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A Method for Defining Carpometacarpal Joint Kinematics from Three-Dimensional Rotations of the Metacarpal Bones Captured *In Vivo* Using Computed Tomography

James H Buffi^{1,2}, Joseph J Crisco³, and Wendy M Murray^{1,2,4,5}

¹Dept. of BME, Northwestern University, Chicago, Illinois

²Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, Illinois

³Dept. of Orthopaedics, Brown University and Rhode Island Hospital, Providence, RI

⁴Research Service, Edward Hines Jr., VA Hospital, Hines, Illinois

⁵Dept. of PM&R, Northwestern University, Chicago, Illinois

Abstract

The carpometacarpal (CMC) joints of the hand facilitate motion of the metacarpals and are critical for functional tasks, especially tasks involving precision grasping. Despite their importance, only limited data describing metacarpal kinematics exist. In this short communication, we quantified *in vivo* metacarpal kinematics from a single subject and used these data to develop the kinematic functions necessary to add rotational degrees of freedom at the CMC joints to a biomechanical model of the hand. Computed tomography (CT) was used to capture three-dimensional rotations of the metacarpal bones of the ring and little fingers of the subject in seven different static postures, chosen to position the fourth and fifth metacarpals throughout a functional range of motion. The CT images were manually segmented, yielding digital surface representations of the metacarpals in each posture. From the surfaces, principal axes of rotation were defined by calculating orthonormal bases of the surface vertices. The three-dimensional rotations of the fourth and fifth metacarpals were quantified in each posture about their principal axes, relative to a designated reference posture. For both metacarpals, ranges of rotations were computed about the principal axes across all seven postures. From the processed data, single axes and angles were calculated that were equivalent to the three dimensional ranges of motion. Finally, kinematic functions were defined that enabled modeling of the formation of a metacarpal arch by movement of the fourth and fifth CMC joints as one degree of freedom, coupled to a single generalized coordinate.

Keywords

Carpometacarpal Joint Kinematics; Computed Tomography; Metacarpal; Finger; Hand; Ranges of Motion

Short Communication Submission Corresponding Author: Wendy M. Murray, PhD 345 E. Superior St., Room 1408B Chicago, IL 60611, Telephone: (312) 238-6965, Fax: (312) 238-2208, w-murray@northwestern.edu.

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Introduction

Over eighty percent of activities of daily living involve grasping or seizing objects with the hand (Katz et al., 1970). The carpometacarpal (CMC) joints of the hand and wrist (the five joints that articulate the distal row of carpal bones and the proximal bases of the five metacarpals) are particularly important for prehensile tasks involving the opposition of the ring and little fingers with the thumb, such as during precision grasping. In addition, impairment of the CMC joints can weaken grip strength (Bora and Didizian, 1974).

The CMC joints of the fingers are difficult to study and there is a paucity of kinematic data characterizing their function, especially relative to other joints in the hand. For example, kinematics of all of the joints of the thumb (including its CMC joint) have been studied *in vitro* (Hollister et al., 1992; Hollister et al., 1995) and *in vivo* (Chang and Pollard, 2008; Goubier et al., 2011). For the index, middle, ring, and little fingers, radiologic methods have also been developed *in vitro* to quantify motion at the MCP, PIP, and DIP joints using the principal axes of the metacarpal and phalangeal bones (Degeorges et al., 2004). In contrast, the kinematic information available for the CMC joints of the fingers remains incomplete. Consequently, biomechanical models that include degrees of freedom for other joints of the hand often exclude kinematics for the CMC joints of the fingers (e. g., Holzbaur et al., 2005, Lee and Zhang, 2009).

Kinematics for the CMC joints of the fingers have been described as the motions of the metacarpal bones that allow the palm to form into an arch during grasping (Sangole and Levin, 2008). In an *in vitro* cadaveric study, the axes of rotation for the CMC joints were described qualitatively, but neither their precise locations nor the orientations of these axes were reported quantitatively (El-shennawy et al., 2001). This method used a combination of imaging and marker techniques to characterize the motion of each metacarpal as it was manually moved through three degrees of freedom separately (flexion-extension, radial-ulnar deviation, and pronation-supination). We are not aware of any studies quantifying three-dimensional rotations of metacarpal bones *in vivo* while subjects voluntarily assume hand positions or grasp objects.

