motion artefacts, in particular for the carpal bones. Fluoroscopic techniques are difficult due to the complex, superimposed arrangement of the small carpal bones that are difficult to individualize on 2D projections. To overcome these problems, and to acquire an accurate characterization of the 3D kinematics of bones involved in thumb opposition, a dynamic CT motion capture protocol was developed and tested.

METHODS

A (unfixed) cadaveric human forearm was placed in a custom-made motion simulator that controls a passive thumb opposition motion. Firstly, a static high-resolution CT scan of the entire specimen in resting position was acquired (Field of View (FOV): 25 cm, slice thickness: 0.625 mm, voxel size: 0.15 mm^3). Thereafter, a dynamic CT scan (FOV: 12 cm, slice thickness: 0.625 mm, voxel size: 0.036 mm^3) of the region of interest, i.e. styloid of the radius, scaphoid, trapezium and first metacarpal, was taken while the motion simulator was set to passively impose a maximal thumb opposition/reposition motion within 5 seconds at a constant speed. During a full thumb opposition/reposition sequence, a time series of 19 CT frames was collected.

Post-processing software (Mimics 14.12) was used to manually segment the radius, scaphoid, trapezium and part of first metacarpal (MC1) from the static HR scan of the entire forearm as well as from each frame of the dynamic scan. This resulted in a time series of 3D bone reconstructions, which were exported as STL-files and imported in Matlab. From the static scan of the entire forearm, a local coordinate system was defined according to standards of the International Society of Biomechanics. The part of the radius that was visible on the dynamic scan was registered onto the mesh of the static scan radius based on iterative closes point algorithm (ICP). Hence, the bone meshes of each frame of the dynamic scan were transformed in the coordinate system of the static radius reference system. The displacement of each bone relative to the static radius was calculated by comparing the displacement of the computed centroids of the individual bones (under the assumption of homogenous density. Using custom Matlab code, the translation vector and rotation matrix were calculated between the bone positions in the different time frames and the instantaneous and average helical axes were calculated for each joint (Figure 1).

To validate the arthrokinematics obtained during the dynamic CT, an additional dynamic CT scanning acquisition was made during which a piece of bone on a Plexiglas rod was moved at a constant speed towards a predetermined angle. 3D reconstruction of these reference positions scans were generated using Mimics and the 3D angles between the bony segments were calculated as described above using custom code. The angles calculated based on the 3D reconstruction of the individual bones were compared with the predetermined angle settings of the device.

RESULTS AND DISCUSSION

During passive thumb opposition, movement in the radiocarpal, scaphotrapezial and trapeziometacarpal joints was confirmed. The maximal displacement of the centroid relative to the static radius can be found in Table 1. Clinical workability was shown with a CT dose index as low as 292 mGy cm for one dynamic scan. The 4D CT images were of high quality, only minor motion blurring and no banding artefacts were shown. The preliminary validation tests show large similarities between the predetermined angles of the bone piece and the calculated angles with an intra-class correlation > 0.6.

CONCLUSIONS

Dynamic CT scanning is a valuable method to directly quantify movements of individual (meta)carpal bones during manipulative tasks. Its main advantage is that it allows direct acquisition of bone geometry during thumb movement, without skin motion artefacts and with a limited radiation dose. As such, this technique enables accurate investigation of 3D thumb kinematics in living subjects, making it a promising method to explore the arthrokinematics of native and diseased joints. Drawbacks of the technique are the limited field of view and the need for manual segmentation of the bones, where the inter- and intra-observer reliability needs to be guarded.

Further validation of this technique will open possibilities to investigate pathological joint function in the presence of degenerative joint disease or total endoprosthesis

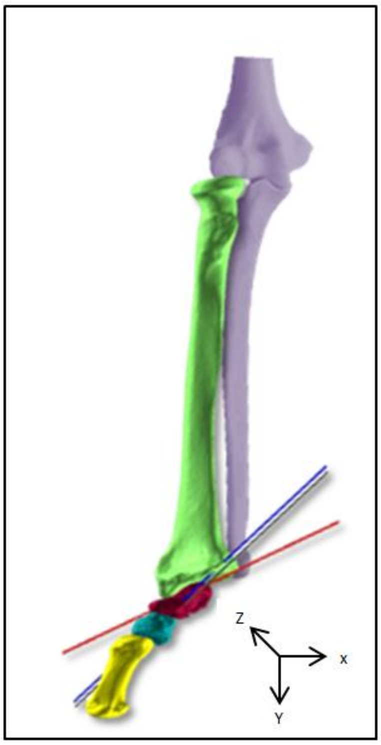

Figure 1: Medial view on a 3D reconstruction of the right forearm with average helical axes. Radius (green),scaphoid (red), trapezius (blue), MC1 (yellow). Average helical axes: scaphoid (red),trapezium (grey), MC1 (blue).

Table 1: Maximal displacement of the centroid of the scaphoid and trapezium in X, Y and Z direction relative to the static radius in mm. The origin of the coordinate system was placed on the medial side of the radial head. The X-axis points towards the radial styloid, Y-axis points towards the dorsal tubercle of the radius and the Z- axis was placed perpendicular to the Y-axis (see Figure 1).

	X (mm)	**Y** (mm)	**X** (mm)
Scaphoid	-0.078	0.493	0.363
Trapezium	-0.787	0.906	3.365