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The Kinesiology of the Thumb Trapeziometacarpal Joint*

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ABSTRACT: To measure the motions of the trapeziometacarpal joint of the thumb quantitatively, a roentgenographic method was developed and tested using T-shaped metal markers, a special cassette-holder, and biplane roentgenograms. Two experiments were performed. In the first one, the metal markers were fixed to the trapezium and third metacarpal in ten cadaver specimens, and a fixed spatial relationship between the trapezium and the third metacarpal was identified roentgenographically. This relationship was that the reference axes of the trapezium were aligned at median angles of 48 degrees of flexion, 38 degrees of abduction, and 80 degrees of pronation with reference to the reference axes of the third metacarpal.

In the second experiment, in the dominant hand of nine male and ten female subjects (average age, twenty-six years) T-shaped markers were fixed to the skin overlying the third metacarpal and the metacarpal and phalanges of the thumb. Using the same roentgenographic technique and coordinate systems employed in the first study, the average total motions of the trapeziometacarpal joint (determined as motions of the first metacarpal with reference to the third metacarpal) were 53 degrees of flexion-extension, 42 degrees of abduction-adduction, and 17 degrees of axial rotation (pronation-supination).

In addition, six functional positions of the thumb were studied: rest, flexion, extension, abduction, tip pinch, and grasp. A position of adduction and flexion of the trapeziometacarpal joint was most common during thumb function, and both the trapeziometacarpal and metacarpophalangeal joints contributed to rotation of the thumb.

CLINICAL RELEVANCE: Although the trapeziometacarpal joint of the thumb commonly is symptomatic as the result of disease, particularly degenerative arthritis, the motions of the joint during function of the thumb have not been measured accurately. More knowledge of these motions is essential for the planning of adequate treatment.

The three joints of the thumb provide 5 degrees of freedom and a wide range of motion for the thumb. The distal (interphalangeal) joint has flexion-extension movement, providing 1 degree of freedom; the proximal (metacarpophalangeal) joint has flexion-extension and abduction-adduction movements, or 2 degrees of freedom; and the basal (trapeziometacarpal) joint has flexion-extension and abduction-adduction motion (2 degrees of freedom) as well as a small, limited amount of axial rotation. Axial rotation of both the metacarpophalangeal joint[15] and the trapeziometacarpal joint[16] can occur passively when the ligaments are lax and the joints' articular surfaces are distracted, but during active motion and function (such as pinch and grasp), muscle forces and the compressive force across these joints constrain rotation and limit it to such an extent that axial rotation is not considered a degree of freedom of the thumb. Both the metacarpophalangeal and the trapeziometacarpal joints of the thumb, therefore, can be considered universal joints[3].

No precise terminology to describe the motions of the trapeziometacarpal joint has been generally accepted[16,22]. Terms such as *abduction palmar and radial to the hand*[12], *circumduction away from the plane of the palm of the hand*[13], and *opposition, retroposition, and transpalmar adduction*[27] have been proposed to describe motion at the base of the thumb. In the absence of clinical techniques to measure the actual motion of the trapeziometacarpal joint, motion at the base of the thumb has been described only as it relates to the rest of the hand[2,12]. This thumb motion is a composite of interphalangeal, metacarpophalangeal, and trapeziometacarpal motions.

Many investigators have attempted to determine the specific movements of the trapeziometacarpal joint by: wire fixation of the two distal joints of the thumb and measurement of the passive motion of the trapeziometacarpal joint[5,13,15]; analysis of the gross anatomy of this joint and of thumb function, with a detailed description of the potential motion of the trapeziometacarpal joint surfaces[16,21]; electrogoniometric measurements[8]; biplane vector analysis[23]; cineradiography[6]; and direct clinical observation[1,19,25]. The joint geometry[13,16,22], ligaments[10,26], and thumb-muscle forces[7,11,14,17] all have been designated as factors that determine trapeziometacarpal motion.

None of these or other studies[4,27,28] presented quantitative analyses of these complex movements *in vivo*. Also, the exact orientations of the trapezium and of the thumb with respect to the hand have not been established

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clearly, and the roles of the various joints of the thumb that participate in thumb rotation remain uncertain[15].

The data presented in this report were derived using an analytical technique that provided a three-dimensional description of the motion of the trapeziometacarpal joint and an accurate measurement of the amount of motion at this articulation.

Methods and Material

Motion of the trapeziometacarpal joint is difficult to measure *in vivo*. The trapezium cannot be palpated easily and the goniometers that presently are available fit on the thumb poorly. To provide a method of measuring this motion, we elected to bypass the trapezium and to employ more easily identified landmarks. As a first step, using cadaver specimens we established the geometric orientation of the trapezium with respect to the hand which we represented by the second and third metacarpals, both known to be the rigid supports of the hand[9].

In the second step (the *in vivo* studies), we used normal subjects and taped T-shaped metal markers to the skin over the dorsum of the metacarpal and proximal phalanx of the thumb, as well as over the dorsum of the third metacarpal. Then, during thumb flexion, extension, and opposition and during pinch and grasp, we measured trapeziometacarpal motions using biplane roentgenograms, from which we could locate the three-dimensional orientation of the T-shaped markers over the proximal phalanx and first metacarpal of the thumb and over the third metacarpal of the hand with respect to common reference coordinates located on a special x-ray grid frame. Because of the fixed relationship between the trapezium and the third metacarpal, previously established from the studies on cadavera, the position of the trapezium did not need to be marked and could be ignored in determining the motions of the trapeziometacarpal joint.

Finally, we developed new terminology to define and describe the motion of the trapeziometacarpal joint and defined a number of new concepts.

Anatomy

According to the classic anatomical description of the trapeziometacarpal (carpometacarpal) joint of the thumb, the surfaces of the joint resemble a saddle (Fig. 1). The reciprocal concave-convex articular surfaces of the trapezium and of the first metacarpal form an interlocking joint mechanism that restricts the direction and range of motion and may be considered the mechanical equivalent of a universal joint.

The central ridge on the trapezial articular surface is the main anatomical landmark on which this concept of a universal joint is based. This ridge, which is concave in one plane and convex in another, permits flexion-extension and abduction-adduction and, during distraction of the joint, some axial rotation. The ridge begins medially near the base of the second metacarpal and runs volarly and laterally to the radial facet of the trapezium. The volar and lateral direction of the ridge forms an angle of approximately 80 degrees to the plane of the palm. The medial side of the ridge is quite convex but the lateral side is flattened, curved, and slightly concave. This flattened lateral aspect provides a smooth surface that articulates with the convex articular surface of the first metacarpal. The convex medial surface of the trapezium mates well with the concave aspect of the proximal end of the first metacarpal and also provides for limited axial rotation. Kuczynski demonstrated that as an object slides across the central ridge from a position analogous to full extension to one analogous to full flexion, there is almost 90 degrees of rotation, which is comparable to the congruent conjunct rotation described by MacConaill and Basmajian.

