Three-Dimensional In Vivo Kinematics of the Shoulder During Humeral Elevation

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Shoulder kinematics, including scapular rotation relative to the trunk and humeral rotation relative to the scapula, were examined during humeral elevation in three vertical planes via video analysis of intracortical pins. Helical axis parameters provided an easily interpretable description of shoulder motion not subject to the limitations associated with Cardan/Euler angles. Between 30 and 150° of elevation in each plane, the scapula rotated almost solely about an axis perpendicular to the scapula. Additional scapular rotation appeared to support the notion that the scapula moves “toward” the plane of elevation. Humeral rotation took place mainly in the plane of the scapula independent of the plane of elevation. Many parameters of shoulder complex kinematics were quite similar across all planes of elevation, suggesting a consistent movement pattern with subtle differences associated with the plane of elevation.

Key Words: motion analysis, helical axis, intracortical pins

The shoulder joint (actually a complex of joints) has the largest range of motion of any joint (or joint complex) in the human body. Accurate and meaningful descriptions of the elaborate motions of the shoulder are required to understand its normal and pathological functions. However, attempts at such descriptions have been limited by (a) movement of soft tissues over the shoulder, which makes surface measurement of bony motion inaccurate, and (b) ill-defined and/or suboptimal methods, reference systems, and parameters used to quantify shoulder motion (Morrey & An, 1990).

Large displacements of soft tissues relative to the underlying bones during shoulder movements render measurements from the surface inaccurate. Thus, investigators have devised both noninvasive and invasive methods to avoid soft tissue artifact. Noninvasive roentgenographic methods have been used for static two-dimensional analysis (Freedman & Munro, 1966; Poppen & Walker, 1976). The “palpator” is a noninvasive device used to palpate bony landmarks through the skin and has been used for static three-dimensional analyses (Pronk, 1988; van der Helm & Pronk, 1995). Invasive methods that allow dynamic analyses involve placing tantalum beads or intracortical pins into the shoulder complex (Hogfors, Peterson, Sigholm, & Herberts; 1991; Inman, Saunders, & Abbott, 1944; Sidles, Harryman, Harris, & Matsen, 1991). However, three-dimensional shoulder motion...
through the full range has not yet been measured using bone-imbedded markers.

Shoulder motion has typically been described using Cardan/Euler angles, which are an ordered sequence of rotations about the axes of a given Cartesian coordinate system (e.g., Hogfors et al., 1991; Pronk, 1988; van der Helm & Pronk, 1995). Such a description is limited because Cardan/Euler angles are undefined for certain shoulder configurations (“gimbal-lock”), and Cardan/Euler angle values depend on the rotation order chosen (Woltring, 1994). Helical axis parameters (Woltring, Huiskes, de Lange, & Veldpaus, 1985), which portray shoulder motion simply as a rotation about a single axis, are not subject to these limitations. In addition, helical axis parameters are less sensitive to measurement errors and to uncertainties in reference system orientations than are Cardan/Euler angles (Woltring, 1994). Despite the advantages of helical axis parameters, no study has used these parameters to describe shoulder motion.

The purpose of this study was to examine the three-dimensional, in vivo kinematics of the normal shoulder complex during humeral elevation through the full range in three vertical planes. Intracortical pins were used to avoid artifacts from soft tissue movement, and helical axis parameters were used to avoid limitations associated with Cardan/Euler angles.

Methods

Subjects and Surgical Procedures

Three healthy subjects (2 male, 1 female) volunteered for participation in this study. None of the subjects had a history of shoulder complex disorder. The protocol was approved by the Institutional Review Board, and each subject provided written informed consent in accordance with institutional policy.

Using standard surgical procedures, we inserted intracortical pins into the scapula and humerus of each subject. First, the skin was cleansed over the acromion process of the scapula and the lateral epicondyle of the humerus. Lidocaine (2%) was then used to anesthetize the skin, subcutaneous tissue, and periosteum. At each location, a small incision was made in the soft tissues, and a threaded intracortical pin (2 mm diameter) was inserted into the bone using a surgical drill (no predrilling was required). A triad of reflective markers (1.25 cm spheres separated by 7.5 cm) was attached to each intracortical pin (cf. Koh, Grabiner, & de Swart 1992, Figure 1), and the stability of the triad–pin–bone junctions was verified. Each triad was visually inspected between each trial of elevation to ensure that triads did not move relative to the bone during the experiment. The subjects reported no discomfort during pin insertion or during data collection. After the experiment, the subjects reported only minor soreness at the insertion sites lasting for 2 to 3 days.

