Variation in the position and orientation of the elbow flexion axis

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We analysed the axis of movement in the normal elbow during flexion in vivo using radiostereometric analysis (RSA). The results show an intraindividual variation in the inclination of the axis ranging from 2.1° to 14.3° in the frontal and from 1.6° to 9.8° in the horizontal plane analysed at 30° increments. The inclination of the mean axis of rotation varied within a range of 12.7° in the frontal and 4.6° in the horizontal plane. In both planes, the mean axes were located close to a line joining the centres of the trochlea and capitellum. The intra- and interindividual variations of the axes of flexion of the elbow were greater than previously reported. These factors should be considered in the development of elbow prostheses.

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The outcome of total joint replacement has improved over recent decades, particularly with regard to the hip and knee.¹⁻³ This can be attributed partly to improved biomechanical understanding of the joints and implants. Replacement of the elbow has become common in order to reduce pain and improve function in patients with rheumatoid arthritis, but the results are proving to be less predictable than those described for the hip and the knee.⁴⁻⁸ The development of elbow prostheses has progressed from hinged to linked and unlinked designs. Critical analysis of the biomechanical features of the different implants is lack-

ing and there are no studies of the long-term results using a single design of prosthesis. Changes in design have therefore been made without a thorough knowledge of the biomechanics.

Dislocation associated with unlinked implants may be due either to incorrect positioning and orientation, or to defective design of the prosthesis.^{9,10} The higher risk of loosening of linked implants may be a consequence of incorrect alignment of the axis of the hinge in relation to the anatomical axis of rotation. Furthermore, a semi-constrained design usually allows about 5° of rotation between the components, which may be insufficient compared with the normal variation in the position and orientation of the joint axes.¹¹ Cadaver studies have shown that malpositioning of either the ulnar or the humeral component modifies the kinematics of the artificial joint and may lead to loosening.^{9,10}

In engineering terms, the movement of flexion and extension of the elbow is referred to as a rotation of the olecranon round the trochlea of the lower end of the humerus. A prerequisite for understanding the biomechanical properties of a joint is knowledge of the position of the axis of rotation. Early studies have described this as a stationary axis passing through the centre of the trochlea.¹²⁻¹⁵ More recent studies, using electromagnetic tracking techniques, indicate that the axis is not fixed but changes in position and orientation throughout the arc of movement.¹⁶⁻¹⁸ Most previous studies have been based on experiments in vitro. Their value, however, is limited since movement may be dependent not only upon the geometry of the surface of the joint but also on physiological muscle function and on an intact capsule and ligaments. Knowledge of the position and orientation of the axis of movement in the normal elbow in vivo is indispensable if improvements in the design of elbow prostheses and operative techniques are to be made.

Radiostereometric analysis (RSA), so useful in the development of hip and knee replacements,¹⁹⁻²² has been predominantly applied to the measurements of movement between the implant and the host bone, in order to detect early loosening. It is also a highly accurate method for determining the axis of rotation in vivo even in a joint as complex as the ankle.²³ We undertook this study to determine the position of the axis of rotation during flexion of the elbow in vivo in normal subjects.

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Fig. 1

Instantaneous axes in the frontal plane for all six subjects during flexion from 0° to 30° (axis 1), 30° to 60° (axis 2), 60° to 90° (axis 3) and 90° to 120° (axis 4). The two dots represent the centres of the trochlea and capitellum joined by the dotted line.

Subjects and Methods

Six healthy volunteers participated in the investigation which was approved by the Ethical Committee of the Karolinska Hospital. All gave their informed consent and had a clinically normal range of movement, suffered from no

musculoskeletal disorders and had no history of trauma to the elbow. There were three women and three men with a mean age of 33 years (25 to 42). We examined the non-dominant elbow which in all subjects was the left. Between four and six tantalum marker beads (diameter 0.8 mm) were implanted into the ulna and humerus, using a spring-loaded

Fig. 2

Instantaneous axes in the horizontal plane for all six subjects during flexion from 0° to 30° (axis 1), 30° to 60° (axis 2), 60° to 90° (axis 3) and 90° to 120° (axis 4).

