A Normative Database of Thumb Circumduction In Vivo: Center of Rotation and Range of Motion

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This article reports a systematic research effort aimed at establishing a normative database of thumb circumduction range of motion (ROM) and related kinematic characteristics in vivo while examining the effects of anthropometry, gender, and direction of rotation. Twenty-eight (14 men, 14 women) anthropometrically diverse participants performed maximum voluntary thumb circumductions as the trajectories of the surface markers placed on their thumb landmarks were recorded by an optoelectronic motion capture system. A globographic representation method was employed to model the measured marker trajectories, determining the center of rotation and central reference axes for thumb circumduction. Thumb ROM was quantified using (a) the joint sinuses expressing the thumb orientation change with respect to the reference axes and (b) cone volumes circumscribed by the thumb at the distal phalangeal, interphalangeal, and metacarpophalangeal levels. Data analyses resulted in statistical summaries of the derived kinematic and ROM measures with significant effects identified and regression equations predicting the cone volumes. Potential applications of this research include ergonomic design of hand-operated controls or devices and evaluation of thumb impairments or disorders.

INTRODUCTION

The thumb has unique kinematic and anatomical characteristics as compared with the other four digits of the hand, and it plays an irreplaceable role in many manipulative tasks. Thumb function is often regarded as accounting for 40% to 50% of the hand’s usefulness (Ateshian et al., 1995; Emerson, Krizek, & Greenwald, 1996; Swanson, Goran-Hagert, & Swanson, 1987). Therefore quantitative knowledge of thumb functional and biomechanical capacities is of fundamental value in the field of ergonomics, serving as the basis for a variety of applications. For instance, functional thumb range of motion (ROM) information is needed in developing design criteria for the location of push buttons on multifunctional hand-operated controls (Gilbert, Hahn, Gilmore, & Schurman, 1988). In addition, a normative ROM database with robust population representations can aid in evaluating functional losses or impairments, many of which result from occupational injuries and disorders. Crushing injury, spinal cord injury, damage to the ulnar and/or median nerves, and secondary osteoarthritis are just a few examples of the occupational traumas that are prevalent in industry and likely to cause compromised functional capacity of the thumb (Absoud & Harpo, 1984; Acheson, Chan, & Clemett, 1970; Putz-Anderson, 1988; U.S. Department of Labor, 1999a, 1999b). However, although some basic hand anthropometric databases exist (Buchholz, Armstrong, & Goldstein, 1992; Garrett, 1971), data on thumb kinematic characteristics in vivo, including the functional ROM, are sparse.

One dilemma in quantifying the thumb functional ROM is that whereas joint ranges of motion have traditionally been presented in a plane or two dimensions (2-D), the thumb motions are hardly planar. The carpometacarpal joint (CMC), which provides the largest motion among the
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thumb joints, is commonly considered as a universal joint permitting two degrees of freedom (Cooney & Chao, 1977; Cooney, Lucca, Chao, & Linscheid, 1981; Kapandji, 1981; Rijpkema & Girard, 1991; Toft & Berme, 1980) with negligible axial rotation (Cooney et al., 1981; Haines, 1944; Napier, 1955). Thus the functional thumb ROM should ideally be measured and modeled in three dimensions (3-D). Nevertheless, in many earlier studies, the measurement or modeling was limited to 2-D (Cooney et al., 1981; Eaton, Glickel, & Littler, 1985; Gilbert et al., 1988; Jacobs & Thompson, 1960; Kuo, Su, Chiu, & Yu, 2002). In fact, the current guidelines of the American Academy of Orthopaedic Surgeons and the International Federation of Societies for Surgery of the Hand still utilize planar data to quantify thumb ROM (Balfour, 1995; Swanson et al., 1987).

