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Original article

Total elbow arthroplasty: Influence of implant positioning on functional outcomes

H. Lenoir[a,*], J.P. Micallef[b], I. Djerbi[a], T. Waitzenegger[a], C. Lazerges[a], M. Chammas[a], B. Coulet[a]

[a] *Hand and Upper Limb Surgical unit, Lapeyronie Teaching Hospital, CHU Lapeyronie, 371, avenue du Doyen-Gaston Giraud, 34295 Montpellier cedex 5, France*
[b] *Research Laboratory: Movement to Health (M2H), EA 2991, STAPS School of Sports Science, Montpellier-1 University, Montpellier, France*

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ABSTRACT

Background: Restoring the axis of rotation is often considered crucial to achieving good functional outcomes of total elbow arthroplasty. The objective of this work was to evaluate whether variations in implant positioning correlated with clinical outcomes.
Hypothesis: Clinical outcomes are dictated by the quality of implant positioning.
Material and methods: A retrospective review was conducted of data from 25 patients (26 elbows). Function was assessed using a pain score, the Disabilities of the Arm, Shoulder, and Hand (DASH) Score, and the Mayo Elbow Performance Score (MEPS). The patients also underwent a clinical evaluation for measurements of motion range and flexion/extension strength. Position of the humeral and ulnar implants was assessed by computed tomography with reconstruction using OsiriX software. Indices reflecting anterior offset, lateral offset, valgus, height, and rotation were computed by subtracting the ulnar value of each of these variables from the corresponding humeral value. These indices provided a quantitative assessment of whether position errors for the two components had additive effects or, on the contrary, counterbalanced each other. Elbows with prosthetic loosening or extensive epiphyseal destruction were excluded.
Results: Of the 26 elbows, 5 were excluded. In the remaining 21 elbows, the discrepancy between the humeral and ulnar lateral offsets was significantly associated with pain intensity ($P \leq 0.05$) and the MEPS ($P \leq 0.05$). Anterior position of the ulna relative to the humerus was associated with decreased extension strength ($P \leq 0.05$) and worse results for all functional parameters ($P \leq 0.05$).
Discussion: In the absence of loosening, positioning errors seem to adversely affect functional outcomes, probably by placing inappropriate stress on the soft tissues.
Level of evidence: III.

1. Introduction

The first total elbow prostheses, introduced in the 1970s, were rigid-hinge joints that were associated with high complication rates [1–4]. Complications are far less common with the newest-generation elbow prostheses [5–11], whose 10-year survival rates exceed 85% [7,12,13]. Nevertheless, the occurrence of complications, most notably loosening, remains a focus of constant concern [14,15]. A number of pathophysiological processes have been suggested to explain these complications [3,8,16–29]. Among contributors to prosthesis failure, the quality of implant positioning plays a preponderant role [8,17,30–38]. Thus, replicating the initial axis of rotation seems crucial to restore normal kinematics and appropriate stresses, thereby ensuring good elbow function.

The objective of this work was to investigate whether prosthesis position in the three planes influenced the clinical outcomes of total elbow arthroplasty.

2. Materials and methods

2.1. Study population

From October 2008 to January 2012, the Discovery^{TM} Elbow System (Biomet, Warsaw, IN, USA) was used for total arthroplasty of 32 elbows in 31 patients. Among these patients, 5 were lost to

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[*] Corresponding author. Service de chirurgie de la main et du membre supérieur, CHU Lapeyronie, 371, avenue du Doyen Gaston-Giraud, 34295 Montpellier cedex 5, France. Tel.: +33 6637 83894.
E-mail address: hubert.lenoir@laposte.net (H. Lenoir).