Data Collection

Two roentgen tubes, oriented generally in an anterior–posterior direction relative to the shoulder, were used to take roentgenograms of the shoulder complex to determine the three-dimensional orientation of the scapula and humerus relative to their respective marker triads. First, the tubes were focused on the scapula and its marker triad, and roentgenograms were taken. Each roentgenogram was then exposed a second time; a calibration frame was recorded in the second exposure to provide information for calculating three-dimensional orientations. Double exposure roentgenograms were also taken of the humerus, its marker triad, and the calibration frame.
Reflective markers were placed on the trunk to define a reference system for the trunk. Reflective markers (2 cm hemispheres) were placed on the skin over the left posterior iliac crest and approximately over the spinous processes of vertebrae T12 and L4 of each subject. Reflective markers were also placed over the left and right acromion processes.

While the subject maintained the anatomical position, the positions of the skin markers and the marker triads were recorded with four video cameras and a motion analysis system (Model 3110, Motion Analysis Corp, Santa Rosa, CA). The markers over the acromia were then removed.

Shoulder complex kinematics were recorded during elevation of the arm in three vertical planes: frontal, midway between frontal and sagittal planes (termed the “middle plane”), and sagittal. Prior to data collection, each subject practiced elevation in each of the three planes and was given targets at which to “point” during elevation. Elevation in the frontal plane began with the upper limb in the anatomical position. Elevation in the other planes began with the upper limb internally rotated such that the hand was in the designated plane. The subjects were asked to reach maximum elevation in 3 s (at an approximate rate of 60°/s) and to keep the elbow fully extended throughout each trial. The subjects were instructed to isolate movements at the shoulder complex and to minimize trunk movements. The subject performed five trials of elevation in each plane while the motions of the markers were recorded at 60 Hz. A calibration frame (different from the one recorded during the roentgenogram data collection) was recorded after data collection to provide information for calculating three-dimensional coordinates of the reflective markers.

Data Reduction

Roentgenograms were digitized with the aid of a custom microcomputer-based digitizing system. First, 14 to 16 calibration points were digitized in each image. Target points were then digitized in each scapular image: the center of each marker of the scapular triad, the inferior scapular angle, the medial border of the scapular spine, and the center of the glenoid fossa. Five targets were digitized in each humeral image: the center of each marker of the humeral triad and two points on the midline of the humeral shaft. The superior/inferior locations of these latter points were demarcated by radiopaque markers placed on the skin overlying the humerus.

The digitized roentgenogram calibration and target data were then used as input to a computer program that employed the direct linear transformation (DLT) algorithm (Abdel-Aziz & Karara, 1971) to calculate three-dimensional coordinates of the calibration and target points. Error in the calculated coordinates of the calibration points was approximately 1 mm.

Three-dimensional coordinates of the reflective markers from the video records were determined using the recorded marker motions, the calibration frame data, and the DLT algorithm. Error in determining positions of these markers was previously estimated as less than 1 mm and error in determining rotations of the marker triads less than 1°, for the same camera setup and calibration volume (Koh et al., 1992). The x-, y-, and z-coordinates of the three-dimensional trajectories of each marker (including data points before and after elevation to avoid endpoint effects) were smoothed independently using a recursive Butterworth low-pass filter with a cutoff frequency of 3 Hz. This cutoff frequency was chosen to minimize noise without affecting signal (verified by checking residual plots).

Rotations of the scapula were described relative to the trunk, and rotations of the humerus were described relative to the scapula using standard coordinate system transfor-
mations. The reference system for the trunk was determined from skin markers. The z-axis was directed superiorly, the y-axis was directed posteriorly, and the x-axis was directed to the left of the subject in the frontal plane (Figure 1). The reference systems for the scapula and humerus were determined from roentgenogram data. For the scapula, the z-axis was directed superiorly along the medial border of the scapula, the y-axis was directed posteriorly, perpendicular to the scapular plane, and the x-axis was directed to the left in the scapular plane. For the humerus, the z-axis was directed superiorly along the long axis of the humerus, the y-axis was directed posteriorly (cross-product of the z-axis and the x-axis of the trunk with the upper limb in the anatomical position), and the x-axis was directed to the left in the frontal plane.

Helical axis parameters (Woltring et al., 1985) were determined for scapular rotation relative to the trunk and humeral rotation relative to the scapula for consecutive 10° steps of elevation throughout the range of elevation in each plane. It was thought that a 10° elevation step would be large enough to allow for accurate determination of the helical axes (Woltring et al., 1985) and small enough to avoid masking important information about shoulder motions. Scapular helical rotation was expressed in both the trunk and scapular systems, and humeral rotation was expressed in both the scapular and humeral systems. Expressing the rotations in two different systems allowed a more complete anatomical interpretation of the data than expression in only one system. Finally, humeral elevation relative to the trunk (termed simply “humeral elevation”) and the orientation of the shoulder complex in the anatomical position were described with projection angles.