The geometry of the surfaces of the joint between the trapezium and metacarpal of the thumb provides the basis for a reference plane that is different from the reference planes of motion of the fingers and can be used to describe motions of the trapeziometacarpal joint. For the thumb (Fig. 1), there is a plane of motion for flexion-extension which is perpendicular to the convex surface of the central ridge of the articular surface of the trapezium, while the plane of motion for abduction-adduction is perpendicular to the flexion-extension plane and parallel to the concave-convex articular surface of the central ridge (Fig. 1). In the position of full adduction and full flexion, there is close contact of the articulating surfaces of the first metacarpal and the trapezium (close-packed position)[18], and under these conditions rotation of the first metacarpal is constrained tightly. In full abduction and full extension, the flattened parts of these concave-convex articular surfaces are in contact over a smaller area and provide very little constraint. Therefore, a greater arc of motion is possible. The middle position (between full flexion and full extension and between full abduction and full adduction) is a loose-packed position which provides the least area of contact of the articular surfaces and maximum axial rotation. Both flexion-extension and abduction-adduction are restricted by the surface architecture of the articulating surfaces of the trapezium and the first metacarpal such that during flexion of the first metacarpal there is simultaneous medial rotation, while during extension there is simultaneous lateral rotation of the metacarpal. Rotation of the first metacarpal, isolated from other motions, can occur only when this bone is articulating with the middle of the central ridge of the trapezium and when the thumb is relaxed and the surfaces of the joint are distracted by one to two millimeters. When more of the articular surfaces are in contact, rotation is restricted.

Coordinate Axes for Orientation of the Trapezium and for Motion of the Trapeziometacarpal Joint

Motion of the trapeziometacarpal joint of the thumb is easier to measure if it is related to its own system of X, Y, and Z coordinates rather than to a system based on the hand or the palm. Flexion-extension and abduction-adduction of the metacarpal of the thumb do not occur about axes that are parallel or perpendicular to the plane of the hand[6,10,11,13,16,21,23]. Movement of the thumb in the plane of the

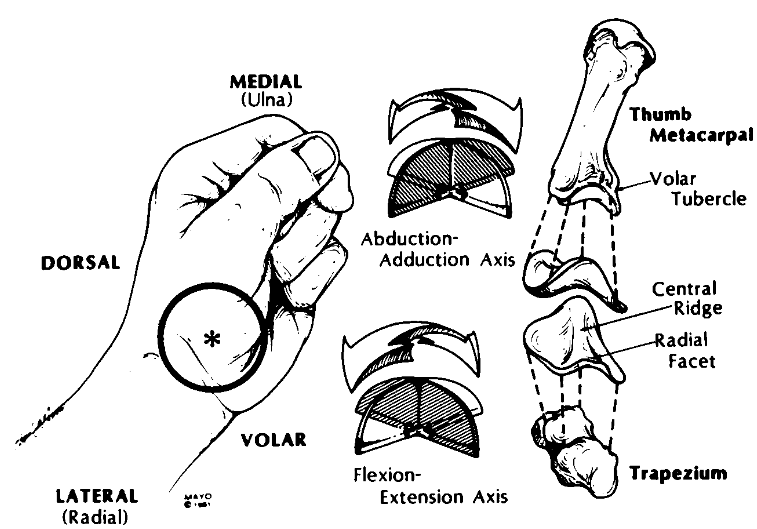

FIG. 1

Anatomy of the trapeziometacarpal joint of the thumb (asterisk in circle) showing both the anatomy and the planes of motion. At 90 degrees to each plane of motion, there is a flexion-extension and an abduction-adduction axis. On the left, the thumb is shown in the position of lateral pinch, with the thumb apposed to the radial side of the index finger. This also represents the position of rest used in this study. In the center, the abduction-adduction and flexion-extension planes and axes of motion are shown. Together these define the trapeziometacarpal joint as a saddle joint which mechanically is represented as a universal joint. On the right, the anatomical basis for this universal-joint concept is shown. This is based on the central ridge of the trapezium and on the mutually reciprocal articular surfaces of the trapezium and first metacarpal.

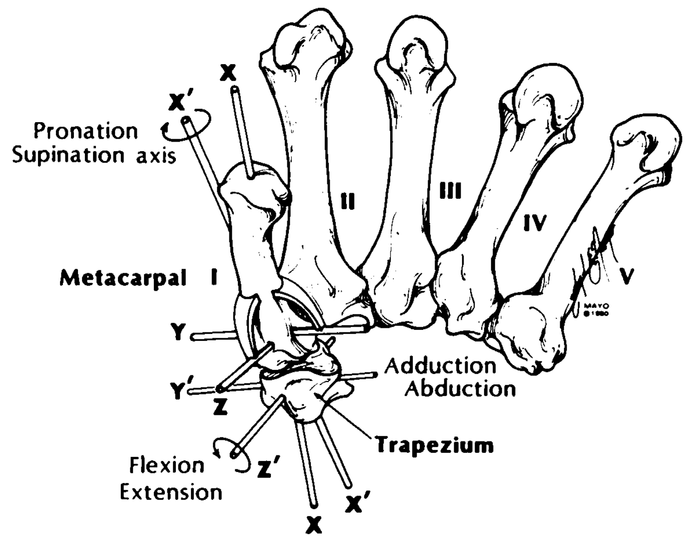

FIG. 2

Two independent systems of coordinate axes used to measure trapeziometacarpal joint motion: (1) X, Y, and Z axes of the first metacarpal (the moving segment), and (2) X', Y', and Z' axes of the trapezium (the fixed segment). These axes are based on the thumb ray itself and not on the palm. Abduction-adduction of the first metacarpal on the trapezium occurs about the Y' axis, while flexion-extension occurs about the Z' axis and pronation-supination, about the X' axis. The trapezium is the central reference for the thumb ray about which these movements take place.

hand (this plane being represented by the long axes of the second and third metacarpals) can occur only as the result of a combination of joint movements. Thus, the first metacarpal cannot be moved along a plane parallel with the dorsal surface of the hand[16].

A *coordinate axis system* for the trapeziometacarpal joint was established at the base of the thumb. The fixed system of coordinates (X', Y', and Z') was based in the trapezium and was the reference from which to measure the motions of flexion-extension, abduction-adduction, and axial rotation (pronation-supination) (Fig. 2). Each axis of this system was established (in cadaver specimens) in relation to discrete bone and joint architectural landmarks identified by dissections. The X' axis (Fig. 3) extended from the exact mid-point of the central ridge of the trapezial saddle proximally through the substance of this bone to the center of the articulation formed by the junction of the scaphoid, trapezium, and trapezoid. Axial rotation of the thumb metacarpal was assumed to occur about this axis. The Y' axis of the trapeziometacarpal joint (Fig. 3) ran in a dorsal-to-volar direction along a line perpendicular to the central ridge of the trapezium and passed through the mid-point of the dorsal surface to the proximal volar pole of the tubercle of the trapezium. This Y' axis defined abduction-adduction of the first metacarpal. The Z' axis (Fig. 3) extended in a medial direction from the radial (or lateral) surface of the trapezium at the distal end of the tubercle to the center of the articulation of the trapezium and the second metacarpal. This Z' axis was aligned perpendicular to the X' and Y' axes and was nearly parallel to the central ridge of the trapezial articular surface, which curves slightly toward the base of the second metacarpal. The Z' axis defined flexion-extension of the first metacarpal.

