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ELBOW KINEMATICS: STUDIES OF THE ELBOW JOINT UNDER NORMAL CONDITIONS AND AFTER JOINT REPLACEMENT.

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Stockholm 2010

Published by Karolinska Institutet. Printed by Larserics Digital Print AB.

ISBN 978-91-7409-975-1

ABSTRACT

Background: Total elbow arthroplasty (TEA) is used for treatment of patients with severe pain and disability due to reumatoid arthritis. Long term results are not as good as for hip and knee replacements. Further development of the implant designs and surgical technique based on proper knowledge of the in vivo biomechanical joint properties are required to improve results.
Aim: To analyse the variation and the position of the instantaneous flexion axes in vivo in the normal elbow joint and after TEA.
Patients and Methods: Radiostereometric analysis (RSA) was used to determine the inclinations of the instantaneous elbow flexion axes in six healthy volunteers (study I) and in 13 patients with TEA (study III). Two of the implants were of a linked type (GSB III) and 11 were unlinked (five Capitellocondylar and six Kudo). Tantalum markers were implanted in the humerus and the ulna, defining two rigid bodies. Simultaneous radiographs were taken in maximum extension, 30, 60, 90, 120 and 150 degrees of flexion. The kinematic analysis defined the instantaneous flexion axes for each flexion increment and these were illustrated in standard drawings.
Computed tomography (CT) was used in study II and IV to determine and visualise the position of the flexion axes relative to the individual joint in 3D. A spiral CT scan of the elbow was performed on the same subjects as in study I and on six of the patients that participated in study III (three Capitellocondylar and three Kudo prostheses). A linear algebraic solution was developed for a conform transformation between the RSA and CT data. Stability parameters were generated during the transformation. The calculated coordinates for the intersect points of the axes lateral and medial to the joint could be imported from RSA and designated in the 3D volume. The positions of the flexion axes could be visualised individually for each subject and patient by connecting the intersect points.
Results: *Study I.* The range of the axis inclinations varied between subjects from 2.2º to 14.3º in the frontal and 1.6º to 9.8º in the horizontal planes. Mean axis inclination varied from 6,5º valgus to 6,2º varus, and from 2,4º internal to 2,2º external rotation.
Study II. The median error between the transformed RSA coordinates and the CT coordinates was 0.22 mm, the rotation error 0.001º-0.006 ºand the scaling factor 0.985-1.035. The kinematic data for the instantaneous flexion axes were successfully transformed to the CT volume and axis position could be visualised in the 3D volume.
Study III. The dispersion of axes varied for the unlinked prostheses from 4.1º to 84.3º (Kudo) and from 0.8º to 19.7º (Capitellocondylar) in the frontal plane. In the horizontal plane the dispersions varied from 3,3º to 45,0º and from 2,3º to 20,9º respectively. The two linked prosthesis (GSB) had axis dispersions of 13.0º and 15.4º in the frontal and 1,9º and 4,6º in the horizontal planes.
Study IV. The prosthesis could be visualised in the CT volume with few or minor artefacts. All markers could be indentified and localised in the CT coordinate system. The RSA data could be fused with the CT data and the flexion axes visualised for the individual prosthesis.
Conclusions: The use of RSA permitted determination of the inclination of the instantaneous elbow flexion axes in vivo in healthy volunteers and in patients after TEA. The proposed algorithm for fusion of RSA and CT data made it possible to also determine and visualise the 3D positions of the axes in the individual joint. As our proposed method for fusing RSA and CT data can be used in vivo in small series without further invasive technique, it can be of value for early in vivo assessment of new implants.

LIST OF PUBLICATIONS

This thesis is based on the following original papers. They are referred to in the text by their Roman numerals:

I. Ericson A, Arndt A, Stark A, Wretenberg P, Lundberg A.

Variation in the position and orientation of the elbow flexion axis.
Journal of Bone and Joint Surgery (Br). 2003;85(4):538-544.

II. Ericson A, Arndt A, Stark A, Noz ME, Maguire GQ, Zeleznik MP, Olivecrona H.

Fusion of radiostereometric analysis data into computed tomography space: Application to the elbow joint.
Journal of Biomechanics. 2007;40:296-304.

III. Ericson A, Stark A, Arndt A.

Variation in the position of the elbow flexion axis after total joint replacement with three different prostheses.
Journal of Shoulder and Elbow Surgery. 2008;17(5):760-767.

IV. Ericson A, Olivecrona H, Stark A, Noz ME, Maguire GQ, Zeleznik MP, Arndt A.

Computed tomography analysis of radiostereometric data to determine flexion axes after total joint replacement: Application to the elbow joint. Epub ahead of print. *Journal of Biomechanics* 2010 April 13. (doi:10.1016/j.jbiomech.2010.03.016)

CONTENTS

LIST OF ABBREVIATIONS

CT	Computed Tomography
3D	Three dimensional
FCR	Flexor Carpi Radialis
FCU	Flexor Carpi Ulnaris
FDS	Flexor Digitorum Superficialis
LCL	Lateral collateral ligament
LUCL	Lateral ulnar collateral ligament
MCL	Medial collateral ligament
MRI	Magnetic Resonance Imaging
PT	Pronator Teres
RA	Reumathoid arthritis
RSA	Radiostereometric Analysis
TEA	Total elbow arthroplasty

1 INTRODUCTION

The elbow serves as a fulcrum for the forearm and normal elbow function is essential for the positioning of the hand in space and to provide power and stability. Conditions leading to pain and stiffness of the elbow can therefore lead to seriously impaired function with inability to perform even ordinary self-care.
Deficiency of the elbow is often due to rheumatoid arthritis (RA), an inflammatory disease of autoimmune genesis with articular manifestations. Combined activity of different inflammatory mediators causes synovites in the affected joints, that eventually can result in both cartilage and bone damage. The prevalence of RA has been estimated between 0,5–1% of the adult population in Northern Europe and North America, with a mean annual incidence of 0,02–0,05% (Alamanos, et al., 2005). In a prospective study on the incidence of elbow involvement in RA it was shown that almost 2/3 of the patients had involvement of the elbow joint after 15 years follow up (Lehtinen, et al., 2001).

Total elbow arthroplasty (TEA) is today an established procedure for treatment of patients with severe pain and disability due to RA. It is also, though less frequently, used for treatment of comminute fractures of the distal aspect of the humerus in elderly patients and for treatment of posttraumatic arthritis. As degenerative osteoarthritis of the elbow is a relatively uncommon problem compared to the hip and knee joints, the number of patients treated with TEA is comparatively few (Rydholm, 2002). The Swedish Elbow Arthroplasty Register reports about 100 arthroplasties/year in Sweden (personal communication). A study on RA-related surgery of the upper limbs showed that though RA-related upper limb surgery decreased in Sweden during 1998-2004, the occurrence of TEA has been stable (Weiss, et al., 2008).

Both unlinked and linked (i.e. hinged), prostheses are used for primary replacements. Unlinked prostheses require preserved bone stock and intact soft tissues to provide stability, whereas indication for a linked implant can also include patients with severe bony destruction and deficient ligament support. If preoperative instability exists, only linked prostheses can be used.

Long term results after TEA have gradually improved but are not as good as for hip and knee replacements. An extensive review on studies of elbow arthroplasties (Little, et al., 2005) showed an overall revision rate of 13% and 9% loosening. The reported revision rate was slightly higher for the unlinked prostheses as compared to the linked. However, the linked prostheses had a higher rate of radiolucencies. In a population-based study from the Finnish Arthroplasty Register the 10-year survivorship after TEA was 83% (Skyttä, et al., 2009). A summary from the Norwegian Arthroplasty Register 2009 reported an 8% revision rate after five years and 15% after 10 years with only minor difference between different implants (Fevang, et al., 2009).

Many of the prosthesis models today available have been modified without proper knowledge of the elbow in vivo biomechanical properties, and there is no consensus on which type of prostheses that should be used for a primary TEA. Prosthesis survival may apart from the surgical technique depend on how well the design of the implant addresses the demands of the joint with respect to normal kinematic characteristics.