The purpose of this study was to present a method for both quantifying functional, three-dimensional rotations of the metacarpal bones *in vivo* and using this data to define the kinematic functions necessary to add rotational degrees of freedom at the CMC joints to biomechanical models of the hand. Rotations in the ring and little fingers (fourth and fifth digits, respectively) were chosen as the focus because the *in vitro* ranges of motion of these metacarpals are much larger than the ranges of the motions in the other fingers (El-shennawy et al., 2001).

Methods

Kinematics for the fourth and fifth CMC joints were defined from three-dimensional rotations of the fourth and fifth metacarpal bones quantified *in vivo* via computed tomography (CT). CT data were collected from a single human subject (male, age 51, with no hand impairments) in seven different static poses, chosen to position the fourth and fifth metacarpals throughout a functional range of motion. Data were collected using a GE Lightspeed 16 CT Scanner (Milwaukee, WI) with an in plane resolution of 0.3×0.3 mm and a slice thickness of 0.625 mm. The imaging protocol was approved by the Institutional Review Board of Brown University, the site of data collection. The CT images were manually segmented using 3D Doctor Software (Lexington, MA) and then principal axes and rotation angles based on the resulting 3D surfaces were calculated using MATLAB (Natick, MA). From these processed data, kinematic functions were defined and

incorporated into an existing kinematic model of the human upper limb (Holzbaur et al., 2005) using SIMM (Software for Interactive Musculoskeletal Modeling; Santa Rosa, CA). Data in this short communication were previously presented in abstract form (Buffi et al., 2012).

Data Collection and Analysis

To characterize the positions of the metacarpal bones during hand function, CT images of the subject's right hand were collected while he assumed seven different, static hand postures. Two grasping postures were included; for these postures the subject was physically grasping appropriately-shaped objects (Fig. 1). The seven postures were chosen to represent a variety of bone positions that span the ranges of motion allowed by the fourth and fifth CMC joints. From the scan of each posture, three-dimensional, digital surface representations of the third, fourth, and fifth metacarpal bones were created via manual segmentation.

To calculate the three-dimensional rotations describing the positions of the fourth and fifth metacarpals relative to their positions in a reference posture, we implemented a method similar to that described by Degeorges (2004). To begin, the orientations of principal axes for the third, fourth, and fifth metacarpals in each of the seven postures were defined by the orthonormal bases of the digitized bone surfaces. The orthonormal basis of each bone of interest was calculated via singular value decomposition, implemented in MATLAB (Natick, MA), under the assumption that the vertices were evenly spaced about the bone surface. All seven postures were then positioned in the same global orientation by aligning the principal axes of each third metacarpal, which has been shown to have a minimal range of motion (El-shennawy et al., 2001). For each posture, the angular deviations of the principal axes of the fourth and fifth digits relative to the corresponding axes in the Extended Posture (Fig. 1) were calculated using a composite, three-dimensional rotation through three angles ($\theta_1, \theta_2, \theta_3$; Eqn. 1). That is,

$$MC_{\text{current}} = \text{Rot}(\theta_3, p_3) * \text{Rot}(\theta_2, p_2) * \text{Rot}(\theta_1, p_1) * MC_{\text{reference}} \quad (1)$$

where MC_{current} is a 3×3 matrix composed of the three orthonormal vectors defining the orientation of the metacarpal in its current posture, $MC_{\text{reference}}$ is a 3×3 matrix defining the orientation of the same bone in the Extended Posture, and each $\text{Rot}(p_i, \theta_i)$ defines the single-axis rotation matrix about the i th principal axis (p_i). The positive flexion-extension axis was defined by the principal axis of the appropriate metacarpal bone that was oriented primarily in the ulnar to radial direction (p_1). The pronation-supination axis corresponded to the longitudinal principal axis of the bone (p_3 , positive directed distally) and the remaining axis defined abduction-adduction with positive directed dorsally (p_2 , Fig. 2).