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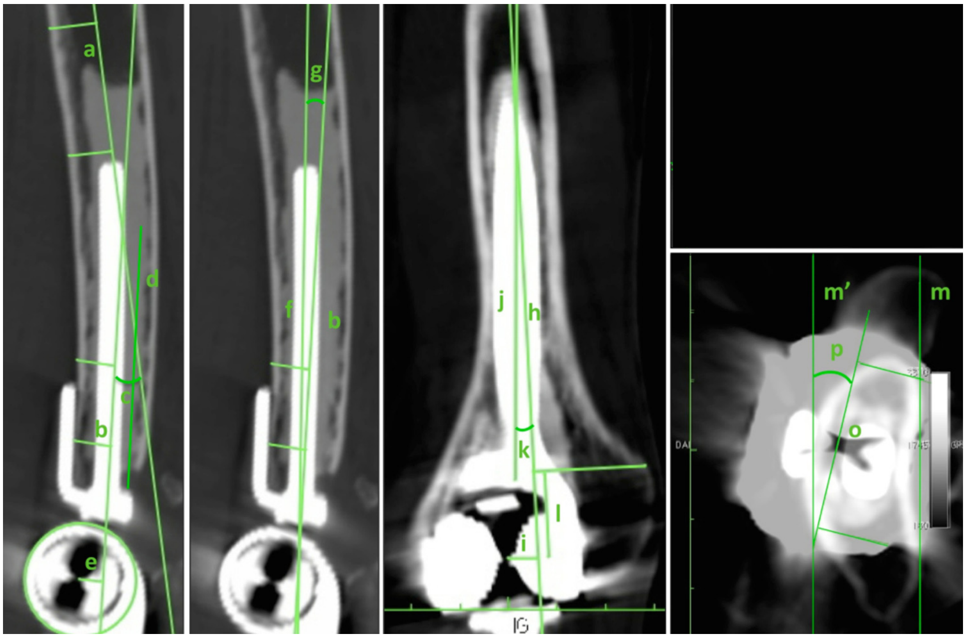

Fig. 1. Measures on computed tomography images of the humerus: a: axis of the proximal humeral shaft in the sagittal plane; b: axis of the distal humeral shaft in the sagittal plane; c: humeral anterior angulation; d: point of humeral anterior angulation; e: anterior offset; f: humeral stem axis in the sagittal plane; g: version of the humeral implant; h: humeral axis in the frontal plane; i: lateral offset; j: humeral stem axis in the frontal plane; k: valgus of the humeral axis; l: height of the humeral implant; m: axis of the distal humerus; m': line parallel to the axis of the distal humerus; n: axis of the hinge; o: rotation of the humeral implant.

follow-up and 1 died, leaving 25 patients (26 elbows) for the study, 18 women and 7 men. Mean age was 64 years (range, 38–82) at last follow-up. Of the 25 patients, 13 (14 elbows) had rheumatoid arthritis and 6 a history of complex trauma. In addition, 2 patients experienced decompensation of rheumatoid arthritis lesions due to a fracture of the radial head or distal humerus, respectively. Of the remaining 4 patients, 1 each had primary elbow osteoarthritis, osteochondromatosis, severe haemophilia, and osteoma after a severe burn injury.

2.2. *Operative technique and post-operative care*

The posterior trans-tricipital approach with decortication of the olecranon was performed in all patients [8]. After radial head resection, ulnar nerve release was performed routinely. The Discovery™ Elbow System was used for all 26 elbows. Mobilisation was started within the first week after surgery. Elbow extension against resistance was postponed for 8 weeks.

2.3. *Clinical evaluation*

At last follow-up, each patient subjectively evaluated pain intensity on a scale from 0 (no pain) to 10 (worst possible pain) and overall elbow function on a scale from 0 (complete loss of function) to 100 (normal function). The Mayo Elbow Performance Score (MEPS) was determined routinely and the results categorised as follows: excellent, 90-100; good, 75–89; fair, 60–74; and poor, <60. The Disabilities of the Arm, Shoulder, and Hand (DASH) Score was also assessed in each patient. Patient satisfaction was rated as follows; very satisfied, satisfied, somewhat satisfied, and dissatisfied.

The physical examination included measurement of the ranges of flexion, extension, pronation, and supination using a goniometer. A dynamometer was used to measure flexion and extension strength with the elbow flexed at 90°. The ratio of extension over flexion strengths was computed.

2.4. *Radiographs and computed tomography (CT)*

Standard antero-posterior radiographs were obtained and CT imaging performed. The status of the bone-cement interface was graded as described by Morrey et al. [23]: type 0, lucent line less than 1 mm thick and involving less than 50% of the interface; type I, lucent line of 1 mm or more involving less than 50% of the interface; type II, more than 1-mm lucency involving more than 50% of the interface; type III, more than 2-mm lucency around the entire interface; and type IV, gross loosening.