Cadaver studies with different total elbow replacements report increased joint laxity compared to the intact elbow (Herren, et al., 2001; An, 2005). The comparatively high degree of loosening might be due to a changed elbow flexion axis post-operatively, causing high rotational stress at the bone- cement interface.
Improved results need further development of implant designs and surgical technique based on proper knowledge of the biomechanical joint properties in the normal, as well as in the replaced elbow in vivo.

The general aims of this thesis were:

- To analyse the variation of the flexion axes and their positions relative to anatomical landmarks in vivo.

- To analyse the variation of the flexion axes and their positions relative to the prosthesis after different elbow prostheses in vivo.

2 OVERVIEW OF ELBOW ANATOMY AND BIOMECHANICS

In biomechanics mechanical principles are applied on organic systems. In musculoskeletal biomechanics dynamic and static loading (kinetics) and motion (kinematics) are studied relative to joint anatomy. Following is a summary of the elbow anatomy and the present state of biomechanical knowledge concerning elbow motion.

2.1 ANATOMY

2.1.1 Osseous anatomy

The elbow joint consists of three articulations within the same joint capsule: the ulnohumeral, the radiohumeral and the proximal radioulnar joints. The ulnohumeral joint consists on the humeral side of the sandglass shaped trochlea, centred in line with the humeral long axis and projecting more distally on its medial side. On the ulnar side the trochlea articulates with the greater sigmoid notch. A ridge passing sagittally in this notch fits into a groove in the trochlea and contributes to a high degree of inherent osseous stability of the joint.

The radiohumeral joint is of the ball and socket type, the ball consisting of the hemispheric-shaped capitellum on the humeral side and the socket of the concave surface on the radial head. The rim of the radial head and the lesser notch of the ulna form the proximal radioulnar joint, allowing supination and pronation of the forearm (Morrey, 1993).

An anatomical transverse axis (not to be mistaken for the kinematic flexion axis) that passes centrally through the trochlea and the capitellum is tilted in valgus with 6-8º in the frontal plane due to the shape of the trochlea. In the horizontal plane, this axis is internally rotated with 5–7º relative to an axis through the epicondyles (Fig 1.). In the sagittal plane the articular surface of the humerus is rotated about 30º ventrally relative to the long axis of the humeral shaft, with the anatomical transverse axis in line with the ventral cortex (Morrey, 1993).

The shaft of the ulna has about 4º valgus angulation relative to the ridge in the greater sigmoid notch and the shaft of the radius approximately 15º valgus angulation relative to the radial neck. These anatomical features, together with the valgus tilt of the anatomical transverse axis trough the humeral condyles, account for the carrying angle of 12–15º of valgus in elbow extension (Morrey, 1993).

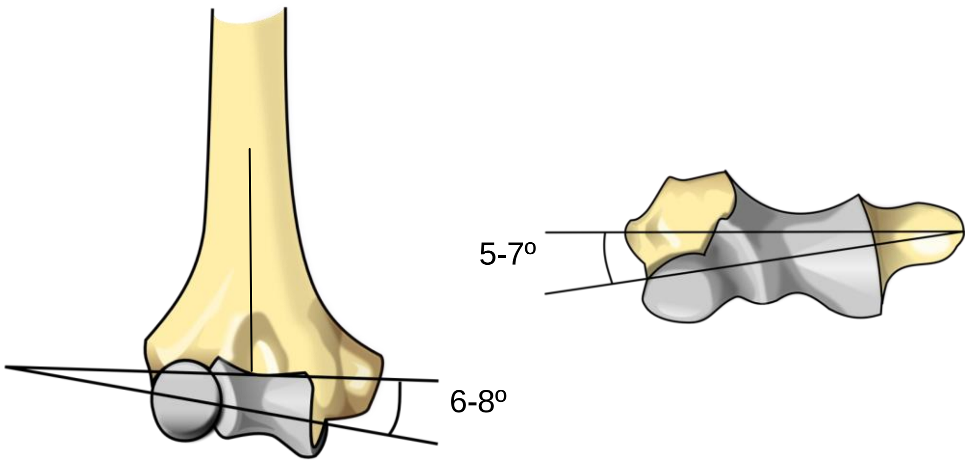

Figure 1. Illustration of the distal humerus, including the inclination of the anatomical transverse axis. **Left:** Frontal view. **Right:** Horizontal view.

2.1.2 Joint capsule

The joint capsule attaches anteriorly just proximal to the radial and coronoid fossae and distally to the anterior margin of the coronoid process. Posteriorly it attaches proximally to the olecranon fossa and distally along the margins of the greater sigmoid notch. On the lateral side the capsule blends with the fibers of the annular ligament. The anterior capsule is strengthened by oblique fibrous bands from the medial side of the trochlea and from above the capitellum on the lateral side (Morrey, 1993).

2.1.3 Ligaments

The medial collateral ligament complex (MCL) consists of three bundles: the anterior, the posterior and the transverse bundle. The anterior and posterior bundles originate under the anterioinferior aspect of the medial epicondyle. The anterior bundle, which is the most distinct structure of the three, inserts at the medial surface of the ulnar coronoid process. The posterior bundle is a thickening of the posterior capsule, inserting on the medial margin of the sigmoid notch. The third component of MCL, the transverse bundle, passes along the medial side of the sigmoid notch, from the olecranon to the coronoid process and does not span the joint (O'Driscoll, 1992; Morrey, 1993; Floris, et al., 1998; Safran, et al., 2005).

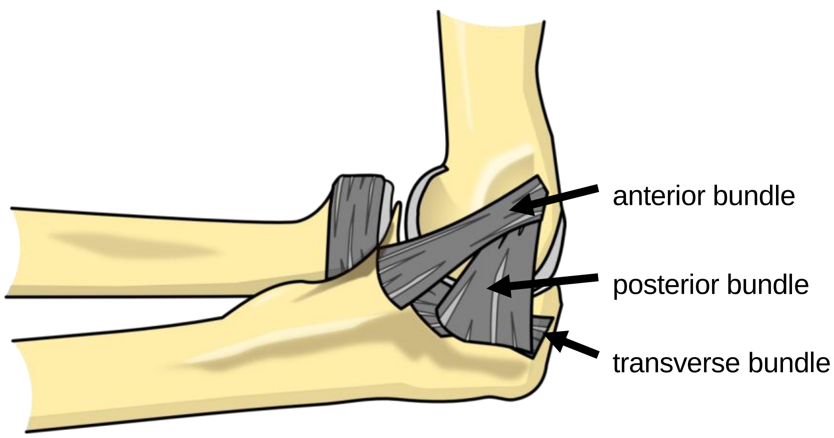

Figure 2. The medial collateral ligament complex.

There is a greater variety in the anatomical pattern of the lateral ligament complex (LCL). It originates on the lateral epicondyle and consisting of four components. The radial collateral ligament is the most anterior part and terminates on the annular ligament. The lateral ulnar collateral ligament (LUCL) passes superficially to the annular ligament and inserts on the ulnar tubercle of the supinator crest. The accessory collateral ligament consists of fibers passing from the annular ligament to the crista supinatorius, further stabilising the annular ligament (Morrey, 1993; Olsen, et al., 1996; Safran, et al., 2005).

