

SIMULATED CONTACT FORCES IN THE TRIQUETRUM-HAMATE JOINT DRIVEN WITH SUBJECT SPECIFIC *IN-VIVO* KINEMATICS

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INTRODUCTION

The articulation of the triquetrum on the hamate (TqH) has been alternatively described as a rotation on the saddle shaped surface of the hamate, a translation along a helicoidal or screw-shaped path, and a rotation on the convex oval surface of the hamate¹. Recently TqH motion was studied along the dart thrower's path² (DTM), wrist motion from radial extension to ulnar flexion, that some suggest to be the most important functional motion of the joint³. It was shown that the articulation of the triquetrum on the hamate was roughly helicoidal as the triquetrum rotated around the convex surface of the hamate. It was qualitatively observed that the triquetrum maintains a distal course along the hamate until it reaches a prominent distal ridge at which point it begins a volar course. However it is difficult to determine whether or not the triquetrum is interacting with the distal ridge of the hamate using standard kinematic measures. The purpose of this study was to compute the orientation and location of the contact force between the triquetrum and hamate as the wrist moved along a dart thrower's path.

METHODS

Following IRB approval and informed consent, 3 male and 3 female, right-handed volunteers, average age 24.3 ± 2.8 yrs were screened for any injury or diseases that would affect carpal motion. The right wrist of each subject was CT scanned using a custom designed jig in the neutral wrist position and 5 static positions along a hammering path. Positions along the path included -40° (windup), -20° , 0° (hammer handle perpendicular to forearm), 20° , and 40° (impact). Separate tessellated 3-D bone surface models representing the outer cortical shell of the third metacarpal, radius, hamate, and triquetrum were generated through segmentation of the neutral CT scan in Mimics 9.11 (Materialize, Leuven, Belgium).

Six-degree-of-freedom global transforms describing the motion of each bone from the neutral wrist position to each hammering position were calculated using a previously established markerless bone registration technique². Transforms describing the relative motion of the TRQ with respect to the HAM along the hammering path were then computed. Cartilage articular facets of the triquetrum and hamate bones were approximated using landmark features of the CT scans, verified by comparison with a high resolution μ CT volume image of a cadaver triquetrum and hamate (age 62). The scans were generated at a resolution of $60 \mu\text{m}$ (isometric voxels) using a desktop micro-computed tomography system (μ CT 40, Scanco Medical, CH). The soft tissue and bony surfaces were manually segmented using Mimics 13. A single three-dimensional (3-D) surface model was generated from the μ CT datasets using minimal smoothing and point reduction. These surfaces were used to identify cartilage on the articular surfaces of the CT bone surfaces (**Fig. 1**). These regions were thickened between 0.5mm-0.75mm, based on known cartilage thickness and with the requirement that the articular surfaces were in contact throughout the entire range of motion studied. These modified models were then smoothed using Geomagic Studio 11 (Geomagic Inc, Durham, NC) and imported into LifeModeler (LifeModeler Inc, San Clemente, CA). LifeModeler was used to compute the contact force between the triquetrum and hamate throughout the hammering path based on the amount of intersection of the two surface meshes. Contact force location and orientation were reported in a capitate-based inertial coordinate system because it aligned well with the dorsal-volar and proximal-distal directions of the hamate. Linear regression was then performed on both location and orientation of the force vector in the proximal-distal and dorsal-volar directions to examine the relationship of each

of these variables with the independent variable of wrist position along the hammering path.

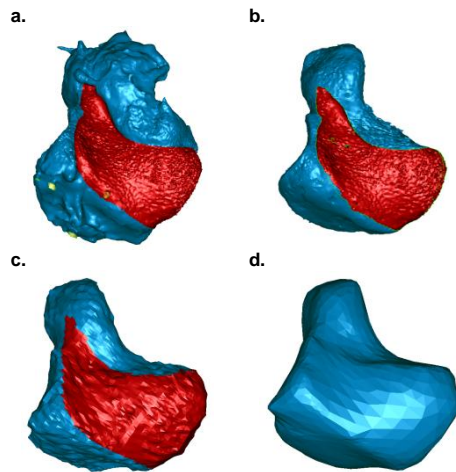


Figure 1. Smooth regions (red) of soft tissue segmented from μ CT (a) were matched with the articular surfaces of the bone surfaces (b) to identify cartilaginous regions. Similar features on each subject's CT bone surface were used to identify the articular region (c). This region was then thickened between 0.5mm-0.75mm, and the entire body was smoothed for use in the LifeMOD simulation (d).

