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Computed tomography analysis of radiostereometric data to determine flexion axes after total joint replacement: Application to the elbow joint

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ABSTRACT

Kinematic analysis for *in vivo* assessment of elbow endoprostheses requires knowledge of the exact positions of motion axes relative to bony landmarks or the prosthesis. A prosthesis-based reference system is required for comparison between individuals and studies. The primary aim of this study was to further develop an earlier described algorithm for fusion of radiostereometric analysis (RSA) data and data obtained in 3D computed tomography (CT) for application to the elbow after total joint replacement. The secondary aim was to propose a method for marking of prostheses in 3D CT, enabling definition of a prosthesis-based reference system. Six patients with elbow endoprostheses were investigated.

The fusion of data made it possible to visualize the motion axes in relation to the prostheses in the 3D CT volume. The differences between two repeated positioning repetitions of the longitudinal prosthesis axis were less than 0.6° in the frontal and sagittal planes. Corresponding values for the transverse axis were less than 0.6° in the frontal and less than 1.4° (in four out of six less than 0.6°) in the horizontal plane.

This study shows that by fusion of CT and RSA data it is possible to determine the accurate position of the flexion axes of the elbow joint after total joint replacement *in vivo*. The proposed method for implant marking and registration of reference axes enables comparison of prosthesis function between patients and studies.

1. Introduction

Elbow joint replacement is an established procedure for treatment of patients with painful destruction of the elbow, especially in rheumatoid arthritis. There are several types of endoprosthesis available, based on different kinematic principles. At present two types predominate; resurfacing unlinked implants and loose-hinged devices. Long-term results (Little et al., 2005) in terms of complication rates and early loosening have not been as good as for hip and knee prostheses (Robertsson et al., 2001; Herberts and Malchau, 2000). The complications after elbow arthroplasty in terms of early loosening and luxation may to some extent be explained by postoperative non-physiological joint kinematics, that do not correspond to the joint function. The preoperative changes already existing in the arthritic joint, with bony and often ligamental destruction, may influence the resulting motion pattern and the survival of the implant.

In order to achieve better results, improvement in both prosthesis design and surgical technique is needed. However, new implants are often introduced and widely used without knowledge of their biomechanical *in vivo* properties. Further development demands knowledge of both the *in vivo* kinematics of the normal elbow joint and the kinematics after joint replacement. However, such biomechanical analyses require a standardized prosthesis-based reference system for comparison of results between patients and also between different studies.

Radiostereometric analysis (RSA) has been shown to be a useful tool to determine *in vivo* motion axes. Accurate 3D kinematics can be determined with a series of radiographs taken at different joint positions whereby the changes in position of radio-opaque tantalum markers inserted into the skeleton around a joint are calculated. This method was used in an earlier study on healthy subjects *in vivo*, showing large intra- and inter-individual variations of the elbow rotation axes during flexion (Ericson et al., 2003). RSA has also been used to determine variation of the

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flexion axes *in vivo* after total elbow joint replacement with different prosthesis designs in patients with rheumatoid arthritis (Ericson et al., 2008).

However, with RSA alone it is not possible to accurately relate the calculated flexion axes to anatomical landmarks or prosthesis-based reference axes. The position of the flexion axes in RSA is determined according to a global coordinate system with its origin in the center of gravity of one of the marker segments. Although this coordinate system can subsequently mathematically be rotated to align with a longitudinal and a transverse axis through a joint or prosthesis, these reference axes are defined according to anatomical landmarks registered as fictive points on the biplanar radiographs. Since these fictive points cannot be matched on the frontal and lateral radiographs with the same precision as the skeletal tantalum markers, the anatomical landmarks and hence the reference axes cannot always be accurately and reliably defined. An additional problem after elbow joint replacement is that the condylar parts of the prosthesis components obscure the anatomical landmarks around the joint on the radiographs. As a result the reference axes determined with fictive points in RSA can be used for illustration, but the exact position of the flexion axes relative to an intact joint or prosthesis cannot be determined with the same degree of accuracy as their relative inclinations.

