OPTIMIZING TOTAL ELBOW ARTHROPLASTY

A COMPREHENSIVE VIEW ON THE PROSTHESIS, PATIENT AND PROCEDURE

DANIELLE MEIJERING

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TABLE OF CONTENTS

Chapter 1

General introduction

THE ELBOW

The elbow is a complex joint. It is made up of the ulnohumeral and radiocapitellar joints performing flexion and extension and the proximal radioulnar joint that, together with the radiocapitellar and distal radioulnar joints, facilitates forearm rotation. The complexity owes not only to this anatomy, but also to the difficult balance between motion and stability, which is a dynamic play between bones and soft tissues. Difficulties in elbow motion or elbow pain can cause severe disabilities in daily functioning and have a negative impact on quality of life, since elbow function is essential to controlling the position of the hand in space.

The elbow is a non-weight-bearing joint and is therefore less susceptible to primary degeneration. However, secondary degeneration due to rheumatoid arthritis or (post) traumatic causes might lead to symptoms. In symptomatic elbow joint degeneration, patients may benefit from open or arthroscopic debridement. Goal of surgical treatment is to remove osteophytes, loose bodies and contract capsules that block motion. Further, excision of accompanying synovitis and adhesions can reduce pain and improve motion (1). Long-term results are promising, demonstrating improved range of motion, better pain scores and good patient satisfaction. Only up to 12% of patients require additional surgery within the first 5-10 years, indicating that in approximately 88% of cases further surgical

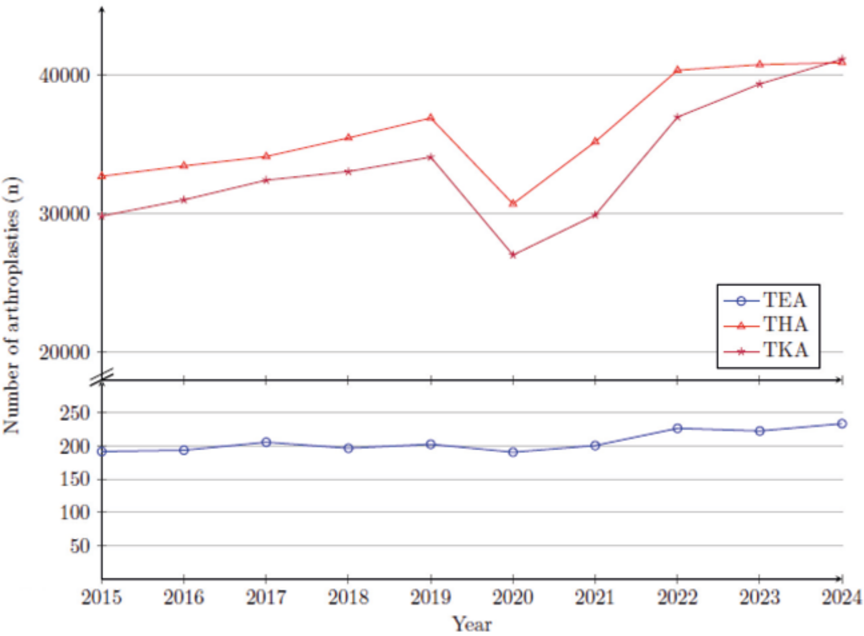

Figure 1. Annual numbers of arthroplasties in The Netherlands. TEA = total elbow arthroplasty, THA = total hip arthroplasty, TKA = total knee arthroplasty (4).

intervention can be postponed for almost a decade (2, 3). In patients with end-stage elbow joint degeneration with profound loss of cartilage, joint-preserving surgery will have poorer results and joint arthroplasty is an option. Resection-interposition arthroplasty is rarely performed nowadays, but total elbow arthroplasty (TEA) is a viable option to relieve pain and improve function in select patients.

Although TEA numbers are still low, they have been rising annually for both primary and revision TEA (4-6). In 2024, 152 primary TEAs and 82 revision TEAs were performed in the Netherlands, compared to 108 primary and 38 revisions in 2014 (Figure 1).

PROSTHETIC DESIGN

The first total elbow prosthesis—which was an ulnohumeral prosthesis—was developed in 1925, but it was not until 1950 that other custom-made designs began to emerge. In the following years, patents for different elbow prostheses were requested. In subsequent decades, more types of prostheses were developed (Figure 2) which eventually became commercially available (7-11). Although use of elbow prostheses became more frequent, multiple problems remained, urging optimization of prosthetic design.