To assess humeral and ulnar implant position, CT reconstructions produced using OsiriX® software (Fondation OsiriX, Geneva, Switzerland) were used (Figs. 1 and 2). The bones near the elbow are characterised by a humeral anterior angulation, ulnar anterior angulation, and ulnar varus angulation. The anatomical axes of the proximal and distal shafts of the humerus and ulna were determined based on previously published data [16,39–46], at a distance from the apices of the humeral anterior angulation and ulnar anterior angulation. Thus, the axis of the distal humeral shaft in the sagittal plane ran through the midpoints of the two line segments connecting the anterior and posterior cortices, with the distal and proximal line segments being located 1 cm and 3 cm from the most distal part of the humerus. The axis of the proximal humeral shaft ran through the middle of two line segments located 8 cm and 11 cm, respectively, from the most distal part of the humerus. In the frontal plane, the humerus has no angulation and the axes of the proximal and distal shafts are therefore the same. This frontal humeral axis ran through the midpoints of two line segments connecting the medial and lateral cortices at, and 8 cm proximal to, the most distal part of the diaphysis. The axis of the proximal ulnar shaft in the sagittal plane ran through the midpoints of two line segments connecting the anterior and posterior cortices, one at the coronoid process and the other 2 cm more distally. The axis of the distal ulnar shaft ran through the midpoints of two other line segments located 7 and 10 cm, respectively, from the tip of the olecranon. In the frontal plane, the axis of the proximal ulnar shaft ran through the midpoints of two line segments connecting the medial and lateral cortices and located 2 and 4 cm, respectively, from the tip of the

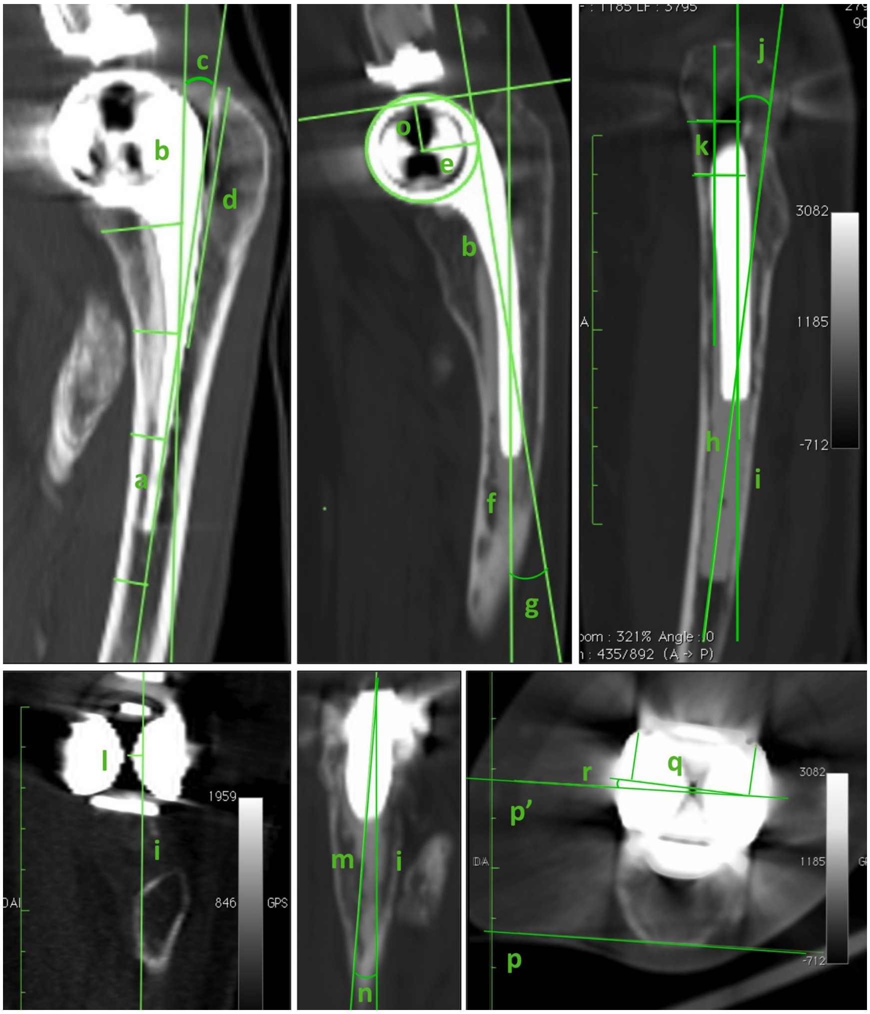

Fig. 2. Measures on computed tomography images of the ulna: a: axis of the distal ulnar shaft in the sagittal plane; b: axis of the proximal ulnar shaft in the sagittal plane; c: ulnar anterior angulation; d: point of ulnar anterior angulation; e: anterior offset; f: ulnar stem axis in the sagittal plane; g: version of the ulnar implant; h: axis of the distal ulnar shaft in the frontal plane; i: axis of the proximal ulnar shaft in the frontal plane; j: ulnar varus angulation; k: point of ulnar varus angulation; l: lateral offset; m: ulnar stem axis in the frontal plane; n: valgus of the ulnar implant; o: height of the ulnar implant; p: axis of the olecranon; p': line parallel to the axis of the olecranon; q: axis of the hinge; r: rotation of the ulnar implant.

olecranon; the axis of the distal ulnar shaft ran through the midpoints of two line segments located 11 cm and 14 cm, respectively, from the tip of the olecranon.

