Assessment of Elbow Joint Kinematics in Passive Motion by Electromagnetic Motion Tracking

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Summary: This research provides a detailed analysis of the kinematics of passive elbow motion. It quantifies how closely humeroulnar kinematics approximates rotation around a fixed axis. The results are clinically relevant for emerging treatment modalities that impose an artificial hinge to the elbow joint, such as total elbow arthroplasty and articulated external fixation. In a cadaveric study of seven specimens, we quantified ulnar rotation around the humerus in terms of instantaneous screw displacement axes calculated from electromagnetic motion-tracking source data. This methodology enabled description of the complex excursion of the elbow axis in terms of translation and orientation changes of the screw displacement axes over the range of motion. Furthermore, we analyzed the envelope of joint laxity for elbow motion under applied small varus and valgus moments. In addition, radiographic landmarks of clinical utility for axis location were evaluated by visualizing the elbow’s radiographic appearance when viewed from along the calculated best-fit (average) rotation axis. Over the normal range of elbow motion, the screw displacement axis varied 2.6–5.7° in orientation and 1.4–2.0 mm in translation. All instantaneous rotation axes nearly intersected on the medial facet of the trochlea. The breadth of the envelope of varus-valgus joint laxity was greatest within the initial 40° of flexion and decreased by a factor of approximately two for flexion angles exceeding 100°.

A number of operative techniques have recently emerged that impose an artificial hinge on the elbow joint. Currently, these include articulated external fixation (e.g., the Compass Hinge: Smith and Nephew, Memphis, TN, U.S.A.) and distraction arthroplasty (14). The success of these emerging treatment modalities depends on precise alignment of the imposed artificial hinge with the natural elbow rotation axis, since the elbow is the articulation that most closely resembles a perfect hinge joint in the human. This study describes how a single fixed axis can be established that best approximates the complex kinematics of passive elbow motion. Furthermore, the deviation of the instant axis of joint rotation from such a single axis is quantitatively analyzed for various experimental parameters, such as direction of elbow motion (flexion or extension), motion under applied varus or valgus moments, and simulated muscle-load configurations (predominantly flexor or extensor forces). The determination of a single approximate elbow axis, in conjunction with the detailed documentation of passive elbow kinematics under consideration of various constraint parameters, provides results relevant for the design and application of total elbow replacements, hinged external fixators, and distraction arthroplasty.

Previously, the axis of rotation of the elbow was estimated by London (11) in a two-dimensional analysis, using planar radiographs and the instant center technique. Morrey and Chao (13) assessed elbow joint motion with biplanar roentgenograms obtained at various flexion angles. They reported three-dimensional joint kinematics; however, imprecision in source data due to radiographic tracing of multiple finite-size markers limited the accuracy of their estimates. Deland et al. (8) determined the average axis of elbow rotation in three-dimensional space using time-lapse photographs of active luminescent marker triads. Despite having three-dimensional source data, however, they approximated the axis location by utilizing a modified instant center two-dimensional technique.

All these results quantitatively refined rather than conceptually extended the early findings of Fischer (9), who in 1911 stated that the instant center of elbow rotation remains within a locus less than 3 mm in diameter. He concluded that, for practical purposes, the elbow joint approximates a fixed hinge joint, with its axis located at the center of the trochlea.

More recently, alternating-current electromagnetic
motion tracking has been applied to the elbow joint (2,10,16,18). However, most of these studies focused on comparing specific kinematic parameters before and after total elbow arthroplasties. Tanaka et al. (18) were the first to describe three-dimensional elbow kinematics, obtained from electromagnetic motion-tracking data. Their data analysis, based on Eulerian angles, provided a thorough description of the orientation angles of the joint axis. However, even in the elbow, the joint axis translates as well as rotates, and translation motions are not accessible in an Eulerian-angle approach.