RESULTS AND DISCUSSION

As the wrist moved from radial-extension toward ulnar-flexion the contact force vector significantly ($P < 0.0001$) travelled 7.2 ± 2.1 mm in the distal direction and 4.2 ± 1.7 mm in the volar direction. The force vector swept through a mean angle of $58.1^\circ \pm 7.0^\circ$ across subjects. The orientation of the force vector significantly ($P < 0.0001$) shifted from a more proximal (but still distal) orientation to a more distal orientation and from a dorsal to volar orientation as the triquetrum moved distally and volarly along the hamate. We qualitatively observed that at the strike position of the hammering task, the contact force vector was located on or near the distal ridge of the hamate (Fig. 2).

CONCLUSIONS

We measured the triquetrum-hamate articular contact force using a rigid body spring model driven by *in vivo* kinematics of the triquetrum with respect to the hamate along a dart throwers path. Our visual understanding of the triquetrum translating along an oblique path over the hamate from proximal and dorsal to distal and volar as the wrist

moved along the dart throwers motion was confirmed by the changes in the computed articular contact forces. We found that as the triquetrum moved distally on the hamate the contact force shifted from its location on the oval articular surface of the hamate to the distal ridge. The orientation of the force vector also shifted from a more dorsal to a volar direction. These data suggest that the distal ridge of the hamate does indeed act as a guide for the triquetrum as the wrist moves through a dart thrower's motion. Primary limitations in this study include the imposed penetration of the articular surfaces of the triquetrum and hamate, as well the lack of adjacent carpal articulations and ligament constraints. Future work will include these structures and the use of kinematics to train a model for forward dynamics simulation.

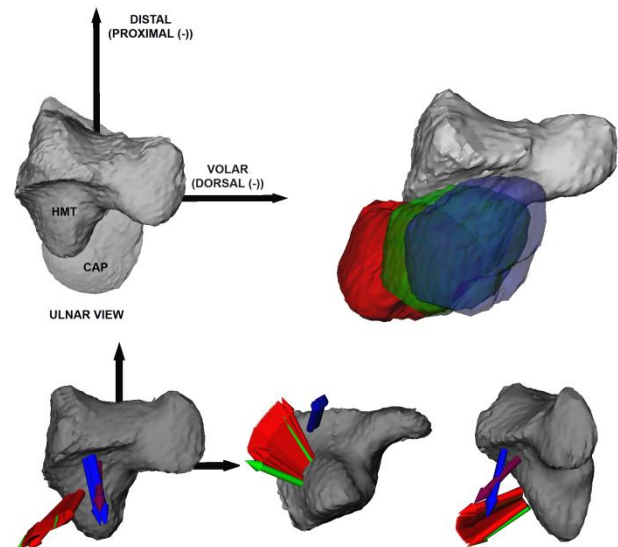


Figure 2. The hamate (HAM) in the capitate (CAP) coordinate system space (Top left). The positions of the TRQ (colored) on the HAM (grey) of a typical subject at the windup (red; wrist at -40°), neutral hammer (green; wrist at 0°), and impact (blue; wrist at 40°) wrist positions (Top right). Three views of the contact force as it sweeps through the range of wrist positions (Bottom Panel). As the triquetrum moved distally on the hamate, the force vector shifted from a distal location and more dorsal orientation (red vector) to a proximal location and a more volar orientation (blue vector).

REFERENCES

1. Moritomo *et al.*, *J Hand Surg [AM]*, 2003.
2. Kamal *et al.*, *ORS Trans* **35**, 2010.
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