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In Vivo Kinematics of the Trapeziometacarpal Joint During Thumb Extension-flexion and Abduction-adduction

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Abstract

Purpose—The primary aim of this study was to determine whether the in vivo kinematics of the trapeziometacarpal (TMC) joint differ as a function of age and sex during thumb extension-flexion and abduction-adduction motions.

Methods—The hands and wrists of 44 subjects (10 men and 11 women aged 18 to 35 years and 10 men and 13 women aged 40 to 75 years) with no symptoms or signs of TMC joint pathology were imaged with computed tomography (CT) during thumb extension, flexion, abduction, and adduction. The kinematics of the TMC joint were computed and compared across direction, age, and sex.

Results—We found no significant effects of age or sex, after normalizing for size, in any of the kinematic parameters. The extension-flexion and abduction-adduction rotation axes did not intersect, and both were oriented obliquely to the saddle-shaped anatomy of the TMC articulation. The extension-flexion axis was located in the trapezium and the abduction-adduction axis was located in the metacarpal. Metacarpal translation and internal rotation occurred primarily during extension-flexion.

Discussion—Our in vivo findings support previous cadaver and modeling studies that have concluded that the functional axes of the TMC joint are non-orthogonal and non-intersecting. However, in contrast to previous studies, we found extension-flexion and adduction-abduction to

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be coupled with internal-external rotation and translation. Specifically, internal rotation and ulnar translation were coupled with flexion, indicating a potential stabilizing screw-home mechanism.

Clinical Relevance—The treatment of TMC pathology and arthroplasty design require a detailed and accurate understanding of TMC function. This study confirms the complexity of TMC kinematics and describes metacarpal translation coupled with internal rotation during extension-flexion, which may explain some of the limitations of current treatment strategies and should help improve implant designs.

Keywords

Thumb; CMC; In vivo; ROM; kinematics

INTRODUCTION

The unique¹ and important² functions of the thumb are achieved largely through motion at the first carpometacarpal (TMC) joint. In their healthy state, the articular surfaces of the TMC joint are saddle-shaped. Based on this morphology, the TMC joint historically has been described to function as a universal joint^{3–5} with 2 orthogonal axes of rotation centered within and aligned with the convex articular surfaces of the trapezium and first metacarpal. However, the limitation of this idealized model was revealed in an elegant cadaver experiment by Hollister et al.⁶ Using a mechanical axis finder, they demonstrated clearly that the extension-flexion and abduction-adduction axes are non-orthogonal and non-intersecting.

Edmunds proposed that the soft tissues surrounding the TMC joint generate a stabilizing screw-home motion at the end of thumb flexion^{7,8}, similar to the previously described screw-home mechanism that occurs at the end of knee extension.⁹ Essential to such screw-home mechanisms are the stabilizing translations and/or rotations that are innately coupled with the primary rotation. However, to date experimental studies have not described translation or rotational coupling of the TMC joint.^{6,10–14} There have been several studies of thumb motion based on data acquired using skin marker-based motion tracking systems.^{15–17} These marker-based studies are limited because they were only capable of approximating true skeletal kinematics due to skin-motion artifact. Moreover, they could not differentiate TMC, scaphotrapezial, or scapho-radial joint motion from total thumb motion. One study directly tracked skeletal motion at the TMC joint of a single subject using an MR image-based tracking methodology.¹⁸ Consistent with the results from previous cadaver studies, it described skewed and non-intersecting extension-flexion and abduction-adduction rotation axes, but no metacarpal translation or coupled rotation.

Our incomplete understanding of TMC mechanics is exemplified by a biomechanical modeling study in which simplified kinematic descriptors resulted in non-realistic predictions of forces at the TMC joint.¹⁹ Advancing our understanding of TMC joint mechanics should improve the understanding and treatment of TMC pathology and provide new insight into the etiology of TMC joint osteoarthritis. The higher prevalence of TMC OA in women compared to men²⁰ has not been fully explained, but differences in thumb use

that result in abnormal joint mechanics is a leading theory.²¹ Implant failure may also reflect the fact that current devices do not accurately replicate in vivo kinematics.^{22–24}

Accordingly, the purpose of this study was to determine whether in vivo TMC joint kinematics differ as a function of age and/or sex. Our secondary aim was to confirm with in vivo data the predictions of previous in vitro studies that the extension-flexion and abduction-adduction rotation axes of the TMC joint are non-orthogonal and non-intersecting.