In this study, we introduce the application of direct-current electromagnetic motion tracking to continuously trace dynamic, passive motion of the natural elbow joint. The high spatial resolution of this system, in combination with a customized method for processing the data after the procedure, allows a comprehensive description of the pathway of the instant axis of elbow rotation. Besides providing a computational

![Diagram of test setup for the application of minimally restrained passive elbow motion, shown for roller configuration A. DoF = degrees of freedom, RS 232 = connection type. d. c. = direct current, $F_a$ = triceps force, $F_b$ = biceps force, and $F_{br}$ = brachialis force. Flock of Birds electromagnetic tracking system (Ascension Technology).](image1)

![Pathway of the screw displacement axis (SDA) with respect to the humerus during elbow flexion from 10 to 130° in roller configuration A. For visualization, the excursion of the axis is exaggerated by tracing the projection onto planes located 200 mm medial and lateral of the trochlea. Note the large scaling difference within, compared with perpendicular to, these intercept planes.](image2)
approach to extract an average rotations axis from the instant axes of joint rotation, we also demonstrate the radiographic appearance of the elbow when viewed from along such a calculated average rotation axis.

MATERIALS AND METHODS

Seven fresh-frozen cadaveric upper extremities with no radiographic or visual evidence of pathologic conditions were amputated at the mid-humeral shaft and disarticulated at the radiocarpal joint. The skin, subcutaneous tissues, and muscles were excised, and the joint capsule, ligaments, and musculotendinous insertions of the biceps, brachialis, and triceps were retained. The mid-diaphysis of the humerus was secured with polymethylmethacrylate in a Plexiglas tube, which in turn was rigidly affixed to a specially designed elbow-motion applicator (Fig. 1). This experimental setup, driven by a direct-current motor, allowed minimally constrained rotation, without manual interference, through the elbow’s range of motion. Elbow rotation was applied at a constant angular velocity (32°/sec) to control for the viscoelastic (i.e., rate-dependent) material properties of the tissues constraining the joint. Consistency of angular velocity proved essential to establish reproducible recordings of the envelope of joint laxity.

A mobile roller, contacting the forearm 150 mm distal to the elbow joint and rotating around an axis that was approximately aligned with the natural elbow axis, induced passive flexion or extension of the elbow. A linear glass-ball bearing atop the roller enabled unrestricted varus/valgus motion of the forearm. Weights were attached to the musculotendinous insertions by nylon cables to simulate a constant applied biceps force (F_b), brachialis force (F_b), and triceps force (F_t). These muscle forces (1) were simulated to ensure continuous contact at the articular surface, as well as contact between the forearm and the roller. The nylon cables were guided in a manner so as to approximate normal muscle moment arms (15).

Elbow rotation was achieved in two distinct roller configurations: A and B. In configuration A, a roller located posteriorly with respect to the ulna guided the forearm into flexion and extension while a predominant extensor force (F_e + F_b = 1 + 1 N, F_b = 20 N) ensured continuous contact between the ulna and the roller over the full range of motion. In configuration B, a roller was located anteriorly with respect to the ulna and induced flexion or extension of the forearm under a predominant flexor force (F_f + F_b = 10 + 10 N, F_f = 2 N).

To map the envelope of joint laxity, a small constant varus or valgus moment (0.5 Nm) was applied by a constant-force torsional spring. This spring was mounted on a lateral or medial extension affixed to the rotating roller and connected to the ulna. The resulting force vector therefore was perpendicular to the
The rotation axis lies in the center of three concentric-appearing ulna and remained perpendicular over the entire range of motion to a plane containing the humerus and the forearm. The pathway of the screw displacement axis for an elbow undergoing flexion over a range of motion from 10 to 130° in roller configuration A is shown in Fig. 2. For visualization, the excursion of the axis is projected with scaling exaggeration onto intercept planes 200

FIG. 5. Radiographic appearance of the elbow with an x-ray beam sited precisely along the average screw displacement axis (SDA). The rotation axis lies in the center of three concentric-appearing shadows formed by (1) the bottom of the trochlear sulcus, (2) the periphery of the capitellum, and (3) the medial facet of the trochlea.