By comparing these anatomical axes to the axes of the implants, five parameters were determined for each implant:

- anterior offset, defined as the shortest distance between the centre of the hinge and the axis of the distal humeral shaft or the axis of proximal ulnar shaft in the sagittal plane;
- lateral offset, defined as the shortest distance between the centre of the hinge and the axis of the humeral shaft or the axis of proximal ulnar shaft in the frontal plane;
- valgus, defined as the angle formed by the axis of the implant stem and the axis of the humeral shaft or the axis of proximal ulnar shaft in the frontal plane;
- height, defined as the distance from the centre of the hinge at the tip of the medial epicondyle and the centre of the hinge at the tip of the olecranon;
- rotation, defined as the angle between the axis of the hinge and either the axis of the distal humerus or the axis of the olecranon. The axis of the hinge connects the centres of the line segments connecting the edges of the two sides of the prosthetic trochlea. The axis of the distal humerus is the most distal tangent to the flat surface of the posterior humeral cortex. The axis of the olecranon is the tangent to the flat spot, i.e., the posterior subcutaneous flat bony surface of the proximal end of the ulna, and is perpendicular to the axis of rotation of the elbow [40].

The rotational axis of the prosthesis is in 5° of internal rotation relative to the axis of the humeral stem. Therefore, measurements of humeral implant rotation were routinely corrected by 5°. The ulnar implant is not straight in the sagittal plane, and 23° of correction relative to the ulnar stem axis was therefore applied to determine the epiphyseal ulnar axis.

The values of all variables were arbitrarily recorded as positive if the implant was in valgus or external rotation or when the hinge was distal to the medial epicondyle or proximal to the tip of the olecranon.

The humeral and ulnar implants are linked to each other by the prosthetic hinge, and their positions should therefore not be evaluated independently. Position indices were computed to quantify the extent to which position errors in the two components had additive effects or, in contrast, counterbalanced each other (Fig. 3). Thus, we computed indices for anterior offset, lateral offset, valgus, height, and rotation by subtracting each variable value for the ulnar component from the corresponding variable value for the humeral

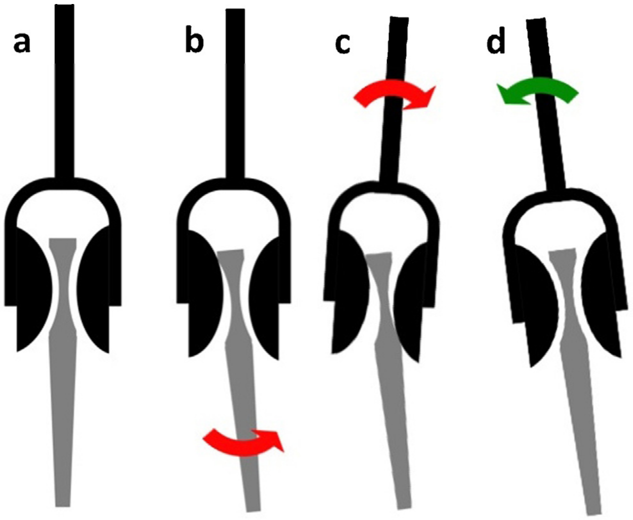

Fig. 3. Concept of linked position errors. The humeral and ulnar implants are linked by the prosthetic hinge (a). The effect of an error in ulnar implant position (b) can therefore be either exacerbated (c) or counterbalanced (d) by an error in humeral implant position.

component. Ideally, lateral offset, valgus, and rotation are equal to 0 at the humerus and ulna. Errors in these variables were classified as counterbalanced when the corresponding indices were equal to 0. Indices that were not equal to 0 were expressed as absolute values, which were therefore proportional to the net positional error.

The ideal values of anterior offset and height are unknown. The corresponding indices were therefore expressed as their measured values.

Implant version and the corresponding index were not computed, as the two components are completely free and unconstrained in this plane during flexion and extension of the elbow.

Elbows with type III or IV loosening were excluded from the analysis of position, as their current position was considered non-representative of their initial position. Epiphyseal bone loss precludes a reliable evaluation of morphology and therefore also led to exclusion from the analysis.

2.5. Statistical analysis

The Shapiro-Wilks Test showed that most of the variables were non-normally distributed. The data are therefore described as median (interquartile range [IQR]).