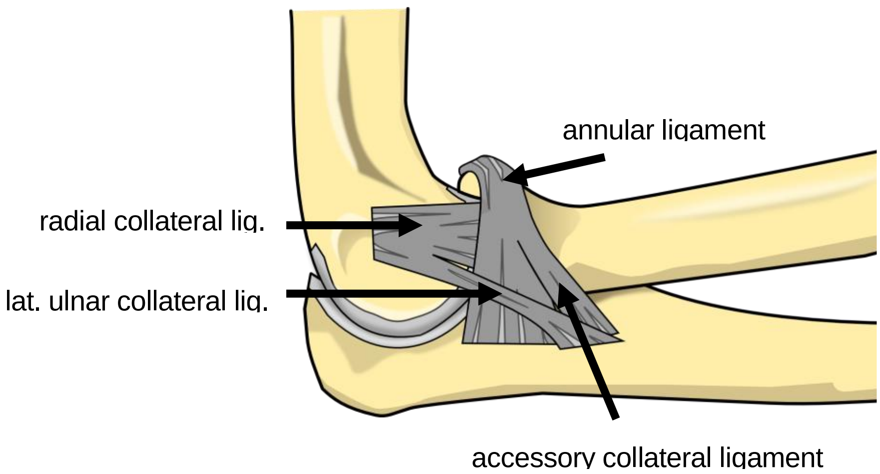

Figure 3. The lateral collateral ligament complex.

2.1.4 Muscles

The major elbow flexors are the biceps, brachialis and brachioradialis muscles. The brachialis muscle inserts on the coronoid and the tuberosity of the ulna. The biceps covers the brachialis and ends in a tendon inserting at the radial tuberosity, and in an aponeurosis that runs obliquely to the medial side, inserting into the deep fascia of the forearm and the posterior margin of the ulna. In a pronated position the biceps thus also supinates the forearm together with the supinator muscle that originates on the lateral epicondyle. The brachioradialis originates on the lateral supracondylar ridge of the humerus and inserts on the distal radial aspect of the radius.
Extension of the elbow is provided by the triceps muscle that insert on the olecranon and the anconeus muscle, originating on the posterior aspect of the lateral epicondyle and inserting proximally on the lateral dorsal surface of the ulna (Morrey, 1993).

The flexor pronator muscle group, originating on the anterosuperior and anteroinferior aspects of the medial epicondyle of the humerus, consists of the pronator teres (PT), the flexor carpi radialis (FCR), flexor carpi ulnaris (FCU) and flexor digitorum superficialis (FDS) muscles. Although the muscles of the flexor pronator group chiefly contribute to pronation of the forearm, finger and wrist flexion, the PT, FCR and FDS also contribute to elbow flexion. FCU has its origin posterior to the anatomical transverse axis of the elbow and hence does not contribute to elbow flexion (Morrey, 1993).
The muscles originating on the lateral aspect, the extensor supinator group, consist of the long and the short extensor carpi radialis muscles, the extensor digitorum communis, the extensor carpi ulnaris and one head of the supinator muscle. The extensor carpi radialis longus originates on the supracondylar ridge of the lateral

humerus, just distally to the brachioradialis muscles, and can act as a week elbow flexor. The rest of the muscles in the extensor group do not contribute to the elbow flexion/extension (Morrey, 1993).

2.2 BIOMECHANICS

2.2.1 Range of motion

Due to a high degree of osseus congruity and strong collateral ligaments, the ulnohumeral joint acts like a hinge joint, allowing flexion and extension with a range of motion of approximately 0°-140°. The radiohumeral and radioulnar joints are functionally of the trochoid type. Since movement of the radius is coupled to the ulna through the annular ligament, a sliding movement of the head of the radius occurs on the capitellum during flexion/extension, and axial rotation on the lesser sigmoid notch during supination/pronation. The normal range of pronation is about 80° and supination about 90° from a neutral position. A range of approximately 30º-130º in flexion and a forearm rotation of about 50º of supination and 50º pronation have been shown to be needed to accomplish activities of daily living (Morrey, 1993).

2.2.2 Stability

Stability of the elbow is dependent on static and dynamic stabilizers. Static stability is apart from the congruous anatomy of the bony articulations provided by the medial and lateral ligament complexes. Dynamic stability is provided by the muscles as they compress the joint. According to Morrey (1993), stability is also provided by the anterior capsule, when taught in extension. The role of the capsule is however not clear. Isolated release of the anterior or the posterior capsule did not lead to instability according to recent studies (Dos Remedios, et al., 2003; Nielsen, et al., 1999).

Elbow stability has been studied in vitro by sequential sectioning of the soft tissues around the joint. Constraint to valgus and internal rotational stress is provided primarily by the medial collateral ligament complex (MCL) and secondarily by the radial head. The anterior bundle has been shown to be of major importance, the fibres being taught during the whole flexion arc. Absence of the radial head with intact ligaments on the medial side did not significantly increase the laxity, while a concomitant sectioning of the MCL resulted in apparent instability, (Morrey, et al., 1991). The posterior bundle of the ligament is taught in 60º-90º of elbow flexion and has been shown to be a secondary stabiliser to valgus instability together with the radial head (Regan, et al., 1991; Safran, et al., 2005).

The lateral collateral ligament complex (LCL) is taught throughout the flexion arc and has been shown to be a primary elbow constraint to varus and external rotational stress. However, the exact role of the different parts of the LCL is not clear. Lesion to the ulnar part of the complex, LUCL, has in earlier studies been estimated to have a major role to prevent posterolateral rotational instability (O´Driscoll, et al., 1991; O´Driscoll, 1999), while later studies indicated that all parts of the LCL act as one functional unit and that the entire LCL must be sectioned to produce gross instability (Olsen, et al., 1996; Dunning, et al., 2001). LUCL has also later been shown to function in unison with the annular ligament (Takigawa, et al., 2005).

The flexor pronator and the extensor supinator groups contribute both to valgus and varus stress and dynamic stability. The flexor group contributes to valgus stability especially in supination and the extensor group to varus stability with the forearm pronated (Seiber, et al., 2009). Of all muscles around the joint, the flexor pronator group has been the object for most studies, and of the muscles included in the group FCU has been shown to function as a primary dynamic stabiliser to valgus stress (Park, et al., 2004; Lin, et al., 2007).

2.2.3 Motion axis

Flexion and extension of the elbow is referred to as rotation of the olecranon round the trochlea of the humerus. From the conception of a stationary axis coinciding with the anatomical transverse axis and passing centrally through the trochlea (Morrey & Chao, 1976; London, 1981), later studies have indicated that the axis is not fixed but changes in position and orientation throughout the flexion arc (Stokdijk, et al., 1999; Bottlang, et al., 2000; Duck, et al., 2003).

3 TOTAL ELBOW ARTHROPLASTY

Development of TEA started in the 1960´s with custom made hinged prostheses that required extensive resection of bone around the joint. Although the initial results in form of pain relief were good, there were considerable problems with early loosening (London, 1993). Prosthesis development has proceeded according to two different principles: from simple resurfacing devices to stemmed unlinked prostheses and from fixed linked to sloppy hinged prostheses (Goldberg, et al., 1988; van der Lugt, et al., 2004; Trigg, 2006).

While the rate of aseptic loosening is similar for both types, a major concern with the unlinked prostheses has been instability and luxation. For the linked implants wear of the coupling mechanism has been a problem (Rydholm, 2002). Apart from the fundamental difference between the linked and unlinked prostheses there are several factors that can have an impact on the pattern of elbow motion and the results after TEA.

The bearing surface of the components of the unlinked prostheses

Kinematically, the unlinked prostheses could be expected to be constrained to a different degree due to the shape of the bearing surfaces of the components, which to a different degree replicate the anatomy of the normal joint. Examples of unlinked prostheses are the Kudo (Howmedica) and the Capitellocondylar (Johnson & Johnson) prostheses. The Kudo has a smooth surface, which in the coronal plane allows a certain sideways gliding between the ulnar and the humeral components, whereas the Capitellocondylar prosthesis is aimed to mimic the normal anatomy and therefore could be expected to be the more constrained of the two.

The coupling mechanism of the linked prostheses

Examples of linked prostheses are the GSB III (Zimmer), the Coonrad/Morrey (Zimmer) and the recently introduced Discovery (Biomet). The sloppy hinge of the linked implants permits a certain movement in valgus/varus and in axial rotation. This is supposed to reduce the stress on the interfaces between cement and bone. The design of the hinge differs between the prostheses models. The coupling of the GSB III is set at 90º to the hinge, while the hinge in the other models also constitutes the coupling. Hinge construction may influence the resulting mobility/stability and final outcome.