A few cadaveric studies in the past have simulated 3-D thumb circumduction in vitro and attempted to characterize the functional ROM. Ou (1980) used six cadaver forearms with fixed metacarpophalangeal (MCP,) and interphalangeal (IP,) joints of the thumb and estimated the tendon moment arms at a few discrete positions along a circumduction. The simulated circumduction, as a conical rotation of a fixated rigid segment following a presumed circular base, was an oversimplified and inaccurate representation of the maximum-range thumb motion. Imaeda, Niebur, Cooney, Linscheid, and An (1994) were the first to realistically quantify the nonsymmetric elliptical base of the cone formed by cadaveric thumb circumduction in vitro. However, only the thumb metacarpal movement was quantified in terms of distance within a plane and flexion-extension and abduction-adduction angles. Continuous angular data for the thumb circumduction motion at the IP1 joint and tip of the distal phalanx (DP1) were not obtained. Imaeda et al. (1994) acknowledged that the primary limitation of their study was the failure to simulate a smooth, coordinated thumb motion. These prior studies illustrated that there could be a significant discrepancy between simulated maximum thumb circumductions in vitro and ones in vivo with tissues and structures intact and free from artificial constraints. Data of the latter kind are most germane to the various aforementioned applications but are currently lacking.

This study was motivated by the need for a normative database of the 3-D thumb ROM in vivo that can be readily utilized in ergonomic design and functional assessment applications. It was also encouraged by the recognition that with the advent of much advanced motion capture technology, it is feasible to measure finger movement in vivo with details at the individual segmental level (Kuo et al., 2002; Rash, Belliappa, Wachowiak, Sophia, & Gupta, 1999; Sophia, Rash, Wachowiak, & Gupta, 1998). Therefore, the specific aims of this study were (a) to measure in vivo maximum thumb circumductions performed by a group of anthropometrically diverse participants and (b), through biomechanical modeling and statistical analysis, to establish a normative database of thumb circumduction ROM and related kinematic characteristics while examining the effects of anthropometry, gender, and circumduction direction.

METHODS

Participants

Participants were selected according to stature through a rigorous screening process, using the following within-gender stratification scheme: 1st, 5th, 25th, 50th, 75th, 95th, and 99th percentile, with reference to a normative database (Eastman Kodak Company, 1986). Four individuals (2 men and 2 women) fitting the appropriate statures, with a tolerance of ±1 cm, were designated to each of the seven strata (Table 1). The 28 participants were all right-handed. The mean (±SD) weight and age were 72.3 (±9.25) kg and 23.6 (±3.3) years for the men and 57.8 (±8.53) kg and 24.4 (±6.3) years for the women. A set of hand anthropometric measures, including hand length, width, and depth (thickness) and individual digit and segment lengths, were recorded off the participants’ right hand in a posture with all digits fully extended and abducted (see the posture in Figure 1a). The mean (±SD) hand length, measured as the distance from the tip of Digit 3 to the palpable dorsal groove between the lunate and capitate bones, was 16.34 (±0.95) cm and 15.25 (±0.78) cm for the men and women, respectively. The mean (±SD) thumb length, measured as the distance from the tip of the thumb to the palpable dorsal groove where the metacarpal meets the
**TABLE 1:** Male and Female Stature Values (cm) at Seven Specified Percentiles

<table>
<thead>
<tr>
<th>Percentile</th>
<th>1st</th>
<th>5th</th>
<th>25th</th>
<th>50th</th>
<th>75th</th>
<th>95th</th>
<th>99th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male stature</td>
<td>159.1</td>
<td>163.7</td>
<td>170.0</td>
<td>174.5</td>
<td>179.0</td>
<td>185.3</td>
<td>189.9</td>
</tr>
<tr>
<td>Female stature</td>
<td>147.8</td>
<td>152.1</td>
<td>157.9</td>
<td>162.1</td>
<td>166.2</td>
<td>172.0</td>
<td>176.3</td>
</tr>
</tbody>
</table>

*Note.* The actual statures of selected participants were within ±1 cm from respective ideal statures.

*Figure 1.* (a) Twenty-one reflective markers were placed over various surface landmarks on the dorsum of participants’ right hand and, during thumb circumduction, were measured by a motion capture system. (b) A local coordinate system $X'-Y'-Z'$ was constructed using measured coordinates of the MCP$_2$, 3, 5 and CMC$_3$ markers.
trapezium, was 9.95 (±0.75) cm and 9.04 (±0.58) cm for the men and women, respectively.

