INTRODUCTION

Few data exist describing the precise kinematics of the human elbow joint although knowledge of position and orientation of the rotation axes are prerequisites for an understanding of the biomechanics of implant design. Elbow joint replacement has become a common technique to reduce pain and increase elbow function in patients with rheumatoid arthritis. Middle term results after elbow joint replacement are generally not as good as those described for hip and knee replacements. Elbow prosthesis development has progressed from originally hinged designs to linked and unlinked implants. Information concerning the biomechanical advantages of these different implants is lacking and no studies of long-term results using a single prosthetic design have been performed. Changes in prosthetic designs have therefore been made without a thorough knowledge of elbow biomechanics.

This information is necessary to avoid incorrect implant rotation axes leading to implant loosening within the bone, or too variable axes resulting in joint luxation. Present knowledge on this subject is predominantly based upon in vitro anatomical studies [1-4]. Accurate, physiological data can, however, only be achieved by determining the flexion axis in vivo, to eliminate external influences from the mechanical manipulation of the rotation. Knowledge of the precise position and orientation of the elbow joint flexion axis is also a prerequisite for accurate mathematical modelling of this joint, for example as a tool for describing injury mechanisms during falling or racquet sports, or for optimising overhead sports technique.

Radiostereometric analysis (RSA) utilises small tantalum balls inserted in the skeleton to define rigid body segments. Double X-ray exposures permit the three-dimensional determination of the positions of these markers. RSA is primarily used in the description of prosthesis micromotion relative to the host bone, however, another application is the calculation of instantaneous axes of rotation between defined increments of segmental rotation [5,6]. This study presented an in vivo RSA analysis of the elbow’s flexion axis.

MATERIAL AND METHODS

Six healthy subjects (mean age 33; 25-42) participated in the study. The left, non-dominant elbow was analysed with the RSA technique. Four to six 0.8 mm diameter tantalum markers were introduced percutaneously into the radial part of the distal humerus and in the proximal part of the ulna using a spring loaded insertion device. In this study marker positioning was, however, restricted to the radial condyle of the distal humerus and to the radial and posterior sections of the ulna in order to avoid interference with the ulnar nerve. Marker insertion was conducted percutaneously under local anesthesia and under aseptic conditions. No complications occurred during or after insertion. Some subjects experienced moderate pain in the elbow the subsequent one to two days but no persistent symptoms were reported.

Figure 1: Lateral (above) and antero-posterior X-ray exposures of the elbow joint with inserted tantalum markers. Additional markers show the calibration cube.

RSA was performed about three months after marker insertion in order to avoid any influence from pain or stiffness. Subjects were seated with the elbow placed in a plexiglas calibration cage.
equipped with X-ray cassette holders (RSA Biomedical, Umeå, Sweden). Anteroposterior and lateral radiographs were exposed simultaneously at flexion angles of 0° (full extension) 30°, 60°, 90° and 120°. One subject (subject 2) also had X-ray exposures taken in 10° increments from 0° to 140° for a more detailed description of elbow flexion. The elbow was actively held at the desired external angle, thus utilising the given anatomy, joint laxity and physiological muscle forces. In vitro anatomical studies where joint angles are primarily determined by external control could not provide these conditions.

The coordinate system was defined by the markers of the calibration cage. The y-axis was oriented proximally parallel to the shaft of the humerus, the x-axis laterally parallel to a plane through the trochlear center and capitulum humeri and the z-axis orthogonally ventrally. Positive rotation about the x-axis represented elbow flexion. Instantaneous axis of rotation for each flexion increment was calculated and represented in the anatomical coordinate system.

As the arms could not be perfectly aligned with the orthogonal cage system during the X-ray procedure, the skeletal system was subsequently 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 humeri was aligned with the x-axis.

Two indicators of RSA accuracy were calculated (Table 1): the mean error describing the accuracy in spatial determination of the marks and the condition number which describes the quality of the rigid body segment defined by the skeletal markers. A limitation of the present study was the small bone volume available for marker placement in the ulna (compared to the pelvis for example) and the condition numbers were therefore, higher than often encountered in studies of the hip or knee.

Table 1: Mean errors and condition numbers.

<table>
<thead>
<tr>
<th>subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean error</td>
<td>Humerus</td>
<td>0.103</td>
<td>0.045</td>
<td>0.072</td>
<td>0.049</td>
<td>0.079</td>
</tr>
<tr>
<td></td>
<td>Ulna</td>
<td>0.075</td>
<td>0.032</td>
<td>0.049</td>
<td>0.109</td>
<td>0.120</td>
</tr>
<tr>
<td>Condition number</td>
<td>Humerus</td>
<td>233</td>
<td>200</td>
<td>152</td>
<td>157</td>
<td>286</td>
</tr>
<tr>
<td></td>
<td>Ulna</td>
<td>238</td>
<td>222</td>
<td>356</td>
<td>148</td>
<td>101</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSION**

The inclinations of the instantaneous axes varied to a differing degree for all subjects during the flexion arc. The position and orientation of the cluster of calculated instantaneous axes approximated 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 2) for each subject varied in the frontal plane from being orientated proximal lateral to distal medial, whereas four subject had a flexion axis oriented in the opposite direction. A greater fluctuation of axis orientation in both the frontal (31.8°) and horizontal planes (32.9°) was seen when 10° flexion increments (subject 2) were used instead of 30° intervals.