Data Analysis

For each subject, mean values and their standard deviations were computed for each helical parameter over the five trials performed for each plane of elevation. Values were calculated for each 10° increment of humeral elevation. Similar values were computed for
the group of subjects for each helical parameter and plane of elevation, using the mean values for the 3 subjects. Ensemble curves were then constructed for each subject and the group of subjects. Each ensemble curve consisted of the mean values ±1 standard deviation for a helical parameter throughout the range of elevation in a given plane.

**Results and Discussion**

Data quality was assessed by the reproducibility of reference system orientations upon repeat measurement and the variability of individual subject data. Scapular and humeral reference system orientations could be reproduced within 3° upon repeat digitization of roentgenograms. The orientations of the marker triads could be determined within 1° during video analysis. Uncertainty in both reference system and marker triad orientations influences uncertainty of helical axis parameters. The small intertrial variability in individual subject data (Figure 2) suggested that (a) the triad markers did not move substantially relative to the underlying bone during the experiment and (b) the subjects could reproduce elevation in a given plane accurately.

The angle between the x-axis (medial–lateral) of the trunk and the projection of the x-axis of the scapula into the xy (horizontal) plane of the trunk was 37.2 ± 4.2° (mean ± standard deviation for 3 subjects; Figure 3). The angle between the z-axis of the trunk and the projection of the z-axis (medial border) of the scapula into the xz (frontal) plane of the trunk was 4.4 ± 4.4°. The angle between the z-axis of the trunk and the projection of the z-axis of the scapula into the yz (sagittal) plane of the trunk was 11.3 ± 5.3°. These angles show general agreement with similar angles reported in a previous study (31, 3, and 19°, respectively), although the method of measurement in the previous study was not precisely defined (Laumann, 1987). The angles between the z-axis (longitudinal) of the trunk and the projections of the z-axis (longitudinal) of the humerus into the xz (frontal) and yz (sagittal) planes of the trunk were 2.2 ± 2.3° and 0.7 ± 7.1°, respectively.

The scapular helical rotation was similar for elevation in the three planes (Figures 4, 5, and 6). However, there appeared to be a trend of less rotation during the first part of elevation and more in the final part, at the scapulothoracic joint, as the plane of elevation moved from frontal to sagittal.

When expressed in the trunk system, the scapular helical axis was directed mainly in the xy plane during humeral elevation in all three planes (Figures 4, 5, and 6). The data indicated an increasing magnitude of the x-component and decreasing magnitude of the y-component as the plane of elevation moved from frontal to sagittal. This trend follows the change in the plane of elevation. For the initial degrees of elevation, the z-component also appeared to increase as the plane of elevation moved from frontal to sagittal. This suggests that the scapula showed an increasing tendency to move horizontally around the rib cage. These findings support the view that the scapula moves “toward” the plane in which the humerus is elevated (Laumann, 1987; Pronk, 1988). In other words, the scapula appears to rotate such that the scapular plane moves toward alignment with the plane of elevation.

When expressed in the scapular system, the scapular helical axis for elevation in all three planes showed rotation almost solely about an axis perpendicular to the plane of the scapula (y-axis) between 30 and 150° of elevation (Figures 4, 5, and 6). The variability was strikingly low for the y-component of the helical axis. Such consistency may be the result of bony constraints, of common muscular control of scapular motion during elevation in different planes, or both. There appeared to be a small amount of rotation about the scapular x-axis with elevation in each plane, which indicated a backward tilt of the scapula. For rotation about the z-axis, there was a trend moving from retraction at the beginning, to
Figure 2 — Ensemble curves showing typical intertrial variability for 1 subject (elevation in the frontal plane): helical axis parameters for scapular rotation. Scapular helical rotation (top) and scapular helical axis direction described in trunk (T) and scapular (S) reference systems (middle and bottom, respectively). Each ensemble curve is mean ± standard deviation for five trials, helical axis expressed as unit vector with components in designated system (squares = x-axis, diamonds = y-axis, circles = z-axis) and with values centered in middle of each 10° step of elevation.
protraction at the end, of elevation in the frontal plane, and the opposite trend for elevation in the sagittal plane.

The data on scapular rotation correspond well with data presented previously (Inman et al., 1944; Laumann, 1987; Pronk, 1988). Exceptions were that Laumann (1987) reported (a) an earlier upward rotation of the scapula during sagittal versus frontal plane elevation and (b) protraction for frontal plane elevation and retraction for sagittal plane elevation. These findings are in contrast to data reported here and by Pronk (1988). The differences may result from differences in the parameters chosen to describe the motions observed. Pronk used Cardan angles; we used helical axis parameters in the present study; and although not explicitly stated, Laumann appeared to use projection angles.