FIG. 6. A: Varus and valgus deviation from the normal motion path due to an applied varus or valgus moment of 0.5 Nm shown at motion increments of 5° over a range of motion of 15-140° (average and standard deviation of seven specimens). B: Influence of varus and valgus moment on the normal pathway of the screw displacement axis. The pathway shown is the screw displacement axis intercept with a plane located 200 mm lateral of the trochleo-capitellar mid-sagittal plane.

RESULTS

The pathway of the screw displacement axis was physically marked in each specimen. A 4-mm hole was drilled with a customized drill guide into the trochlea along the axis. To avoid migration due to the oblique insertion angle, this was done with a four-flute end mill. A brass tube with an outer diameter of 4 mm and an inner diameter of 1.5 mm was inserted into the hole. Using fluoroscopy, we visualized the location of the average screw displacement axis with respect to the trochlea by sighting down the tube lumen. We then recorded the radiographic appearance of the distal humerus from the viewpoint of an x-ray beam oriented precisely along the average screw displacement axis. Anterior-posterior radiographs were used to obtain the longitudinal axis of the humerus and ulna by fitting a line to the geometric center of the diaphyseal shaft. To enable further correlation between the screw displacement axis and anatomical structures, the location of the medial border of the trochlear facet and the lateral border of the capitellum were digitized. This experimental work, involving human cadaveric specimens, was approved by the institutional review board committee.

Joint Laxity:
neutral, varus, valgus

A

B proximal (+) [mm] distal (+)

-10 -5 0 5 10

-5 0 5

-2 -1 0 1 2 3

valgus neutral varus

-3 -2 -1 0 1 2 3

flexion [degrees]

Joint Laxity:
neutral, varus, valgus

A

B proximal (+) [mm] distal (+)

-10 -5 0 5 10

-5 0 5

-2 -1 0 1 2 3

valgus neutral varus

-3 -2 -1 0 1 2 3

flexion [degrees]
TABLE 1. Frustum parameters and waist location for neutral elbow flexion (roller configuration A) compared with flexion under applied varus or valgus moments of 0.5 Nm

<table>
<thead>
<tr>
<th>Flexion mode</th>
<th>( t_0 ) (mm)</th>
<th>( t_1 ) (mm)</th>
<th>( \alpha_u ) (°)</th>
<th>( \alpha_l ) (°)</th>
<th>Frustum waist location* (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>1.4 ± 0.3</td>
<td>2.0 ± 0.6</td>
<td>5.7 ± 2.2</td>
<td>2.6 ± 1.0</td>
<td>19.9 ± 4.4</td>
</tr>
<tr>
<td>Varus</td>
<td>1.8 ± 0.6</td>
<td>2.0 ± 0.7</td>
<td>7.3 ± 2.3</td>
<td>4.2 ± 1.7</td>
<td>18.7 ± 8.3</td>
</tr>
<tr>
<td>Valgus</td>
<td>1.6 ± 0.4</td>
<td>2.1 ± 0.8</td>
<td>6.8 ± 1.9</td>
<td>2.6 ± 0.7</td>
<td>26.0 ± 8.6</td>
</tr>
</tbody>
</table>

\( t_0 \) and \( t_1 \) = screw displacement axis translations, and \( \alpha_u \) and \( \alpha_l \) = frustum vertex angles in the horizontal and frontal planes, respectively. *Frustum waist location is given in millimeters medial of a trochleo-capitellar midsagittal plane, obtained for a normalized trochleo-capitellar width of 50 mm.

mm medial and lateral from the geometric center of the trochlea.