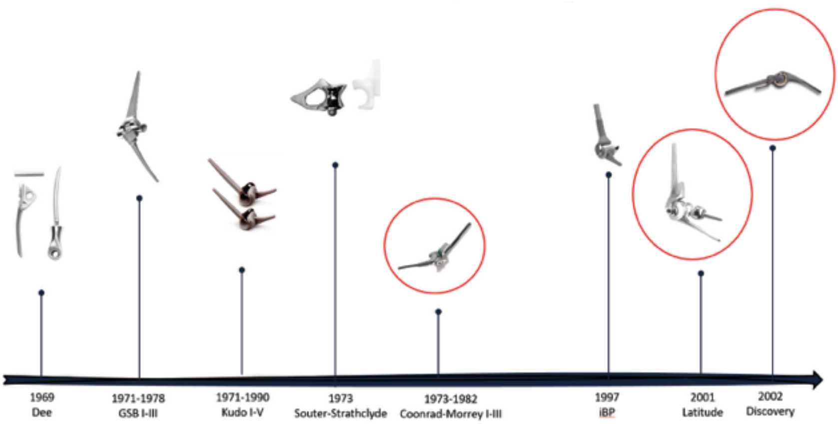

Figure 2. Historical overview of total elbow prostheses designs. Red circles indicate current commercial availability.

In general, designs can be categorized as linked or unlinked, depending on whether the humeral and ulnar components are mechanically connected. Linked designs provide inherent stability, unlinked designs rely on the patient's ligaments and soft tissues for stability. Prostheses can be further categorized as constrained, semi-constrained or unconstrained. Constrained prostheses offer maximum stability, restricting motion strictly to the joint axis. Semi-constrained prostheses provide stability but allowing for some degrees of freedom around the joint axis. Unconstrained prostheses do not offer inherent stability other than the patients' ligaments and soft tissues. It is important to note that "linked" and "constrained" are distinct concepts—for example, a prosthesis may be unlinked while still providing a certain degree of constraint due to its shape, like the Souter Strathclyde.

The first designs were linked and fully constrained, not allowing any laxity, which is necessary during normal elbow motion. The absence of laxity caused high stresses on the implant-bone interface, leading to early loosening of the prosthesis. Unlinked designs were also available, requiring integrity or reconstruction of the ligaments and muscles for stability. This is often insufficient in patients with end-stage elbow disease, so unlinked designs led to dysfunction, instability and dislocations. Later on, linked semi-constrained designs (i.e. sloppy hinge) became available; these allow some varus-valgus laxity to prevent early loosening plus overcome the instability issues (10, 12, 13). Several types of sloppy hinge and unlinked designs are currently available (Figure 2). In the last decade a convertible design, developed to restore the natural anatomy, was created. This Latitude total elbow prosthesis (Stryker, Portage, Michigan, USA) can be either linked or unlinked, and it is the first prosthesis to also offer the option to replace the radial head with a component. Beside design optimizations, over the last decades improvements in coatings, fixation methods and polyethylene (PE) materials have been made as well, all aiming to improve long-term survival (14).

PATIENT FACTORS

The main goal of a total elbow prosthesis is to reduce pain and regain elbow motion. In the past, indications for TEA were mainly rheumatoid arthritis and other inflammatory arthropathies, but nowadays it is also used for post-traumatic arthritis and as a primary option for non-reconstructable comminuted distal humerus fractures or complex elbow dislocations in the elderly (15). Based on patient-reported outcome measures (PROMs), TEA is considered a successful procedure, with good scores on patient satisfaction, relatively good function and low pain scores, especially in older and low-demand patients (16-22). Unfortunately, younger and more active patients have shown less satisfying outcomes (15). Since the mentioned shift in indication leads to a younger and higher-demand patient category, future results will presumably lead to lower patient satisfaction (15, 23).

Although PROMs are still relatively good, 10-year survival rates for TEA remain low, at 80–85%; this lags far behind numbers for knee and hip arthroplasty, which approximate 95% (Figure 3) (4). Considering the rising TEA numbers, it is necessary to focus on causes for these low survival rates so improvements can be made. Main reasons for revision are infection and aseptic loosening. The latter is hypothesized to be caused by either overloading the prosthetic joint during activities of daily living (ADL), ultimately causing polyethylene (PE) wear, or inadequate cement fixation. Both result in bone and tissue destruction and loosening of the implant (24), forcing revision surgery. In an attempt to reduce overloading, most orthopedic surgeons recommend some sort of activity restriction following TEA. However, recent research conducted by our group showed a wide variety in postoperative care modalities and a lack of standardized instructions (25).

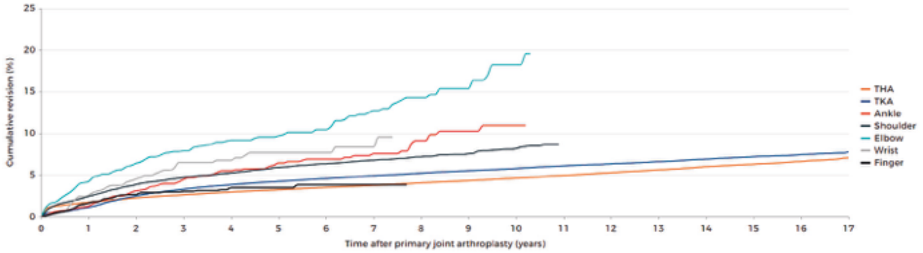

Figure 3. Revision rates following primary joint arthroplasties in the Netherlands (26).