**Experimental Procedure**

Miniature (5-mm diameter) reflective markers were secured to the dorsum of the participants’ right hand at 21 palpable surface landmarks (Figure 1). Note that only the labeled markers in Figure 1b were relevant to the current study. The participants were seated with the right forearm comfortably strapped to an armrest. Practice was allowed prior to the performance of trials that were actually recorded. Each participant performed maximum voluntary circumduction of the right thumb four times, twice in a clockwise (CW) direction (as viewed from proximal to distal) and twice in a counterclockwise (CCW) direction, at a self-preferred speed, while stiffening the MCP1 and IP1 joints as much as possible. The hand posture in the initial and terminal positions was semiprone with the thumb in full extension and abduction and pointing vertically.

As the participants were performing the thumb circumduction movements, a five-camera Vicon 250 optoelectronic motion capture system (Oxford Metrics Ltd., Oxford, UK) recorded the reflective marker trajectories at a sampling frequency of 120 Hz. The system tracked and then output the time-varying marker coordinates in a 3-D (X-Y-Z) laboratory coordinate system established through prior calibration. The measurement of miniature marker motions within a relatively small space required a unique “close-up” camera setting and a custom-made calibration wand. The experimental protocol was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign.

**Globographic Modeling**

A dorsum-based local coordinate system, X’-Y’-Z’, was established to facilitate kinematic descriptions and definitions (Figure 1b). The origin of this local coordinate system was the marker placed at the CMC joint of Digit 3 (CMC3). The \( \text{CMC}^3\text{-MCP}_2 \) and \( \text{CMC}^3\text{-MCP}_3 \) vectors (i.e., the vectors connecting the respective markers) formed a plane of the coordinate system. The \( X’ \) axis was the projection of the \( \text{CMC}^3\text{-MCP}_3 \) vector onto this plane. The \( Y’ \) axis lay in the plane, pointing radially while being perpendicular to the \( X’ \) axis. The \( Z’ \) axis was therefore normal to the plane, pointing dorsally. Coordinates of the four markers on the thumb measured in the global or laboratory coordinate system (X-Y-Z) were then transformed and expressed in the local coordinate system (X’-Y’-Z’).

A globographic representation method (Engin & Chen, 1986) was adapted for modeling the measured trajectories of three thumb markers (MCP1, IP1, and DP1). An optimization procedure was formulated to identify the best-fitting sphere for each thumb marker trajectory. This procedure assumed that three marker trajectories lay on three concentric spheres, as the CMC joint dominated thumb circumduction and the participants were instructed to inhibit the movement of the MCP1 and IP1 joints as much as possible. Thus, three concentric spheres were fitted to the three marker trajectories, determining the CMC joint center and sphere radii. The least-squares fitting process minimized the following error term:

\[
E_i = \sum_{j=1}^{P} \sum_{c} \left( (x'_i(t) - x'_c)^2 + (y'_i(t) - y'_c)^2 + (z'_i(t) - z'_c)^2 - r_i^2 \right)^2, 
\]

in which \((x'_c, y'_c, z'_c)\) are the local coordinates of the center of three spheres, considered as the CMC joint center and the center of rotation for thumb circumduction; \(r_i\) (i = 1, 2, 3) are the radii of the MCP1, IP1, and DP1 spheres, respectively; and \((x'_i(t), y'_i(t), z'_i(t))\) are the respective time-varying marker coordinates in the local coordinate system (X’-Y’-Z’). Once the center and the radii were determined, the root mean square error (RMSE) in fitting each of the three marker trajectories was then individually assessed.

**Derivation of Joint Sinus**

A joint sinus depicts the movement of a thumb marker as an angle-angle representation: the deviation of the marker vector (the vector pointing from the joint center to the marker) from a central reference axis versus the rotation around the axis. The joint sinus derivation for each of the three marker trajectories (note that hereafter the subscript \(i\) for marker designation will be omitted) proceeded in two steps.