A roentgenographic grid coordinate reference system was used for the measurements of the motions of the trapeziometacarpal joint *in vivo*. As shown in Figure 4, this system of coordinates included a global reference system (X', Y', Z'), a fixed reference system (X, Y, Z), and a moving reference system (x, y, z). The global reference system was located by radiopaque lines on the plastic cassette-holders that were fixed to the support frame and were used to make the roentgenograms[20]. This reference system provided for three-dimensional orientation of the hand in space.

From the global reference system (X', Y', Z'), the spatial relationship between the fixed reference system (X, Y, Z) on the third metacarpal (representing the hand) and the moving reference system (x, y, z) on the first metacarpal could be determined. The fixed and moving reference systems were located by T-shaped metal markers that were attached to the skin over the first and third metacarpals and were used for roentgenographic location of the three-dimensional positions of these bones in space. For the moving reference system, the T-shaped marker was aligned over the first metacarpal so that the stem of the marker (x axis) was parallel with the long axis of the first metacarpal and the crossbar of the marker (z axis) was oriented parallel with the articular surface at the base of this metacarpal and perpendicular to the concave-convex central groove of this articular surface. This groove is convex in the lateral-to-medial direction and concave in the anterior-to-posterior direction, and is the reciprocal of the saddle-like ridge of the articular surface of the trapezium.

For the fixed reference system, the marker was located over the third metacarpal so that the stem of the T (X axis) was aligned along the shaft of this metacarpal

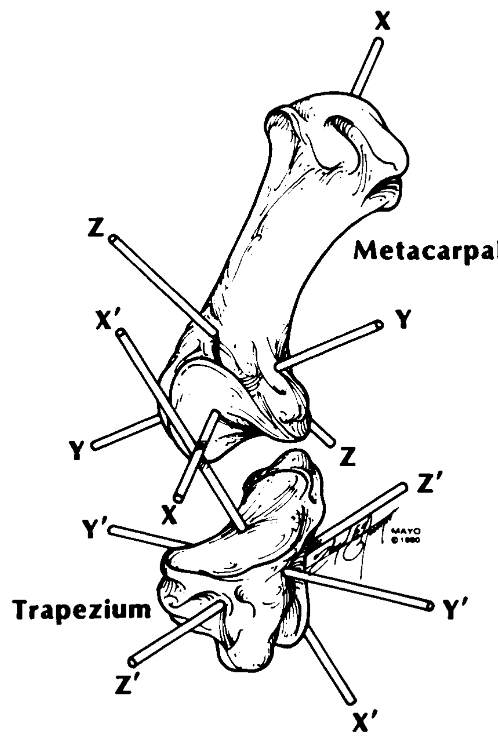

FIG. 3

Anatomical locations of the X', Y', and Z' axes of the trapezium and the X, Y, and Z axes of the thumb metacarpal, based on identifiable bone landmarks and on gross observations of passive motions of the thumb metacarpal on the trapezium. The X', Y', and Z' axes are orthogonal to each other and form a fixed reference system on which to base motion of the thumb. (See text for anatomical description and location of each axis.)

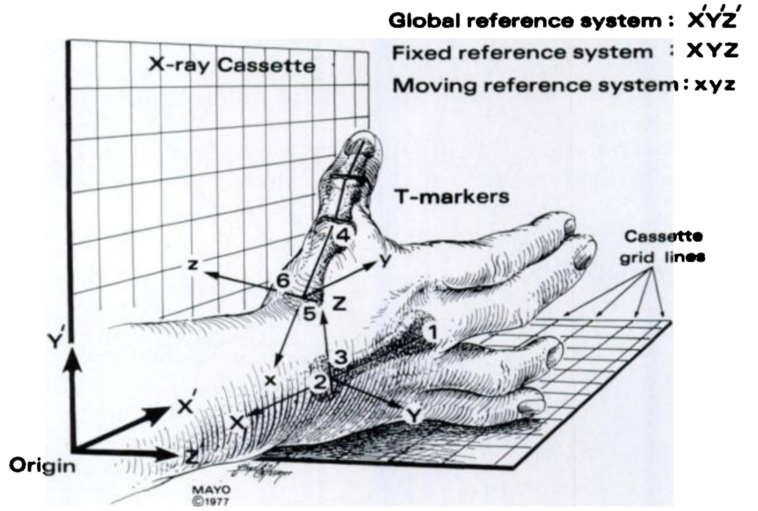

FIG. 4

The three reference coordinate systems used to determine the motions of the trapeziometacarpal joint *in vivo*: (1) the global system (X', Y', Z'), which is established by the grid lines on the cassette-holders for the anteroposterior and lateral roentgenograms; (2) the fixed system (X, Y, Z), which is located over the third metacarpal and fixes the position of the hand in space; and (3) the moving system (x, y, z), which is located over the first metacarpal and describes its position with respect to the third metacarpal (hand). The numbers on the third (1, 2, 3) and on the first (4, 5, 6) metacarpal identify non-colinear points on T-shaped markers that can be identified in any position of the hand and permit a vectorial solution for the determination of the orientation of the moving coordinate system (thumb) relative to the fixed coordinate system (hand). A T-shaped marker is shown over the distal phalanx, but motion of the interphalangeal joint was not studied.

and the crossbar of the T (Z axis) was parallel with the articular surface of the base of this bone. In both reference systems the y axis, by definition, was orthogonal (at 90 degrees) to the x and z axes. Anteroposterior and lateral roentgenograms of the hand were made to confirm the correct transverse, rotational, and longitudinal alignment of the markers with respect to the axes of the first and third metacarpals, and based on these roentgenograms any rotation or malplacement of the T-shaped markers was corrected. Because three non-colinear points can be identified on each marker (the end of the stem of the T, the end of the radially directed limb of the crossbar of the T, and the junction between the stem and the crossbar), these markers could be used to determine the movements of the first metacarpal.

The orientation angles of the trapezium (Fig. 5) defined the position of the trapezium with respect to the palm. Kuczynski described the trapezium as being rotated (pronated) 60 to 70 degrees from the plane of the palm, while Napier[21] believed that this angle was 80 degrees. Neither author considered the other two angles of orientation of the trapezium to the palm; that is, the flexion-extension and adduction-abduction angles. Littler reported that there is an angular relationship between the trapezium and the fixed second metacarpal, and that this relationship allows the mobile metacarpal of the thumb to be positioned so that the intermetacarpal angle (between the thumb and second metacarpal) is 36 degrees of radial abduction and 24 degrees of palmar flexion, but he did not describe the third component, rotational alignment.

Since the trapezium is oriented obliquely with respect to the plane of the hand, we separately measured *orientation angles* that would exactly establish the orientation of the trapezium in relation to the third metacarpal. By using three reference planes (transverse, longitudinal, and coronal) for the hand, the position of the trapezium could be defined in terms of angles of flexion-extension, abduction-adduction, and rotation with respect to the classic anatomical position of the hand. To do this, X', Y', and Z' coordinates previously established in the trapezium (Fig. 3) were located in relation to fixed coordinates in the third metacarpal. Then we used these measurements to describe the orientation angles of the trapezium in degrees of palmar flexion, radial abduction, and palmar rotation (pronation toward the palm).

