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The Envelope of Physiological Motion of the First Carpometacarpal Joint

Much of the hand's functional capacity is due to the versatility of the motions at the thumb carpometacarpal (CMC) joint, which are presently incompletely defined. The aim of this study was to develop a mathematical model to completely describe the envelope of physiological motion of the thumb CMC joint and then to examine if there were differences in the kinematic envelope between women and men. In vivo kinematics of the first metacarpal with respect to the trapezium were computed from computed tomography (CT) volume images of 44 subjects (20M, 24F, 40.3 ± 17.7 yr) with no signs of CMC joint pathology. Kinematics of the first metacarpal were described with respect to the trapezium using helical axis of motion (HAM) variables and then modeled with discrete Fourier analysis. Each HAM variable was fit in a cyclic domain as a function of screw axis orientation in the trapezial articular plane; the RMSE of the fits was 14.5 deg, 1.4 mm, and 0.8 mm for the elevation, location, and translation, respectively. After normalizing for the larger bone size in men, no differences in the kinematic variables between sexes could be identified. Analysis of the kinematic data also revealed notable coupling of the primary rotations of the thumb with translation and internal and external rotations. This study advances our basic understanding of thumb CMC joint function and provides a complete description of the CMC joint for incorporation into future models of hand function. From a clinical perspective, our findings provide a basis for evaluating CMC pathology, especially the mechanically mediated aspects of osteoarthritis (OA), and should be used to inform artificial joint design, where accurate replication of kinematics is essential for long-term success. [DOI: 10.1115/1.4031117]

Introduction

The hand's capacity for precision and power gripping, as well as fine manipulation, is largely due to the dexterity of the thumb, which in turn owes much of its versatility to the motions at the articulation between the trapezium and first metacarpal. Although the thumb CMC joint's unique anatomy permits multiplanar motion, its primary motions are generally considered to be extension, flexion, abduction, and adduction; internal and external rotations are considered secondary motions as they are not controlled independently. The kinematics of extension–flexion and abduction–adduction were described in an elegant cadaver study by Hollister et al. [1] that clearly demonstrated the axes of extension–flexion and abduction–adduction are nonorthogonal and nonintersecting. Subsequently, in a review of thumb CMC instability and dislocation, Edmunds proposed that the soft tissues surrounding the CMC joint generate a stabilizing screw-home motion at the end of thumb opposition, indicating a coupling between flexion and internal rotation [2,3]. Previous experimental studies, however, have not reported translational or a rotational coupling motions of the thumb CMC joint consistent with such a screw-home mechanism [1,4–8].

In a recent study of thumb CMC joint kinematics, we reaffirmed the findings of Hollister et al. [1] in vivo, in that we determined that the primary rotation axes of extension–flexion and abduction–adduction are angled with respect to each other by 124 deg (SD: 19 deg and CI: 6 deg) and offset from one another by 9.2 mm (SD: 2.5 mm and CI: 0.7 mm), with the extension–flexion

rotation axis located in the trapezium, and the abduction–adduction rotation axis located in the base of the first metacarpal [9]. We also found that both of these primary motions were coupled with internal–external rotations and with translations along the primary rotation (or screw) axes [9]. At this point, the sources of the couplings remain to be determined. They could be caused by the shape of the CMC articulation, ligamentous constraints, neuromuscular control, or any combination of the three. While the existing studies have advanced our understanding of CMC kinematics, they have been limited to the analysis of the primary directions of thumb extension, flexion, abduction, and adduction.

We postulate that the physiological thumb motions during many functional tasks could be described as being intermediate between the primary motions of extension–flexion and abduction–adduction. For example, motion of the thumb in a direction between pure flexion and pure adduction would have a unique screw axis that would be oriented and located in 3D space somewhere between the screw axes for these motions. What is less clear is whether the coupled internal–external rotations or the translation of the combined motion would be a linear or nonlinear combination of these coupled motions from flexion and adduction. Borrowing from the extensive studies on knee kinematics that have identified an envelope, or set, of screw axes that vary continuously in 3D space during knee extension [10–13], we postulate that the screw axes of the primary motions of the thumb CMC joint also lie on a continuous surface, and that this surface contains the screw axes for all possible physiological motions of the thumb, including combined motions and circumduction.

Accordingly, we used a large set of in vivo kinematic data to develop a mathematical model of the envelope of screw axes, which completely defines the in vivo kinematics of the thumb

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Manuscript received January 10, 2015; final manuscript received July 17, 2015; published online August 6, 2015. Assoc. Editor: Zong-Ming Li.

CMC joint during normal physiologic motions. We then used the model to examine if there were differences in the kinematic envelope between women and men.

Methods

Subjects and Imaging. After receiving approval from our Institutional Review Board and obtaining informed consents, 44 subjects (20M, 24F, mean $\pm$ SD age of 40.3 ± 17.7 yr) with no symptoms of CMC pathology were recruited as part of a broader study of CMC joint biomechanics and OA initiation and progression [14–18]. The dominant wrists and thumbs of each subject were scanned in a neutral position braced with a modified thumb spica splint (Rolyan Original, Patterson Medical, Bolingbrook, IL) and with the thumb at four maximum active range-of-motion (ROM) positions: extension, flexion, abduction, and adduction (Fig. 1). Custom-designed polycarbonate fixtures were used to standardize the ROM positioning across subjects. Extension–flexion was supported with a vertical polycarbonate plate, angled at 30 deg to the dorsum of the hand, while abduction–adduction

was supported by a horizontal polycarbonate plate abutting the radial surface of the index digit. Image volumes were generated with a 16-slice clinical CT scanner (GE LightSpeed[®] 16; General Electric, Milwaukee, WI) at tube settings of 80 kVp and 80 mA (neutral) and 40 mA (ROM positions), slice thickness of 0.625 mm, and an in-plane resolution 0.4×0.4 mm or better. The average effective dose of radiation received by the participants in this study was 0.25 mSv for the five CT scans.