First, in order to establish a central reference axis, a plane was fitted to each marker trajectory (see Figure 2). The normal direction of this plane was found by minimizing \(E_2\) as the sum of
squared distances from the time-varying marker position to the plane,

\[ E_t = \sum_{t=1}^{T} \left( \sqrt{A'x'(t) + B'y'(t) + C'z'(t) + D} \right), \]

in which vector \([A, B, C]\) represents the normal direction of the plane, \(D\) is a constant, and \((x'(t), y'(t), z'(t))\) are again the time-varying marker coordinates. The normal vector passing through the sphere center was determined as the reference axis (see Figure 2). Each reference axis was oriented with respect to the \(X'-Y'-Z'\) coordinate system by two angles: \(\alpha\) as the angle subtended by its projection onto the \(X'-Z'\) plane and the \(X'\) axis and \(\delta\) as the angle subtended by its projection onto the \(X'-Y'\) plane and the \(X'\) axis; the sign of the angles was determined by the rotation from the \(X'\) axis to the respective projection, adhering to the right-hand rule.

Second, each marker trajectory in 3-D was expressed as the changing orientation of the marker vector with respect to the established reference axis: its rotation \(\phi\) about and deviation \(\theta\) from the axis (Figure 3). A joint sinus was simply created by plotting \(\theta\) as a function of \(\phi\) (see Figure 4 for an example). Each joint sinus was examined in terms of its pattern, the minimum and maximum values of \(\theta\) over a full 360° range of \(\phi\), with \(\phi = 0°\) corresponding to the initial thumb posture (which remained consistent across all participants).

**Calculation of Cone Volume**

The rotation of each marker vector around the reference axis formed a cone encompassing the 3-D space that the thumb was capable of circum-scribing at each segmental level (i.e., metacarpal, proximal phalangeal, and distal phalangeal). The volume of this cone was calculated and used as another measure of functional thumb ROM, in addition to the measures related to the joint sinus. To calculate the cone volume, we first fitted a
Figure 3. A representative cone circumscribed by a DP₁ marker trajectory in the $X'$-$Y'$-$Z'$ local coordinate system.

Figure 4. A representative joint sinus profile along with the fitted polynomial for a DP₁ marker trajectory.
high-order polynomial to the joint sinus data such that the RMSE was less than 0.5°, thus expressing $\theta$ as a continuous function of $\phi$ (see Figure 4). The surface area of the “crown” of the cone was computed by the following integral,

$$S = r^2 \int_{\phi=0}^{\phi=2\pi} [1 - \cos(\theta(\phi))] d\phi,$$

in which $r$ is the radius of the fitted sphere (see Equation 1). The cone volume was then simply determined as

$$V = \frac{1}{3} r S.$$

All the preceding analysis and modeling routines were implemented as MATLAB® (The MathWorks, Inc., Natick, MA) programs.

**Statistical Analyses**

We performed regression analyses to examine the effects of anthropometry, gender, and circumduction direction on the following four groups of 18 dependent measures: Group 1, the CMC$_1$ joint center coordinates ($x'_c$, $y'_c$, $z'_c$); Group 2, the reference axis orientation $\alpha$ and $\delta$ angles; Group 3, the minimum and maximum values of the $\theta$ angles; and Group 4, the cone volumes. Note that Groups 2 through 4 were derived for MCP$_1$, IP$_1$, and DP$_1$, constituting a total of 15 measures.

We administered the regression analyses in a stepwise fashion ($\alpha$ to enter = .10; $\alpha$ to remove = .10), with the intent of achieving a parsimonious model identifying all significant factors. The model took the following general form:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5^2 + \beta_6 x_5^3 + \varepsilon,$$

in which $Y$ represents a dependent measure; $x_i$ through $x_5$ represent, respectively, the repetition (Trial 1 or 2), gender (male = 1 or female = –1), direction of circumduction (CCW = 1 or CW = –1), and an anthropometric predictor. Note that the second- and third-order terms of the anthropometric predictor ($x_5$) were included because it was deemed that some of the cone volume measures should relate to the anthropometry in a nonlinear manner (see Equations 3 and 4).