In Vitro Analysis

Ten cadaver hands were studied to determine the exact orientation of the trapezium with respect to the third metacarpal. This study established so-called orientation angles that defined the three-dimensional position of the trapezium with

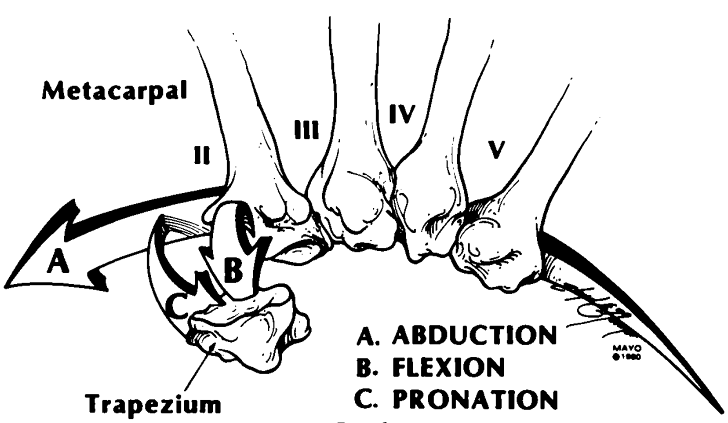

FIG. 5

Orientation angles of the trapezium defined the spatial location of the trapezium with respect to the fixed reference of the hand, which in this study was assumed to be represented by the second and third metacarpals. The trapezium is oriented obliquely in 38 degrees of abduction (A), 48 degrees of flexion (B), and 81 degrees of pronation (C) with respect to the coronal plane of the hand.

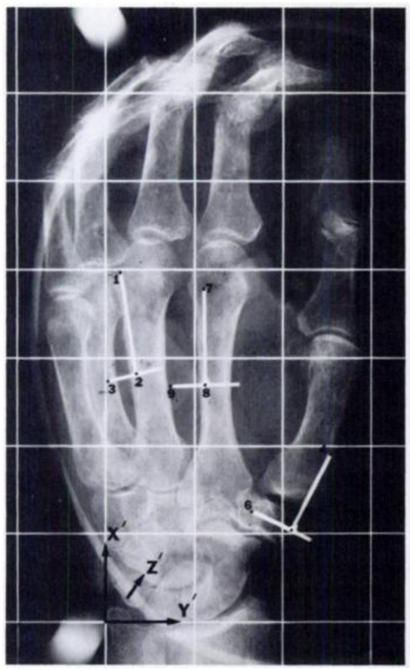

FIG. 6-A

Roentgenogram showing orientation of the trapezium with respect to the third metacarpal (palm). This orientation is determined by two sets of coordinate axes, one fixed to the trapezium and the other fixed to the third metacarpal. The system on the third metacarpal is defined by marker points 1, 2, and 3, while the system on the trapezium is determined by points 4, 5, and 6. Marker points 7, 8, and 9 (over the second metacarpal) are used to check the accuracy of the method and, at the same time, to verify the assumption that no relative motion occurs between the second and third metacarpals and the trapezium. Metal grid lines on the cassette-holder are used to construct the global reference system X', Y', Z'.

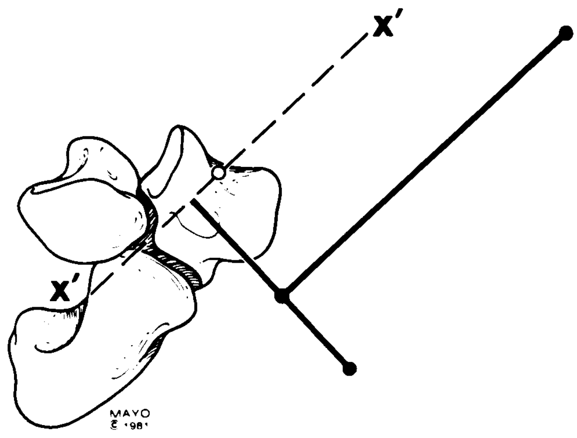

FIG. 6-B

Drawing showing how the exact orientation of the trapezium was determined by inserting a T-shaped marker into the trapezium. This marker was oriented so that the short stem of the T was parallel to the central ridge of the articular surface of the trapezium and the long stem was parallel with the X' axis of the coordinate axis system of the trapezium (see text and Fig. 3). This X' axis of the trapezium (X' — X') was defined as the line extending from a distal point located at the mid-point of the central ridge of the trapezial saddle-shaped distal articular surface through the substance of the trapezium to a proximal point located at the center of the articulation formed by the scaphoid, trapezoid, and trapezium. This proximal point was identified anatomically at the time when the T-shaped marker was inserted.

respect to the palm of the hand. Biplane roentgenograms (Fig. 6-A) were made of the cadaver hands, with T-shaped metal markers located on the trapezium and on the third metacarpal. Two x-ray beams directed at 90 degrees to each other were used to make orthogonal-projection roentgenograms of the hand and markers. The metal wires embedded in the plastic cassette-holder formed a grid system which was projected onto the roentgenograms. From these roentgenograms, which showed a grid system of known area and a known center of reference, the exact three-dimensional orientation of the trapezial and third metacarpal T-shaped markers could be obtained.

In each cadaver hand the proximal phalanx, metacarpal, and trapezium of the thumb, as well as the third metacarpal, were exposed by anatomical dissection. The orientations of the bones and of the joint-surface landmarks were established so that T-shaped markers could be inserted in relation to the previously described coordinate axis systems. To insert the trapezial marker, the central ridge of the trapeziometacarpal articular surface, the volar tubercle, and the flat radial (lateral) side of the trapezium were identified, as well as the medial articulation of the trapezium and the second metacarpal. The marker was inserted in the trapezium so that its crossbar was parallel to the central ridge of the articular surface of the trapezium (Z' axis in Figure 3) while the stem of the T was aligned parallel with the X' axis, defined proximally by the scaphoid-trapezium-trapezoid articulation and distally by the middle of the central ridge of the trapezium (Fig. 6-B).

To position the markers on the second and third metacarpals, a marker was placed directly on each bone so that its stem was aligned along the shaft and its crossbar was aligned parallel with the articular surface on the base of the corresponding metacarpal. These markers were sutured to the periosteum to hold them in position. The marker on the second metacarpal was used as a check to ensure proper alignment of the marker on the third metacarpal. True anteroposterior and lateral roentgenograms of both the hand and the thumb were made to confirm correct alignment. The tip of the stem, one tip of the crossbar, and the junction of the stem and crossbar of each marker served as non-colinear points. They were easily visible on the roentgenograms and were used to identify the exact three-dimensional location of the trapezium and the third metacarpal.