With computer tomography (CT) technique it is possible to define bony landmarks and hip prostheses in a 3D CT data volume with a high degree of accuracy (Olivecrona et al., 2002; Olivecrona et al., 2003). This method was used in an earlier study (Ericson et al., 2007) on healthy volunteers, in which it was shown that it is possible to fuse RSA kinematic data from an intact elbow joint into a 3D CT space. The combination of RSA and CT made it possible to relate the flexion axes according to the individual joint anatomy without loss of the RSA accuracy.

The aim of the present study was to further develop the earlier described algorithm for fusion of RSA data with 3D CT data for application after elbow joint replacement in patients, in order to enable accurate positioning and visualization of the motion axes relative to the prostheses. A secondary aim was to propose a method for marking elbow prostheses in 3D CT and define a reference system in the implants.

2. Materials and methods

2.1. Patients

Eleven patients, who took part in the earlier radiostereometric analysis (using the UMRSA software package, RSA Biomedical, Umeå, Sweden) of the flexion axes in the elbow joint after total elbow replacement (Ericson et al., 2008), were initially chosen for the study. Five of these patients had been provided with a non-constrained Capitello-condylar prosthesis (Johnson & Johnson Orthopaedics Inc., Raynham, MA) and six patients with the equally non-constrained Kudo prosthesis (Biomet UK Ltd., Swindon, UK).

At the time of the present study one of these patients was deceased. The remaining ten patients were invited to participate in the study. Four of the patients declined participation due to general health reasons, which left six patients: three with a Kudo and three with a Capitello-condylar prosthesis. Further patient particulars are presented in Table 1.

The study was approved by the Stockholm Regional Ethical Committee, Sweden and all patients gave their informed consent.

2.2. Computed tomography

Commercially available multi-slice CT scanners were used. The patients underwent the CT-examination positioned supine on the scanning table. During the procedure the patients kept the relevant elbow as extended as possible. To minimize radiation exposure the examination was limited to 12 cm proximal and 12 cm distal to the joint.

Table 1
Patient details.

Prosthesis	Patient	Age	Gender	Side	Classification	RSA	CT
Kudo	1	34	F	L	II	3	88
	2	29	F	R	IIIA	9	79
	3	66	F	R	II	7	37
Mean Kudo		43				6.3	68
Capitello	4	68	F	R	IIIA	3	67
	5	46	F	R	IIIA	4	56
	6	46	F	R	II	4	55
Mean Capitello		53.3				3.7	59.3
Mean All		48.2				5	63.7

Age (years) at time of operation, gender (F=female, M=male), operated side (R=right, L=left), radiological classification of the rheumatoid involvement according to the Mayo clinic score, time between operation and RSA investigation (months) and time between operation and CT-scan (months).

2.3. Registration between RSA and CT

The RSA data from the earlier study of the motion axes in patients (Ericson et al., 2008) were fused with the CT volume by registering the positions of co-homologous tantalum marker beads that during the operation had been implanted around the joint and in the marrow bone of the humeral shaft. For post-processing of the CT volumes, a validated 3D volume fusion tool was used (Gorniak et al., 2003; Maguire et al., 1991; Noz et al., 2001; Olivecrona et al., 2002; Olivecrona et al., 2003; Olivecrona et al., 2003; Olivecrona et al., 2004).

The tantalum markers in the humerus were localized in the CT volumes. The coordinates of the center of each marker were calculated by superimposing a three-dimensional sphere on simultaneous axial, coronal, and sagittal views (Olivecrona et al., 2003). The coordinates for the markers obtained in the earlier study were then transformed from the RSA to the CT coordinate system using the previously described conformal transformation between the RSA data and the CT volumes (Ericson et al., 2007). Since both CT and RSA have millimetre-based coordinate systems, the scaling factor was set to 1, i.e. a rigid body transformation. Stability parameters providing an indication of the robustness of the rigid body segments were generated during the transformation. Each coordinate point of the imported RSA data corresponding to a marker was graphically evaluated, and its placement relative to the marker in the CT volume was visually confirmed. All markers were shown to be stable between the RSA and CT analyses.