Kinematic Measurements. The trapezia and first metacarpals (MC1s) were segmented semi-automatically from the neutral CT volumes using a commercial software package (MIMICS[®], Materialise, Leuven, BE) and the bone models exported as meshed surfaces. The articular surface of the trapezium was manually selected and the principal directions of curvature were used to construct a trapezium-based coordinate system [19] (Fig. 2(a)). Briefly, the z-axis of the coordinate system was aligned with the vector average of the principal direction of curvature in the ulnar–radial direction. The y-axis was obtained by crossing the z-axis and the vector average of the principal direction of curvature in the

Fig. 1 Surface renderings (a) and density-based renderings (b) from CT images acquired at the targeted thumb positions of neutral (N), flexion (F), adduction (Ad), extension (E), and abduction (Ab). The horizontal and vertical polycarbonate plates used to standardize and stabilize the hand during imaging are also shown. The larger cylinder supported the extended fingers. The thumb spica splint used to standardize the neutral thumb position is not visible due to its low density.

Fig. 2 Volar view of the trapezium with the TCS (a). The +X direction is volar, +Y direction is proximal, and +Z direction is radial. The orientation of the screw axes (HAM) was described by two angles: an azimuth angle (azi) within the X–Z (trapezium) plane (0 deg aligned with the positive x-axis) and an elevation angle (ele) out of the X–Z plane. In a schematic distal-to-proximal view of the TCS (b), the screw axes for the idealized motions of pure flexion (F_{TCS}), adduction (Ad_{TCS}), extension (E_{TCS}), and abduction (Ab_{TCS}) were directed along the Z (azi = 90 deg), X (azi = 0), –Z (azi = –90 deg), and –X (azi = 180 deg) axes, respectively. The screw axes for these pure motions are labeled and the direction of rotation about the screw axis is illustrated using the right-hand rule (thumb along the axis, fingers curling in the positive direction of thumb rotation).

dorsal–volar direction. And finally, the x -axis was obtained by crossing the y and z axes. The coordinate system was centered at the inflection point of the articular surface. The plane of the trapezoidal articular surface was defined as the X – Z plane.

The absolute positions of the trapezium and first metacarpal within the global imaging space were computed with an established automatic markerless bone registration algorithm [20]. Kinematic transforms for motion of the first metacarpal with respect to the trapezium were then computed for ten separate pairs of positions: neutral to flexion, neutral to adduction, neutral to extension, neutral to abduction, extension to flexion, abduction to adduction, extension to abduction, abduction to flexion, adduction to extension, and flexion to adduction. This yielded a total of 440 kinematic transforms available for model fitting.

Kinematic Description. HAM variables [21] were used to uniquely describe the six degrees-of-freedom (DOF) kinematic transforms of the first metacarpal with respect to the trapezium for each position pair. For each transform, the HAM variables consisted of a single rigid-body rotation (θ) about, and a single rigid-body translation (t) along, a unique screw axis, which was completely described by its orientation and location with respect to the trapezoidal coordinate system (TCS). For the purposes of this study, the orientation of the screw axis was described by two angles: an azimuth angle (azi) within the trapezoidal articular plane (X – Z) and an elevation (ele) angle out of the plane (Fig. 2(a)). For reference, the idealized azimuth angles for abduction (Ab_{TCS}), extension (E_{TCS}), adduction (Ad_{TCS}), and flexion (F_{TCS}) relative to the TCS are located at azi values of 180 deg (dorsal), -90 deg (ulnar), 0 deg (volar), and 90 deg (radial), respectively (Fig. 2(b)). Any nonzero ele angle indicates coupling with internal–external rotations. A positive ele angle, where the screw axis points in the proximal direction, indicates coupling with internal rotation, while a negative ele angle, where the screw axis points in the distal direction, indicates coupling with external rotation. The location of the screw axis in the TCS was described by the coordinates of the point Q (Qx, Qy, Qz), which was defined as the point on the screw axis that was closest to the origin of the TCS. To explore inherent sex-based differences in axis location in men and women, we normalized for the larger male bone size by dividing the coordinates of the axis location by the cube root of each subject's trapezoidal bone volume.

It is important to note that for descriptive purposes each of the ten sets of transforms were categorized by the nominal positions used in the calculations (i.e., neutral to flexion, neutral to adduction, neutral to extension, etc.), when in fact the computed transforms resulted in distributions of thumb motions (Fig. 3). For example, the orientation of the screw axis for the thumb motion from neutral to flexion, which would ideally have had an azi value of 90 deg (labeled F_{TCS} in Fig. 2(b)), actually had a distribution of azi values with a mean (1SD) of 117 deg (31 deg). Similar distributions were seen for the other motions as well (i.e., neutral to adduction, neutral to extension, etc., Fig. 3).