METHODS

Subjects

After approval from our institutional review board, 44 asymptomatic subjects with no history of thumb injury were recruited as part of a larger cohort in a study on biomechanics and TMC joint OA.^{25–27} Recruiting was designed to yield 4 sub-cohorts stratified by age and sex: younger participants, aged 18 to 35 years (10 young men, age = 23 ± 3 yrs. and 11 young women, age = 24 ± 1 yrs.), and older participants, aged 40 to 75 years (10 older men, age = 57 ± 9 yrs. and 13 older women, age = 55 ± 8 yrs.). In the larger cohort we previously analyzed articular shape^{25,26} and the subtle motion of the TMC joint that occurred during 3 isometric functional tasks.²⁷

Imaging and Image Processing

Computed tomography (CT) volume images of the dominant wrists of all subjects were acquired at maximum thumb extension, flexion, abduction, and adduction. Custom-designed polycarbonate fixtures were used to standardize the directions of thumb motion (Figure 1). A vertical polycarbonate plate, angled at 30° to the dorsum of the hand, supported thumb extension-flexion, and a horizontal polycarbonate plate abutting the radial surface of the index digit supported thumb abduction-adduction. 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 or 40 mA, slice thickness of 0.625 mm, and an in-plane resolution of at least 0.4×0.4 mm. The average effective radiation dose for the imaging involved in this study was 0.25 mSv per participant (maximum 0.53 mSv).

The complete outer cortical bone surfaces of the trapezium and first metacarpal were segmented, or digitally extracted, from the neutral CT volumes using a commercially available software package (Mimics® v.13.1, Materialise, Leuven, Belgium). The bone surfaces were exported as meshed objects and the principal directions of curvature for the articular surfaces of each trapezium were used to construct bone-fixed coordinate systems.²⁸ The coordinate systems were oriented such that the positive x-axis was volar, the positive y-axis was proximal, and the positive z-axis was radial (Figure 2); the inflection point of the saddle-shaped surface defined the origin. The X-Z plane was referred to as the trapezial articular plane.

Bone Kinematics

Three-dimensional (3-D) kinematics from extension to flexion (extension-flexion) and from abduction to adduction (abduction-adduction) were determined for each bone using a well-established markerless bone registration methodology.²⁹ Motion of the first metacarpal (MC1) with respect to the trapezium was described using helical axes of motion (HAM) variables,³⁰ which efficiently express the complete 3-D motion of the first metacarpal with respect to the trapezium as a rotation about and a translation along a unique axis in 3-D space. This unique HAM axis describes the physical axis about which the bone rotates. The HAM translation is the component of the bone's translation along this axis, not along the coordinate axes. For background, the instantaneous center of rotation is the point of intersection of the HAM axis with the plane of rotation. There are specific HAM axes for each direction of motion, and they are not necessarily aligned with the coordinate axes. We elected not to use Euler (Cardan) angles for two principal reasons. First, Euler angles have six possible solutions, and for rotations that do not occur primarily about one of the coordinate axes, the difference in the solutions can be as large as the motions themselves. Second, Euler angles do not provide a description of the actual axis about which a bone rotates.

The orientation of each HAM axis (also referred to as the rotation axis) was described in terms of the azimuth angle within and elevation angle out of the trapezial articular plane (X-Z) (Figure 2). The location of the rotation axis was described by the points where the axis intersected the planes of the trapezial coordinate system. To compare axis locations in men and women, the larger male bone size was normalized by dividing the coordinates of the axis location by the cube root of the subject's trapezial bone volume.

Statistical Analysis

Differences in the means of the helical-axis variables (rotations, translations, axis orientations, and locations) for extension-flexion and abduction-adduction were assessed using independent two-way (age $\times$ sex) analysis of variance tests. *P* values less than or equal to 0.05 were considered statistically significant.

RESULTS

There were no fundamental differences in thumb flexion-extension and abduction-adduction motion as a function of age or sex. Age had no significant effect on any of the kinematic variables used to describe the motion of the first metacarpal with respect to the trapezium (*P* = 0.97). The only kinematic variable that differed as a function of sex was the proximal-distal location of the abduction-adduction axis, which we found to be significantly more distal in men than women by a mean of 1.2 mm (*P* = 0.047). However, this difference disappeared after normalizing for bone size. Therefore, the kinematic data for all subjects were pooled and the HAM axis data were reported for the entire cohort of subjects.

The mean extension-flexion rotation axis was oriented 63° (SD: 13°, CI: 4°) radial to the dorsal (-X) coordinate axis and elevated a mean of 21° (SD: 13°, CI: 34°) in the proximal direction from the trapezial articular plane (X-Z) (Figure 3c and 3a, respectively). The mean

extension-flexion rotation axis was located in the distal trapezium, intersecting the dorsal volar (X-Y) plane 3.1 mm (SD: 1.9 mm, CI: 0.6 mm) proximal and 2.1 mm (SD: 1.6 mm, CI: 0.5 mm) dorsal to the origin of the trapezoidal coordinate system (Figure 3a and 3c). The mean extension-flexion range of motion was 45° (SD: 15°, CI: 5°), and this rotation was associated with a mean of 3.3 mm (SD: 1.9 mm, CI: 0.5 mm) of MC1 translation along the rotation axis in an ulnar direction. With an axis elevation of 21° in the proximal direction, the 45° of Ex-Fl range of motion was associated with approximately 16° of internal rotation.