The interaction terms lacked viable physical interpretation and thus were not included.

The 15 dimensional or angular measures in Groups 1 through 3 and the three cone volume measures were treated differently in the regression analyses based on the same model. For the dimensional or angular measures, two most relevant hand dimensions, hand length and thumb length, were tried as alternative anthropometric predictors (i.e., used singly along with other factors). Hand breadth and depth were also incorporated at times as additional anthropometric predictors of, for example, the CMC$_1$ joint center coordinates ($x'_c$, $y'_c$, $z'_c$). Condition indices and variance decomposition proportions (Belsley, Kuh, & Welsch, 1980) were calculated to test for possible multicollinearity between the independent variables. For the cone volumes, the thumb length was used as the sole anthropometric predictor, with the understanding that it was most closely related to the volumes and the relationship was likely to be nonlinear. All statistical analyses were performed using SAS® (SAS Institute Inc., Cary, NC).

**RESULTS**

First of all, the mean ($\pm SD$) RMSEs in fitting three concentric spheres to the marker trajectories were 1.31 ($\pm 0.497$), 1.21 ($\pm 0.653$), and 1.41 ($\pm 0.604$) mm for MCP$_1$, IP$_1$, and DP$_1$, respectively. The corresponding mean ($\pm SD$) of the computed sphere radii were 48.1 ($\pm 9.56$), 72.5 ($\pm 10.5$), and 94.4 ($\pm 11.5$) mm. The overall high level of fitting accuracy ensured the adequacy of globographic representation, upon which the subsequent modeling and analyses were based.

Statistical summaries of the 18 measures derived to describe the thumb circumduction kinematics and ROM, presented in Tables 2 and 3, where they are stratified by gender and by direction of circumduction, respectively. Gender did not significantly affect measures other than the $y'_c$ and $z'_c$ coordinates, which was confirmed by an additional paired $t$ test with stature-matched male and female subgroups (note that the differences presented in Table 2 were attributable to combined effects of anthropometry and gender). The average center of rotation for the men was 3.4 mm distal, 4.9 mm radial, and 4.2 mm palmar to that for the women. The direction of
### TABLE 2: Means and Standard Deviations of the 18 Dependent Measures Used To Describe Thumb Circumduction Kinematics, by Gender

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>$x'_c$ coordinate (mm)</td>
<td>5.08</td>
<td>8.32</td>
</tr>
<tr>
<td>$y'_c$ coordinate (mm)*</td>
<td>12.3</td>
<td>7.42</td>
</tr>
<tr>
<td>$z'_c$ coordinate (mm)*</td>
<td>-36.2</td>
<td>3.22</td>
</tr>
<tr>
<td>MCP$_1$ $\alpha$ (°)</td>
<td>26.7</td>
<td>11.9</td>
</tr>
<tr>
<td>MCP$_1$ $\delta$ (°)</td>
<td>46.5</td>
<td>8.09</td>
</tr>
<tr>
<td>IP$_1$ $\alpha$ (°)</td>
<td>21.3</td>
<td>4.26</td>
</tr>
<tr>
<td>IP$_1$ $\delta$ (°)</td>
<td>28.6</td>
<td>6.55</td>
</tr>
<tr>
<td>DP$_1$ $\alpha$ (°)</td>
<td>20.0</td>
<td>6.02</td>
</tr>
<tr>
<td>DP$_1$ $\delta$ (°)</td>
<td>23.5</td>
<td>9.07</td>
</tr>
<tr>
<td>MCP$_1$ maximum $\theta$ (°)</td>
<td>34.7</td>
<td>7.40</td>
</tr>
<tr>
<td>MCP$_1$ minimum $\theta$ (°)</td>
<td>10.3</td>
<td>5.40</td>
</tr>
<tr>
<td>IP$_1$ maximum $\theta$ (°)</td>
<td>38.0</td>
<td>7.80</td>
</tr>
<tr>
<td>IP$_1$ minimum $\theta$ (°)</td>
<td>19.0</td>
<td>4.45</td>
</tr>
<tr>
<td>DP$_1$ maximum $\theta$ (°)</td>
<td>42.3</td>
<td>8.48</td>
</tr>
<tr>
<td>DP$_1$ minimum $\theta$ (°)</td>
<td>19.9</td>
<td>4.81</td>
</tr>
<tr>
<td>MCP$_1$ cone volume (cm$^3$)</td>
<td>19.1</td>
<td>11.8</td>
</tr>
<tr>
<td>IP$_1$ cone volume (cm$^3$)</td>
<td>109.9</td>
<td>48.3</td>
</tr>
<tr>
<td>DP$_1$ cone volume (cm$^3$)</td>
<td>293.9</td>
<td>99.8</td>
</tr>
</tbody>
</table>