Kinematic Model. Setting the azimuth angle (azi) of the screw axis as the independent variable, plots of the raw data revealed that each HAM variable in the set $\{ele, Qx, Qy, Qz, t\}$ varied harmonically as a function of azi . Accordingly, discrete Fourier analysis was used to estimate each $f(azi)$

$$f(azi) = \sum_{h \in H} (A_h \cos(h \cdot azi + \phi_h)) + \text{mean}(y) \quad (1)$$

where azi is the azimuth angle, H is the set of harmonics (which is specified as h with values of $0, 1$, or 2), A_h is the amplitude, ϕ_h is the phase shift of the h th harmonic, and y is the respective variable in the set $\{ele, Qx, Qy, Qz, t\}$.

A_h and ϕ_h were solved numerically as

$$A_h = 2 \|\text{mean}(Y_h \cdot X_h)\| \quad (2)$$

Fig. 3 Azimuth distribution functions of all subjects for each computed transform (neutral to flexion: N to F , neutral to adduction: N to Ad , neutral to extension: N to E , neutral to abduction: N to Ab , extension to flexion: E to F , abduction to adduction: Ab to Ad , extension to abduction: E to Ab , adduction to flexion: Ad to F , adduction to extension: Ad to E , and flexion to adduction: F to Ad). The azimuth orientation of the screw axis is specified by the TCS with idealized motion directions from the neutral to pure abduction (Ab_{TCS}), extension (E_{TCS}), adduction (Ad_{TCS}), and flexion (F_{TCS}) at azimuth angles of 180 deg, -90 deg, 0 deg, and 90 deg, respectively.

and

$$\phi_h = \text{phase angle}(\text{mean}(Y_h \cdot X_h)) \quad (3)$$

where

$$Y_h = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \\ \vdots \\ y_n \end{bmatrix} \text{ and } X_h = \begin{bmatrix} e^{-ih \cdot azi_1} \\ e^{-ih \cdot azi_2} \\ \vdots \\ e^{-ih \cdot azi_k} \\ \vdots \\ e^{-ih \cdot azi_n} \end{bmatrix} \quad (4)$$

and y_k and azi_k are the corresponding data points (total = n). The number and set of harmonics for each $f(azi)$ were determined a priori by visual inspection of the plotted data.

Inspection of the plotted data revealed that screw axis elevation (ele) and screw axis location (Q) varied solely as a function of azimuth angle (azi). However, plots of the translation (t) along the screw axis revealed t to depend on the magnitude of the first metacarpal rotation (θ), as well as azi . Therefore, for t we modified our approach and modeled translation using second harmonics, fitting t to azi separately for each of five 10 deg bins of θ ($[0-10$ deg], $[10-20$ deg], $[20-30$ deg], $[30-40$ deg], $[40-50$ deg], and $[50-60$ deg]). First, A_2 was computed as described above, and then ϕ_2 was fixed at $-\pi/2$. The mean of the data was not added to the fit curve because of the lack of symmetry in the data at the higher values of θ . The goodness of fit for each HAM variable ($f(azi)$) was assessed by computing the RMSE values.

Comparison of Kinematic Differences in Men and Women.

Once the general model was established, Eq. (1) was fit to the data sets for the men (200 transforms) and women (240 transforms) separately and the amplitude coefficients of the harmonics, A_h , were compared. For comparisons within the single function harmonics (ele , Qy , Qx , and Qy), a two-tailed t test was used. For translation, where the amplitude coefficients varied as a function of metacarpal rotation (θ), a two-way analysis of variance (ANOVA) methodology was used, with the categorical factors

being sex and rotation (θ) bin. The ANOVAs were performed using Prism[®] (Graphpad Software, LaJolla, CA), with the amplitude coefficients used as the group mean, the root mean squared errors (RMSEs) of the harmonic fit used as the group variation, and the number of subjects in each group (sex and rotation bin) used as sample size. Statistical significance for all comparisons was set at $P < 0.05$. Differences between men and women are reported below after describing the mathematical model that was fit to the data pooled from all subjects.

Results

Across all subjects and transforms evaluated ($n = 440$), MC1 rotation (θ) ranged from 1.5 deg to 77 deg (Fig. 4). The two directions of MC1 rotation that occurred most commonly—and included MC1 motions of the greatest magnitude (highest θ)—occurred about screw axes with azi values of approximately -15 deg and 130 deg (Fig. 4). An azi direction of -15 deg corresponded to MC1 motions of both flexion to adduction and abduction to adduction (transforms F to Ad and Ab to Ad , Fig. 3), while an azi direction of 130 deg corresponded to MC1 motions of neutral to flexion, neutral to abduction, extension to flexion, and extension to abduction (transforms N to F , N to Ab , E to F , and E to Ab , Fig. 3).

Elevation (ele) of the screw axis varied as a first-order harmonic of the azimuth angle, azi, with an amplitude of 36.6 deg (Fig. 5 and Table 1). The peak negative fitted ele was approximately -30 deg and it occurred at an azi angle of -45 deg, which corresponded to an MC1 motion intermediate between extension and adduction (Fig. 5). Similarly, the peak positive fitted value was approximately 45 deg, which occurred at an azi angle of 130 deg, corresponding to an MC1 motion intermediate between flexion and abduction (Fig. 5). The ele of the flexion (90 deg) and abduction (180 deg) screw axes were both positive, indicating that the screw axes were directed proximally and coupled with internal rotation. In contrast, the ele of both extension (-90 deg) and adduction (0 deg) was negative, indicating that the screw axes were directed distally and coupled with external rotation. The first-order harmonic fit of ele to azi had an RMSE of 14.5 deg.