SURGICAL PROCEDURES

Beside low survival rates, reported complication rates following TEA remain high too, with reported rates reaching 45% (27). Frequently reported complications are triceps insufficiency and ulnar nerve neuropathy. In an attempt to reduce complication rates, several advancements in surgical approaches have been made over the past decades. The approaches can be categorized into triceps-sparing approaches, where the triceps muscle remains intact at its insertion on the olecranon, and triceps-detaching approaches, where either a splitting, flap or reflecting technique is used to gain access to the joint (Figure 4). Recent studies show functional outcomes favoring triceps-sparing approaches, yet full insight into benefits and drawbacks of the different approaches is still lacking (28).

Both the low survival rates and high complication rates are vastly impacting patients' daily functioning and quality of life in the short and long term. Further, since the mentioned shift in indications leads to a younger and more demanding population with consequently less satisfying outcomes and higher revision rates, it is necessary to focus on improvements in surgical procedures.

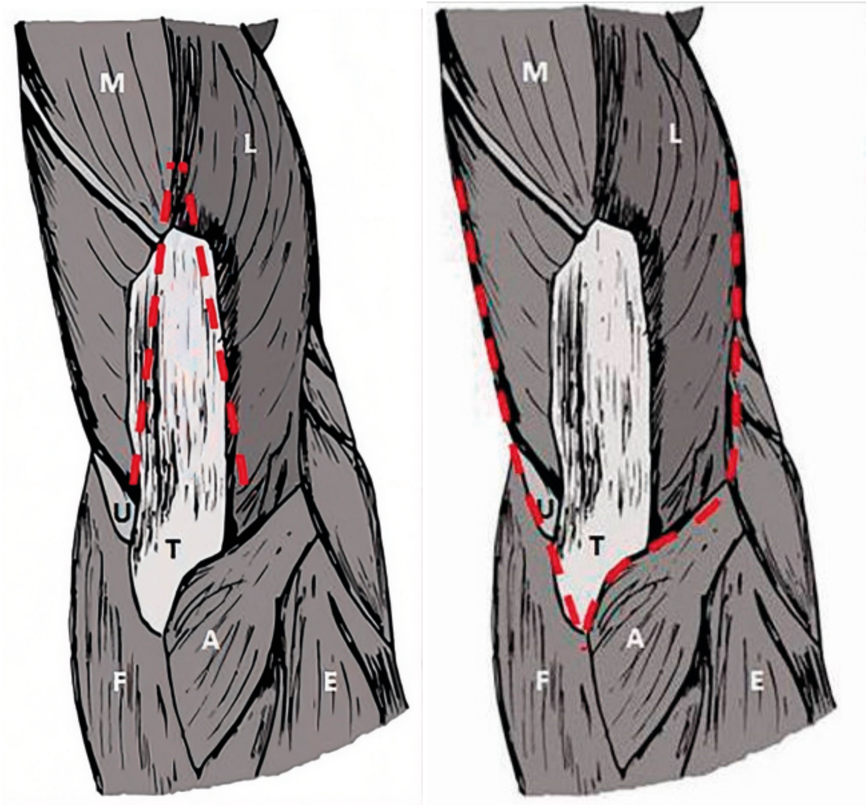

Figure 4. Schematic illustrations (red lines) of a triceps-flap (triceps-detaching) approach (left) and a triceps-sparing approach (right). M Medial head triceps, L lateral head triceps, T triceps, U ulnar nerve, F flexor origo, A anconeus, E extensor origo (29).

AIMS AND OUTLINE OF THE THESIS

The overall aim of this thesis is optimizing total elbow arthroplasty. To this end, the thesis examines prosthetic design, patient factors and surgical procedure as interdependent factors that together determine post-TEA outcome.

The thesis is divided into three parts. **Part 1** focuses on creating insight into clinical and radiological outcomes of elbow prostheses. **Part 2** focuses on optimizing elbow joint loading in patients and prevention of overloading. **Part 3** focuses on optimization of surgical procedures.

Part 1 contains two retrospective studies, to yield insight into the current functioning of two commonly used total elbow prostheses. **Chapter 2** analyzes the long-term results of the iBP total elbow prosthesis, which is an unlinked prosthesis. **Chapter 3** analyzes the mid-term results of the Latitude total elbow prosthesis, which is a convertible device with the option to replace the radial head with a prosthesis as well.

Part 2 focuses on optimizing elbow loads in patients, and contains biomechanical research that was conducted in collaboration with the Department of Human Movement Sciences of UMCG. The aim of this Part was to create insight into elbow loading and overloading, ultimately working toward a postoperative instruction for patients in order to prevent overloading and improve long-term survival of the prosthesis. **Chapter 4** is a narrative review, to study existing literature on available information on elbow joint load during ADL. **Chapter 5** focuses on actual measurements and calculations of elbow joint loads during ADL, and was conducted to fill the knowledge gap identified in Chapter 3. ADL were performed by healthy participants in the Human Movement Sciences lab. The efficacy of the current postoperative instruction for patients following TEA was tested too.

Part 3 focuses on optimization of surgical procedures. **Chapter 6** is a systematic review focusing on triceps insufficiency, one of the major complications following TEA. The effect of surgical approach, as well as incidence, risk factors, clinical presentation, diagnosis and treatment are described. **Chapter 7** is a protocol for a prospective comparative multicenter study on surgical approaches. Different surgical approaches exist, categorized as triceps-sparing and triceps-detaching, but it is not known which one is "best". The outcomes of this study will help understand the benefits and drawbacks of two frequently used approaches. **Chapter 8** presents the results of this prospective study, conducted in six hospitals in the Netherlands.