Table I. Ulnohumeral angles, in degrees, relative to the fully extended (0°) position in the sagittal plane as calculated by RSA at the four elbow positions analysed

Subject	30	60	90	120
1	32.9	54.7	106.2	137.2
2	23.7	66.0	83.5	115.1
3	24.4	44.4	88.2	127.4
4	35.1	58.4	88.8	129.5
5	25.9	59.2	91.2	118.0
6	35.6	51.8	74.6	113.0
Mean (SD)	29.6 (7.7)	56.4 (7.1)	88.9 (7.7)	122.9 (6.4)

device with a 1.4 mm diameter cannula. Accuracy of RSA is greatest when markers are inserted into a substantial volume of bone. However, we restricted the positioning of the markers to the radial condyle of the distal humerus and to the radial and posterior surfaces of the ulna in order to avoid interference with the ulnar nerve. No complications occurred during or after insertion. Some subjects experienced discomfort in the elbow for a day or two, but none reported persistent symptoms.

In order to avoid any influence from initial pain or stiffness, we carried out the radiostereometry approximately three months after the markers had been inserted.²⁴ The subject was seated with the elbow placed in a plexiglass calibration cage equipped with two perpendicularly disposed x-ray cassette holders (calibration cage no 10; RSA Biomedical, Umeå, Sweden). The laboratory co-ordinate system was defined by markers positioned in this cage (positional accuracy 0.001 mm). The x-ray tubes were placed at right angles to each other and to the calibration cage, one anterior and one lateral to the elbow. The distance

between the x-ray tubes and the films was 1 metre. Exposure of the anteroposterior (AP) and mediolateral radiographs was simultaneous. Pairs of films were taken at maximal extension (zero flexion) and at 30°, 60°, 90° and 120° of flexion with the hand in a supinated position. The angles of flexion were measured using a surface goniometer and the subject actively held each position of the elbow during radiography. The corresponding, precisely determined angles calculated by RSA are presented in Table I.

The radiographs were scanned digitally for analysis using the UMRSA software package (RSA Biomedical, Umeå, Sweden), which was also used to calculate the three-dimensional position of the tantalum markers and for the kinematic analysis.²²

We calculated rotation of the ulnar marker segment relative to that for the humerus for each increment of flexion. The resulting rotations were described in relation to the axes of a fixed orthogonal co-ordinate system defined with its origin at the centre of gravity of the humeral marker segment. The y-axis was directed proximally, the x-axis laterally and the z-axis ventrally, orthogonal to the x- and y-axes. Positive rotation about the x-axis corresponded to elbow flexion. The long axis of the humerus was defined as a line through the centre of the straight, distal third of the diaphysis in both the frontal and sagittal planes. The central points of the circular arcs representing the trochlea and the capitellum on the lateral radiographs defined a line through these anatomical structures. These points were plotted on the AP radiograph, perpendicular to the tangents of the most distal points of the trochlea and the capitellum, respectively, using the radius of each arc. The arms could not be perfectly aligned with the orthogonal cage system during the radio-

Table II. Mean (ranges; degrees) axis inclinations in the frontal (positive inclination: proximal lateral to distal medial) and the horizontal (positive inclination: internally rotated plane)

Subject	Gender	Orientation	
		Frontal plane	Horizontal plane
1	F	0.0 (-1.3 to 0.9)	-0.3 (-1.3 to 0.3)
2	M	6.5 (3.5 to 10.0)	2.4 (-3.0 to 6.8)
3	M	-1.4 (-6.5 to 7.8)	0.6 (-2.2 to 2.3)
4	F	-1.8 (-4.0 to 2.6)	2.0 (-1.7 to 5.0)
5	F	-5.4 (-6.9 to -1.9)	-2.2 (-4.9 to 0.6)
6	M	-6.2 (-9.5 to -2.2)	1.1 (-0.6 to 4.6)

graphic procedure. The skeletal system therefore was mathematically rotated so that the long axis of the humeral shaft was aligned with the y-axis and the line through the trochlea and capitellum was aligned with the x-axis in the horizontal plane.

We calculated the instantaneous screw axis for the resultant movement which had occurred in each step of rotation and determined the co-ordinates of this axis in the frontal and horizontal planes. The four axes represented the rotations 0° to 30°, 30° to 60°, 60° to 90° and 90° to 120°. The intercept of the instantaneous screw axis with the sagittal plane, 200 mm lateral to the centre of the joint, illustrated its progression during flexion of the elbow. We plotted all instantaneous axes for each subject in the frontal (XY) and horizontal (XZ) planes and constructed a diagram of the elbow to show the position and orientation of the axes relative to the joint. Positioning these axes in the different planes on the diagrams were made according to the x- and y-axes within the humerus.