Note. The between-gender difference in the mean cone volume was attributable to the anthropometric difference. A paired $t$-test with stature-matched subgroups confirmed the gender effect on the cone volume was not significant.

*Significant gender effect at the $p < .05$ level.

### TABLE 3: Means and Standard Deviations of the 18 Dependent Measures Used To Describe Thumb Circumduction Kinematics, by Direction of Circumduction

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>CCW</th>
<th>CW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>$x'_c$ coordinate (mm)</td>
<td>3.82</td>
<td>7.92</td>
</tr>
<tr>
<td>$y'_c$ coordinate (mm)</td>
<td>9.65</td>
<td>6.87</td>
</tr>
<tr>
<td>$z'_c$ coordinate (mm)*</td>
<td>-32.7</td>
<td>5.23</td>
</tr>
<tr>
<td>MCP$_1$ $\alpha$ (°)*</td>
<td>33.2</td>
<td>11.6</td>
</tr>
<tr>
<td>MCP$_1$ $\delta$ (°)</td>
<td>45.5</td>
<td>6.15</td>
</tr>
<tr>
<td>IP$_1$ $\alpha$ (°)*</td>
<td>23.3</td>
<td>4.85</td>
</tr>
<tr>
<td>IP$_1$ $\delta$ (°)*</td>
<td>27.9</td>
<td>5.39</td>
</tr>
<tr>
<td>DP$_1$ $\alpha$ (°)*</td>
<td>22.3</td>
<td>6.45</td>
</tr>
<tr>
<td>DP$_1$ $\delta$ (°)*</td>
<td>23.7</td>
<td>7.66</td>
</tr>
<tr>
<td>MCP$_1$ maximum $\theta$ (°)*</td>
<td>36.3</td>
<td>7.62</td>
</tr>
<tr>
<td>MCP$_1$ minimum $\theta$ (°)</td>
<td>10.0</td>
<td>5.99</td>
</tr>
<tr>
<td>IP$_1$ maximum $\theta$ (°)*</td>
<td>39.3</td>
<td>7.49</td>
</tr>
<tr>
<td>IP$_1$ minimum $\theta$ (°)</td>
<td>17.8</td>
<td>4.95</td>
</tr>
<tr>
<td>DP$_1$ maximum $\theta$ (°)*</td>
<td>43.5</td>
<td>8.41</td>
</tr>
<tr>
<td>DP$_1$ minimum $\theta$ (°)</td>
<td>18.9</td>
<td>5.83</td>
</tr>
<tr>
<td>MCP$_1$ cone volume (cm$^3$)</td>
<td>16.5</td>
<td>9.0</td>
</tr>
<tr>
<td>IP$_1$ cone volume (cm$^3$)</td>
<td>98.0</td>
<td>46.0</td>
</tr>
<tr>
<td>DP$_1$ cone volume (cm$^3$)*</td>
<td>267.1</td>
<td>106.9</td>
</tr>
</tbody>
</table>

*Significant direction effect at the $p < .05$ level.
circumduction affected 10 out of the 18 measures. More specifically, during CCW circumductions, the reference axes tended to have a greater $\alpha$ angle and a smaller $\delta$ angle (all significant except $\delta$ at the MCP level) – which translates into a more palmar and less radial orientation – than did those during CW circumductions. The thumb range of motion, measured by the joint sinus limits and cone volumes, was greater in the CCW direction than in the CW direction (statistically significant at the DP level), although the difference diminished along the proximal direction. No significant between-trial difference was found in any of the 18 measures.