The (axode) pathway of the screw displacement axis traces the surface of a double quasi-conic frustum of a nominally elliptical cross section (Fig. 3). To distinguish between translation and orientation changes of the screw displacement axis, the complex three-dimensional excursion of the axis over the range of motion was differentiated into translations \( t_0 \) and \( t_1 \) in the horizontal and frontal planes, respectively, as determined by the dimension of the frustum waist, and the changes in orientation were depicted by the frustum vertex angles \( \alpha_u \) and \( \alpha_l \). These frustum parameters are reported for roller configuration A. In the absence of varus/valgus moment over this range of motion, the screw displacement axis experienced excursions in the frontal plane (which includes the longitudinal axis of the fixed humerus) of \( t_1 = 2.0 \) mm (SD = 0.62 mm) and \( \alpha_l = 2.6\)° (SD = 0.6°). The excursions in the horizontal plane were \( t_0 = 1.4 \) mm (SD = 0.32 mm) and \( \alpha_u = 5.7\)° (SD = 2.19°). The center of the frustum waist was located 20 mm (SD = 4.4 mm) medial to a parasagittal plane centered between the medial border of the trochlear facet and the lateral border of the capitellum. The location of the frustum waist was obtained by normalizing the trochleo-capitellar width to the series average of 50 mm and corresponds to a point within the medial facet of the trochlea.

The calculated average screw displacement axis penetrated the inferior anterior aspect of the medial epicondyle, the center of the trochlea, and the center of the projection of the capitellum onto a parasagittal plane. For the fully extended elbow viewed in the frontal plane, the average screw displacement axis formed an angle of 86.1° (SD = 2.5°) with the longitudinal axis of the humerus and an angle of 85.4° (SD = 3.8°) with the longitudinal axis of the ulna (Fig. 4). In a medial-lateral radiographic view (Fig. 5), with the x-ray beam axis oriented precisely along the average screw displacement axis, the axis lies in the center of three concentric-appearing shadows. These shadows are formed by the bottom of the trochlear sulcus, the periphery of the capitellum, and the medial facet of the trochlea, respectively, as determined in a (sub-
neutral dissected flexion A 1.3
neutral dissected flexion A
valgus dissected flexion A
neutral dissected extension A
neutral dissected flexion B

200
these landmarks sometimes proved problematic. In
the trochlear sulcus and the capitellum overlapped
three of the seven specimens, the circular shadows of
in roller configuration A) due to an applied varus or
valgus moment of 0.5 Nm was recorded for motion
specimens, the medial facet of the trochlea was not
detectable.

The deviation of the screw displacement axis from
the normal (neutral) motion path (i.e., flexion motion
in roller configuration A) due to an applied varus or
valgus moment of 0.5 Nm was recorded for motion
increments of 5° over a range of motion of 15-140°
(Fig. 6A). The range of joint laxity toward varus
and valgus moments was nominally symmetric with re-
spect to the neutral motion path. Joint laxity was
largest within the initial 40° of flexion (to 1.8 and 1.9°
of varus and valgus rotation, respectively) and de-
creased by roughly 50% for flexion angles exceeding
100°. The effect of the varus/valgus moment on the
elevation axis is alternatively depicted in Fig. 6B in
terms of the pathway of the screw displacement axis
intercept with a plane located 200 mm lateral of the
trochlear center. The corresponding values for \( t_x \), \( t_y \), \( a_\theta \), and \( a_{\phi} \) and the location of the frustum waist are
listed in Table 1.

The screw displacement axis intercept with the 200-
mm lateral plane was further used to illustrate trial-
to-trial reproducibility (depicted by two sequential
elbow flexions and extensions of one specimen, Fig.
7A) and the influence of the roller configuration (Fig.
7B). Quantitative assessment of the reproducibility of
the reported kinematic results (location of the screw
displacement axis and \( t_x, t_y, a_\theta, \) and \( a_{\phi} \)), as well as their
sensitivity to various experimental parameters, are
summarized in Table 2. These results were obtained
from a single specimen, tested first before dissection,
then when dissected, and then in various motion
modes. The reported location of the average screw
displacement axis was measured relative to the aver-
age of three repetitive recordings of elbow flexion in
roller configuration A of the dissected specimen (Ta-
ble 2, row 1, depicting trial-to-trial reproducibility).

**DISCUSSION**

Real-time electromagnetic motion tracking enabled
thorough quantitative assessment of the complex ki-
netics of the elbow joint. The rigid-body motion of
the ulna with respect to a coordinate system affixed to
the humerus was expressed in a unique and complete
manner in terms of the screw displacement axis, gen-
erating results in a clinically conventional format that
is applicable to arthroplasty or fixator application, or
both.