The thesis concludes in **Chapter 9** with a general discussion, including clinical implications and recommendations for future research.

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PART 1: THE PROSTHESIS

Chapter 2

Long-term results of the iBP elbow prosthesis: Beware of destructive metallosis!

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BMC Musculoskelet Disord. 2019;20(1):415.

ABSTRACT

Background: The aim of this study was to review the long-term results of the instrumented Bone Preserving (iBP) elbow prosthesis.

Methods: 31 Patients (10M, 21F, 28-77year) were retrospectively evaluated using the Oxford Elbow Score (OES), Disabilities of Arm, Shoulder and Hand Outcome Measure (DASH), Mayo Elbow Performance Score (MEPS), physical examination and standard radiographs. Kaplan-Meier survival analysis was used.

Results: 37 Primary iBPs have been placed in 31 patients between 2000 and 2007. Six patients (8 prostheses) had died, 10 elbows had been revised and 3 patients (4 prostheses) were lost to follow-up. 14 patients (15 prostheses) were available for follow-up. The main indication for surgery was rheumatoid arthritis. Mean follow-up was 11 years (8-15). Kaplan-Meier survival analysis showed a survival of 81% at 10 years after surgery. Main reason for revision was particle disease and loosening due to instability and malalignment. 11 Of 14 patients were satisfied, although radiographs showed radiolucencies in 11 patients.

Conclusion: The iBP elbow prosthesis gives a survival rate of 81% ten years after surgery with a progressive decline beyond 10 years. However, many patients have radiolucencies. Discrepancy between clinical signs and radiological results warrants structural follow-up, to assure quality of bone stock in case revision surgery is indicated.

BACKGROUND

Joint destruction due to inflammatory arthritis is still the main reason for a total elbow arthroplasty (TEA), although nowadays posttraumatic osteoarthritis is a more common indication for a replacement (1, 2). As the prevalence of TEA is low compared to knee and hip arthroplasties, reports with long-term follow-up are rather scarce.

Over the last 40 years there have been many improvements in the design of total elbow prostheses. In general, three types of prostheses are available: unlinked devices, linked devices and convertible devices, which can be used as either a linked or an unlinked system. The instrumented Bone Preserving (iBP) (Biomet, Warsaw, IN, USA) elbow prosthesis is an unlinked, ulnohumeral prosthesis, designed by Pooley. The iBP elbow prosthesis is a modification of the Kudo type 5, developed to preserve more bone stock (Figure 1) (3). A study with a mean follow-up of 49 months by Kleinlugtenbelt et al. (4) showed a discrepancy between clinical outcome and radiological signs. Patients scoring good-to-excellent on the Mayo Elbow Performance Score (MEPS) did show radiolucencies around their ulnar component, while patients with a poor MEPS score did not. As a result of this discrepancy, progressive radiolucency can occur without any clinical symptoms, which results in bone loss, hampering the results of revision surgery. In a study with a mean follow-up of 7.5 years, Dalemans et al. (5) reported a drop in survival 6 years after surgery due to instability, infection and metallosis, but they did not see loosening of the components in their patients. The aim of this study was to assess the long-term results of the iBP elbow prosthesis.

Figure 1 iBP uncemented (left) and cemented (right) ulnar and humeral components

METHODS

Between April 2000 and June 2009 37 primary iBP total elbow arthroplasties in 31 patients have been performed at University Medical Center of Groningen by 4 different orthopedic surgeons. All 31 patients (37 elbows) with a primary iBP were included in this study. Nineteen elbows were left and 18 were right elbows. Mean age of the patients was 55 at the time of surgery. Ten patients were male, 21 female. Indications for surgery were painful destruction of the elbow joint due to rheumatoid arthritis in 23 patients (28 elbows), posttraumatic osteoarthritis in 3 patients and haemophilic arthropathy in 5 patients (6 elbows). Patients' characteristics are shown in Table 1.

The study was reviewed and approved by the Medical Ethical Committee of UMCG (METc2016/038). None of the surgeons was involved in the design of the implant.