In contrast to the ele, which varied as a first-order harmonic of the azimuth angle, the location of the screw axis (Q_x , Q_y , and Q_z) varied as second-order harmonic of azi (Fig. 6). This behavior was most pronounced with Q_y , which had peak proximal locations at azi values of approximately -90 deg and 90 deg (extension and flexion, respectively), and peak distal locations at 180 deg and

Fig. 4 First metacarpal (MC1) rotation (θ) as a function of azimuth angle (azi) for all 440 positions used for model fitting. Thumb rotation ranged from a low of 1.5 deg to a high of 77.0 deg across all directions of thumb motion. Peak rotations (and the highest data density) occurred at azimuth angles of -15 deg and 130 deg.

Fig. 5 First metacarpal (MC1) screw axis elevation (ele) as a function of azimuth angle (azi). Peak elevations occurred at azimuth angles of approximately -45 deg and 130 deg, indicating coupling with external rotation and with internal rotation, respectively.

Table 1 Coefficients for Eq. (1) when fitting ele and Q

	Ele	Q_x	Q_y	Q_z
Harmonic order	1	2	2	2
Amplitude (deg or mm)	36.566	2.181	5.521	1.140
Phase shift (rad)	-2.347	-2.197	-3.075	-0.861

0 deg (abduction and adduction, respectively). The peaks in the harmonic fit for Q_y ranged from 4 mm proximal to the trapezoid plane to 7 mm distal to the trapezoid plane, reflecting an 11 mm proximal–distal shift in the screw axis location between extension–flexion and abduction–adduction (azi). The behaviors for Q_x and Q_z were analogous to that of Q_y in that they could be modeled with a second-order harmonic, however, the magnitudes of the location changes for these two directions were smaller (approximately 3.5 mm for Q_x and 2.1 mm for Q_z) and their peaks did not fall directly on the extension–flexion and abduction–adduction azimuth angles. The second-order harmonic fits of Q_x , Q_y , and Q_z had RMSE values of 1.4 mm, 1.3 mm, and 1.1 mm, respectively.

Similar to the screw axis locations, translation (t) along the screw axis varied as a second-order harmonic of azi. However, translation also varied approximately linearly with the magnitude of MC1 rotation (θ) (Fig. 7), by a factor of approximately 0.1 (Table 2). Interestingly, t converged to 0 mm at azi values of 180 deg, -90 deg, 0 deg, and 90 deg, regardless of the magnitude of θ . This suggests that idealized abduction, extension, adduction, and flexion involve almost pure rotation of the MC1, with no corresponding translation. In contrast, translation (t) was maximum at azi values of -135 deg and 45 deg and -45 deg and 135 deg, peaking at approximately 6 mm and -6 mm, respectively. The second-order harmonic fits resulted in RMSEs of 0.3 mm, 0.5 mm, 0.8 mm, 0.8 mm, 0.8 mm, and 0.8 mm for each 10 deg bin of θ (Table 2).

Evaluating Eq. (1) for both ele and Q over the range of azi values results in an envelope of screw axes that lie on a continuous surface (Fig. 8). This surface undulates harmonically with respect to the trapezoid and it contains the screw axes for all physiological directions of thumb motion. The complete description of the physiological motion of the thumb is obtained by choosing a direction (i.e., selecting a screw axis) and specifying θ , which defines t .

There were no significant differences in the amplitude coefficients of ele, Q_x , Q_z , or t between men and women. The only sex-related difference that was found to be statistically significant ($P = 0.01$) was that the amplitude of the harmonic fit for Q_y in

Fig. 6 First metacarpal (MC1) screw axis location (Q_x , Q_y , and Q_z) as a function of azimuth angle (azi). Screw axis location varied as a second-order harmonic of azi . The locations of the fitted screw axes ranged approximately from 0 to -3 mm, 4 to -7 , and 0 to -2 mm for Q_x , Q_y , and Q_z , respectively. Q_x was always dorsal biased, Q_y alternated between proximal and distal, and Q_z was ulnar biased. The peak proximal and distal locations of the screw axis (Q_y) occurred during the primary motions of abduction, extension, adduction, and flexion. (Note the Q_y axis is inverted to align with a distal orientation of the trapezium in the figures.)

men (6.1 mm, RMSE of 1.3 mm), which was 1.1 mm greater than the amplitude in women (5.0 mm, RMSE of 1.3 mm). After normalizing for bone size, there was no difference in Q_y between men and women ($P = 0.930$).

Fig. 7 Translation (t) as a function of azimuth angle (azi). As with screw axis location, translation was fit with a second-order harmonic. However, translation also increased ~ 1 mm for each 10 deg increase in MC1 rotation (θ), so separate fits were performed for each 10 deg increment of rotation, from 0 deg to 60 deg ([0–10 deg], [10–20 deg], [20–30 deg], [30–40 deg], [40–50 deg], and [50–60 deg]). For each fit, t converged to 0 mm at azi values of 180 deg, -90 deg, 0 deg, and 90 deg, suggesting that pure abduction, extension, adduction, and flexion involve no corresponding translation, while t was maximum at azi values of -135 deg and 45 deg and minimum at azi values of -45 deg and 135 deg.

Discussion

A mathematical model of the healthy CMC joint during active tasks was developed by fitting harmonic trigonometric functions to a large set of in vivo kinematic data. The model fits were quite reasonable, as indicated by the relatively small RMSE values. The models demonstrated that screw axis inclination (ele) varied as a first-order harmonic of the azimuth angle (azi) and that the location (Q) varied as second-order harmonic. The models also illustrated that translation (t) varied as a second-order harmonic of azi , while increasing roughly linearly by a factor of 0.1, or ~ 1 mm for every 10 deg increase in θ .