Results

The orientation of each instantaneous axis is illustrated for 30° increments for all subjects in the frontal (Fig. 1) and horizontal planes (Fig. 2). The mean axis inclinations are presented in Table II and inclinations for the different flexion intervals are summarised in Table III.

The inclination of the instantaneous axes varied between subjects within the arc of flexion. The position and orientation of the cluster of calculated instantaneous axes approxi-

mated the anatomical line through the points defining the centres of the trochlea and capitellum, for all subjects in both planes. The calculated mean axis (Table II) for each elbow varied in the frontal plane, from being orientated proximally medially to distally laterally in subjects 3, 4, 5 and 6, and to being orientated in the opposite directions in subjects 1 and 2. In the horizontal plane the mean axis varied between the subjects, from being inclined slightly internally to slightly externally, relative to a line through the centre of the trochlea and the capitellum (x-axis).

There was no clear relationship between the position of the axis in the frontal plane and that in the horizontal plane; a predominantly internal rotation was not necessarily coupled with a positive inclination in the frontal plane. There were no differences in the pattern of orientation of the axis between men and women. The intercept points of the instantaneous axes with the sagittal plane, 200 mm lateral to the humerus, are illustrated in Figure 3.

The pathways of the intercept points did not follow a clear one-way helical or circular progression. In three elbows (subjects 2, 4 and 6) there was a clockwise rotation. Two of the elbows (subjects 1 and 3) had an anti-clockwise rotation and one had an irregular pattern (subject 5). In four subjects (3, 4, 5 and 6) the intercept point of the 30° to 60° axis was the most proximal, whereas in the remaining two, the intercept point of the 60° to 90° increment was the most proximal. In most subjects the intercept points for the most extended and most flexed increments (0° to 30° and 90° to 120°) were situated distally. The intercept points for all subjects lay within an area of 3 x 2 mm in a plane through the longitudinal axis of the humerus in the centre of the trochlea. For two of the subjects this area was less than 1 x 1 mm.

Discussion

We have used the RSA technique to determine the position and orientation of the axis of the ulnohumeral joint in healthy adults. The flexion axes were described relative to the perpendicular of the long axis of the humerus. When necessary, we have converted data from previous studies for comparison. The advantage of the methodology was that the technique could be done in vivo facilitating the description

Table III. Summary of elbow flexion axes (degrees) in the frontal and horizontal planes. Positive inclination in the frontal plane is proximal lateral to distal medial; positive inclination in the horizontal plane is internally rotated

Subject	Orientation							
	Frontal plane				Horizontal plane			
	0 to 30	30 to 60	60 to 90	90 to 120	0 to 30	30 to 60	60 to 90	90 to 120
1	-	+	+	-	-	+	-	-
2	+	+	+	+	+	-	-	+
3	-	+	-	-	+	-	+	+
4	-	+	-	-	+	+	+	-
5	-	-	-	-	+	-	+	-
6	-	-	-	-	-	-	+	+

Fig. 3

Progression of the flexion axis plotted 200 mm lateral to the humerus for all six subjects: 0° to 30°, 30° to 60°, 60° to 90° and 90° to 120°. Orientation: +ve Y: proximal, +ve Z: ventral.

of active movement. The physiological activity of the different muscles may have an influence on the pattern of movement during active flexion, especially when considering the valgus and varus laxity of the elbow reported in a number of studies.^{16,18,24} The variation in instantaneous axis inclination and the irregular pathway of the intercept points in the

sagittal plane support this hypothesis and our results differ from those of earlier studies on cadaver specimens in this respect. Apart from joint laxity and active muscular control, differences in the contours of the joint surfaces may explain the interindividual variation found in this and previous studies.