Intra-observer variability of the measurements was assessed by having the same observer perform the measurements twice at an interval of 1 month. Agreement between the two values for each variable was then assessed by computing the intra-class coefficient (ICC). ICC values >0.7 were taken to indicate acceptable intra-observer variability.

The clinical outcome variables were compared to the implant position indices. Relations between two quantitative variables were evaluated by computing Spearman's non-parametric correlation coefficient, which was tested against the null hypothesis. For all tests, *P* values $\leq$0.05 were considered significant. Statistical analyses were performed using SAS software version 9 (SAS Institute, Cary, NC, USA).

3. Results

3.1. Overall clinical outcomes

After a mean follow-up of 23 months (range, 6–44), median pain intensity on the 10-point scale had decreased from 7.75 (IQR, 7–8) before surgery to 2 (IQR, 0–3) ($P \leq 0.001$). Median subjective elbow function on the 100-point scale was 80 (IQR, 65–80). The pre-operative MEPS was available for 21 patients; the median MEPS value increased from 40 (IQR, 35–60) pre-operatively to 85 (IQR, 80–100) at last follow-up ($P \leq 0.001$) (Fig. 4). The outcome categorised based on the MEPS at last follow-up was excellent in 11 elbows, good in 10, fair in 2, and poor in 3. The median DASH score was 33.3 (IQR, 24.2–47.4). Of the 25 patients, 19 were very satisfied, 3 satisfied, 1 somewhat satisfied, and 2 (including the patient with bilateral arthroplasty) dissatisfied.

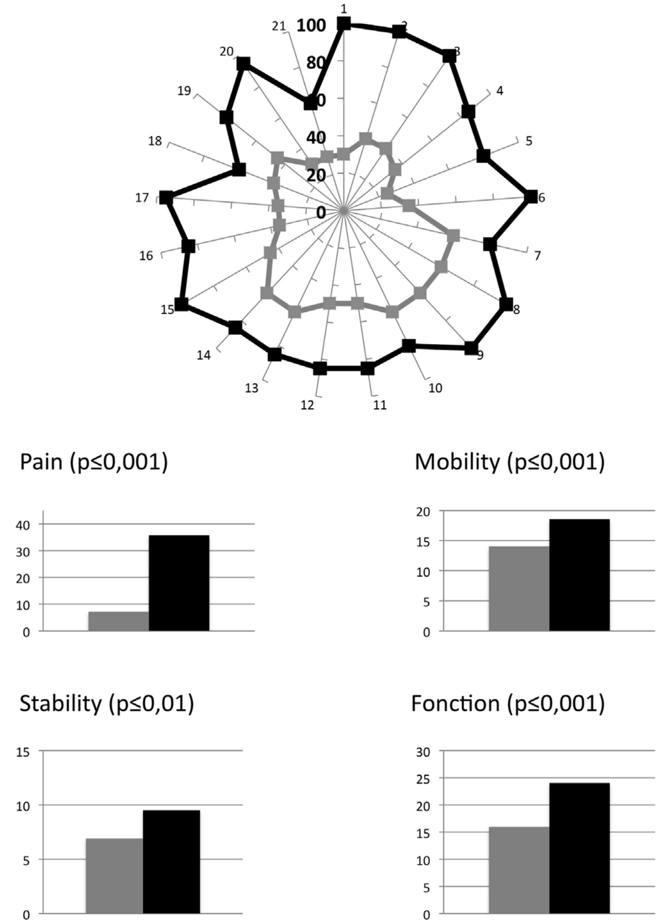

Fig. 4. Mayo Elbow Performance Score (MEPS) values before (grey) and after (black) surgery. The first graph shows the total MEPS for each of the 21 patients. The histograms depict the median values of each of the items considered in the MEPS.

Median range of flexion increased from 130° (IQR, 110/140) to 140° (IQR, 130/150) and median extension lag decreased from –50° (IQR, –60/–40) to –25° (IQR, –40/–20) ($P \leq 0.001$). The increase in the pronation/supination arc was not statistically significant.

3.2. Associations linking implant position to clinical outcomes

Five elbows were excluded from the analysis of implant position. Table 1 reports the position indices.

For the humeral component, the ICCs were 0.76 (95% confidence interval [95%CI], 0.51–0.89) for anterior offset, 0.84 (95%CI, 0.65–0.93) for lateral offset, 0.89 (95%CI, 0.76–0.85) for valgus, 0.74 (95%CI, 0.45–0.88) for height, and 0.95 (95%CI, 0.88–0.98) for rotation. For the ulnar component, the ICCs were 0.91 (95%CI, 0.79–0.96) for anterior offset, 0.97 (95%CI, 0.92–0.99) for lateral offset, 0.92 (95%CI, 0.81–0.97) for valgus, 0.94 (95%CI, 0.85–0.97) for height, and 0.97 (95%CI, 0.92–0.99) for rotation.