The inclination between stem and bearing surface of the components

In order to adapt to the normal anatomy of the humerus and ulna the prostheses have different degrees of inclination of the bearing surface relative to the stem of the components. Both the Kudo and the Capitellocondylar prostheses have an inbuilt 5° valgus tilt of the humeral component. Some of the linked prostheses have the humeral stem set perpendicular to the hinge mechanism, as is the case with the GSB III and Coonrad/Morrey prostheses.

Most prostheses have ulnar stems that to a varying degree are inclined in a radial direction relative to the bearing surface. The GSB III on the other hand is an example where the ulnar stem is set in 90º of angulation relative to the hinge, and aligned with the humeral stem. Finally, the bearing surfaces of the humeral component have differing degrees of ventral inclination (offset) in relation to the humeral long axis.

Surgical technique

Another factor that could be expected to have an impact on the resulting motion pattern after TEA is the surgical technique. Recommendations concerning the degree of soft tissue release differ, as do the recommended degree of rotation of the humeral component. The humeral component of the Kudo prosthesis, for instance, has been recommended to be inserted in a neutral rotation, whereas that of the Capitellocondylar should be placed in about 5º of internal rotation.

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4 SPECIFIC AIMS

Study I

To analyse the variation and position of the axes of rotation during flexion in the normal elbow under muscle load in vivo.

Study II

To propose a method to visualise the position of rotation axes relative to well defined bony landmarks in the individual elbow joint in vivo.

Study III

To analyse the variation and position of the axes of rotation during flexion after TEA with different prostheses in vivo.

Study IV

To visualise the position of the motion axes relative to the elbow prostheses and to define a prosthesis based reference system in 3D.

5 OVERVIEW OF METHODOLOGY

5.1 SUBJECTS AND PATIENTS

5.1.1 Study I and II

Three women and three men took part in the first and the second study. The mean age at the time of the first study was 33 (25-42) years, and at the time of the second investigation 43 (34–47) years. All subjects were healthy and free from musculoskeletal disorders with a normal range of movement and no previous elbow trauma. The non-dominant elbow was examined, which for all subjects was the left one. One of the subjects had to be excluded in study II due to one unstable RSA marker.

5.1.2 Study III and IV

Sixteen patients with RA, who due to severe pain and impaired function of the elbow had been scheduled for TEA, were invited to participate in the study. All except one patient were females. Classification of elbow arthritis was according to the Mayo classification of rheumatoid involvement of the elbow (Inglis & Figgie 1993). The score has four radiological grades: Grade I = no radiological changes, grade II = joint narrowing, grade IIA = moderate architectural changes, grade IIIB = severe architectural changes and IV = gross destruction.
At the time of the study, unlinked Kudo and Capitellocondylar elbow prostheses were commonly used in Sweden. Patients with a stable elbow joint (varus/valgus laxity clinically less than 10º in the frontal plane) were allocated for either of the two implants, resulting in eight patients with a Kudo and six with a Capitellocondylar prosthesis. Two patients with unstable elbow joints preoperatively, were operated with the linked endoprosthesis GSB III. Mean age at surgery was 56,8 (29-79) years in the Kudo group and 51,8 (41-68) years in the Capitellocondylar group. The two patients with GSB prostheses were 77 and 79 years respectively.
Two of the patients with the Kudo and one with the Capitellocondylar prosthesis had to be excluded from the analysis due to some RSA markers being obscured by the prosthesis in the radiographs. For further patient details see table 1.

All surgical procedures were performed by the same two surgeons. All operations were done with a posterior approach releasing the triceps as a distally based flap. If still present, the radial head was excised. Release of the soft tissues was only performed to an extent allowing adequate preparation for insertion of the components. All components were cemented, except for the humeral components of the Kudo prostheses, in which case the porous coated component for cementless fixation was used. A dorsal plaster splint was used for two weeks postoperatively to protect the wound, whereupon mobilisation was permitted under supervision of a physiotherapist. The patients with the unlinked prostheses wore an articulated orthosis for another four weeks to protect the elbow from valgus/varus load until the soft tissues were healed.

The eleven patients with unlinked prostheses analysed in study III were chosen to participate in study IV. At the time of the this study one of these patients was deceased and four patients declined participation due to health reasons, which left six patients, three with a Kudo and three with a Capitellocondylar prosthesis. The CT scan for study IV was performed 63,7 (mean value) months after the operation.

Prosthesis	Patient	Age	Gender	Side	Classification	RSA	CT
Kudo	1*	34	F	L	II	3	88
	2	79	F	R	IIIA	16	
	3*	29	F	R	IIIA	9	79
	4	56	F	R	IIIA	28	
	5	77	F	L	IV	4	
	6*	66	F	R	II	7	37
Mean		56,8				11,2	68
Capitello	7*	68	F	R	IIIA	3	67
	8	41	F	R	II	4	
	9*	46	F	R	IIIA	4	56
	10*	46	F	R	II	4	55
	11	58	F	L	II	3	
Mean		51,8				3,6	59,3
GSB III	12	74	M	L	IV	7	
	13	77	F	R	IIIA	12	
Mean		75,5				9,5	63,7

Table 1: Patient details study III and IV. Age (years) at time of operation, gender (F=female, M=male), operated side (R=right, L=left), radiological classification, time between operation and RSA investigation (months) and time between operation and CT-scan (months). Patients furnished with an asterisk took part in study IV.

5.2 RADIOSTEREOMETRIC ANALYSIS (STUDIES I AND III)

Kinematics is the science analysing movements between bodies. A body’s position and orientation can be described by discrete points, that mathematically can be determined through coordinates (x, y, z) related to an orthogonal coordinate system. For a rigid body at least three points are needed and the positions of the points must be invariable. When rotation occurs between two rigid bodies (e.g. skeletal segments) a line on which the distance to all points are consistent throughout the movement defines the rotation axis.

For the kinematic analyses of study I and III, radiostereometric analysis (RSA) was used. In RSA the points defining the rigid body consist of bone anchored radio-opaque 0.8 or 1mm diameter tantalum markers and movements can be registered with repeated radiographs. RSA was developed by Selvik (Selvik, 1989). The method has been widely used, predominantly for measurement of migration of hip and knee endoprostheses in order to detect early loosening. It was also used in a series of kinematic studies to determine the axes of rotation of the ankle joint (Lundberg, et al., 1989).

The RSA procedure (UmRSA software, RSA Biomedical, Umeå, Sweden) was conducted as follows. In study I (healthy volunteers), four to six radio-opaque tantalum markers (diameter 0.8mm) were percutaneously implanted into the cortical bone of the distal humerus and the proximal ulna under local anaesthesia with the use of a spring-loaded injector. The markers were implanted on the radial side to avoid interference with the ulnar nerve. There were no complications though some subjects experienced moderate pain in the elbow the subsequent one to two days. No persistent symptoms were reported.
In study III (patients) the tantalum markers were implanted around the joint and in the marrow bone of the humerus and ulna peroperatively, prior to insertion of the implant.

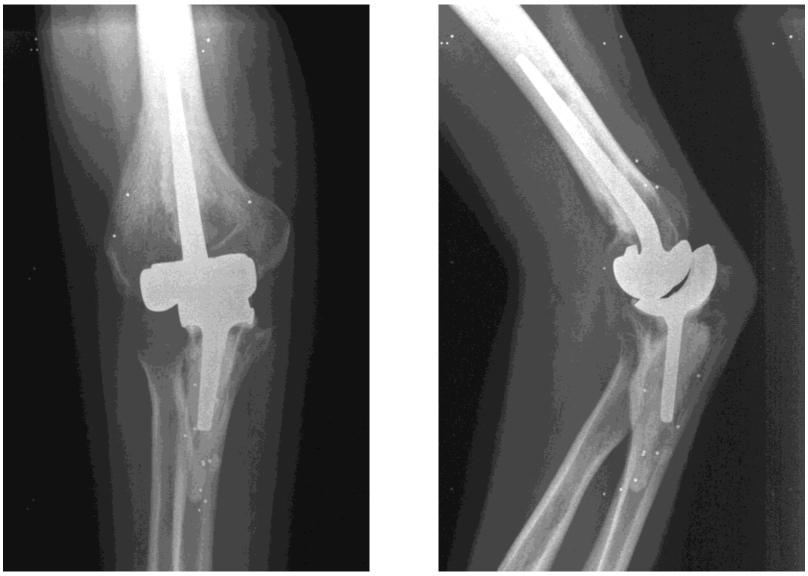

Figure 4. Radiograph of an elbow with a Capitellocondylar prosthesis and tantalum markers. **Left:** Frontal view. **Right:** Sagittal view.