The models were used to evaluate potential differences in CMC motion as a function of sex, revealing that only the difference in proximal–distal location of the extension–flexion and abduction–adduction screw axis was greater in men than women, as the amplitudes of their harmonic fits of Q_y differed by 1.1 mm. We attribute this difference simply to scaling as, on average, the bones in men are larger than the bones in women. The mean (SD) volume of the male trapezia was 2463 mm³ (465 mm³), while the mean (SD) volume of the female trapezia was 1759 mm³ (368 mm³). The cube root of these volumes, a measure of the linear dimensions of the trapezium, was 13.5 mm (0.8 mm) and 12.0 (0.8 mm) for male and females, respectively, the difference in which is similar to the difference in amplitude of the model fit to Q_y . The 1.1 mm difference in amplitude is also very consistent with the findings of our previous study in which we analyzed the primary motions of extension–flexion and abduction–adduction using this dataset and determined that the combined extension to flexion screw axis was located 1.2 mm more distal in men than in women [9].

The strengths of our approach include the extensiveness of our kinematic data set and the fact that the data were computed directly from skeletal motions. Moreover, the kinematics were described using an anatomy-based coordinate system aligned with the principal curvatures of the trapezial articular surface. Our approach to the mathematical model was based on the precept that the thumb CMC joint has two primary directions of motion, extension–flexion and abduction–adduction, and that all the other motions are components of these two primary motions. This observation enabled us to define the azimuth (azi) orientation of the screw axis in the articular plane as an independent variable with a cyclic domain. As such, once the magnitude of the thumb

Table 2 Coefficients of Eq. (1) for fitting t in each 10 deg range of θ . Phase shift for translation was set to $-\pi/2$.

	Translation					
	θ (0–10 deg)	θ (10–20 deg)	θ (20–30 deg)	θ (30–40 deg)	θ (40–50 deg)	θ (50–60 deg)
Harmonic order	2	2	2	2	2	2
Amplitude (deg or mm)	0.3088	1.2138	2.9054	3.3835	4.6666	6.0891
Phase shift (rad)	-1.571	-1.571	-1.571	-1.571	-1.571	-1.571

Fig. 8 Visualization of the complete envelope of screw axes for the physiological motion of the thumb CMC joint with respect to the TCS from three orthogonal views ((a), (b), and (c)) and an oblique view (d), revealing a first-order variation in screw axis elevation as a function of azimuth angle (azi) and second-order shifts in screw axis location (Q). The set of screw axes (36 represented) is color-coded by their azimuth (azi) orientation given below the color bar, which is also labeled by the idealized directions of the screw axes for the primary motions. The spheres represent the point Q that is associated with each similarly colored screw axis. θ and t are not shown. θ is independent of both orientation and location of the screw axis, and t is dependent on θ .

rotation was specified, the orientation and location of the screw axis and the associated translations were completely defined by the harmonic functions. The choice of a harmonic function was based on visualization of the raw kinematic data, and the desire to use the simplest possible cyclic function that best fit the data.

There are several assumptions and limitations that could potentially influence the interpretation of our data. To start, our methodology involved the calculation of screw rotation axes from bone position data obtained via sequential static CT scans. The chief assumptions for this methodology are that (1) static imaging yields a reasonable estimate of dynamic motion and (2) there is a continuous path between the terminal static positions. Both of these are reasonable assumptions, the first based on work demonstrating minimal hysteresis (0 deg to 2.5 deg) with dynamic motion of the carpus [22] and the fact that the methodology we use is accurate to 0.45 deg of rotation and 0.25 mm of translation [20] and the second based on the unique anatomy of the thumb CMC joint which allows essentially unrestricted motion of MC1

with respect to the trapezium. Moreover, our analysis yielded very consistent HAM variables across subjects. Thus, if the HAM variables do indeed vary within a given motion, our data suggest that this variation is quite small compared to the variation across subjects. Additional potential limitations include our use of fixtures to support thumb positioning, which could have biased our kinematic outputs, and the use of relatively few imaged positions per subject. However, the broad spectrum of MC1 position data we recorded—both in direction (azi) and magnitude (thumb rotation, θ) (Fig. 4)—strongly mitigates against either of these introducing significant bias. Although each fixture was used to target a given direction of motion, the noninvasive nature of the protocol precludes rigorous positioning of the joint, resulting in variability within each targeted motion across subjects. The various shapes of the distributions generated from each targeted transform are evidence of this variability (Fig. 3). We speculate that the transforms with low variability were associated with thumb positions that were more easily obtained by the subjects, possibly because they are more physiologic.

The findings of this study demonstrate that the screw axes for the primary motions of extension–flexion and abduction–adduction are not discrete but lie on an envelope that varies as a continuous function of the direction of thumb motion. The locations and orientations of the extension–flexion and abduction–adduction axes we reported are consistent with those reported in previous studies [1,5,23–25]. However, this study advances our understanding of CMC kinematics by demonstrating that coupling of the primary motions with internal–external rotations and translation along the screw axes are continuous functions of the direction of motion. This is in contrast to other studies that have reported minimal or no coupled motions, perhaps because those studies were focused on the primary motions [1,4,6–8,23,26–28], or because the kinematic data were acquired using surface marker-based motion capture systems where skin motion artifact can be large enough to mask the more modest coupled motions. Coupling with internal–external rotations is evident by the nonzero value of ele, in which positive values of ele indicate coupling with internal rotations and negative values of ele indicate coupling with external rotation. The amount of internal–external rotations varies with θ and can be computed as the product of θ and $\sin(\text{ele})$. Interestingly, the largest coupling with internal rotation occurred during the composite thumb motion of flexion and abduction (a motion similar to opposition with $\text{azi} = 135$ deg, Fig. 5).