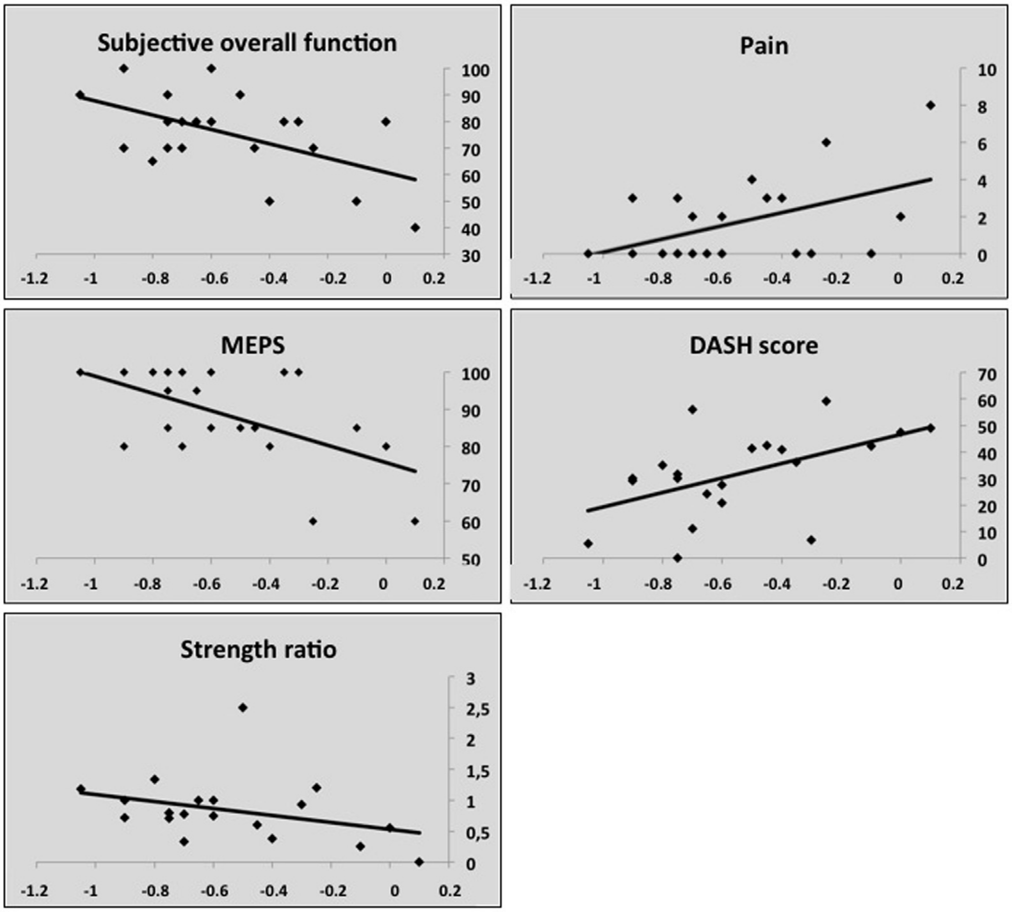

Fig. 5. Clinical outcomes according to the anterior offset index.

Table 1
Position.

Case	Ant. offset	Lat. offset	Valgus	Height	Rotation
1	−0.6	0	0.3	0	7.9
2	−0.9	0.55	9.5	1.45	14.45
3	−1.05	0.5	11.05	−0.25	1.75
4	Excl.	Excl.	Excl.	Excl.	Excl.
5	Excl.	Excl.	Excl.	Excl.	Excl.
6	−0.45	0.4	11.8	1.25	10.65
7	0	0.75	6.75	1.9	11.25
8	−0.8	0.2	0.75	0.8	4.45
9	−0.4	0.25	9.3	0.95	20.15
10	−0.75	0.4	3.45	0.1	0.75
11	−0.7	0.1	13.25	0.35	14.3
12	−0.7	0.15	3.6	0.15	12.05
13	−0.65	0.4	5.45	0.8	10.45
14	−0.5	0.2	2.85	0.75	14.8
15	−0.75	1.2	11.3	0.65	28.55
16	−0.35	0.1	7.4	ND	12.85
17	Excl.	Excl.	Excl.	Excl.	Excl.
18	−0.1	0.05	7.05	1.3	9.25
19	−0.6	0.8	12.2	0.5	−6.8
20	−0.3	0.85	17.9	0.25	21.75
21	ND	ND	ND	ND	ND
22	−0.75	0.95	13.9	0.55	8.15
23	−0.25	1.05	16.35	−0.95	20.55
24	−0.9	1.3	10.7	0.2	6.75
25	ND	ND	ND	ND	ND
26	0.1	1.2	15.65	ND	ND
Median	−0.6	0.4	9.5	0.55	10.95

ND: value not determined, because measuring the position parameters was not feasible; Excl.: elbows excluded from the study because of type III or IV loosening.