Table 1 Patient characteristics

Patient	Age range	Etiology	Side	Fixation	Survival (years)	Reason Revision	OES	DASH	MEPS	Flexion	Extension	Complication	
1	3	HA	L	H	14		40	42	60	70	30	ULN	
2	3	RA	R	H	14		42	69	90	135	20	ULN	
3	1	RA	L	H	14		22	70	70	130	25		
4	5	HA	R	H	12		48	21	95	125	40		
5	3	PTA	L	H	9		24	52	55	125	25		
6	5	RA	L	H	8		39	32	85	125	30		
7	5	RA	R	C	15		14	61	45	120	55		
8	3	RA	R	H	9		35	50	75	115	50		
9	4	RA	R	C	0	INST							
	4		L	H	9		37	54	90	130	30		
10	3	HA	R	H	13	MET						ULN, INF	
	3		L	C	8		16	42	70	115	70		
11	3	RA	R	H	9		32	17	90	120	45		
12	5	RA	R	H	13		43	46	100	130	30		
13	4	RA	R	H	10		39	28	95	140	30		
	4		L	H	9		38	28	100	145	35		
14	5	RA	R	C	15		42	45	75	130	5		
15	4	RA	R	H	11								
16	3	PTA	L	C	15	MET						DIS	
17	2	RA	R	H	13	MET							
18	6	RA	R	H	14							DIS	†
	6		L	H	10							ULN	†
19	3	RA	L	H	8								†
20	3	RA	L	H	2	AL							
21	3	HA	L	H	13	MET							
22	4	RA	L	H	4	INST							
23	6	RA	R	H	7								†
24	6	RA	L	H	1								†
25	5	RA	L	H	3							ULN	†
	5		R	H	2								†
26	6	PTA	R	H	10	MET							
27	4	RA	L	H	11								
	4		R	H	9								
28	3	RA	L	H	7							INF	†
29	4	RA	L	H	2	INF							
30	5	HA	L	H	2	AL							
31	4	RA	R	C	16								
Med	4	23 RA 3 PTA 5 HA			11		38	45	85	125	30		

Age range (years): 1=20-29, 2=30-39, 3=40-49, 4=50-59, 5=60-69, 6=70-79,

HA = haemophilic arthropathy, RA = rheumatoid arthritis, PTA = post-traumatic arthritis, C= cemented, H= hybrid (humeral component cementless), AL = aseptic loosening, INF = infection, INST = instability, MET = metallosis, ULN = ulnaropathy, DIS = dislocation, † = died

2

Age range (years): 1=20-29, 2=30-39, 3=40-49, 4=50-59, 5=60-69, 6=70-79,
HA = haemophilic arthropathy, RA = rheumatoid arthritis, PTA = post-traumatic arthritis, C= cemented, H= hybrid (humeral component cementless), AL = aseptic loosening, INF = infection, INST = instability, MET = metallosis, ULN = ulnaropathy, DIS = dislocation, † = died

Surgical technique

In all cases a posterior approach was used with a triceps split technique as described by Pooley (3,6). The ulnar nerve was released and protected during the procedure. Release of the collateral ligaments were performed in case of contractures. The radial head was excised in all cases. The humerus and ulna were prepared with preservation of as much bone as possible according to the philosophy of this prosthesis. All humeral components were inserted without cement, except for 6 elbow prostheses in which poor bone quality urged to the use of cement. All ulnar components were cemented.

Post-operatively the elbow was protected by a removable cast for 4 weeks, avoiding active extension. Thereafter, the elbow was mobilized without brace and active triceps training was allowed. Patients were advised to limit weight bearing up to 1 kg repetitively and to 5 kg incidentally.

Outcome measures

To assess pain, elbow function and social-psychological status, the Oxford Elbow Score (OES)(7) was used. Disabilities of Arm, Shoulder and Hand Outcome Measure (DASH) (8) was used to assess upper-limb function. The Mayo Elbow Performance Score (MEPS) (9) was used to assess pain, range of motion and stability. Health-related quality of life was determined by using the EQ5D-3L VAS score (10). Pain at rest and during activities was scored from 0 (no pain) to 10 (severe pain) using visual analogue scales (VAS). Patients were also asked whether they were satisfied with their elbow function. By means of physical examination we determined the active range of motion (ROM). The integrity of the ulnar nerve was assessed using careful clinical examination. The stability of the

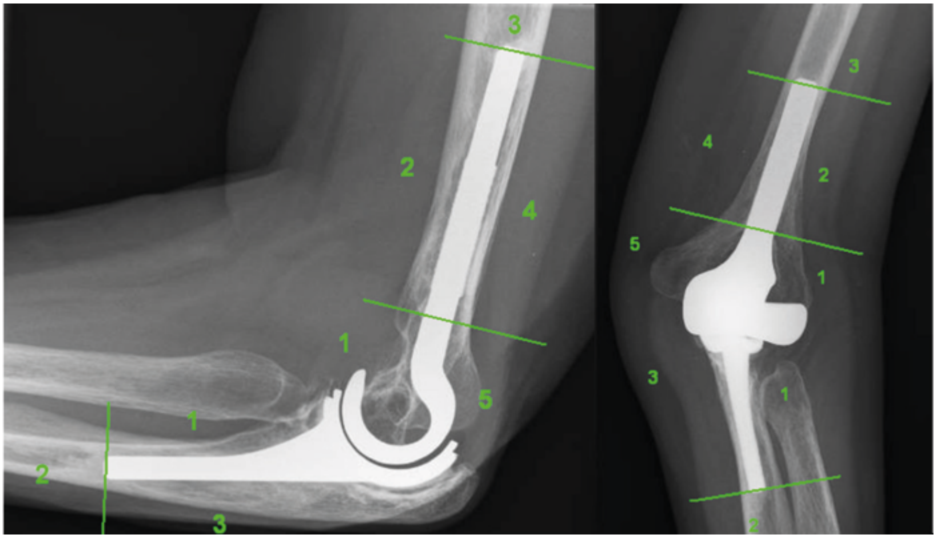

Figure 2 Classification of radiological analysis as described by Wagener et al. In each zone we looked for the presence of radiolucencies

medial and lateral collateral ligaments was scored as grade 0, no instability; grade 1, moderate instability (<10°) and grade 2 severe instability (>10°). All patients had standard anteroposterior (AP) and lateral radiographs of the elbow. Loosening of the implants was classified using the system described by Wagener et al. (11) (Figure 2). Radiographs were also assessed of dislocation of the prosthesis, subluxation, periprosthetic fractures and signs of metallosis.