Table 2: Means (ranges) of axis inclinations in the horizontal (+ve inclination: internally rotated) and frontal (+ve inclination: prox. lat. to dist. med.) planes. Values in degrees. (Reproduced with permission from the Journal of Bone and Joint Surgery).

<table>
<thead>
<tr>
<th>subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>sex</td>
<td>F</td>
<td>M</td>
<td>M</td>
<td>F</td>
<td>F</td>
<td>M</td>
</tr>
<tr>
<td>horiz.</td>
<td>-0.3</td>
<td>2.4</td>
<td>0.6</td>
<td>2.0</td>
<td>-2.2</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>(1.6)</td>
<td>(9.8)</td>
<td>(4.6)</td>
<td>(5.0)</td>
<td>(5.5)</td>
<td>(5.2)</td>
</tr>
<tr>
<td>front.</td>
<td>0.0</td>
<td>6.5</td>
<td>-1.4</td>
<td>-1.8</td>
<td>-5.4</td>
<td>-6.2</td>
</tr>
<tr>
<td></td>
<td>(2.1)</td>
<td>(6.5)</td>
<td>(14.3)</td>
<td>(6.6)</td>
<td>(5.0)</td>
<td>(7.3)</td>
</tr>
</tbody>
</table>

Figure 2: Instantaneous axes of rotation in 10° increments for one subject, frontal plane (above) and horizontal plane. Axis descriptions: axis 1: 0° - 10°, axis 2: 10° - 20°.... axis 14: 130° - 140°. The two marked points represent the centres of the trochlea and capitellum humeri joined by the dotted line.

Intraindividual variation in axis orientation depending upon flexion increment is seen in Figures 2 and 3. The advantage of the methodology was its in vivo nature enabling the description of active motion. Physiological activity of the different muscles may be expected to influence the pattern of motion during active flexion, especially when considering the valgus and varus laxity of the elbow joint reported in a number of studies. The variation in instantaneous axis inclination supports this hypothesis and the presented results differ most compared to earlier studies on cadaver specimens in this respect. Apart from joint laxity and active
Figure 3: Elbow flexion instantaneous axes for all six subjects in the frontal and horizontal planes during flexion from 0° - 30° (axis 1), 30° - 60° (axis 2), 60° - 90° (axis 3) and 90° - 120° (axis 4). The two marked points represent the centres of the trochlea and capitellum humeri joined by the dotted line. Note all orientations were from proximal medial to lateral distal in the frontal plane, except for subjects 1 and 2.

Muscular control, differences in the contours of the joint surfaces may explain the inter-individual variation found in the present as well as in previous studies. The proximal medial to lateral distal orientation of the mean elbow flexion axis in the frontal plane in three subjects was something not previously described. Furthermore, the study reported considerable intraindividual fluctuation of the flexion axis during the complete flexion arc (max. nearly 10° in the horizontal and nearly 15° in the frontal plane). This may be due to a certain joint laxity, joint surface conformity and ligament and muscle influences.

There was no clear relation between the position of the axis in the frontal plane and the position of the axis in the horizontal plane, i.e. a predominantly internal rotation was not necessarily coupled to a positive inclination in the frontal plane. No differences were found in the pattern of axis orientation between the female and male subjects.

In accordance with studies describing the motion axis in terms of a mean or optimum axis, we found inter-individual differences in the inclination of the calculated mean axis. The range of this inter-individual variation was 12.7° in the frontal plane and 4.6° in the horizontal plane, whereas greater variations in the horizontal (11.9°) than in the frontal plane (4.6°) have previously been reported.

We also found the screw axes to pass through a very small area in the centre of the trochlea, comparable to the earlier described loci of instant centres of rotation, although Stokdijk et al. [10] described a dispersion of about 2 cm. Small loci were previously considered as proof of a fixed motion axis. In the present study, however, the flexion axis did not have a fixed position. 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). A direct comparison of axis
inclination between studies is difficult due to the fact that the instantaneous axis inclinations in the studies using electromagnetic tracking were generally expressed in terms of mean values only. Another reason which renders a comparison difficult is inconsistent definition of the humerus long axis. A clear, uniform definition is lacking. However, differences in the position of the humerus long axis cannot fully explain the large difference in mean axis inclination in the frontal plane that we found in our study relative to others.

These factors should be considered in the development of elbow joint implants as the insertion of a single, standard implant presumably will not be suitable for all. Follow-up research examining elbow kinematics in patients with various implant designs is underway.

REFERENCES


Footnote: Some material in this abstract is based on a paper (reference [6]) from the Journal of Bone and Joint Surgery.