The kinematic analysis data from the previous RSA study (Ericson et al., 2008) defined the inclination of the instantaneous flexion axes of the elbow during 30° flexion increments. For presentation of these axes in the CT-volume, their intersections with a sagittal plane 70 mm medial and lateral to the midline of the humeral stem were chosen. The coordinates for these intersection points were calculated using a trigonometric tangent function and then transformed to the CT-volume. The axes could then be visualized with respect to the prosthesis by connecting the intersect points.

2.4. Construction of prosthetic-based reference axes

A reference system based on the humeral prosthetic component was constructed. The axes of this reference system were defined as follows:

1. Transverse prosthetic axis. For the transverse prosthetic axis the medial and lateral aspects of the joint surface of the component were marked with multiple surface points on the prosthesis using a 3D isosurface landmarking mode. A computer pointing device was used to move a cursor over a 3D-representation of the prosthesis and multiple points were designated. The software automatically detected the surface and designated approximately 10 points per second. The marking was conducted so that the points would represent surface points on spheres (Fig. 1).
   Using a previously described algorithm, the geometrical center point for each sphere was calculated, representing the lateral and medial aspects of the transverse joint axis (Olivecrona et al., 2003). The isosurface representation of the prosthesis always contains some image artefacts due to the metal. If there was a mismatch between the prosthetic surface and a sphere, the position of the sphere was manually adjusted.
2. Longitudinal prosthetic axis. The humeral stem of both the Capitello-condylar and the Kudo prostheses appear curved in the sagittal plane. Definition of the longitudinal axis was based upon the fact that slightly more than half of the Kudo stem is straight, and that the Capitello-condylar is straight down to a