In addition to being harmonically related to azi, translation along the screw axis (t) was also shown to be linearly related to the magnitude of MC1 rotation (θ) by a factor of 0.1. Translations peaked at the four directions of peak rotation, which were offset 45 deg from the primary directions of extension–flexion and abduction–adduction, while translations converged to effectively zero, regardless of the magnitude of rotation (θ) at azi values of 180 deg, 90 deg, and 0 deg. These values of azi correspond to the directions of principal curvatures of the trapezoidal articular surfaces and the primary directions of thumb rotations. These findings suggest that when the MC1 rotates along the principal curvatures of the saddle-shaped trapezoidal articulation there is minimal screw translation. As with elevation and internal rotation, the largest coupling with translation occurred in a direction of opposition ($\text{azi} = 135$ deg, Fig. 7). The coupling of internal rotation and

proximal translation during opposition are consistent with a potential screw-home mechanism during thumb opposition [2,3]. The cause of these coupled motions, whether due to ligaments [29], articular shape [30], neuromuscular control, or some combination, could not be identified in the current study.

In addition to advancing our basic understanding of CMC joint function, an accurate and complete understating of CMC kinematics provides a basis for evaluating CMC pathology, such as mechanically mediated aspects of OA [14], and it can inform the design of implants, where accurate replication of kinematics is essential for long-term success [15–17]. There is growing clinical evidence that implant failure is associated with the failure to replicate normal kinematics in the spine [31–36], wrist [37], knee [38,39], and shoulder [40–45]. In modeling, simplifying the thumb CMC joint as a ball-and-socket articulation rather than with the more complex harmonic profiles we identified, where the location of the screw axis can vary by >1 cm, could lead to substantial errors in the computation of ligament strains, cartilage stresses, and muscle moment arms. A recent musculoskeletal model of the thumb has demonstrated that simplified modeling of the CMC joint as a 2DOF structure does not accurately predict the muscle forces at the thumb tip [46]. It is possible that the kinematic model presented here could improve the accuracy of such musculoskeletal models of the thumb.

Acknowledgment

The research reported in this publication was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under Award No. AR059185.

Nomenclature

A_h	= amplitude of harmonic fit for h th harmonic
Ab_{TCS}	= idealized screw axis direction for abduction (azi = 180 deg) as defined by the TCS
Ad_{TCS}	= idealized screw axis direction for adduction (azi = 0 deg) as defined by the TCS
azi	= orientation angle of the screw axis in the X – Z plane
E_{TCS}	= idealized screw axis direction for extension (azi = –90 deg) as defined by the TCS
ele	= orientation angle of the screw axis out of the X – Z plane
F_{TCS}	= idealized screw axis direction for flexion (azi = 90 deg) as defined by the TCS
HAM	= helical axis of motion
Q	= a point on the screw axis, closest to the origin, with coordinates (Q_x , Q_y , and Q_z), which defines the location of the screw axis
t	= rigid-body translation along screw axis
TCS	= trapezoidal coordinate system (Fig. 2(a))
θ	= rigid-body rotation about screw axis
ϕ_h	= phase shift of the h th harmonic

References

- [1] Hollister, A., Buford, W. L., Myers, L. M., Giurintano, D. J., and Novick, A., 1992, "The Axes of Rotation of the Thumb Carpometacarpal Joint," *J. Orthop. Res.*, **10**(3), pp. 454–460.
- [2] Edmunds, J. O., 2006, "Traumatic Dislocations and Instability of the Trapezometacarpal Joint of the Thumb," *Hand Clin.*, **22**(3), pp. 365–392.
- [3] Edmunds, J. O., 2011, "Current Concepts of the Anatomy of the Thumb Trapezometacarpal Joint," *J. Hand Surg.*, **36**(1), pp. 170–182.
- [4] Cheze, L., Dumas, R., Comtet, J. J., and Rumelhart, C., 2011, "What is the Number of Independent Degrees of Freedom of the Trapezometacarpal Joint? Preliminary In Vitro Results," *Comput. Methods Biomech. Biomed. Eng.*, **14**(Suppl. 1), pp. 17–18.
- [5] Hollister, A., and Giurintano, D. J., 1995, "Thumb Movements, Motions, and Moments," *J. Hand Ther.*, **8**(2), pp. 106–114.
- [6] Miura, T., Ohe, T., and Masuko, T., 2004, "Comparative In Vivo Kinematic Analysis of Normal and Osteoarthritic Trapezometacarpal Joints," *J. Hand Surg.*, **29**(2), pp. 252–257.