Ranges of motion for the fourth and fifth metacarpals were calculated as the difference between the maximum and minimum angles about each of the three principal axes across all seven postures. To minimize any errors introduced by the choice of the order in which we solved for the rotation angles, the average ranges of motion were calculated from all six possible orders of the three rotations.

To quantify the effect of manual segmentation errors on the orientations of the principal axes, we compared 3D surfaces of each of the seven, aligned representations of the third metacarpal. To begin, we interpolated between vertices such that we could compare the 3D surfaces of the seven metacarpal reconstructions at identical locations along their longitudinal axes. From there, we calculated absolute differences in the three Cartesian coordinates of corresponding vertices between the seven metacarpal surfaces, using the third

metacarpal from the Cylinder Grasp posture (Fig. 1) as a reference. For each of the six remaining metacarpal surfaces, this resulted in three sets of coordinate errors (one for each orthogonal direction) spanning all surface vertices. We then systematically rotated the surface 360° about each of its principal axes and identified the angle where the sum of the means of the coordinate errors was minimized. This process provided three angular deviations from the original principal axes for each of the six surfaces. If the identified principal axes were insensitive to the manual segmentation process, the aligned third metacarpal surfaces would be coplanar and the angular deviations would be zero for each surface.

Definition of CMC Kinematic Functions for Digits 4 and 5

Using the ranges of motion calculated from the CT data and the 3D surface geometry of the metacarpal bones available in an existing kinematic model of the upper limb (Holzbaur et al. 2005), we defined kinematic functions for the fourth and fifth CMC joints that enable formation of a metacarpal arch (Sangole and Levin, 2008). In this implementation, the two kinematic functions are coupled to a single generalized coordinate (*metacarpal flexion*).

To begin, static centers of rotations of the two new CMC joints were defined based on the 3D surface representations of the metacarpal bones in the existing model (Holzbaur et al. 2005). For each CMC joint, the location of the center of rotation for all three axes was defined by the center of a sphere fit to the base of the appropriate digitized metacarpal bone surface in the existing model, similar to qualitative descriptions in the literature (El-shennawy et al., 2001). Next, the orientations of the fourth and fifth metacarpal bones, and concomitantly the proximal, middle, and distal phalanges of both digits, were re-aligned relative to their default position in the existing model, which does not include kinematic representations of any joints for digits 3, 4, or 5. In particular, the fourth and fifth metacarpals were rotated such that the palm approximated a flat surface: the centers of the distal ends of all four metacarpal bones approximated a line and the dorsally oriented principal axes of the proximal phalanges were oriented parallel to each other. The rotation angles of the fourth and fifth metacarpals about all 3 principal axes were defined to be zero in this orientation as it corresponds to the neutral position described in the literature (Kapandji, 1982). Principal axes were calculated from the 3D surface geometry of the relevant bones in the model as described for the CT data.

Using the principal axes of the metacarpal bones in the model, we calculated a single, equivalent axis of rotation (p_{ieq}) and the corresponding angle (θ_{ieq}) that transformed the orientation of the appropriate metacarpal ($i = 4, 5$) from the neutral position to the orientation defined by the maximum range of motion (θ_{MC}) calculated from the CT data. That is,

$$\text{Rot}(p_{ieq}, \theta_{ieq}) = \text{Rot}(p_{i3}, \Delta\theta_{i3}) * \text{Rot}(p_{i2}, \Delta\theta_{i2}) * \text{Rot}(p_{i1}, \Delta\theta_{i1}); i=4, 5. \quad (2)$$

For both the fourth and fifth CMC joints, the appropriate axis of rotation (p_{ieq}) was positioned at the center of rotation identified from the 3D surface geometry of the model, and θ_{ieq} was defined to be a linear function of the generalized coordinate *metacarpal flexion* (θ_{MC}). Specifically,

$$\theta_{CMC4} = \theta_{MC}; 0 \leq \theta_{MC} \leq \theta_{4eq} \quad (3)$$

$$\theta_{CMC5} = \left(\frac{\theta_{5eq}}{\theta_{4eq}} \right) \theta_{MC}; 0 \leq \theta_{MC} \leq \theta_{4eq}. \quad (4)$$

Results

For both the fourth and fifth metacarpals, there were measureable ranges of motion about all three principal axes (Table 1). The posture with the largest deviations from the reference posture was the Jar Top Grasp Posture (Table 2). Bone orientation about the pronation-supination axis was the most sensitive to manual segmentation; absolute angular errors about this axis were $6.17^\circ (\pm 3.06^\circ)$. Errors about the flexion-extension and abduction-adduction axes were $1.17^\circ (\pm 0.75^\circ)$ and $1.17^\circ (\pm 0.98^\circ)$, respectively.