The regression analyses of the 15 dimensional or angular measures did not achieve even a modest level of coefficient of determination: $R^2$ values ranged from .08 to .35, with the majority below .20. The anthropometric predictor, either hand or thumb length, significantly affected only 2 of the 15 measures ($z'_c$ coordinate and MCP$_1$ $\alpha$). The choice of anthropometric predictor (i.e., hand length vs. thumb length) did not make a difference in the resulting $R^2$ values, nor did the addition of higher order (up to the third) terms, the hand breadth and depth. In fact, it was found that the threshold limits for multicollinearity were exceeded when any two or more anthropometric measures were simultaneously implemented as regressors.

The regression analyses of three cone volumes (in cubic centimeters) resulted in the following prediction equations with modest coefficients of determination:

$$V_{\text{MCP}} = 445 - 95.57x_4 + 5.27x_4^3, \quad (R^2 = .40), \quad (6)$$
$$V_{\text{IP}} = 1890 - 409.5x_4 + 23.0x_4^2, \quad (R^2 = .58), \quad (7)$$
$$V_{\text{DP}} = 3120 + 15.145x_3 - 683.5x_4 + 59.8x_4^2, \quad (R^2 = .61), \quad (8)$$

in which $x_3$ is the circumduction direction (+1 for CCW, −1 for CW) and $x_4$ is the thumb length in centimeters.

Noteworthy also are some characteristic patterns or trends exhibited by the thumb circumduction and a few measures. The joint sinuses for saddle-shaped marker trajectories largely resembled sine waves, as illustrated by a representative profile in Figure 4. Both the maximum and minimum $\theta$ values increased for the more distal joint sinuses, whereas the $\alpha$ and $\delta$ angles decreased for the more distal reference axes. This latter trend means a more ulnar and dorsal orientation for the more distal axes and seems to indicate an inherent propensity to oppose the thumb to the distal palmar crease.

**DISCUSSION**

A number of previous studies have described thumb ROM with several basic planar measures (Cooney et al., 1981; Eaton et al., 1985; Jacobs & Thompson, 1960; Kapandji, 1981; Kuo et al., 2002; Smith & Buterbaugh, 1994). There have also been attempts to investigate thumb circumduction ROM through the use of cadaver specimens (Imaeda et al., 1994; Ou, 1980). However, an adequate database describing the 3-D functional thumb ROM in vivo has been lacking. The present study has established such a database and investigated personal as well as task effects on a series of thumb ROM measures.

A globographic representation method (Engin & Chen, 1986) was adapted by assuming that the MCP$_1$, IP$_1$, and DP$_1$ marker trajectories could be closely fitted to three concentric spheres. The applicability of this modeling approach was supported by the low fitting errors and the plausible physical location of the estimated CMC$_1$ joint center. Further, the modeling approach did not mask the fact that the three joints of the thumb do not naturally remain completely rigid during a conical rotation or circumduction (Kapandji, 1981), despite the participants’ attempt to stiffen the IP$_1$ and MCP$_1$ joints as much as possible. The cone volume along each successive distal level increased not only because of a dependence on an increasing cone radius but also because of a slight increase in the $\theta$ angles produced by the more distal marker trajectory (see Table 2 or 3). The extent to which the $\theta$ angles varied across three joints is indicative of how much the IP$_1$ and MCP$_1$ joints were held rigid: Had they been completely rigid, no change in the $\theta$ angles would have occurred.