The abduction-adduction rotation axis was oriented a mean of 4° (SD: 11°, CI: 3°) from the volar (X) coordinate axis in the ulnar direction, and it was elevated a mean of 25° (SD: 14°, CI: 4°) from the trapezoidal articular plane in a distal direction (Figure 3c and 3b, respectively). The mean abduction-adduction rotation axis was located in the proximal MC1, intersecting the radial-ulnar (Y-Z) plane 9.2 mm (SD: 2.0 mm, CI: 0.6 mm) distal and 0.6 mm (SD: 1.5 mm, CI: 0.4 mm) ulnar from the origin of the trapezoidal coordinate system (Figure 3b, 3c, and 3d). The mean abduction to adduction range of motion was 42° (SD: 10°, CI: 3°) and this rotation was associated with a mean of 0.6 mm (SD: 1.7 mm, CI: 0.5 mm) of MC1 translation along the rotation axis in dorsal direction. With an axis elevation of 25° in the distal direction, the 42° of Ab-Ad range of motion was associated with approximately 18° of external rotation.

The mean minimum distance between the extension-flexion axis and the abduction-adduction axis was 9.2 mm (SD: 2.5 mm, CI: 0.7 mm). The mean angle between the extension-flexion axis and the abduction-adduction axis was 124° (SD: 19°, CI: 6°) (Figure 4).

DISCUSSION

The primary aim of this study was to quantify the in vivo kinematics of the TMC joint during extension-flexion and abduction-adduction, and to determine if the kinematics differ as a function of age or sex. Since the current understanding of TMC joint kinematics of both normal and arthritic joints is largely based on cadaver studies, this investigation focused on asymptomatic living subjects with no signs of disease.

We did not detect any fundamental differences in TMC kinematics as a function of either age or sex. Consistent with previous studies,^{6,10-14} we found that the extension-flexion and abduction-adduction rotation axes were located within the distal trapezium and proximal metacarpal, respectively, and that they were oriented oblique to each other and to the anatomy of the saddle-shaped TMC joint. In this study we also found measurable internal-external rotation that was coupled with both extension-flexion and abduction-adduction. Coupling with extension-flexion was evidenced by the fact that the extension-flexion rotation axis was elevated in the proximal direction, indicating that as the first metacarpal moved from extension to flexion it also rotated internally. Conversely, in abduction-adduction, the rotation axis was elevated from the trapezoidal plane in the distal direction, indicating that the first metacarpal rotated externally with adduction.

Given the larger size of carpal bones from the male subjects compared to the bones from the female subjects³¹, we anticipated, and found, sex-related differences in the proximal-distal location of the abduction-adduction rotation axis. However, after normalizing for bone size the sex-related differences disappeared. Moreover, the kinematic variables that were not dependent on bone size, specifically the axis orientations and ranges of motion, did not differ with sex. Taken together, this suggests that TMC joint kinematics are not inherently different between women and men but vary slightly as a function of bone size. The shape of the TMC articulation changes with age²⁶, which could also change axis location. However, we found no change in the location of either rotation axis with age. There might have been subtle kinematic differences that we were unable to detect, despite the relatively large sample size. Technically, our ability to track the trapezium and first metacarpal was comparable to our ability to track the other carpal bones, which we can do with an accuracy better than 1° of rotation and 0.3 mm of translation.²⁹

Limitations of our methodology included our focus on only extension-flexion and abduction-adduction, our standardization of thumb positioning using jigs, and our use of a static imaging protocol. We focused on extension-flexion and abduction-adduction because they have been postulated to align with the saddle-shaped articular geometry of the TMC joint and are typically considered the primary degrees of freedom in the joint. We chose an angle of 30° from the dorsum of the hand for the orientation of the flexion-extension jig to best align motion along the path of ideal TMC joint flexion. Other jig orientations would likely yield different results, but would also likely increase coupled motions. Our imaging protocol was limited to one extreme static position for each motion, therefore only one axis was computed for each direction of motion. Consequently, it was not possible to determine if the location and orientation of the rotation axis varied with the path of TMC joint motion. However, the low variability in the orientations and locations of the axes gave us confidence that the axes were relatively stable for the directions of motion studied. The fact that we used a static imaging protocol should not alter our conclusions, as previous studies evaluating dynamic carpal kinematics found that the hysteresis due to viscoelasticity was very small (0° to 3°)³². Finally, we did not record EMG data; therefore we cannot determine whether the kinematics were driven by passive structures (i.e. joint geometry and ligamentous constraints), neuromuscular control, or a combination of both.