In Vivo Analysis

In nineteen adults (nine male and ten female subjects) with no evidence of thumb-joint disease or injury, we selected the following six positions of the thumb to represent extremes of motion as well as functional activities and determined the

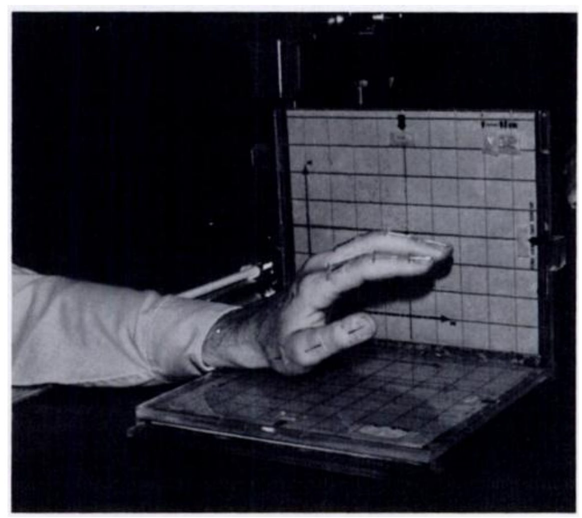

FIG. 7

Procedure for making the biplane (anteroposterior and lateral) roentgenograms that were used to provide the three-dimensional orientation of the thumb joints studied in the various functional configurations. Exact measurements of the position of each individual T-shaped marker located over the phalanges and metacarpal of the thumb and over the third metacarpal provided the necessary data to determine the angular motions of the thumb joints.

positions of the trapeziometacarpal joint: resting position, flexion, extension, abduction (opposition), tip pinch, and grasp. The zero (neutral) position, which was determined from the movements of the trapeziometacarpal joint in cadaver hands, was established as the mid-position, in which the long axis of the first metacarpal and the long axis of the trapezium were colinear.

In vivo, the resting position was simulated by having the subject position the thumb for lateral or key pinch with the thumb in apposition to the lateral (radial) side of the distal phalanx of the index finger. Flexion was performed by moving the thumb ulnarward in a plane nearly parallel to the plane of the dorsal surfaces of the

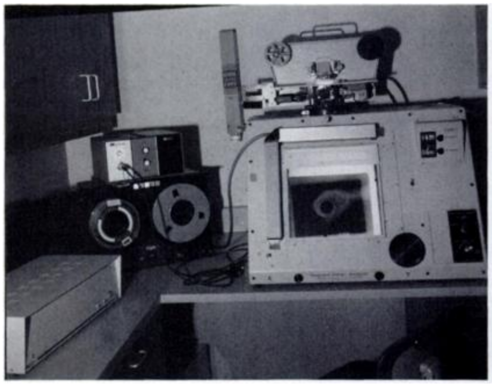

FIG. 8-A

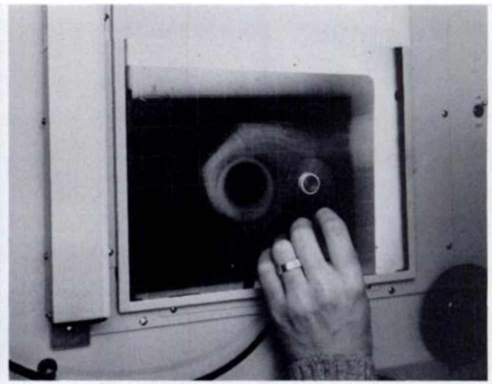

FIG. 8-B

Figs. 8-A and 8-B: Sonic digitizer used to determine the locations of the three non-colinear points on each T-shaped marker. A Cursor stylus, when held over each point, produces a sound pulse (spark), which is received by the L-shaped microphone sensor (on the left and on the top of the viewing screen). The point of interest is located by the x and y sensors in terms of the times needed by the sound to travel from the Cursor stylus to the two sensors. These times are converted to distances by the control unit, and the X, Y, and Z coordinates of each point (tip of the stem, radial tip of the crossbar, and junction of the stem and crossbar of the T-shaped marker) are recorded on tape automatically.

Fig. 8-A: Graf pen and sonic-digitizer unit.

Fig. 8-B: Cursor stylus (hand-held), locating points on the T-shaped marker shown on the roentgenogram of a thumb during grasp.

second and third metacarpals until it touched the base of the little finger (the head of the fifth metacarpal). This movement was referred to by some authors as adduction or flexion-adduction[12,26]. Extension was performed by moving the thumb radially in a plane parallel with the dorsum of the palm or at the least in a plane within 20 degrees of being parallel to the dorsal plane of the palm. Rotation of the thumb from a position of pronation and flexion to one of supination and extension occurred within this same arc of motion. Abduction of the trapeziometacarpal joint was performed by moving the thumb in a volar direction away from the second metacarpal, a movement that clinically is recognized as palmar abduction. For tip pinch, the distal part of the thumb pulp was opposed to the distal part of the pulp of the index finger, and for grasp the thumb and fingers were wrapped around a cylinder measuring 3.5 centimeters in diameter.

For the measurement of *in vivo* motions, T-shaped markers were taped securely on the skin over the first and third metacarpals and over the phalanges of the thumb. The stem of each marker was oriented along the long axis of the corresponding bone, and the crossbar of each marker was located proximally. The markers did not restrict motion of the joint.

Biplane roentgenograms of the hand, with the thumb held comfortably in the six functional positions described, were made using the previously described cassette-holders and grid system (Fig. 7). The orthogonal (anteroposterior and lateral) roentgenograms of the thumb were projected on a Vanguard motion analyzer which displayed the roentgenograms and set the x, y, and z axes. A sonic digitizer (Figs. 8-A and 8-B), equipped with two microphone receivers oriented perpendicular to each other and a sonic pen stylus, was employed to record the position of each T-shaped marker in the global coordinate system. The data points were recorded on magnetic tape and the joint motions were determined using a computer program. The fixed coordinate axis system, located on the third metacarpal, represented the trapezium in this *in vivo* study. The orientation angles of the trapezium, previously measured in the *in vitro* cadaver study, were used to transpose the fixed coordinate axis from the third metacarpal to the trapezium so that motion of the trapeziometacarpal joint could be determined.

Analytical Method

The calculation of the motion of the trapeziometacarpal joint in the living subjects was based on the following rationale: (1) if three non-colinear points on a T-shaped marker fixed on the moving part of a system (here, the thumb metacarpal) can be identified at any position of function, and (2) if the locations of three non-colinear points on the moving part can be measured with respect to a fixed coordinate reference system, then (3) a reproducible relationship in terms of final motion can be constructed vectorially and can be used to define the position of the moving coordinate system.

The biplane roentgenograms defined the positions of the non-colinear points in two planes when the thumb was placed in the six positions studied. Once the locations of these points had been determined roentgenographically for these positions of the thumb, the relationships of the markers to each other were calculated, and

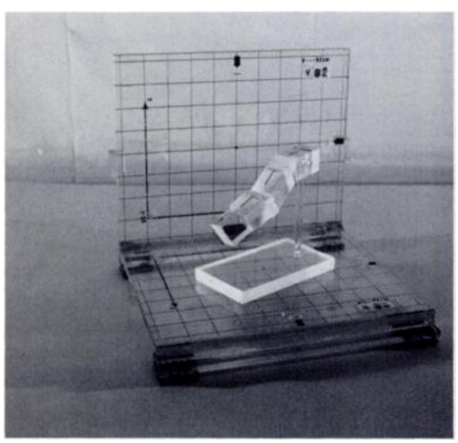

FIG. 9-A

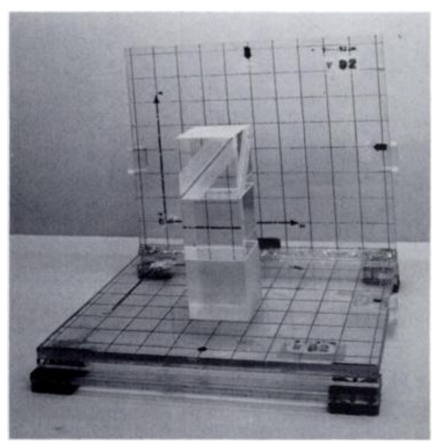

FIG. 9-B

Figs. 9-A and 9-B: The plastic model that was used to validate the technique.