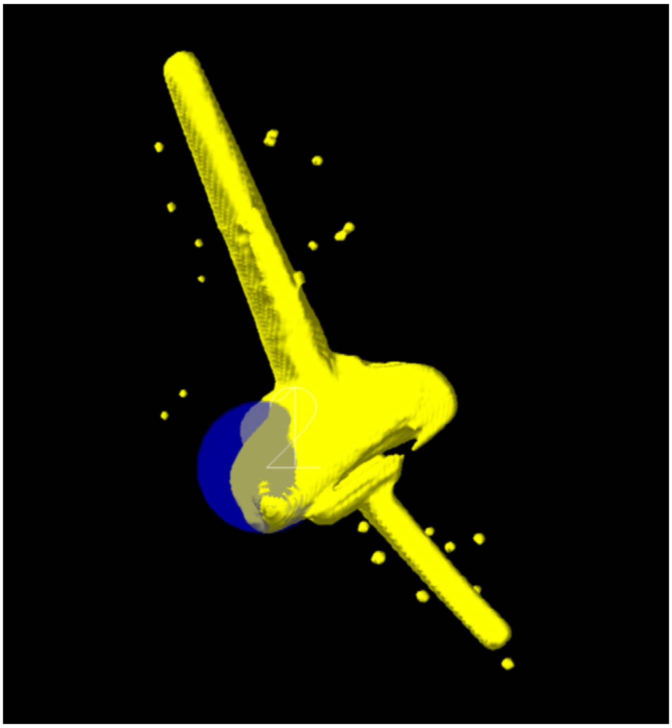

Fig. 1. CT volume showing the marking for the transverse reference axis of patient 1 (Kudo prosthesis). The RSA bone-embedded tantalum markers are clearly seen. The blue point cloud on the medial aspect of the prosthesis represents surface points on a sphere. The geometrical center point of this sphere defined the medial aspect of the transverse reference axis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bend just proximal to the condylar part. Using these known geometric features, geometrically correct longitudinal axes could be constructed. For the Kudo, surface marking in 3D on the proximal and distal aspect of the straight part of the stem was applied, using the computer pointing device as described for the transverse axis. The centers of the corresponding spheres were calculated, defining center-points in the stem. The longitudinal axis was determined to pass through these points and to be directed proximally. For the Capitello-condylar prosthesis three distal and three proximal points in the straight part of the stem were designated in the CT-volume using spheres placed around the stem. The weight-points of the proximal and distal group of center-points for these spheres were constructed and the longitudinal axis was determined to pass through these weight-points and to be directed proximally. Since this mode of calculating prosthetic axes was new, the marking procedure was repeated twice by the same observer for an indication of measurement reliability.

The mean values for the positions of the reference axes defined by this method were compared with the positions of the reference axes defined in the RSA coordinate system (Ericson et al., 2008), where the longitudinal axis of the humeral component was parallel to the *Y*-axis in the frontal and sagittal planes and the transverse axis, passing centrally through the condylar part, was parallel to the *X*-axis in the horizontal plane. To enable this comparison, the axes of the 3D CT prosthetic reference system were projected as global vectors on to an orthogonal coordinate system. As the form of the Kudo stem in its proximal part is conically narrowing towards the straight anterior aspect, the axis in the RSA study had a 2° ventral tilt compared to the definition used in this study.

The reference axes were also used for positioning the image of the elbow on the display. A plane including the longitudinal and transverse axes was coplanar to the screen in the frontal view. In the horizontal view the longitudinal axis was positioned perpendicular to the screen and the transverse axis parallel to the baseline of the screen (Figs. 2a, b).

3. Results

The prostheses could be visualized in the CT-volume with very few and minor artefacts. All tantalum markers could be identified in the CT volume and localized in the CT coordinate system. The kinematic data defining the instantaneous motion axes during flexion of the elbow were successfully superimposed on the CT volume and could be visualized in relation to the prostheses. The results of one patient (patient 1) with Kudo prosthesis are shown in Fig. 2a–c.

The global difference between the repeated positioning of the reference axes in the CT volume varied for the longitudinal axis between 0.4° and 0.6° for the Kudo and from 0.2° to 0.4° for the Capitello-condylar prostheses (Fig. 3). Corresponding values for the transverse axes varied from 0.4° to 2.0° and from 0.0° to 1.5°, respectively (Fig. 4). The differences between the longitudinal axes, when projected on the frontal (*XY*) and sagittal (*YZ*) planes and between the transverse axes projected on the frontal and horizontal (*XZ*) planes, are presented in the same figures. Projection of the longitudinal axis on the horizontal plane has not been presented as it is difficult to interpret and not required for coordinate system alignment. Similarly projections of the transverse axes on the sagittal plane were excluded.

The differences between the longitudinal reference axes as defined in the CT-volume and the axes in the RSA coordinate system varied in the frontal plane for the Kudo stem from 0.0° to 0.5° and for the Capitello-condylar stem from 0.4° to 2.1°. In the sagittal plane the differences varied between 0.6° and 2.4° and from 0.0° to 1.0°, respectively (Fig. 5).

The comparison between the CT and the corresponding RSA transverse reference axes is presented in Fig. 6. The differences varied between 0.3° and 3.5° for the Kudo prostheses and between 0.1° and 5.7° for the Capitello-condylar prostheses. No comparison of the transverse axes could be made in the frontal plane since the RSA axis was not defined in that plane.

4. Discussion

We have shown that it is possible to visualize elbow prostheses in a 3D CT volume with only minor artefacts. This clear visualization is a prerequisite for the positioning of landmarks in the prosthesis components. All of the tantalum markers around the joint could be detected in the CT volume. The RSA coordinates for the tantalum markers and the kinematic data for the flexion axes were successfully transformed to the CT coordinate system allowing visualization of the flexion axes relative to the prosthesis for each individual patient.