Humeral helical rotation past 150° of elevation appeared to be smaller during elevation in the middle and sagittal planes than in the frontal plane (Figures 7, 8, and 9). The opposite trend was seen for scapular rotation (Figures 4, 5, and 6). This may indicate a change in the contributions of humeral and scapular rotations to humeral elevation with changes in the plane of elevation.

The humeral helical axis was directed primarily along the scapular y-axis for elevation in the three planes (Figures 7, 8, and 9). This was particularly evident for elevation in the middle plane. These data indicated that most humeral rotation took place in
Figure 4 — Group ensemble curves for elevation in the frontal plane: helical axis parameters for scapular rotation. Scapular helical rotation (top) and scapular helical axis direction described in trunk (T) and scapular (S) reference systems (middle and bottom, respectively). For this and all remaining figures, each ensemble curve is mean ± standard deviation for 3 subjects. Helical axis direction expressed as unit vector with components in designated system (squares = x-axis, diamonds = y-axis, circles = z-axis) and with values centered in middle of each 10° step of elevation.
Figure 5 — Group ensemble curves for elevation in the frontal plane: helical axis parameters for humeral rotation. Humeral helical rotation (top) and humeral helical axis direction described in scapular (S) and humeral (H) reference systems (middle and bottom, respectively). Helical axis direction in designated system: squares = x-axis, diamonds = y-axis, circles = z-axis.
Figure 6 — Group ensemble curves for elevation in the middle plane: helical axis parameters for scapular rotation. Scapular helical rotation (top) and scapular helical axis direction described in trunk (T) and scapular (S) reference systems (middle and bottom, respectively). Helical axis direction in designated system: squares = x-axis, diamonds = y-axis, circles = z-axis.
Figure 7 — Group ensemble curves for elevation in the middle plane: helical axis parameters for humeral rotation. Humeral helical rotation (top) and humeral helical axis direction described in scapular (S) and humeral (H) reference systems (middle and bottom, respectively). Helical axis direction in designated system: squares = x-axis, diamonds = y-axis, circles = z-axis.
Figure 8 — Group ensemble curves for elevation in the sagittal plane: helical axis parameters for scapular rotation. Scapular helical rotation (top) and scapular helical axis direction described in trunk (T) and scapular (S) reference systems (middle and bottom, respectively). Helical axis direction in designated system: squares = x-axis, diamonds = y-axis, circles = z-axis.
Figure 9 — Group ensemble curves for elevation in the sagittal plane: helical axis parameters for humeral rotation. Humeral helical rotation (top) and humeral helical axis direction described in scapular (S) and humeral (H) reference systems (middle and bottom, respectively). Helical axis direction in designated system: squares = x-axis, diamonds = y-axis, circles = z-axis.
the plane of the scapula independent of the plane of elevation, and that elevation in the middle plane showed almost no evidence of humeral rotation in other planes. The small component of the helical axis directed along the negative humeral z-axis at the end of elevation in each plane suggested that a small amount of external rotation may have taken place.

In general, there was relatively large variability in many of the helical parameters at the beginning and end of elevation. This variability at the beginning of elevation was observed previously (Inman et al., 1944; Laumann, 1987) and was termed “the setting” phase.

The present study was limited by placement of skin markers on the trunk as opposed to implanted bone markers. Thus, measurements of scapular and humeral movements relative to the trunk could be affected by soft tissue artifact. However, trunk system rotation was always less than 0.3°/10° humeral elevation as measured by skin markers, so extraneous soft tissue movement appeared not to appreciably influence the measured shoulder complex motions.

In summary, certain parameters of shoulder complex motion were surprisingly similar for elevation in all three planes (e.g., scapular and humeral helical axis directions expressed in the scapular system). Such similarity suggests that elevation in different planes may be controlled in a similar manner for a large part of the range of motion with subtle changes accounting for the changing plane of elevation. Further study could provide descriptions of pathological shoulder complex motion, which could involve loss of shoulder motion control. In addition, quantitative evaluation of clinical interventions for shoulder injuries could provide useful information for treating such injuries.

The helical axis parameters used in the present study provided easily interpretable and anatomically meaningful data. Previously, shoulder motion has been described using Cardan/Euler angles (Hogfors et al., 1991; Pronk, 1988; van der Helm & Pronk, 1995). Cardan/Euler angles are undefined for certain shoulder configurations (“gimbal-lock”), and Cardan/Euler angle values depend on the rotation order chosen (Woltring, 1994). Helical axis parameters do not suffer from these problems. In addition, helical axis parameters are less sensitive to measurement errors and to uncertainties in reference system orientations (Woltring 1994). Hence, helical axis parameters seem better suited for describing shoulder complex motions.

References


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**Acknowledgments**

We would like to thank Jon Feuerbach, Thomas Lundin, Julee Kasprisin, and Dr. Rob deSwart for their help with the data collection.