Fig. 9-A: Roentgenograms of plastic cubes with T-shaped markers oriented at known angles are made into two planes, and the orientation of the plastic blocks with respect to each other is determined using the method described.

Fig. 9-B: Wire markers of known length are taped to plastic cubes, and the plastic cubes are placed in different orientations and positions on the cassettes. The length and alignment of the wires in different positions of the cubes are determined from the biplane roentgenograms and are compared with the actual length and alignment.

the motions of the trapeziometacarpal joint that were required to assume the six positions were determined (in degrees) using a rigid-body transformation matrix of these data points. The motions were expressed as Eulerian angles[3] and coincided with the clinically recognized motions of flexion-extension, abduction-adduction, and axial rotation. These determinations were carried out as previously described for the elbow[20].

Validation of the Experimental Technique

To assess the accuracy of the roentgenographic method, we used a model made of plastic blocks which were oriented at measured angles with respect to one another (Fig. 9-A). T-shaped markers taped to the surface of each block served as reference points for the construction of the different coordinate axes. Biplane roentgenograms were made of the model, and the angles, determined by the method already described, were compared with the measured angles.

We also assessed the effect of the soft tissues between the markers on the skin and those on the underlying bones. T-shaped markers were placed on both the skin and the bones of four fresh-frozen and thawed upper-limb specimens, and biplane roentgenograms were made (Fig. 10) with the thumb placed in positions of rest, flexion, extension, and abduction. The resulting motions of the metacarpophalangeal and the trapeziometacarpal joints, determined by means of the two sets of markers, then were measured and compared.

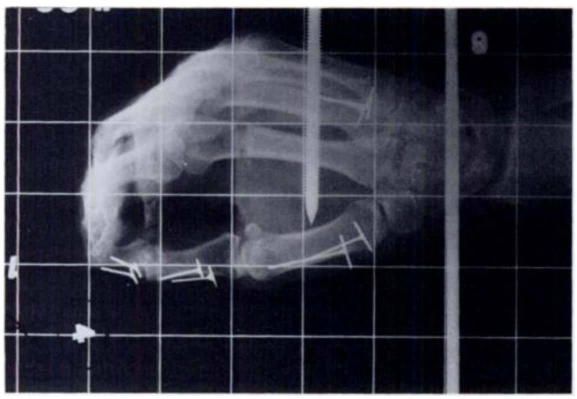

FIG. 10

T-shaped markers were placed both on the skin and directly on the bones of the thumb and on the third metacarpal of four cadaver hands. In various positions of the thumb, the angles of the thumb joints measured by the skin and skeletal T-shaped markers were compared to determine the effect of soft tissues on the measurements made using skin markers.

As an additional test of the reliability of the measurements made by the marker technique, we secured markers of known length on plastic cubes with known dimensions and placed the cubes in different known locations and positions on the cassette grid (Fig. 9-B). Biplane roentgenograms were made of the cubes in each situation to determine if changes in position altered the length of the projections of the markers on the roentgenograms.

Finally, to assess the accuracy of the examiner and of the recorded data, two additional measurements were used. The first was the magnitude of the common perpendicular, S, described in a previous study[20]. Graphically, S can be described as the shortest distance between two x-ray beams at the marker point where theoretically they should intersect. Because of the invariable divergence of x-rays, the beams rarely do intersect, but the small distance between them can be measured. The mid-point of the distance (S) can be assumed to approximate the position of the marker point. If S is small, then the error of measurement is insignificant.

The second measurement that was used to examine the accuracy of the data was the orthogonality of the coordinate axes — in other words, did the stem and crossbar of the T-shaped marker intersect at 90 degrees when measured on the anteroposterior and lateral biplane roentgenograms? The orientations of the reference coordinate axes are based on the positions of the markers. If the S values are large and the marker angles are not 90 degrees, deviations from the correct orientation of the T-shaped markers are present. On the other hand, if the deviations from 90 degrees are small, the accuracy of the technique is confirmed.

Results

Orientation Angles of the Trapezium

The fixed relationship between the trapezium and the third metacarpal, as determined in the ten cadaver hands that were studied, indicated that the trapezium was deviated from the third metacarpal at *mean* angles of 46 degrees of palmar flexion, 35 degrees of radial abduction, and 82 degrees of medial rotation (pronation). This deviation (Table I) ranged from 40 to 53 degrees of flexion, from 25 to 43 degrees of abduction, and from 75 to 89 degrees of rotation. The *median* values of 48 degrees of flexion, 38 degrees of abduction, and 80 degrees of pronation were used for the *in vivo* measurements of trapeziometacarpal motion.

TABLE I

ORIENTATION ANGLES OF THE TRAPEZIUM: RELATIONSHIP OF THE TRAPEZIUM TO THE THIRD METACARPAL (AS DETERMINED IN TEN CADAVER HANDS)

Specimen	Flexion *(Degrees)*	Abduction *(Degrees)*	Pronation *(Degrees)*
1	48	28	78
2	45	30	80
3	49	43	88
4	49	41	77
5	53	25	80
6	52	30	80
7	44	43	85
8	48	43	89
9	50	38	84
10	40	32	75
Mean	46	35	82
Range	40-53	25-43	75-89
Median*	48	38	80

* The median orientation angles of the trapezium were used in the *in vivo* studies of joint motion.

Trapeziometacarpal Joint Motion

In the nineteen normal adults, whose average age was twenty-six years (range, twenty-two to thirty-nine years), the median arcs of trapeziometacarpal motion (Table II), recorded for all of the functional thumb configurations studied, were 53 degrees of flexion-extension, 42 degrees of abduction-adduction, and 17 degrees of rotation. The studies demonstrated that flexion, adduction, and pronation of the metacarpal were the most frequent positions during thumb function. The potential ranges of motion as well as the differences between the maximum thumb positions varied among the nineteen subjects. The resting position of the trapeziometacarpal joint was taken to be its position when the thumb was in the posture that it naturally assumes when it is not in active use — that is, with the thumb in apposition to the mid-portion of the distal phalanx of the index finger and the interphalangeal and

TABLE II

MEDIAN ARCS OF ACTIVE MOTION AT THE TRAPEZIOMETACARPAL JOINT (MEAN AND STANDARD DEVIATION) DURING FUNCTION OF THE THUMB

Sex	No. of Subjects	Flexion-Extension *(Degrees)*	Abduction-Adduction *(Degrees)*	Pronation-Supination *(Degrees)*
Men	9	54.7 ± 15.3	44.6 ± 4.2	20.0 ± 10.6
Women	10	51.4 ± 6.7	41.0 ± 2.6	14.6 ± 8.2
Over-all values	19	52.9 ± 11.4	42.4 ± 4.0	17.2 ± 9.5