- [7] Nataraj, R., and Li, Z.-M., 2013, "Robust Identification of Three-Dimensional Thumb and Index Finger Kinematics With a Minimal Set of Markers," *ASME J. Biomech. Eng.*, **135**(9), p. 91002.
- [8] Imaeda, T., Niebur, G., Cooney, W. P., 3rd, Linscheid, R. L., and An, K. N., 1994, "Kinematics of the Normal Trapezometacarpal Joint," *J. Orthop. Res.*, **12**(2), pp. 197–204.
- [9] Crisco, J. J., Halilaj, E., Moore, D. C., Patel, T., Weiss, A.-P. C., and Ladd, A. L., "In Vivo Kinematics of the Trapezometacarpal Joint During Thumb Extension-Flexion and Abduction-Adduction," *J. Hand Surg.*, **40**(2), pp. 289–296.
- [10] Blankevoort, L., Huijskes, R., and de Lange, A., 1988, "The Envelope of Passive Knee Joint Motion," *J. Biomech.*, **21**(9), pp. 705–720.
- [11] McLeod, W. D., Moschi, A., Andrews, J. R., and Hughston, J. C., 1977, "Tibial Plateau Topography," *Am. J. Sports Med.*, **5**(1), pp. 13–18.
- [12] Moglo, K. E., and Shirazi-Adl, A., 2005, "Cruciate Coupling and Screw-Home Mechanism in Passive Knee Joint During Extension-Flexion," *J. Biomech.*, **38**(5), pp. 1075–1083.
- [13] Wilson, D. R., Feikes, J. D., Zavatsky, A. B., and O'Connor, J. J., 2000, "The Components of Passive Knee Movement are Coupled to Flexion Angle," *J. Biomech.*, **33**(4), pp. 465–473.
- [14] Halilaj, E., Rainbow, M. J., Got, C., Schwartz, J. B., Moore, D. C., Weiss, A.-P. C., Ladd, A. L., and Crisco, J. J., 2014, "In Vivo Kinematics of the Thumb Carpometacarpal Joint During Three Isometric Functional Tasks," *Clin. Orthop.*, **472**(4), pp. 1114–1122.
- [15] Halilaj, E., Moore, D. C., Laidlaw, D. H., Got, C. J., Weiss, A.-P. C., Ladd, A. L., and Crisco, J. J., 2014, "The Morphology of the Thumb Carpometacarpal Joint Does Not Differ Between Men and Women, but Changes With Aging and Early Osteoarthritis," *J. Biomech.*, **47**(11), pp. 2709–2714.
- [16] Halilaj, E., Laidlaw, D. H., Moore, D. C., and Crisco, J. J., 2014, "Polar Histograms of Curvature for Quantifying Skeletal Joint Shape and Congruence," *ASME J. Biomech. Eng.*, **136**(9), p. 094503.
- [17] Halilaj, E., Laidlaw, D. H., Moore, D. C., and Crisco, J. J., 2014, "How Do Sex, Age, and Osteoarthritis Affect Cartilage Thickness at the Thumb Carpometacarpal Joint? Insights From Subject-Specific Cartilage Modeling," *Bio-Imaging and Visualization for Patient-Customized Simulations*, J. M. R. S. Tavares, X. Luo, and S. Li, eds., Springer International Publishing, Cham, Switzerland, pp. 103–111.
- [18] Halilaj, E., Moore, D. C., Patel, T. K., Laidlaw, D. H., Ladd, A. L., Weiss, A.-P. C., and Crisco, J. J., 2014, "Thumb Carpometacarpal Joint Congruence During Functional Tasks and Thumb Range-of-Motion Activities," 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Chicago, IL, Aug. 26–30, pp. 4354–4357.
- [19] Halilaj, E., Rainbow, M. J., Got, C. J., Moore, D. C., and Crisco, J. J., 2013, "A Thumb Carpometacarpal Joint Coordinate System Based on Articular Surface Geometry," *J. Biomech.*, **46**(5), pp. 1031–1034.
- [20] Marai, G. E., Laidlaw, D. H., and Crisco, J. J., 2006, "Super-Resolution Registration Using Tissue-Classified Distance Fields," *IEEE Trans. Med. Imaging*, **25**(2), pp. 177–187.
- [21] Panjabi, M. M., Krag, M. H., and Goel, V. K., 1981, "A Technique for Measurement and Description of Three-Dimensional Six Degree-of-Freedom Motion of a Body Joint With an Application to the Human Spine," *J. Biomech.*, **14**(7), pp. 447–460.
- [22] Short, W. H., Werner, F. W., Fortino, M. D., and Mann, K. A., 1997, "Analysis of the Kinematics of the Scaphoid and Lunate in the Intact Wrist Joint," *Hand Clin.*, **13**(1), pp. 93–108.
- [23] Cooney, W. P., 3rd, Lucca, M. J., Chao, E. Y., and Linscheid, R. L., 1981, "The Kinesiology of the Thumb Trapezometacarpal Joint," *J. Bone Jt. Surg. Am.*, **63**(9), pp. 1371–1381.
- [24] Kapandji, A., 1981, "Functional Anatomy and Biomechanics of the Metacarpophalangeal Joint of the Thumb," *Ann. Chir.*, **35**(4), pp. 261–267 (author transl.).
- [25] Cerveri, P., De Momi, E., Marchente, M., Baud-Bovy, G., Scifo, P., Barros, R. M. L., and Ferrigno, G., 2010, "Method for the Estimation of a Double Hinge Kinematic Model for the Trapezometacarpal Joint Using MR Imaging," *Comput. Methods Biomech. Biomed. Eng.*, **13**(3), pp. 387–396.
- [26] Chang, L. Y., and Pollard, N. S., 2008, "Method for Determining Kinematic Parameters of the In Vivo Thumb Carpometacarpal Joint," *IEEE Trans. Biomed. Eng.*, **55**(7), pp. 1897–1906.
- [27] Chêze, L., Dumas, R., Comtet, J.-J., Rumelhart, C., and Fayet, M., 2012, "Determination of the Number of Degrees of Freedom of the Trapezometacarpal Joint—An In Vitro Study," *IRBM*, **33**(4), pp. 272–277.
- [28] Goubier, J.-N., Devun, L., Mitton, D., Lavaste, F., and Papadogeorgou, E., 2009, "Normal Range-of-Motion of Trapezometacarpal Joint," *Chir. Main*, **28**(5), pp. 297–300.
- [29] Haines, R. W., 1944, "The Mechanism of Rotation at the First Carpo-Metacarpal Joint," *J. Anat.*, **78**(1–2), pp. 44–46.
- [30] Kuczyński, K., 1975, "The Thumb and the Saddle," *Hand*, **7**(2), pp. 120–122.
- [31] Huang, R. C., Girardi, F. P., Cammisa, F. P., and Wright, T. M., 2003, "The Implications of Constraint in Lumbar Total Disc Replacement," *J. Spinal Disord. Tech.*, **16**(4), pp. 412–417.
- [32] Galbusera, F., Bellini, C. M., Raimondi, M. T., Fomari, M., and Assietti, R., 2008, "Cervical Spine Biomechanics Following Implantation of a Disc Prosthesis," *Med. Eng. Phys.*, **30**(9), pp. 1127–1133.
- [33] Schmidt, H., Midderhoff, S., Adkins, K., and Wilke, H.-J., 2009, "The Effect of Different Design Concepts in Lumbar Total Disc Arthroplasty on the Range of Motion, Facet Joint Forces and Instantaneous Center of Rotation of a L4-5 Segment," *Eur. Spine J.*, **18**(11), pp. 1695–1705.
- [34] Galbusera, F., Anasetti, F., Bellini, C. M., Costa, F., and Fornari, M., 2010, "The Influence of the Axial, Antero-Posterior and Lateral Positions of the