Statistical analysis

SPSS statistical software (version 24.0, IBM SPSS, Chicago) was used. Descriptive statistics were used to describe patients' characteristics, clinical outcomes and scores on the questionnaires. Kaplan-Meier survival analysis was performed with revision as an end point. Kruskal-Wallis Test for independent samples was used to analyze differences in indication for surgery.

RESULTS

The mean follow-up of this study is 11 (8-15) years. At follow-up 6 patients (8 elbows) had died. Ten elbow prostheses in 10 patients had already been revised, leaving 19 primary prostheses in 17 patients in situ. Unfortunately, 3 patients (4 elbows) could not participate in our follow-up, as they were physically unable to come to the hospital. However, they did not have complaints of their elbow. 14 patients with 15 primary iBP elbow prostheses were available for clinical assessment (Figure 3).

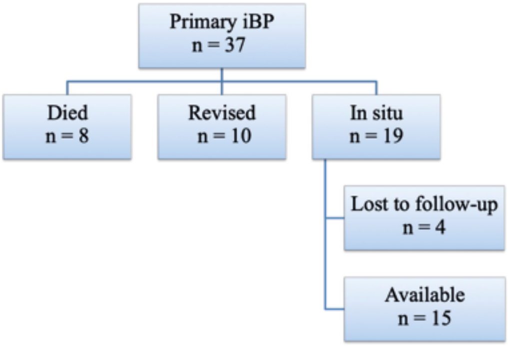

Figure 3 Flow diagram of iBP elbow prostheses

Survival

The Kaplan-Meier survival analysis (Figure 4) showed survival rates of 88% and 81% respectively at 5 and 10 years after surgery. All 37 primary iBP's were included in this analysis. Furthermore, a progressive decline in survival is visible beyond 10 years. Ten out of 37 iBP elbow prostheses had been revised. The reasons for early revision were infection in 1 patient, aseptic loosening in 2 patients and instability in 2 patients, which occurred in the first 4 years after surgery. The reason for late revision (after 9 years) was loosening with severe polyethylene wear and as a consequence metallosis in 5 patients (Figure 5,6). Arrows show radiolucency (orange) around the prosthesis and severe pseudotumor (blue), indicating metallosis.

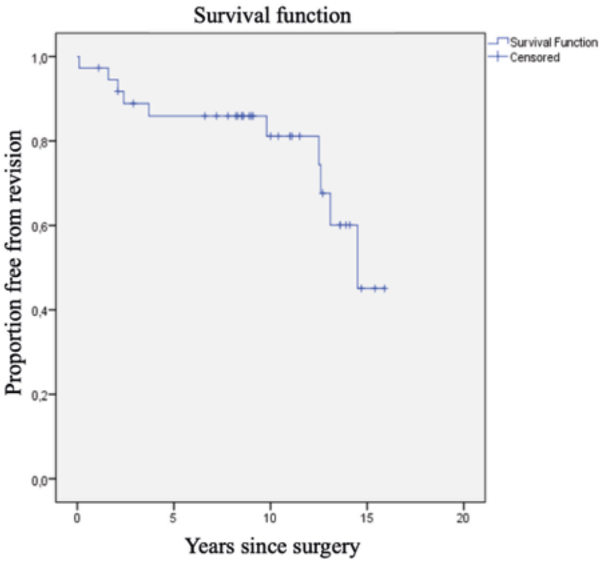

Figure 4 Kaplan-Meier survival analysis curve with revision for any reasons as an endpoint