The radiological examination for RSA was performed a minimum of three months after marker insertion (study I) or TEA (study III) to avoid influence of pain and stiffness. The subjects and patients held their elbow in a plexiglass calibration cage (Fig. 5). The cage was equipped with markers imbedded with a high degree of precision in the plexiglass (positional accuracy 0,001mm). These markers defined a global laboratory coordinate system. The cage was also equipped with two perpendicular film cassette holders. Simultaneous biplanar anteroposterior and mediolateral radiographs were taken while the elbow was actively held in maximum extension and in 30, 60, 90, and where possible 120 and 150 degrees of flexion (Fig. 5.). Elbow position was determined by a surface goniometer. The number of exposures in study III varied as a result of limitations in the range of motion of some patients.


Figure 5. Left: Picture of the calibration cage with film cassettes. **Right:** Subject seated with the elbow held in the calibration cage and X-ray tubes to the left and above.

The positions of the cage and bone anchored markers were determined in digitised images of the radiographs. The 2D positions on each radiograph were determined and the 3D positions of the markers defining the humeral and ulnar rigid body segments were calculated according to the laboratory coordinate system (UMRSA analysis software, RSA Biomedical, Umeå, Sweden).
The motion between the rigid body segments representing the humerus and the ulna could then be calculated using the 3D positions from the examinations in different degrees of elbow flexion. The ulna was chosen as the rotating segment and the humerus as the fixed segment.

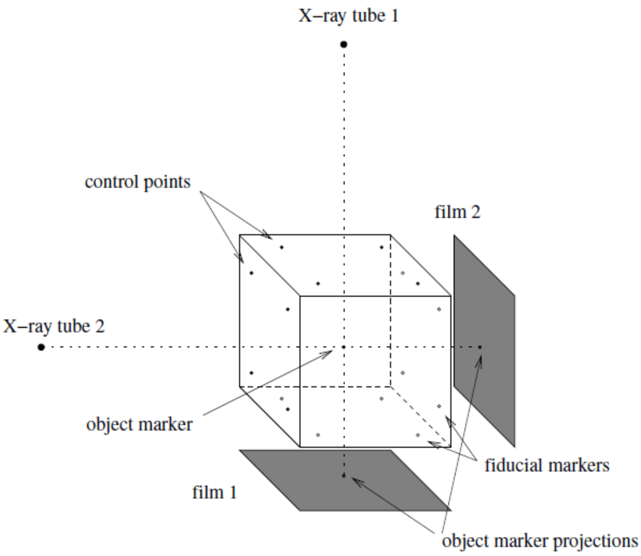

Figure 6. A schematic figure of the calibration cage used in RSA. Fiducial markers and control points are the markers imbedded in the plexiglass and define the laboratory coordinate system. Object markers are the tantalum markers imbedded in the bony segments. From Börlin, 2000. Model-based measurements in digital radiographs. PhD thesis, Umeå University, Sweden. With permission.

A longitudinal axis of the humerus, defined by fictive points manually marked on the radiographs in the centre of the distal third of the humerus as seen in the frontal and sagittal planes (Y-axis), and a transverse axis passing centrally through the arcs of the trochlea and the capitellum defined the reference coordinate system in study I. The longitudinal humeral axis in study III was defined by fictive points marked in the centre of the humeral shaft of the prosthesis components (Y-axis) and the transverse axis by the centre of the arcs of the medial and lateral side of the condylar part of the humeral component. In both studies, the Y-axis was aligned with the corresponding Y-axis in the calibration cage coordinate system and the transverse axis was aligned with the calibration system X-axis in the horizontal plane.

The kinematic analysis could then be conducted to define the instantaneous flexion axes from the 3D positions of the segments from the different examinations.
Based on the calculated axes´ intercept points lateral and medial to the joint, the axes could be illustrated in standard drawings representing the humerus (study I) and the different prostheses (study III).

5.3 COMPUTED TOMOGRAPHY (STUDIES II AND IV)

RSA provides accurate information about motion axes and their related inclinations, but does not relate the axes to anatomical landmarks in the individual joint with the same degree of accuracy.

Advances in computed tomography (CT) techniques have made it possible to suppress metal artefacts facilitating the localisation of metal bodies within bone, and can offer a spatial resolution well below 1mm without significant distortion. Furthermore, 3D data of designated points can be visualised in a 3D volume. Current techniques also allow volume fusion of multiple sets of data, either from the same or from different modalities for display and other analysis.
In studies II and IV this CT 3D technique was further developed in order to visualise the positions of elbow motion axes in a 3D volume. For this purpose the subjects in study I and the patients in study III underwent a spiral CT scan of the elbow.

The tantalum markers were first localised in the 3D volume and the coordinates for the centres of the markers in the 3D volume registered by super-imposing a sphere over the marker in three orthogonal views simultaneously (Fig. 7.).
The coordinates for the co-homologous markers in the RSA studies were then imported to the CT volume and the coordinates for each marker were graphically evaluated by visually confirming its placement relative to the marker in the CT volume. For evaluation of the reliability in localising the tantalum markers three of the subjects underwent a second CT scan and the same observer localised the markers.

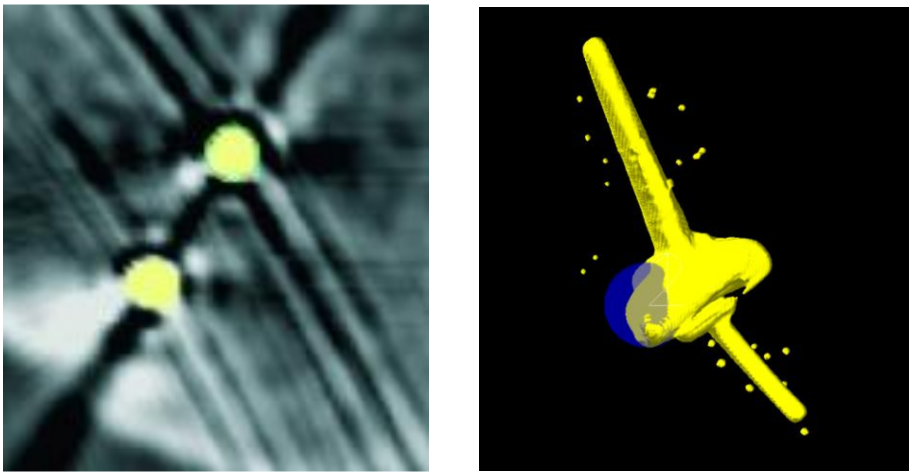

Figure 7. Illustration of the marking modes in the CT volume. **Left:** Tantalum marker with a superimposed sphere (green line). The centre of the sphere determines the CT coordinates. **Right:** CT volume of a Kudo prosthesis. The blue cloud represents surface points on a sphere. The transverse axis passes through the geometrical centre point of the sphere.

A linear algebraic solution was developed for a conform transformation between the RSA and CT data. A conform transformation is composed of a translation of data followed by rotation and scaling. Stability parameters providing an indication of the robustness of the rigid body segments were generated during the transformation. The RSA data for the intersect points of the instantaneous flexion axes laterally and medially to the joint was imported to the 3D volume and the axes could be visualised by connecting the intersect points.