Both equivalent axes were oriented obliquely to the principal axes of the fourth and fifth metacarpals (Fig. 3). The equivalent angle that rotated the fourth metacarpal through the range of motion quantified from the CT data ($\theta_{4eq} = 11.64^\circ$) was approximately three times smaller than the equivalent angle for the fifth metacarpal ($\theta_{5eq} = 31.67^\circ$). Implementing the re-oriented bones of the hand, the axes of rotation, and the kinematic functions (see Equation 3 and 4) using SIMM produced a metacarpal arch (Fig. 4).

Discussion

In this communication, a method was presented for defining kinematic functions for the fourth and fifth CMC joints from three-dimensional rotations of the metacarpal bones quantified *in vivo* via CT imaging. For both the fourth and fifth metacarpals we observed motion about all three principal axes, resulting in skewed, equivalent, individual axes for both the fourth and fifth CMC joints. Adding these joints to a biomechanical model allowed the metacarpal bones to form a metacarpal arch as they moved through their ranges of motion (Fig. 4) consistent with previous work depicting the arching of the palm during reaching and grasping tasks (Sangole and Levin, 2008). The metacarpal arch degree of freedom allows the hand to conform to the shape of an object and provide grip during a prehensile task.

In vivo ranges of motion reported here for the fourth metacarpal about all three principal axes are smaller compared to the ranges of motion found in the previous cadaveric study on CMC kinematics (El-shennawy et al., 2001). The smaller ranges of motion *in vivo* may be attributed to the fact that in the cadaveric experiment, motion was produced artificially by the experimenters. However, definitive conclusions on *in vivo* versus *in vitro* metacarpal kinematics would require a larger sample size.

To our knowledge, this is the first explicit description of a method for incorporating *in vivo* metacarpal kinematics into biomechanical models. The ability to model these *in vivo* ranges of motion for the fourth and fifth metacarpals is important for diagnosing pathologies of the CMC joints as well as understanding and studying complex hand functions; including grasping and other forms of object manipulation.

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Figure 1.
The seven postures used to evaluate metacarpal motion.

Figure 2.

The principal axes of the metacarpal bones of digits 4 and 5 (dorsal view). Axis 1 corresponds to flexion-extension (positive directed from ulna to radius). Axis 2 corresponds to abduction-adduction (positive directed dorsally). Axis 3 corresponds to pronation-supination (positive directed distally).

Figure 3.
The orientations of the equivalent individual axes for the fourth (yellow) and fifth (blue) metacarpals.

Palmar View

Ulnar View

Figure 4.

(A) The updated biomechanical model in neutral, visualized using SIMM. (B) The updated biomechanical model, visualized using SIMM, with the fourth and fifth metacarpals at their maximum ranges of motion. The upper panels are palmar views and the lower panels are ulnar views.

Table 1

Motion of the metacarpals (MCs) at the fourth and fifth CMC joints.

Joint	Degree of Freedom	Mean Range (°)	St. Dev. (°)
4th MC	Pronation/Supination	8.44	0.02
	Flexion/Extension	7.65	0.04
	Abduction/Adduction	3.07	0.02
5th MC	Pronation/Supination	27.30	0.50
	Flexion/Extension	14.67	1.69
	Abduction/Adduction	11.37	1.62

Table 2

Angular deviations from reference posture (Extended) to Jar Top Grasp posture.

Joint	Degree of Freedom	Angle (°)
4th MC	Pronation/Supination	3.60
	Flexion/Extension	3.19
	Abduction/Adduction	2.37
5th MC	Pronation/Supination	23.77
	Flexion/Extension	5.34
	Abduction/Adduction	8.58