TABLE III

POSITIONS OF THE TRAPEZIOMETACARPAL JOINT (MEAN AND STANDARD DEVIATION) IN THE SIX FUNCTIONAL CONFIGURATIONS OF THE THUMB STUDIED

Functional Position of Thumb	No. of Subjects	Flexion-Extension* (Degrees)	Abduction-Adduction* (Degrees)	Pronation-Supination (Degrees)
Resting†	19	20.5 ± 10	−23.2 ± 5	13.6 ± 9
Flexion	19	35.5 ± 12	−21.3 ± 7	19.5 ± 6
Extension	18	−12.6 ± 7	−26.0 ± 8	2.8 ± 9‡
Abduction	17	6.2 ± 10	15.6 ± 12	19.5 ± 12
Tip pinch	18	28.0 ± 13	−18.2 ± 10	18.7 ± 9
Grasp	17	24.6 ± 15	9.8 ± 8	19.8 ± 11

* The angles with negative signs signify extension, adduction, or supination of the trapeziometacarpal joint; the positive angles indicate flexion, abduction, or pronation.

† When the thumb is in the resting position, the first metacarpal is in adduction with respect to the trapezium. In this position of the thumb, the thumb pulp is in apposition to the radial side of the index finger (in the lateral pinch position).

‡ The thumb supinates during extension from the resting position.

metacarpophalangeal joints each flexed 10 to 15 degrees. In this position, the trapeziometacarpal joint was in 21 degrees (±10 degrees) of flexion, 23 degrees (±5 degrees) of adduction, and 14 degrees (±9 degrees) of pronation (Table III). The angles that were calculated varied with the size and anatomical variations of the different subjects' hands. Flexion-extension, abduction-adduction, and pronation-supination of the trapeziometacarpal joint during maximum active flexion, extension, and abduction of the thumb, as well as during grasp and tip pinch, were determined also (Table III). The first metacarpal was adducted with respect to the trapezium in all positions except abduction and grasp, and the first metacarpal was pronated on the trapezium in all positions except extension.

The resting position of the trapeziometacarpal joint, which was measured in all nineteen subjects, was also important in determining the starting point for the measurement of other motions of the thumb and in describing the types of thumb motion used in daily function of the hand. The motions of the trapeziometacarpal joint described in these terms were angular movements of the first metacarpal in relation to the trapezium. The results indicated that, because of the constraints on the motion of the trapeziometacarpal joint (imposed by the geometry of the joint surfaces and by the ligaments), pure rotation of the trapeziometacarpal joint with respect to a single axis did not occur. During full active flexion of the thumb, the average movements of the trapeziometacarpal joint from the resting position were 15 degrees of flexion, 2 degrees of abduction, and 6 degrees of pronation. Similarly, during full active extension of the thumb, the average motions of the trapeziometacarpal joint from the resting position were 33 degrees of extension, 3 degrees of adduction, and 11 degrees of supination. Pure active abduction of the thumb produced 14 degrees of extension, 38 degrees of abduction, and 6 degrees of pronation of the trapeziometacarpal joint. During tip pinch, the average motions of this joint were 8 degrees of flexion, 5 degrees of abduction, and 5 degrees of pronation; and during grasp, 4 degrees of flexion, 33 degrees of abduction, and 6 degrees of pronation. These movements occurred simultaneously rather than sequentially and reflected the fact that the trapeziometacarpal joint is a compound joint in which pure angulation and pure rotation about a single axis do not occur.

To separate the contributions to over-all thumb motion of the trapeziometacarpal joint from those of the metacarpophalangeal joint, the motions of each of these joints were determined using the described technique. Motion of the metacarpophalangeal joint was determined with respect to the previously described x, y, z axis system based on the trapezium without reference to the hand. When the thumb was moved from the resting position into flexion, extension, or abduction, or it performed tip pinch or grasp, the mean arcs of motion (± standard deviation) of the metacarpophalangeal joint were: flexion-extension, 56 ± 15 degrees; abduction-adduction, 19 ± 8.8 degrees; and rotation, 22 ± 4 degrees.

A comparison of the male and female subjects suggested that the men had slightly larger ranges of motion in all directions (Table II), particularly axial rotation, in which the range was greater in men by approximately 6 degrees. However, a paired t test, performed with a confidence interval of $p < 0.01$, indicated no significant difference between the ranges of motion of the trapeziometacarpal joints of the two sexes.

Validity and Reliability

The tests on the plastic models indicated that the angles for four different locations of the blocks, determined by the technique described, differed from the actual angles by an average of 6 per cent (Table IV). The largest errors occurred when the model was located near the margin of the cassette field or when certain marker points overlapped one another. Comparing the different motions, the greatest error was in the determination of axial rotation (pronation-supination), a determination in which the angle was most affected by the accuracy of the positioning of the non-colinear points.

The four cadaver hands with both skin and skeletal markers were analyzed with the thumb in the resting posi-

TABLE IV

VERIFICATION OF ACCURACY OF TECHNIQUE USING PLASTIC MODELS WITH KNOWN ANGLES PLACED IN FOUR DIFFERENT POSITIONS

Orientation Angles (*Degrees*)	Measured True Value	Position 1		Position 2		Position 3		Position 4		Mean	
		Value	Error	Value	Error	Value	Error	Value	Error	Value	Error
Flexion-extension	30.9	31.7	−0.8	29.8	+1.0	30.5	+0.4	31.6	−0.7	30.9	−0.05
Abduction-adduction	20.6	18.1	+2.5	19.8	+0.8	18.2	−2.4	18.4	+2.2	18.6	−0.05
Supination-pronation	27.5	27.7	−0.2	24.6	−2.9	28.0	−0.5	31.2	−3.7	27.9	−0.40

tion and in flexion, extension, and abduction. At the extremes of these motions the average difference, comparing the measurements made using the skin markers with those made using the skeletal markers, was 7 degrees (range, 1 to 11 degrees). However, when the arcs of movement from the resting position to full flexion, extension, and abduction were determined from the two sets of T-shaped markers and compared, the average difference was only 5 per cent.

The tests on the cube blocks using markers of known length showed that the average difference between the actual lengths and the measured lengths, determined from the biplane roentgenograms after changing the position of the cubes, was 2 per cent.

In the error analysis the largest value for the common perpendicular S was 1.27 centimeters, and this was associated with the worst experimental conditions. The mean common perpendicular for all subjects tested in the various functional configurations was 0.38 centimeter, which indicates that the biplane technique was reliable in detecting minute angular changes in the trapeziometacarpal joint. In the assessment of the orthogonality of the T-shaped markers, the maximum deviation from 90 degrees was ±4 degrees. The average angle for the orthogonality of the markers in the nineteen subjects, as determined by the computer program, was 89 degrees.