The CT volume can be rotated arbitrarily. For screen presentation of the elbow a 3D reference axis system was required. In study II a transverse axis was determined to pass through the most prominent point of each epicondyle. A longitudinal axis was defined to pass the centre of the humeral head and the midpoint of the transepicondylar line. In study IV, a reference system based on the humeral component was constructed. For the transverse prosthetic axis, the medial and lateral aspects of the bearing surface of the component were marked with multiple surface points. The marking was conducted so that the points would represent surface points on spheres (Fig. 7.). The transverse axis was determined to pass the centre point for each sphere.

For the Kudo, the longitudinal axis was constructed through surface marking on the proximal and distal aspect of the straight, rectangular part of the stem. The longitudinal axis was determined to pass through the centres of the corresponding spheres. For the Capitellocondylar prosthesis, three distal and three proximal spheres were placed around the conical part of the stem. The longitudinal axis was determined to pass through the weight-points of each group of spheres. Since this mode of calculating prosthetic axes was new, the marking procedure was repeated twice 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 in study III.

6 RESULTS AND DISCUSSION

6.1 STUDY I

6.1.1 Results

- The instantaneous axis inclinations varied between subjects within a range from 2,2º to 14,3º in the frontal and from 1,6º to 9,8º in the horizontal plane.

- The axes oscillated around the anatomical axis that passes centrally through the arcs of the capitellum and trochlea both in a frontal and horizontal plane.

- Mean axis inclination varied between subjects from 6,5º valgus to 6,2º varus in the frontal plane, and from 2,4º internal rotation to 2,2º external rotation in the horizontal plane.

- The inclination of the axes did not vary in a regular way. The intercept points of the axes in a sagittal plane lateral to the joint showed both a clockwise and anti-clockwise progression.

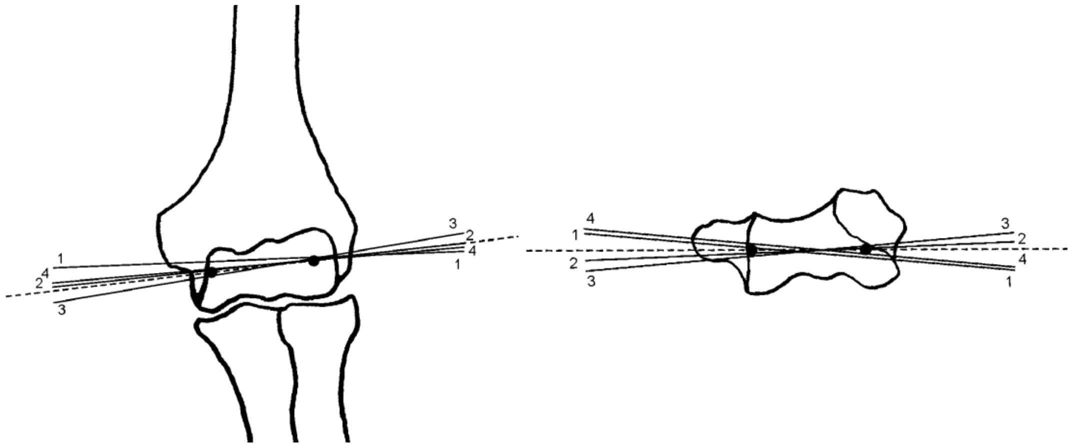

Figure 8. Illustration of the instantaneous flexion axes for one subject. Dotted line represents the anatomical transverse axis. **Left:** Frontal view. **Right:** Horizontal view.

6.1.2 Discussion

There are few earlier studies describing the variation of the elbow motion axes through the flexion arc. Compared to the previous studies, our results showed greater variations both in the inclinations of the instantaneous flexion axes and the calculated individual mean axes. In the only in vivo study prior to ours, Stokdijk, et al., (1999) used an electromagnetic technique to show dispersions of about 5º in thee instantaneous axes during flexion. In a cadaver study, Bottlang, et al., (2000), reported a variation of the axis inclinations of about 2,6º in the frontal and about 5,7º in the horizontal planes. Tanaka, et al., (1998) applied varus and valgus stress during induced motion on cadaver specimens and found that the direction of the axis changed 1,2º- 4,0º in the valgus and 1,2º-2,0º in the varus direction. On the other hand, in a later 3D in vivo study, Goto, et al., (2004) reported larger variations of the axes' inclinations using a proximity mapping technique with magnetic resonance imaging (MRI). Despite the fact that a special posture devise was used for keeping the elbow in a desired flexion angle during image acquisition, the axes' inclinations varied from 5,7º to 17,2º in the horizontal and from 7,8º to 19,4º in the frontal plane, with a counter clockwise progression lateral to the joint.

The mean flexion axis is generally described to more or less coincide with the anatomical transverse axis. Although the flexion axes in our study oscillated around this axis, we found great variation in the inclination of the calculated mean flexion axes, with a range between subjects of 12,7º in the frontal and 4,6º in the horizontal planes. Greater variation in the horizontal plane (11,9º) than in the frontal plane (4,6º) was reported by Tanaka, et al., (1998).

One reason for the difference between the results may be the use of different methods. The electromagnetic technique has the advantage that dynamic motions can be studied. However, as skin markers must be applied during electromagnetic tracking in vivo, the results cannot be based on optimal rigid body segments and the accuracy is not comparable to that of RSA. Measurement noise should be less when cadaver specimens are used, but apart from the fact that muscles and ligaments are not intact, the motion must be induced mechanically by pulling on selected muscles, for instance the biceps, brachialis, and triceps. The physiological muscular forces across the joint, including the varus and valgus load as well as the stabilizing effect induced by the flexor pronator and the extensor supinator groups, are therefore not considered.

Other factors that make direct comparisons with other studies difficult are differing and often unspecific definitions of the humeral long axis and also different calculations of the motion axes.

Conclusion

Using RSA we were able to demonstrate that the inclination of the elbow flexion axes in vivo varies. Our results show that the dispersion of the axes can vary with greater interindividual differences and greater excursions than has been shown in the earlier studies. The results can be of importance for the design of both linked and unlinked implants for the elbow.

6.2 STUDY II

6.2.1 Results

- All tantalum markers could be localised in the CT coordinate system.
- The mean error in localising the markers in the CT volume was 0,29 (0-0,8) mm.
- The median error between the transformed RSA coordinates and the CT coordinates was 0,22 (0,07-0,52) mm.
- The median maximal rotation error (all directions considered) between the RSA and CT rigid body was 0,003º (0,001º-0,006º).
- The scaling factor for each subject varied from 0,985 to 1,035 (ideal 1,000).
- The RSA data for the flexion axes were successfully superimposed on the CT volume.

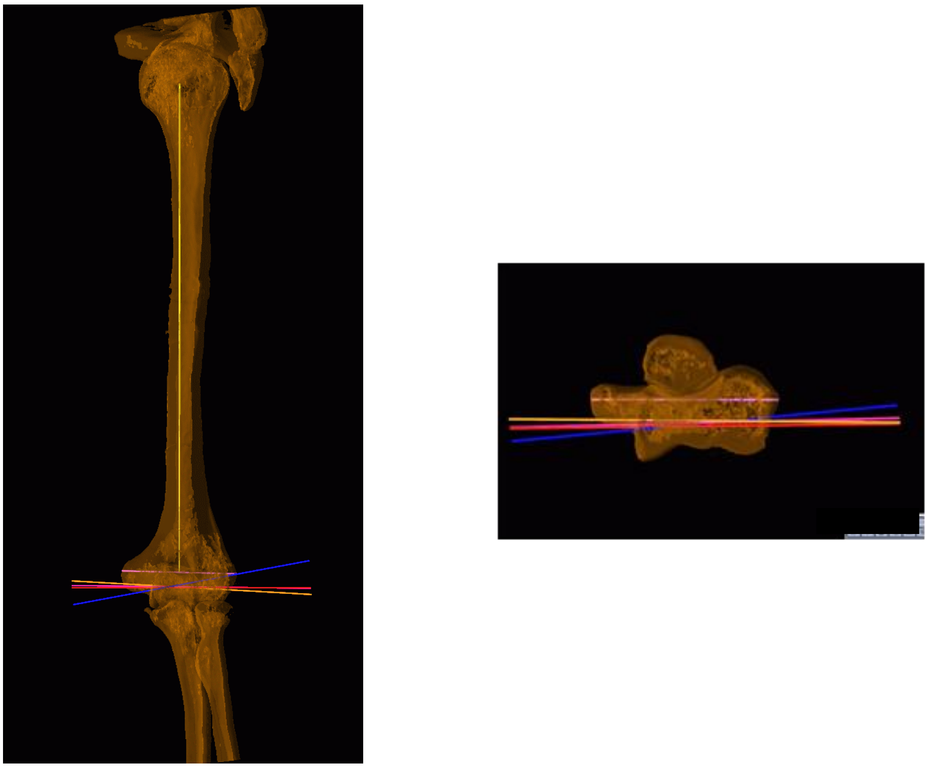

Figure 9. Illustration of the results for one subject. The longitudinal reference axis is shown in yellow, the transverse reference axis in pink. **Left:** Frontal plane. **Right:** Horizontal plane.