We have described a method for marking elbow prostheses in a 3D CT volume. The results of the two marking repetitions showed good reliability with differences less than 0.7° for the longitudinal axis, and less than 2.0° (in four out of six less than 0.8°) for the transverse axis. The differences between the first and the second positioning of the longitudinal axis projected on the frontal and sagittal planes were below 0.5° in both planes. The projections of the transverse axes on the frontal and horizontal planes showed differences less than 0.6° and 1.4° (in four out of six less than 0.6°), respectively. The slightly higher values for the transverse axes reflect the difficulty in designating landmarks on the condylar part of the component of the two prostheses models.

Coordinates for the longitudinal and transverse axes determined in the 3D CT volume could be transferred to the RSA coordinate system. The reference longitudinal axis in the RSA study coincided with the *Y*-axis in the frontal and sagittal planes. The RSA transverse axis was defined centrally through the condylar part of the prostheses and parallel to the *X*-axis in the horizontal plane. A comparison of the position of the CT axes relative to the RSA coordinate system gives an indication of the precision in prosthesis marking with fictive points in the RSA system. The differences between the two reference systems were greatest for the axes in the horizontal plane, which may reflect the

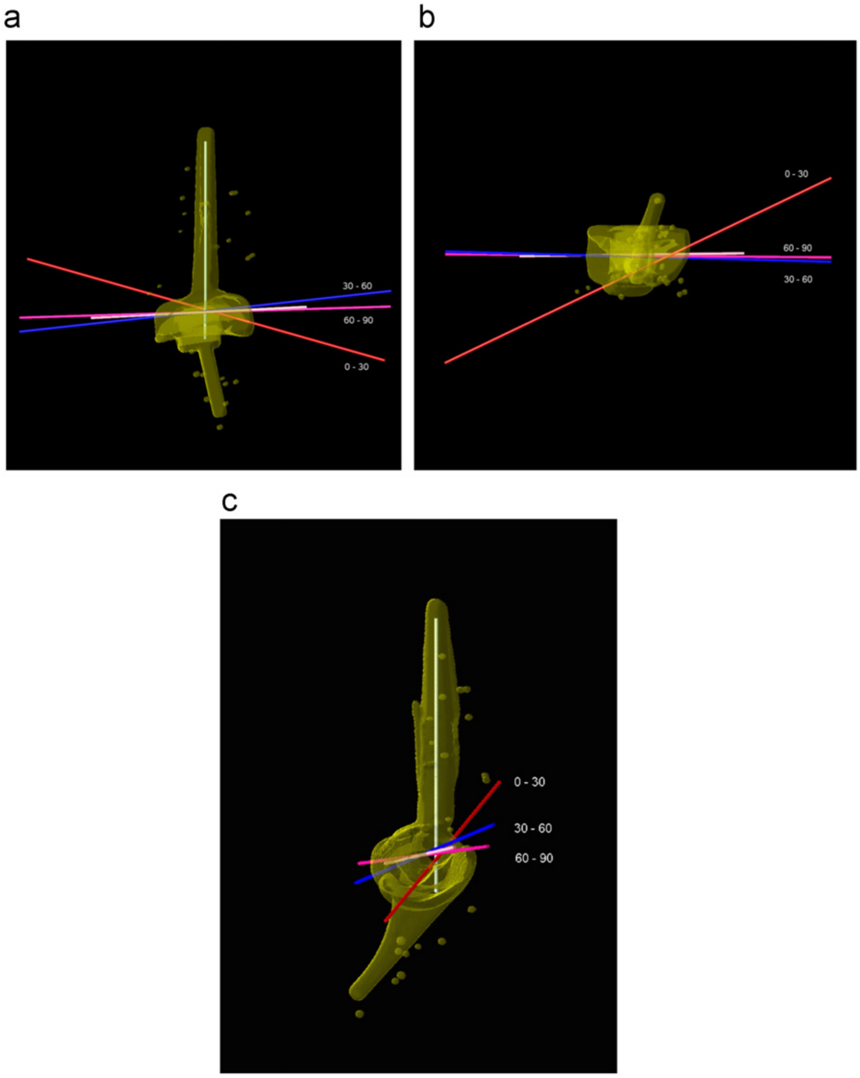

Fig. 2. CT volume of patient 1 showing the prosthesis (Kudo) with the longitudinal and transverse reference axes (white) together with the instantaneous flexion axes in a frontal (a), horizontal (b) and oblique (c) view. The flexion axes are marked red for 0–30°, blue for 30–60° and mauve for 60–90°. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