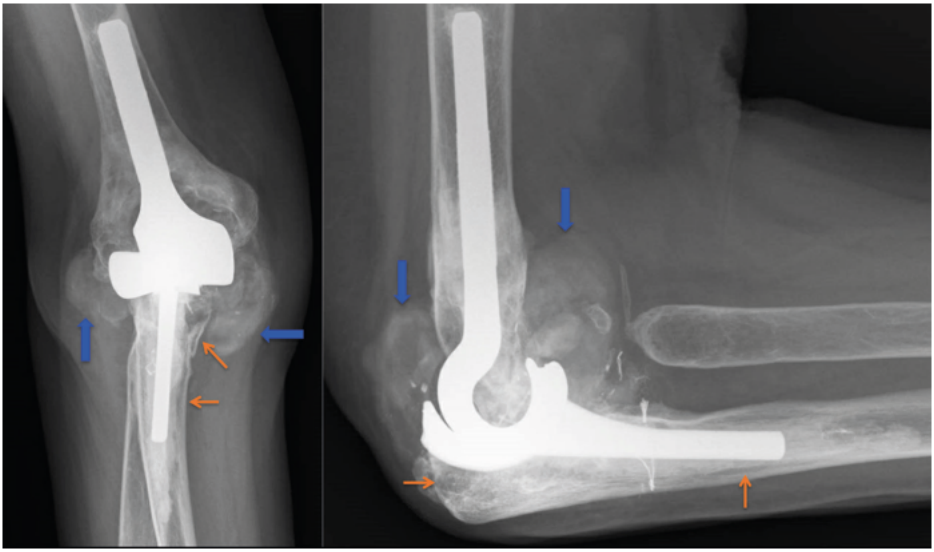

Figure 5 Radiological signs of PE wear and metallosis. Orange arrows showing radiolucencies, blue arrows showing pseudotumor

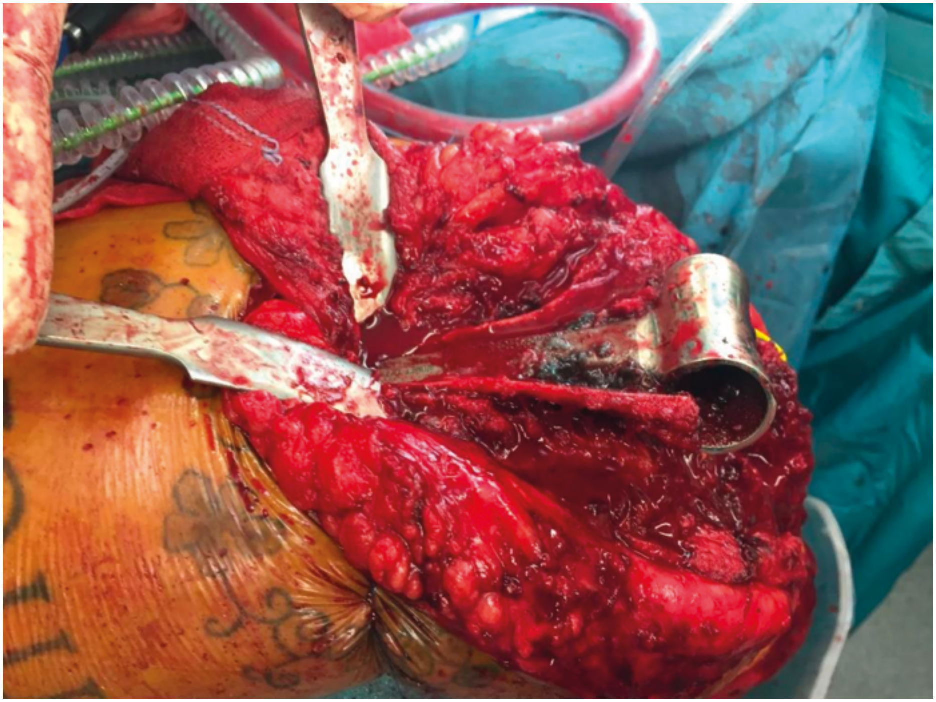

Figure 6 Revision arthroplasty by humeral osteotomy: severe metallosis

2

Clinical assessment

Overall, most patients were satisfied with their iBP elbow prosthesis. Only 2 out of 14 patients were not satisfied with the result. One patient was not satisfied, because of ulnar neuropathy and loss of function. Another patient was no longer satisfied because of loosening of the ulnar component that had led to loss of function. No revision arthroplasty was planned though because of severe comorbidities. One patient was indifferent, which left 11 patients (12 elbows) being satisfied with their iBP elbow prosthesis.

Mean MEPS score was 80 points (45-100) indicating a fair-to-good result. Lower scores indicated pain in most cases. Mean DASH score was 44 points (17-70) and mean OES 34 points (14-48). This score usually indicates mild-to-moderate elbow complaints. The underlying disease, rheumatoid arthritis, mainly influenced both scores, as illustrated by the health-related quality of life score: 6 (4-8). Assessment of pain on a 0-10 point scale scored a mean of 2 (0-7), indicating low pain levels.

Mean ROM was 90º (40º-125º), mean flexion 125º (70º-145º), mean extension deficit 35º (5º-70º). Mean pronation 70º (40º-95º), mean supination 75º (40º-95º). Seven out of 15 elbows were unstable. Two of them were grossly unstable and 5 were moderately unstable, although this was not clinically relevant in terms of dislocation. Three of 14 patients had signs of persistent ulnar neuropathy. There were no significant differences in clinical outcomes and survival between indication for surgery.

Radiological assessment

At the assessment, one out of 15 cases showed loosening of the ulnar component with a fracture in zone 3. Eleven out of 15 cases showed radiolucent lines, especially in zones 1 and 3 of the ulna. Three cases showed incongruity and another 3 cases showed signs of metallosis and pseudotumor (Table 2). Looking back at the already revised cases, 5 of 10 cases (all late revisions) had severe radiolucencies (especially zones 1 and 3 of the ulna) and signs of metallosis, which was confirmed at revision surgery.