If a joint sinus were a straight line with no slope, the marker trajectory would be perfectly circular. The joint sinus profiles derived in the current study indicate that the trajectories of thumb joints during circumduction form a slightly asymmetrical saddle shape in 3-D and an elliptical shape in a transverse cross-sectional plane.
(see Figures 2 and 3). This finding coincides with previous annotations that the conical movement of thumb circumduction reflects the nature of the CMC1 articular joint surface (Imaeda et al., 1994; Kapandji, 1981). Because the initial and terminal positions of thumb circumduction are known, the maximum and minimum θ values can be related to the corresponding φ values via the joint sinuses. This means that not only the maximum and minimum θ values are known, but where they occur in 3-D space is also known. The maximum θ values occur near 0° and 180° of φ, whereas the minimum θ values occur near 90° and 270° of φ (see Figure 4). Although it seems difficult to make individual-specific predictions of the reference axis orientation with respect to which the φ is defined, the interperson variability in the orientation is rather low at the IP1 and DP1 level, as suggested by relatively small standard deviations in α and δ (see Table 2 or 3). Figure 5 illustrates the DP1 reference axes for the CCW thumb circumductions performed by all female participants.

As a normative database is being constructed, it is important to elucidate the effects of personal factors, including anthropometry and gender, and task variables such as the circumduction direction in the current study. The most relevant anthropometric measure, the thumb length, does not have even a modest association with any of the dependent measures other than the cone volumes (for which $R^2$ ranges from .40 to .61). This is consistent with the assessment that thumb circumduction originating at the CMC1 joint is largely dependent on the saddle-shaped joint construct but not much on anthropometric measures (Imaeda et al., 1994; Kuczynski, 1974, 1975). Although the thumb length should closely relate to the cone radii, which are the key parameters in determining the cone volumes, the joint sinus (i.e., θ as a function of φ) also poses an apparent effect lessening the predictability (see Equation 3). With regard to the gender effect, although females are generally considered to have greater joint mobility than males (Chaffin, Andersson, & Martin,
1999, p. 99), no significant between-gender difference in the joint sinus measures and cone volumes was discovered. It can thus be concluded that the thumb ROM is not affected by the gender, and unisex guidelines may be established for design of handheld devices as well as diagnosis of thumb-related impairments.

Compared with the anthropometry and gender factors, the direction of rotation had a significant effect on more aspects of thumb circumduction kinematics. The opposing directions of rotation formed two cones of somewhat different orientations, shapes, and volumes. This may be attributable to dissimilar neuromuscular activation and mechanical constraints. For instance, the muscles controlling the thumb motion are innervated by different and sometimes overlapping branches of the median, ulnar, and radial nerves, which do not act entirely independent of one another (Jenkins, 1998). Further, the agonist and antagonist muscles of the thumb would most likely behave differently depending on the order and combination in which they are activated, and the passive forces of these muscles would also differ depending on the orientation and movement direction of the thumb in a 3-D space. Given the identified differences, the direction of circumduction should be taken into account as an important variable of thumb ROM.

The current study has resulted in much needed data and insights for future biomechanical modeling of in vivo hand motion and for applications such as ergonomic hand-tool design and medical diagnosis. For example, the center of rotation coordinates determined in this study can be considered as the thumb attachment point to the palm segment in constructing a biomechanical linkage model of the hand. In computer-aided design or prototyping of handheld devices or controls, visualization of the thumb ROM can help rapid decision making on issues such as where the feasible or preferred locations for thumb activation should be. In addition, the normative asymptomatic database established in this work could be a valuable asset for clinical applications based on motion analysis. Such applications include diagnosis of thumb functional loss caused by impairments or disorders (e.g., carpal tunnel syndrome, arthritis) and evaluation of recovery progress or surgical success.

Thumb circumduction has proven to be a complex movement, and there remain many issues that merit more in-depth investigation. For instance, a more comprehensive understanding of the thumb biomechanics in vivo will require studying natural motions—not just extreme motions or range of motion—and the force producing capability as a function of position and velocity. Another notable limitation of the current study was that a young participant pool was employed. The implication of this is twofold: First, caution must be exercised when the database and findings are applied in the design or diagnosis for different age groups; second, it would be worthwhile to develop similar databases of various age groups and investigate the age effect.

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REFERENCES


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