Our results are in some respects comparable with those of previous studies. The cluster of instantaneous screw axes approximated to a line through the centre of the trochlea and the capitellum, both in the frontal and horizontal planes. This finding coincides with the perception that the axis of movement is situated in the centre of these anatomical structures.^{13-15,18} We also found the screw axes to pass through a very small area in the centre of the trochlea, comparable with the loci of instant centres of rotation earlier described,^{12,13,15} although Stokdijk et al¹⁷ described a dispersion of about 2 cm. Small loci were previously considered as proof of a fixed axis of movement. In our study, however, the flexion axis did not have a fixed position. In accordance with later studies we found variations in the orientation of the instantaneous axes during flexion of the elbow.^{18,25} The axes pivoted with individual variations ranging from 2.1° (-1.3° to 0.9°) to 14.3° (-6.5° to 7.8°) in the frontal plane and from 1.6° (-1.3° to 0.3°) to 9.8° (-3.0° to 6.8°) in the horizontal plane. Bottlang et al¹⁸ calculated these variations to be $2.6^\circ \pm 1.0^\circ$ in the frontal and $5.7^\circ \pm 2.2^\circ$ in the horizontal plane, while Ishizuki²⁵ mentioned a variation of up to 17° without stating which plane.

Variation of the instantaneous axis of orientation during flexion of the elbow can be described as a dispersion of the axis intercept points in the sagittal plane. In accordance with Ishizuki,²⁵ the pathway of these intercept points in our study did not follow the regular pattern described by Bottlang et al,¹⁸ who found an elliptically shaped conical configuration using a method with mechanically-induced movement in cadaver specimens. The distal position of the intercept points in the most extended and flexed positions and the proximal position of the intercept points in the middle of the flexion arc, coincided with the pattern of axis migration presented by Bottlang et al.¹⁸

Comparing studies describing the axis of movement in terms of a mean or an optimum flexion axis, we found inter-individual differences in the inclination of the calculated mean axis.^{16,17} The range of this variation was 12.7° in the frontal plane and 4.6° in the horizontal plane; greater variations in the horizontal (11.9°) than in the frontal plane (2.6° to 4.6°) have previously been reported.¹⁶⁻¹⁸ The greater interindividual variation described in an in vivo study by Stokdijk et al¹⁷ may have been due to the use of skin markers, which at best provide an imprecise definition of axes of rotation and optimal rigid body segments.

In many studies, it is described as an axiom that the flexion axis passes through the centres of the trochlea and the capitellum. In an anatomical study this centred line was described as having a distal medial inclination of 2.5° in the frontal plane,²⁶ while a somewhat greater medial inclination of between 4° and 8° has also been described.¹⁵ Studies using electromagnetic tracking have reported the mean axis in the frontal plane to have a similar medial inclination.¹⁶⁻¹⁸ In our study, four of the subjects had an inclination of the mean axis in the opposite direction, that is from proximal-medial to distal-lateral, varying between 1.4° and 6.2°. Sub-

ject 1 had a mean axis orientated almost parallel to the x-axis (0.0°). Only subject 2 had a mean axis orientated in the same direction as reported in previous studies (6.5° distally and medially).

The inclination of the mean axis in the horizontal plane differed little from the line through the centres of the trochlea and the capitellum (defined as the x-axis). The range was between 2.4° of internal rotation and 2.2° of external rotation. Using the same line as reference, a somewhat greater interindividual variation from 4.7° of external to 7.2° of internal rotation has previously been reported.¹⁶ Horizontal plane reconstructions of the mean instantaneous axes on drawings of the distal humerus showed an internal rotation of between 5° and 8° relative to the transepicondylar plane which is comparable to the internal rotation of between 3° and 8°, described by London.¹⁵

A direct comparison of axes of inclination between studies is difficult because the instantaneous inclinations in the studies using electromagnetic tracking were generally expressed in terms of mean values only. Another factor rendering a comparison difficult is the variable definition of the long axis of the humerus, but differences in its position cannot fully explain the differences which we found in the mean axis of inclination in the frontal plane compared with previous studies.

Our observations concerning the instantaneous screw axes of the elbow are relevant for the design of elbow prostheses. They confirm that the elbow does not act as a simple hinge. In view of the great interindividual differences in orientation of mean axes and intra-individual variations of the instantaneous screw axes during flexion of the elbow, an unlinked implant allowing a greater freedom of laxity may be the method of choice in primary replacement of a stable elbow. More constrained linked implants may be required for elbows which are unstable because of bone loss or soft-tissue pathology. A greater degree of freedom in the coupling of the components may lessen the problem of early loosening of these implants.

The precise pattern of movement after replacement of the elbow remains to be studied but a method allowing a more reliable positioning of the calculated axis according to anatomical landmarks would assist the interpretation and comparison of kinematic studies.

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