The lateral offset index correlated with pain intensity ($P \leq 0.05$) and the MEPS ($P \leq 0.05$). Thus, better counterbalancing of lateral offset was associated with decreased pain intensity and improved MEPS values. The subjective assessment of elbow function and the DASH score were also better when the hinge was properly centred, although the differences were not statistically significant.

Better counterbalancing for the valgus and rotation indices was associated with less pain and with improved function as assessed by the MEPS, but the differences were not statistically significant.

Higher values for the anterior offset index (Fig. 5) were associated with a significant increase in pain intensity ($P \leq 0.05$), a poorer subjective assessment of overall elbow function ($p \leq 0.05$), poorer function as assessed by the MEPS ($P \leq 0.01$) and DASH score ($P \leq 0.05$), and decreased extension strength ($P \leq 0.05$). Higher anterior offset values were non-significantly associated with increased flexion strength and a decrease in the ratio of extension over flexion strengths.

The implant height index was not associated with any of the functional or clinical outcomes.

4. Discussion

Very few clinical data are available on the effects of elbow implant position [31,32,47]. In a study of pre-operative and immediate post-operative radiographs, Figgie et al. demonstrated that functional outcomes, implant survival, and complication rates correlated with restoration of anterior offset of the humeral and ulnar components [31]. Nevertheless, their study exhibits several sources of bias. Of the 54 arthroplasties, 42 were performed because of

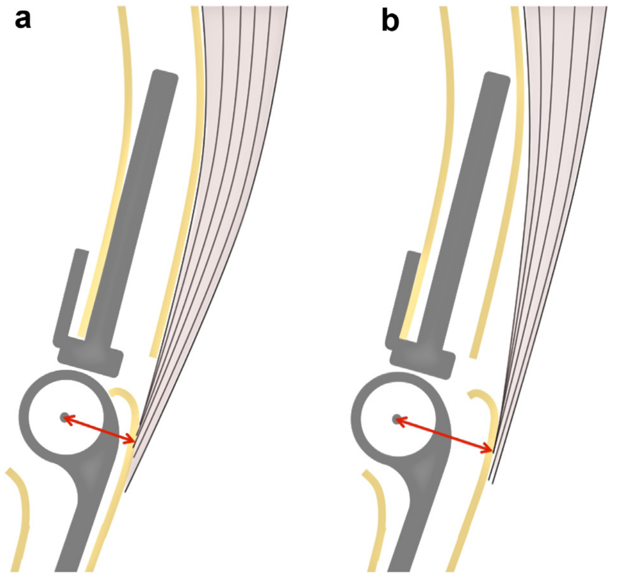

Fig. 6. Effect of the anterior offset index on triceps work. A low anterior offset index reflects anterior positioning of the ulnar implant relative to the humerus (a). A more favourable ulnar implant position is associated with a high anterior offset index (b). In this situation, the more anterior position of the humerus enhances the pulley effect of the triceps around the hinge. A more posterior position of the ulnar implant also increases the lever arm, by increasing the distance between the attachment of the triceps and the centre of rotation of the hinge (red double arrow). This configuration results in less work for the triceps.

rheumatoid arthritis, a disease associated with extensive joint destruction that can preclude determination of the native centre of rotation of the elbow. This determination is probably even more challenging in complex elbow injuries, which were the reason for arthroplasty in the 14 remaining cases. Furthermore, the natural changes in direction of the humeral and ulnar axes were not taken into account in this study. Thus, the authors considered that there was a single diaphyseal axis. However, the distal humerus angles forwards [16,39,48], as does the proximal ulna [40–44]. In addition, the proximal ulna has a varus angle [41,42,45,46].

Futai et al. used fluoroscopy to investigate the kinematics of unconstrained elbow prostheses [32]. They showed that valgus position of the humeral implant relative to the humeral axis was associated with edge-loading of the articular surface. The authors did not report whether these parameters influenced the clinical outcomes or complication rates.

Van Der Lugt et al. reported that lucent lines at the posterior aspect of the humeral implant and medial column were associated with greater anterior version of the humeral implant and greater valgus of the humeral stem [47]. However, these lucent lines were not progressive, and implant position seemed to have no influence on the clinical outcomes or loosening rate.