Several studies have reported the non-orthogonal and non-intersection nature of the extension-flexion and abduction-adduction axes.^{3,4,6,11,18} Hollister et al. used a mechanical axis finder in a cadaveric model to locate the rotation axes of the TMC joint.^{6,11} They reported that the extension-flexion axis was located in the trapezium, the abduction-adduction axis was located in the first metacarpal, and both were fixed throughout the range of motion. In contrast to Cooney et al.³ and Kapandji et al.⁴, who concluded that the extension-flexion and abduction-adduction axes were perpendicular to each other, Hollister et al. reported an angle of $73 \text{ (or } 107^\circ) \pm 8^\circ$ between the axes, whereas Cerveri et al.¹⁸ reported an angle of 111° . Our findings ($124^\circ \pm 19^\circ$) were roughly in agreement with these results. Additionally, we found that the minimum distance between the extension-flexion and the abduction-adduction axes was $9.2 \pm 2.5 \text{ mm}$, which was larger than the 5 mm reported by Cerveri et al. in their one-subject MRI image-based study.¹⁸ This discrepancy may be a result of differences in the joint postures that were captured and/or the size of the

participants studied. While these studies collectively demonstrate that the extension-flexion and the abduction-adduction axes are largely fixed relative to the trapezium, it is important to understand that these axes are unique and specific for these motions. Thumb motion that combines, for example, flexion with adduction, would have its own unique axis that would likely be located somewhere between the axes for pure flexion and pure adduction. We postulate that the axes for all physiologically possible thumb rotations lie on a continuous surface. Additional work will be necessary to confirm this.

We found that there was substantial coupling of internal rotation and translation of the first metacarpal with respect to the trapezium, primarily during extension-flexion. This contrasts with other studies that reported either minimal translation or that were silent on the subject.^{3,6,10,12–14,16,33} While our methodology was limited to motions computed from extreme positions and therefore could not determine if the observed internal rotation and translation occur throughout the range of motion or just at the extreme position, it was quite consistent with the screw-home mechanism proposed by Edmunds.^{7,8} The mechanism associated with this screw-home motion, whether due to ligaments³⁴, articular shape³⁵, neuromuscular control, or some combination, remains to be determined. Regardless, the screw-home mechanism may impart positional stability to a joint that has otherwise evolved to be lax.

Clinically, our findings are anticipated to be of most value in informing soft tissue reconstructive procedures that spare the TMC joint and in the design of implants for advanced arthritis treatment. With the potential to determine specific trapezial kinematics associated with wear patterns and degenerative changes, intervention to stabilize the joint prior to the occurrence of substantial cartilage pathology would alter treatment algorithms and aggressiveness in remediating continued joint degeneration. Understanding potential damage-promoting mechanisms is essential to designing successful surgical procedures capable of altering the progression of TMC osteoarthritis, as opposed to simply treating the end result. Similarly, implant design could be influenced by these same factors since restored kinematics are essential components of a predictable joint replacement.

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Figure 1. Reconstructed CT images illustrating the thumb positions analyzed for this study (A. Extension, B. Flexion, C. Abduction, D. Adduction). The grey geometrical objects are polycarbonate plates used to help standardize the direction of motion across subjects.

Figure 2.

Volar view of a right wrist and TMC joint (A) with the trapezial coordinate system (B), in which the X-Z plane is referred as the trapezial articular plane. The +x direction is volar, +y direction is proximal, and +z direction is radial. The orientation of a rotation axis was described by 2 angles: the azimuth angle within the X-Z plane (0° azimuth aligned with the positive x-axis) and the elevation angle out of the X-Z plane.

Figure 3.

Orientation of the extension-flexion and abduction-adduction axes with respect to the trapezial coordinate system. In the volar view (A), the extension-flexion axis was elevated at a mean of 21° in the proximal direction from the trapezial articular plane. From the radial view (B), the abduction-adduction axis was elevated a mean of 25° in the distal direction. From the distal view (C), the extension-flexion axis was oriented 63° in the radial direction from the dorsal direction (-x), while the abduction-adduction axis was oriented at 4° in ulnar direction from the volar direction. Location of the extension-flexion axis was (3.1 mm) proximal and (2.1 mm) dorsal from the origin of the trapezial coordinate system, while abduction-adduction axis was located (9.2 mm) distally and (0.6 mm) in the ulnar direction from the origin of the trapezial coordinate system.

Figure 4.

Views of the TMC joint illustrating the extension-flexion and abduction-adduction axes passing through trapezium and first metacarpal, respectively (A). The closest distance between the axes was a mean $d = 9.2$ mm (B), while the mean angle between the axes was a mean $\alpha = 124^\circ$ (C).