The present findings are consistent with previous
literature. Fischer’s (9) original study, later quoted by
Steindler (17), used tracings of the spatial motion of
the tips of three needles affixed to the ulna to identify
distinct rotation axes that intersected slightly medial of
the trochlear center. Fischer described these axes as
lying on a cone of irregular cross section with a vertex
angle of 4-10° and with a cone-tip excursion of 1-2
mm. Deland et al. (8) found the instant center of rota-
tion to be within circles 3 and 1 mm in diameter on the
lateral and medial sides of the elbow, respectively.

They determined that the average axis of rotation for
five specimens formed an angle of 80 ± 3° with the
longitudinal axis of the humerus, whereas Tanaka et
al. (18) reported an angle of 84.3 ± 1.7° between an
optimum axis of rotation and the longitudinal axis of
the humerus. London (11) identified a single rotation
axis for the elbow that formed an angle of 82-86° with
the humerus. He reported that only for the last 5-10°
of the range of motion did the axis of rotation migrate
proximally, a phenomenon that he attributed to a
change from sliding to rolling joint motion accompa-
nied by partial widening of the joint space. Although
he noted the appearance of three concentric shadows
on “true lateral” roentgenograms, the inconsistent
visibility of these landmarks, especially of the medial
facet of the trochlea, was not mentioned.

**TABLE 2. Sensitivity of the reported kinematic results to experimental parameters**

<table>
<thead>
<tr>
<th>Location of average SDA*</th>
<th>Location of average SDA*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prox. (+)</td>
<td>Dist. (-)</td>
</tr>
<tr>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>0.0 ± 0.08</td>
<td>0.0 ± 0.03</td>
</tr>
</tbody>
</table>

*The location of the average screw displacement axis (SDA), as it intersects the midsagittal plane of the trochlea, is measured relative to the midsagittal intersection for recordings (row 1) of elbow flexion in roller configuration A for the dissected specimen.

\( t_x \) and \( t_y \) = screw displacement axis translations, and \( a_\theta \) and \( a_{\phi} \) = frustum vertex angles in the horizontal and frontal planes, respectively.
O'Driscoll et al. (16) reported a maximum of 2.7 ± 1.5° varus-valgus joint laxity due to applied varus-valgus moments of 1.2 Nm. Tanaka et al. (18) observed that varus-valgus laxity was greatest at 20-30° of flexion and that it decreased during further flexion. They reported an average total varus-valgus laxity of 7.6° due to a moment caused by the weight of the forearm (estimated to be 2.2 Nm). To provide a point of reference for their findings, we additionally subjected one specimen to 0.4-Nm incremental varus or valgus moments generated by the weight of the forearm itself. A moment of 0.5 Nm is considerably smaller than the moment (2.0-2.4 Nm) (20) if elbow motion occurs in the horizontal plane.

The muscle-load configuration used in this study was chosen to simultaneously satisfy two requirements. It had to ensure continuous contact between the roller and the ulna and yet the total applied forces had to be kept minimal, to permit passive motion along a motion path constrained primarily by the articular surfaces and ligamentous structures. Therefore, a minimal predominant flexor or extensor force of 20 N was necessary to achieve continuous roller-ulna contact over the entire range of motion. To avoid potentially confounding viscoelastic effects, the present study treated muscle forces (F_m, F_m, and F_n) used by Tanaka et al., since muscle forces provide dynamic stability to varus and valgus loads (16). Our applied varus-valgus moment of 0.5 Nm is considerably smaller than the moment generated by the weight of the forearm itself (2.0-2.4 Nm) (20) if elbow motion occurs in the horizontal plane.

For purposes of total elbow arthroplasty, the present data rigorously describe the motion path and the amount of varus-valgus laxity in the natural elbow joint. Prosthesis design cannot be based solely on kinematic considerations; however, the present results suggest a need for accurate hinge placement for operative techniques that impose an artificial hinge to the elbow (6). Furthermore, the radiographic appearance as viewed from along the average screw displacement axis proves to be efficient for closely approximating the complex elbow kinematics in terms of a single fixed axis.

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