All three above-mentioned studies used plain radiographs, which have limited precision compared to a three-dimensional assessment. None of them assessed implant position in the three planes. Our use of CT eliminated these two weaknesses. Our measurements seem reliable, since the ICC was consistently deemed acceptable.

Rather than viewing the humeral and ulnar components as two separate entities, we assessed them as a whole, since they are linked by a hinge. We believe that position indices are more appropriate than isolated parameters.

Counterbalancing of lateral offset was associated with decreased pain intensity and improved MEPS values. The poorer functional outcomes seen when the offsets were not consistent for the two components may be ascribable to inappropriate stresses applied to the soft tissues.

Lower anterior offset index values were associated with a significant increase in extension strength. These lower values indicated a more posterior position of the ulna relative to the humerus (Fig. 6). Anterior translation of the humerus increases the pulley effect (the extensor mechanism can be likened to a rope wrapped around the prosthetic hinge). Furthermore, the lever-arm effect is more marked when the ulna is in a more posterior position, as this increases the distance between the attachment of the triceps and the centre of rotation of the hinge. The increased lever-arm effect decreases the work of the triceps. The trend towards a decrease in elbow flexion strength under the same conditions is ascribable, in contrast, to an increase in the moment of force. Secondary changes in stresses may explain the pain exacerbation and function-score impairments associated with an increase in the anterior offset index. These findings are consistent with a report by Figgie et al. that a decrease in anterior offset of the humeral offset predicted better functional outcomes [30] and with a study by Van der Lugt et al. showing that radiolucencies were significantly increased in the event of anterior version of the humeral component [47].

In our study, neither the valgus index nor the rotation index was associated with the clinical outcomes. Nevertheless, experimental work conducted by Schuind et al. [35,36] and Brownhill et al. [30] showed that variations in valgus and rotation influenced the moments of force and the stresses applied to the elbow. A number of limitations of our study probably explain that the rotation index had no influence on the clinical and functional parameters. First, the axis of the hinge was determined based on the orientation of the two sides of the prosthetic trochlea linked to the humeral implant. However, the prosthesis is designed to have about 7° of laxity between the humeral and ulnar components (Fig. 7). Thus, the measurement of ulnar implant rotation had up to 3.5° of imprecision. Second, the olecranon was decorticated during the surgical approach. This procedure may have diminished our ability to reliably identify the posterior subcutaneous surface of the olecranon used to measure rotation. Third, for the measurements of humeral component rotation, the landmark was the flat surface of the posterior cortex of the distal humerus. This was the only anatomical

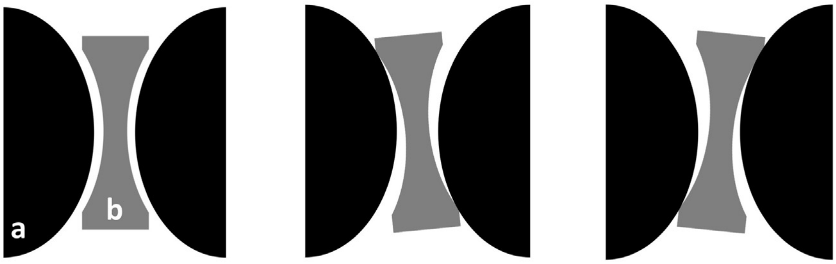

Fig. 7. Laxity of the Discovery^{TM} Elbow System. The configuration of the hinge at the time of computed tomography image acquisition was unknown. The two sides of the trochlea linked to the humerus (a) were used to measure rotation of the ulnar implant (b). Thus, the lack of precision in the measurement of this variable was equivalent to the hinge laxity.

landmark that was easily identifiable in every case. It was identified as close as possible to the joint space to minimise measurement errors due to variations in torsion of the distal humerus [49]. We nevertheless likened it to the axis of rotation of the elbow, in the absence of supporting evidence from anatomical studies.

Our study showed no effect of implant position on loosening. No data on implant position were available for the three loosened prostheses. Loosening was probably ascribable to unfavourable local conditions, since this complication occurred after the second revision in 2 cases and during an infection in the 3rd case.

In conclusion, errors in elbow implant position influence the clinical and functional outcomes. We recommend slight posterior offset of the humeral component and slight anterior offset of the ulnar component. In the frontal plane, the implants should be aligned on the native anatomical axes. The development of modular implants and navigation systems may help to optimise implant position in the future.

Medium- and long-term follow-up data from this case-series will show whether position errors are associated with loosening.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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