Discussion

Motions of the trapeziometacarpal joint of the thumb have been studied both clinically and experimentally because of the importance of this joint in the prehensile functions of daily activities[1,9]. Previous studies employed indirect methods. Tubiana and Valentin, de la Caffinière, and other authors[11,28] used a method involving movement of the thumb away from the palm of the hand, on the assumption that this is the main function of the basal joint of the thumb (for example, antepulsion and retropulsion). The International Federation of Societies for Surgery of the Hand characterized the motions of the thumb in relation to the remainder of the hand. In this scheme, extension is defined as abduction in a plane parallel to the plane of the palm; abduction, as volar displacement in a plane perpendicular to the palm; and opposition, as the position of the thumb achieved by circumduction of the first metacarpal, internal rotation of the ray of the thumb, and extension of the metacarpal and interphalangeal joints. These are useful clinical terms, but they are not indicators of the true motions of the trapeziometacarpal joint. Lack of clear definitions for coordinate axes and angular motion has created problems in the exchange of knowledge concerning the quantitation of thumb movements.

In the present study, the third metacarpal was used to represent the palm and to establish a separate system of coordinates for the thumb at the level of the trapezium. The motions of the trapeziometacarpal joint then could be defined with respect to axes that had a fixed relationship to the trapezium. Our results revealed that the maximum standard deviations were ±11 degrees for flexion-extension, ±4 degrees for abduction-adduction, and ±10 degrees for pronation-supination in our sample group of nineteen normal hands tested *in vivo*. The differences were due mainly to variations in the normal population, although errors due to the measuring technique could not be excluded. Factors contributing to the variability were believed to be the clarity with which the marker points were shown on the roentgenograms, movement of the hand between the times when the two consecutive orthogonal roentgenograms were made, and experimental error in placing the marker on the subject's thumb. Motion of the T-shaped markers on the skin relative to the underlying bones was relatively small, as determined by the comparative analyses of the four fresh-frozen and thawed specimens on which both skin and skeletal markers were used. These measurements demonstrated a close correlation between the movements of the markers on the skin and those of the underlying skeletal markers. However, we could not repeat the passive motions with enough accuracy to establish the reproducibility of the results obtained with the marker technique. *In vivo* measurements repeated on several patients by different examiners showed only small differences in the measurements.

The range of flexion-extension of 53 ± 11 degrees at the trapeziometacarpal joint determined in the present study is comparable to the range of 45 to 60 degrees described by Steindler, but less than the 50 to 90 degrees described by Kapandji and by Van Wetter. Kuczynski believed that flexion and extension of the trapeziometacarpal joint are accomplished by movement of the metacarpal along a curved groove on the trapezium, the axis of movement changing. Napier[21], however, concluded that flexion and extension are sliding movements. Haines observed that the plane of flexion-extension passes through the most convex part of the articular surface of the trapezium and through the most concave part of the articular surface of the first metacarpal. The results of the present study seem to agree with the conclusions of both Kuczynski and Haines. In addition, the present study provides clear definitions of how the orientations of the bones were established and how the angles were measured. Furthermore, exact measurements of extension (12 ± 7 degrees) and of flexion (35 ± 12 degrees), as defined by coordinate axes set in the articular surface of the trapezium, could be determined.

The range of abduction-adduction at the trapeziometacarpal joint measured in this study was 42 ± 4 degrees. The range according to Steindler was 35 to 40 degrees, and according to Kapandji, it was 40 to 50 degrees. In our study, active rather than passive motion was measured, and the exact axis and range of abduction-adduction were defined. The plane of abduction-adduction of the trapeziometacarpal joint was specified with respect to the articular surface of the trapezium, which is oriented at an angle of 38 degrees of abduction with respect to the plane of the palm. The maximum abduction recorded at the trapeziometacarpal joint was 16 degrees. This actual abduction (16 degrees), added to the 38-degree abduction posture of the trapezium, is reflected in the clinical measurement of palmar abduction as the angle between the first and third metacarpals — an angle that ranges from 45 to 50 degrees. Using our technique, we could define metacarpophalangeal joint motion with respect to its own coordinate system, and based on these definitions we could separate thumb metacarpophalangeal-joint abduction from trapeziometacarpal abduction and determine that both joints contribute to abduction and opposition of the thumb. Of greater significance was the consistent finding of *adduction* of the trapeziometacarpal joint in all functional positions except abduction (opposition) and grasp. Adduction is an unstable position for the thumb, which in daily use must resist forces that are ten to thirteen times the applied force[3]. This position may have some bearing on the loss of motion, subluxation, and osteoarthritis that frequently are seen in this joint[24].

The range of axial rotation (pronation-supination) of the first metacarpal at the trapeziometacarpal joint during all functional thumb movements was 17 ± 10 degrees. This motion was completely independent of the axial rotation of the proximal phalanx at the metacarpophalangeal joint, in which the average axial rotation was 22 ± 4 degrees. Kaplan[14,15] concluded that axial rotation of the trapeziometacarpal joint ranges from 15 to 20 degrees but occurs only when the joint is in flexion. He also thought that no axial rotation of the trapeziometacarpal joint occurs during abduction and adduction. Eaton and Littler observed a range of 20 to 30 degrees of axial rotation of the metacarpal during opposition of the thumb, but did not measure this rotation separately from the other components of this complex movement. We found that 6 to 7 degrees of pronation of the metacarpal occurred during pinch and grasp, and that when the thumb was abducted there was also some associated metacarpal rotation. Haines, Kuczynski, and McFarlane stated that rotation of the first metacarpal occurs during abduction because the trapeziometacarpal ligaments tighten in abduction and because the flatter parts of the trapeziometacarpal joint surfaces are in contact in this position. Our results and the results of others[4,16] showed that axial rotation of the thumb metacarpal occurs primarily during flexion and extension of the thumb, due in part to the curved groove on the articular surface of the trapezium along which the first metacarpal moves during flexion and extension.

Our results demonstrate that the combined motions of abduction and flexion of the trapeziometacarpal joint contribute to opposition and circumduction of the thumb. Axial rotation of the trapeziometacarpal joint is an important part of these motions but is not the main component. The conjunctive thumb motion of opposition[18,21] is a special function of the trapeziometacarpal joint and is dependent not only on the geometry of the joint but also on muscle action and on ligament constraints, all of which participate in defining those motions of the thumb that make purposeful functioning of the hand possible.

Conclusions

Because the trapeziometacarpal joint of the thumb is commonly involved by disease, more knowledge of its motion is essential for the planning of adequate treatment. The motion of this joint has been difficult to measure quantitatively because of constraints imposed by the geometry of the joint surfaces and by the soft tissues. Using the method described, in which: (1) external markers are secured to the skin over the bones of the thumb and third metacarpal, (2) the marker points are located on biplane roentgenograms, and (3) defined reference coordinate systems are used, it is possible to calculate the spatial orientations of the trapeziometacarpal joint in extreme positions.

During flexion and extension, as well as during pinch functions, the trapeziometacarpal joint of the thumb remains in an *adducted* position. Axial rotation of the trapeziometacarpal joint does not occur independently, but only as part of the conjunct movements of flexion and adduction, of flexion and abduction (opposition), and of extension and abduction of the thumb. The trapeziometacarpal and metacarpophalangeal joints together contribute to the axial rotation of the thumb that occurs during both opposition and circumduction.

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