6.2.2 Discussion

In RSA the inclinations of the flexion axes can be determined relative to an orthogonal coordinate system with a high degree of accuracy, while the positions of these axes can only be illustrated schematically on standard drawings of the joint. In order to visualise the axes relative to anatomical landmarks we developed an algorithm for the fusion of RSA and CT data. The high degree of precision in designation of the markers in the CT volume in our study was fundamental for the fusion. Stability parameters indicated that this algorithm could provide nearly identical rigid bodies in CT and RSA. We could therefore combine two highly accurate methods without losing accuracy. This was a prerequisite for illustrating the individual positions of the elbow flexion axes.

In the 3D volume the axes were shown to pass in a dispersed manner through the antero-inferior aspect of the medial epicondyle which coincides with the origin of the anterior and posterior bundles of the MCL (Morrey & An 1985; O´Driscoll, et al., 1992). The dispersion of the flexion axes at the medial side of the trochlea demonstrated in 3D (e.g. see cover illustration) may reflect the function of the different portions of the ligament complex through the flexion arc and their relationship with the instantaneous flexion axes.

A difficulty when comparing results from different studies on elbow flexion axes is, as stated before, the different and often unspecific definitions of reference axes. The curved aspect of the humerus in the sagittal plane is a contributory factor and may be one reason why definitions of reference system in the literature mostly only specify the humeral longitudinal axis in the frontal plane.

Conclusion

We have shown that it is possible to fuse RSA data and CT data for visualisation of the position of the in vivo flexion axes in the individual joint. The proposed definition for reference axes could be of use for calculation of the inclinations of the axes. We have constructed a reference system in 3D, which enabled a distinct definition of both a longitudinal and a transverse axis relative to the joint, which can be useful for future elbow studies.

6.3 STUDY III

6.3.1 Results

- The dispersion of the axis inclinations varied for the Kudo prostheses from 4,1º to 84,3º in the frontal and from 3,3º to 45,0º in the horizontal plane. Mean axis inclination varied between 9,0º valgus to 8,5º varus and from 9,7º internal to 3,4º external rotation.

- Elbows with a Capitellocondylar prosthesis showed dispersions of the instantaneous flexion axes from 0,8º to 19,7º in the frontal and from 2,3º to

20,9º in the horizontal plane. Mean axis inclinations varied in valgus between 0,5º to 5,1º and in external rotation between 0,7º to 3,6º.

- The two linked GSB III prosthesis showed dispersions of the flexion axes with 13,0º and 15,4º in the frontal and with 1,9º and 4,6º in the horizontal plane. All axes were tilted in varus (4,3º and 5,1º) and internally rotated (1,1º and 4,8º).

- There was no clear relationship between the radiological scoring of the arthritis and the outcome.

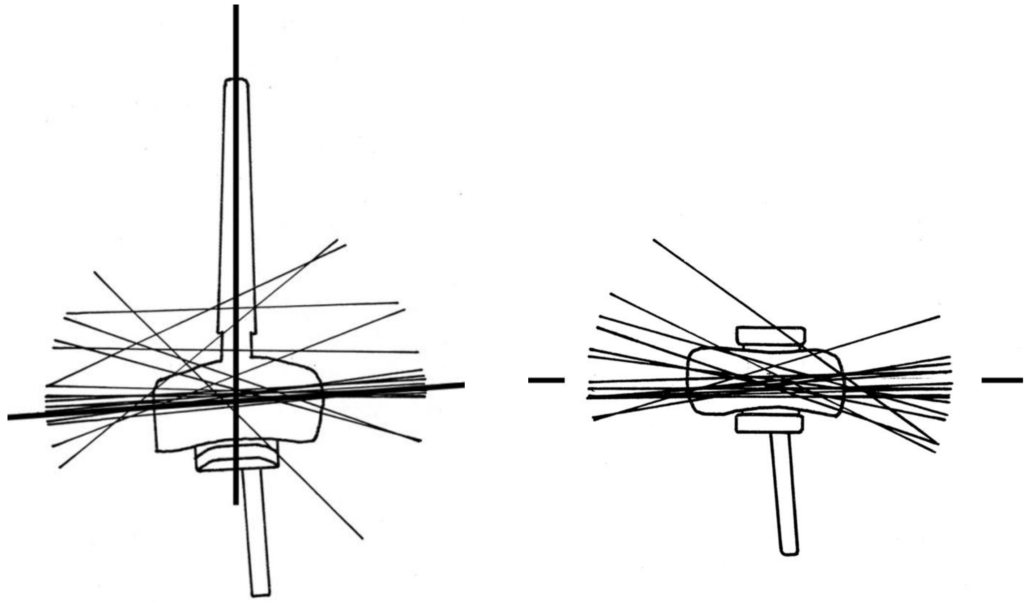

Figure 10. Schematic drawing of a Kudo prosthesis showing the flexion axes for the six Kudo-patients superimposed on a left elbow humeral component. **Left:** Frontal view; **Right:** Horizontal view.

6.3.2 Discussion

This is to our knowledge the first published in vivo study of the elbow pattern of motion after TEA. RSA could be used without further invasive procedures as the tantalum markers were implanted peroperatively. Technically the main problem was to avoid the prosthesis components obscuring the markers on the radiographs. Another technical problem was, as in the study on the healthy subjects, the small bone stock of the ulnar segment, which reduced the volume available for marker insertion. Another limitation was the general health of the patients and the due to RA limited range of elbow motion, which resulted in fewer possible flexion increments than in the study on the healthy subjects. Most patients had an extension deficit of about 30º.

The results showed that the inclinations of the instantaneous axes for all three implants varied more through the flexion arc than in the normal elbows. This was more evident for the two unlinked prostheses, although there were great interindividual differences.
The larger dispersions found for the Kudo compared to the Capitellocondylar and the linked GSB III prostheses, indicated that prosthesis design has an impact on the motion

pattern after TEA. Our results contradict those of an earlier study where the Kudo was described to more closely approximate the behaviour of the normal elbow than the Capitellocondylar (Kamineni, et al., 2005). However, as this was an in vitro study the results are not directly comparable.

There are several possible reasons for the greater dispersions found after TEA as compared to the normal elbow. In TEA, the collateral ligaments have to be partly divided to enable implantation of the prosthesis components. A cadaver study on the laxity of the Capitellocondylar prosthesis showed an obviously increased laxity when either MCL or LCL was sectioned (King, et. al., 1994). Compressive load has been shown to increase the intrinsic constraint of the prostheses (An, 2005). In the rheumatoid patients the compressive forces exerted by the elbow muscles may not be strong enough to compensate for the loss of intact ligaments. Another destabilising factor is the excision of the radial head, which is part of the standard surgical procedure. In a cadaver study Morrey, at al., (1991) reported that release of the MCL together with excision of the radial head resulted in “gross instability” and dislocation. The role of the radial head in total elbow arthroplasty is debated and significant studies are lacking.
Lastly, insertion of the components is often conducted without optimal mechanical guidance. When the operations in our study were performed, effective jigs did not exist for the Kudo and the Capitellocondylar prostheses. Malrotation, even to a small degree, of any of the components can theoretically explain an abnormal motion pattern (Schuind, et al., 1995).