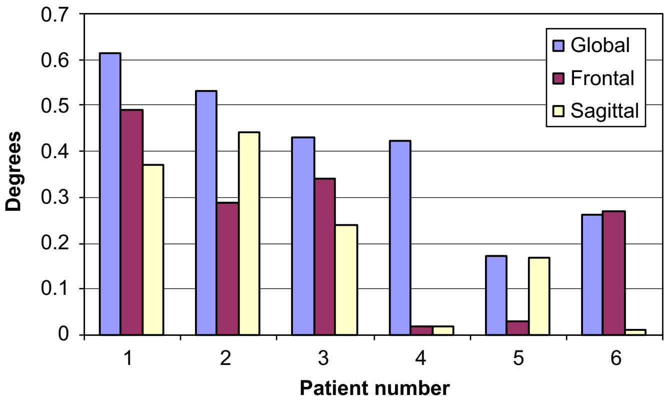

Fig. 3. The global difference (degrees) between the two positioning repetitions for the longitudinal reference axis and the differences for these axes projected on to the frontal (*XY*) and the sagittal (*YZ*) planes for each patient.

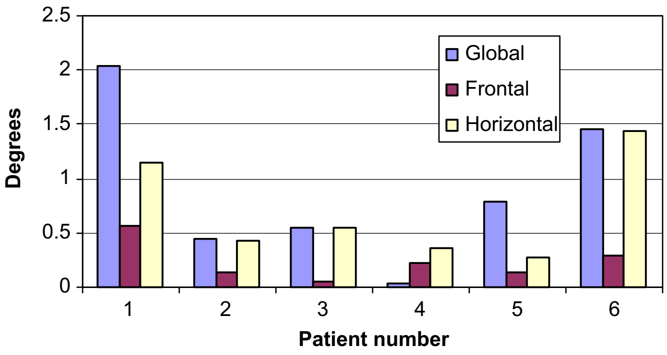

Fig. 4. The global difference (degrees) between the two positioning repetitions for the transverse reference axis and the differences for these axes projected on to the frontal (*XY*) and horizontal (*XZ*) planes for each patient.

difficulty in finding landmarks for positioning of fictive points especially on the condylar parts of the prosthesis. The differences between the two reference systems were less for the longitudinal axes. The higher values in the sagittal plane for the Kudo prostheses compared to those for the Capitello-condylar can be explained by the different definitions for the Kudo longitudinal axis by Ericson et al. (2008) and the present study. The axis constructed in the CT volume passes in the sagittal plane parallel to the ventral aspect of the stem. In the RSA study the axis was

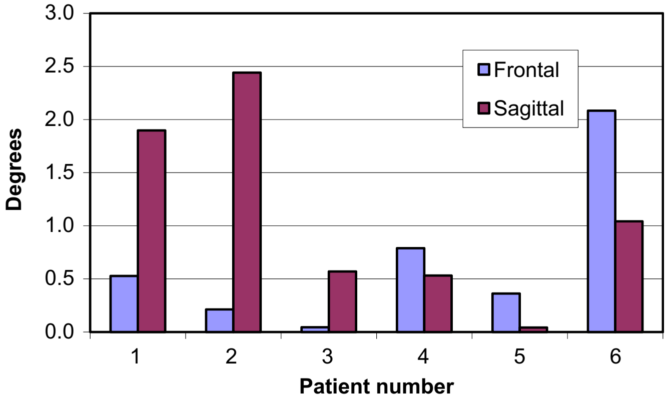

Fig. 5. The differences (degrees) between the 3D CT longitudinal reference axes (mean value of two positioning repetitions) and the RSA longitudinal reference axis projected on to the frontal (*XY*) and sagittal (*YZ*) planes.