- Center of Rotation of a Ball-and-Socket Disc Prosthesis on the Cervical Spine Biomechanics," *Clin. Biomech. (Bristol Avon)*, **25**(5), pp. 397–401.
- [35] Goel, V. K., Faizan, A., Palepu, V., and Bhattacharya, S., 2012, "Parameters That Effect Spine Biomechanics Following Cervical Disc Replacement," *Eur. Spine J.*, **21**(Suppl. 5), pp. S688–699.
- [36] Wilke, H.-J., Schmidt, R., Richter, M., Schmoelz, W., Reichel, H., and Cakir, B., 2012, "The Role of Prosthesis Design on Segmental Biomechanics: Semi-Constrained Versus Unconstrained Prostheses and Anterior Versus Posterior Centre of Rotation," *Eur. Spine J.*, **21**(Suppl. 5), pp. S577–584.
- [37] Shepherd, D. E. T., and Johnstone, A. J., 2002, "Design Considerations for a Wrist Implant," *Med. Eng. Phys.*, **24**(10), pp. 641–650.
- [38] Banks, S. A., and Hodge, W. A., 2004, "Implant Design Affects Knee Arthroplasty Kinematics During Stair-Stepping," *Clin. Orthop.*, **426**, pp. 187–193.
- [39] Banks, S. A., and Hodge, W. A., 2004, "2003 Hap Paul Award Paper of the International Society for Technology in Arthroplasty. Design and Activity Dependence of Kinematics in Fixed and Mobile-Bearing Knee Arthroplasties," *J. Arthroplasty*, **19**(7), pp. 809–816.
- [40] Franta, A. K., Lenters, T. R., Mounce, D., Neradilek, B., and Matsen, F. A., 2007, "The Complex Characteristics of 282 Unsatisfactory Shoulder Arthroplasties," *J. Shoulder Elbow Surg.*, **16**(5), pp. 555–562.
- [41] Gregory, T., Hansen, U., Emery, R. J., Augereau, B., and Amis, A. A., 2007, "Developments in Shoulder Arthroplasty," *Proc. Inst. Mech. Eng., Part H*, **221**(1), pp. 87–96.
- [42] Gregory, T. M., Sankey, A., Augereau, B., Vandenbussche, E., Amis, A., Emery, R., and Hansen, U., 2013, "Accuracy of Glenoid Component Placement in Total Shoulder Arthroplasty and Its Effect on Clinical and Radiological Outcome in a Retrospective, Longitudinal, Monocentric Open Study," *PLoS One*, **8**(10), p. e75791.
- [43] Nikooyan, A. A., van der Helm, F. C. T., Westerhoff, P., Graichen, F., Bergmann, G., and Veeger, H. E. J. D., 2011, "Comparison of Two Methods for In Vivo Estimation of the Glenohumeral Joint Rotation Center (GH-JRC) of the Patients With Shoulder Hemiarthroplasty," *PLoS One*, **6**(3), p. e18488.
- [44] Pearl, M. L., 2005, "Proximal Humeral Anatomy in Shoulder Arthroplasty: Implications for Prosthetic Design and Surgical Technique," *J. Shoulder Elbow Surg.*, **14**(1 Suppl. S), pp. 99S–104S.
- [45] Pearl, M. L., and Kurutz, S., 1999, "Geometric Analysis of Commonly Used Prosthetic Systems for Proximal Humeral Replacement," *J. Bone Jt. Surg. Am.*, **81**(5), pp. 660–671.
- [46] Valero-Cuevas, F. J., Johanson, M. E., and Towles, J. D., 2003, "Towards a Realistic Biomechanical Model of the Thumb: The Choice of Kinematic Description May Be More Critical Than the Solution Method or the Variability/Uncertainty of Musculoskeletal Parameters," *J. Biomech.*, **36**(7), pp. 1019–1030.