Conclusion
Our study showed that the motion pattern in vivo after TEA was less constrained than in the normal elbow. This was more obvious in the unlinked prostheses. The results also indicated that the design of the implant affects the motion pattern.

6.4 STUDY IV

6.4.1 Results

- The prostheses could be visualised in the CT volume with few and minor artefacts.

- All markers could be identified and localised in the CT coordinate system.

- All markers were stable between the RSA and CT analysis.

- The kinematic data defining the flexion axes were successfully superimposed on the CT volume and the instantaneous flexion axes could be visualised according to the individual prosthesis.

- Repeated marking of the prostheses and construction of the longitudinal reference axes in the CT volume varied less than 0,5º in the frontal and sagittal planes.

- Repeated marking of the prostheses and construction of the transverse reference axes in the CT volume varied less than 0,6º in the frontal and 1,4º in the horizontal plane.

- The difference between the long axes determined in RSA and in the CT volume varied in the frontal plane from 0,4º to 2,1° and in the sagittal plane from 0,0º to 2,4°.

- The difference between the transverse axes determined in RSA and in the CT volume varied from 0,3º to 5,7º in the horizontal plane.

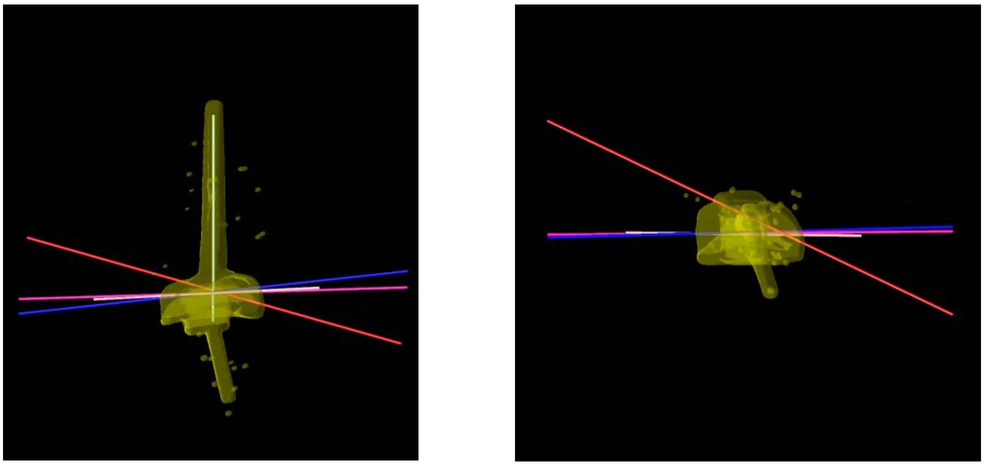

Figure 11. Illustration of the positions of the instantaneous flexion axes for one of the Kudp-patients. Longitudinal reference axis is shown in yellow, the transverse reference axis in pink. **Left:** Frontal view. **Right:** Horizontal view.

6.4.2 Discussion

We were able to visualise the flexion axes after TEA in vivo by fusing RSA and CT data. No other previous study describing the inclinations as well as the positions of the instantaneous flexion axes in vivo were found in the literature.

Our proposed method for marking the prostheses for construction of prosthetic reference axes showed small differences between the repeated markings. The slightly higher values for the transverse axis in the horizontal plane may reflecte a certain difficulty in designating landmarks on the condylar parts of the prostheses. Although the differences were 1,4º for one of the Capitellocondylar and 1,1º for one Kudo prosthesis, the difference for the remaining four was below 0,6º. The comparison of the reference systems in RSA and CT showed small differences for the longitudinal axis and somewhat larger values for the transverse axis. As the repeated marking of the prostheses in the CT volume showed good reliability, the larger values for the difference between the transverse axes in the two modalities may reflect a difficulty to find landmarks for positioning of fictive marks in the radiographs.

Another possible modality for presentation of flexion axes in 3D could theoretically be MRI, which has been used for an in vivo study on healthy subjects (Goto, et. al., 2004). Up to date metal artefacts have prevented the use of this method in studies after total joint replacements. It remains to be seen what advantages and disadvantages this method may have.

Conclusion

In this study we could visualise the positions of the instantaneous flexion axes in vivo after TEA by fusing RSA data and CT data. A method was developed for defining a reference system with good reliability. This could be of value for safer calculation of the positions of the flexion axes.

7 CONCLUSIONS

The main achievement of this thesis was that we were able to show how the inclination of the flexion axes of the elbow joint varied in vivo, both in the normal elbow and after TEA. We have also been able to show the positions of these axes in relation to the individual joint. The results indicate that soft tissue balance as well as the choice of implant is of importance in total elbow replacement.

The use of RSA permitted accurate mathematical determination of the inclination of flexion axes according to an orthogonal coordinate system. To visualise and determine the positions of the axes in 3D, we developed an algorithm for fusion of RSA and CT data. The algorithm made it possible to combine RSA with the excellent 3D skeletal imaging that CT offers without loss of accuracy.

Changes in implant design have been made without thorough knowledge of the resulting kinematics. As our proposed method for fusing RSA and CT data can be used in vivo in small series and without further invasive technique, it can be of value for early in vivo assessment before new implants are introduced on the market.

8 ACKNOWLEDGEMENTS

I would like to express my sincere and warm gratitude to everyone who in various ways have contributed to this thesis. In particular I wish to thank:

André Stark. My primary supervisor and head coach who made this project most enjoyable by his enthusiasm, scientific knowledge and unfailing support. Thanks for all the fun and all memorable moments that we have shared throughout all the years we have been colleagues and friends.

Toni Arndt. My second supervisor. Thanks for your patient guidance in the difficult science of biomechanics. Without you this thesis would have come to nothing. You have learnt me a lot, and I do appreciate your sense for quality. I will try to remember not to be "too wordy" in future manuscripts.

Henrik Olivecrona. My colleague and third supervisor. One of the mathematical geniuses who helped to realize the idea about the visualisation of the flexion axes in CT. Your share in this thesis is of such great importance.

Marylin Noz, Gerald Maguire and Michael Zeleznik. Co-authors and mathematicians. I am deeply grateful for your valuable contribution to this thesis.

Arne Lundberg. Co-author and once supervisor. You helped to start this project and taught me the basics in RSA. I will always remember our research meetings at the restaurant Orientexpressen. Drinking beer with radiographs spread over the table, discussing the direction of Y-axes and X-axes.

Per Wretenberg. Colleague and co-author. Thanks for all support and friendship.

Lennart Lagerbäck. Nurse at the Dept of Radiology. Thanks for all kind and patient help with the radiographs for the RSA analyses.

Mats Beckman and Joakim Crafoord. Collegues at the Dept of Radiology. Thanks for excellent help to plan and do the CT-scans.

Kristina Källbom. Former nurse at the clinic. Thanks for all help with administration of the patients.

Lars Weidenhielm. My professor. Thanks for providing me with time for research.

Subjects and patients. Thanks for so willingly giving me your time.

Maria Bringland. Colleague and a dear friend. Thanks for all morning coffee breakes sharing experiences and thoughts. You keep me updated in the medical field.

Richard Wallensten. Colleague and friend for many years. Thanks for so willingly taking “remisskorgarna” when needed.

All the rest of my colleagues and the staff at the clinic. I am happy to have the privilege to work in such a positive atmosphere that makes Monday mornings enjoyable. A special thank to the staff at the out-patient department, my “home” at the clinic.

Gunilla Bolinder. Colleague and director for KTC. I appreciate your warm friendship and all support with KUM.

The thesis was supported by grants from Svensk Reumakirurgisk förening and from Sven Noréns Memory Foundation.

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