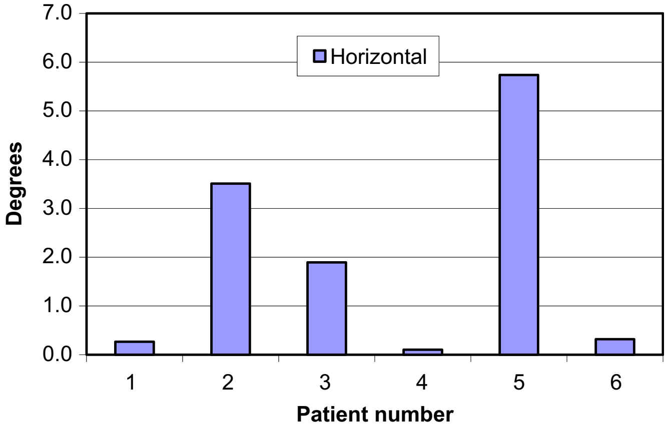

Fig. 6. The difference (degrees) between the 3D CT transverse reference axis (mean value of two positioning repetitions) and the RSA transverse reference axis projected on to the horizontal (*XZ*) plane.

defined to pass centrally through the whole length of the stem. The 2° difference in the ventral tilt between the two definitions explains the difference of approximately 2° between the RSA and CT longitudinal axes in the sagittal plane for patient 1 and 2 (Fig. 4).

Earlier *in vivo* studies of elbow kinematics after elbow joint replacement are sparse. Apart from the cited RSA study (Ericson et al., 2008) no other *in vivo* studies describing the variation of the positions and directions of the flexion axes were found in the literature. Other existing kinematic studies after elbow joint replacement have been conducted on cadaver elbows and have used an electromagnetic technique focusing on valgus/varus stability (An, 2005; King et al., 1994; Ramsey et al., 2003; O'Driscoll et al., 1992). This technique can also be used for determination of the position and orientation of flexion axes (Stokdijk et al., 2003), but these are usually presented as one average axis and do not reflect changes in the flexion axis positions throughout the motion arc. However, studies on cadaver elbows after elbow total joint replacement are limited by the absence of intact muscles and ligaments and can therefore not be directly compared to this *in vivo* study.

The electromagnetic technique has also been used to describe the mean optimal helical motion axes in the normal elbow *in vivo* (Stokdijk et al., 1999). The method has the advantage of being non-invasive, but considering that surface sensors have to be used and skin movements relative to the underlying elbow/prosthesis during movement can occur, the accuracy of the results is inferior to the use of bone anchored markers. In most of these electromagnetic studies the reference systems are not clearly defined and the method has the same disadvantage as RSA in that the exact position of the axes relative to bone or prosthesis cannot be determined. The electromagnetic technique, without bony anchoring, cannot be combined with CT to overcome this disadvantage.

No studies were found in which MRI has been used to study motion axes after joint replacements. It remains to be seen what advantages and disadvantages this modality may have.

In conclusion the results of this study show that it is possible to determine the position of the *in vivo* flexion axes in the elbow after total joint replacement by combining RSA with 3D CT data without diminishing the RSA accuracy. We have also proposed a method for marking the implant in 3D CT, with which a stable reference system can be generated within the prosthesis. By combining RSA and 3D CT a biomechanical *in vivo* analysis of different implants can thus be made. This is relevant for early assessment of new prosthesis. A precise implant marking and registration of reference axes enables comparison between patients and studies.

Conflict of interest statement

No author had any financial or personal relationships with other people or organisations that could inappropriately influence (bias) this work.

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