All together in 15 of 25 cases (revisions and survivals) the radiographs indicated bone loss due to particle disease with PE wear and metallosis as to be expected. The case shown in Figure 5 demonstrated radiolucencies and pseudotumor, suggestive for metallosis. Painful loosening 10 years after primary surgery led to a revision in which severe bone loss was encountered.

Table 2 Radiological analysis

Patient	AP humerus	AP ulna	Lat humerus	Lat ulna	Pseudotumor
1	5	1,3		1,2,3	Yes
2	1			3	
3					
4				1,3	
5				3	
6	2	3	2,4	1,3	Yes
7	2,4	1	2,5		
8					
9					
10		1,3	1	1,3	
11	1		3	1	
12					
13	1	3	1	1,3	
			1,2	1,3	
14	1,2,5	1,3	1,5	1,3	Yes

AP = anteroposterior, Lat = Lateral. Numbers indicate zone of radiolucency.

AP = anteroposterior, Lat = Lateral. Numbers indicate zone of radiolucency as described in Fig 2.

DISCUSSION

The iBP elbow prosthesis is an unlinked prosthesis. The stability of the joint is provided by the soft tissues, therefore the risk of dislocation is higher than in a linked-type prosthesis (12,13). The theoretical advantage of this design is the lower risk of loosening, because of minimal stress on the bone-implant interface (5).

Our study shows survival rates for the iBP elbow prosthesis of 88% and 81% respectively at 5 and 10 years postoperatively with a progressive decline in survival beyond 10 years. Eleven of 14 patients were satisfied with their elbow as reflected in the scores of the questionnaires. In our study the main reason for revision was loosening with polyethylene wear and metallosis (50%), which is higher compared to the results of Dalemans et al. (33%), but they only had a follow-up of 7.5 years with their series of the iBP elbow prosthesis(5,12,13). In their series with the Kudo 5, an unlinked prosthesis with a mean follow-up of 14.5 years, the main reason for revision was loosening and metallosis as well (61%). The unlinked prostheses were originally developed to render less loosening than linked prostheses, but Voloshin et al. showed in their systematic review no significant difference in clinically relevant loosening between linked and unlinked elbow prostheses (12).

Over the last years improvements in the quality of PE have been made. A recent study by Popoola et al. (14) showed that vitamin E blended and crosslinked polyethylene gives lower in vitro wear compared to conventional gamma-irradiated polyethylene in two types of linked, semiconstrained total elbow prostheses. Probably motion in combination with the thin polyethylene in the design of the iBP prosthesis eventually leads to wear, metallosis and loosening.

When revising the iBP we had to revise the ulnar component in 3 of 10 cases.

In 6 of 10 cases persistent instability due to debridement of soft tissue and insufficiency of the collateral ligaments, required revision to a linked-type total elbow prosthesis. In one case a complete iBP revision was performed.

The relatively short survival and the described wear problems and loosening of the ulnar component in combination with the difficulties experienced in revision of an even well-fixed humeral stem have made us decide to stop using this prosthesis.

Another well-known complication after TEA is ulnar neuropathy (15-18). In our study 3 patients (20%) had some form of permanent ulnaropathy, despite the ulnar nerve was mobilized and protected during surgery. The reported outcomes on neuropathy after elbow prosthetic joint placement are conflicting. Tanaka et al. did not find ulnaropathy after release of the nerve (18). On the other hand, not mobilizing the ulnar nerve as shown by

Kleinlugtenbelt et al. resulted in 6% ulnaropathy(4), by Brinkman et al. a high rate of 20% ulnar neuropathy was found (15). Postoperative ulnar neuropathy rates appear to vary, so we recommend further research to determine whether mobilization of the ulnar nerve is preferred.

Mean arc of motion in our study was 90º, with a mean flexion of 125º and a mean extension deficit of 35º. Mean pronation was 70º and mean supination 75º. Morrey et al. (19) described that the functional arc of motion required for activities in daily life was 120/30 for flexion/ extension and 50/50º for pronation/supination. Five out of 14 patients had a range of motion inferior to this standard. Most of the patients were nonetheless satisfied with their elbow function.

Few studies have been conducted to determine the long-term outcome of the iBP elbow prosthesis. One study by Kleinlugtenbelt et al. (4) showed a discrepancy between clinical evaluation and radiological signs at short-term follow-up, with a mean follow-up of 4 years. Our study showed this discrepancy too.

Loosening of the ulnar component was seen in 11 patients, although 8 of them did not have any complaints of their elbow. In 9 of these 11 patients radiolucencies around the humeral component were seen. Seven patients had some degree of elbow instability at physical examination without dislocation; 3 of them did show radiological signs of subluxation.

Our current ‘care as usual’ does not routinely include medium or long term follow-up. The outcome of this study has changed our policy and we routinely do a structural follow-up. Patient related outcome measures only will not be sufficient to assess the integrity of these implants. Following this study, another three prostheses have been revised. All three of them with severe polyethylene wear and metallosis.

LIMITATIONS

We were only able to examine a small number of patients. Our study had a retrospective design, which entailed an important loss of patients. The strength of this study is the length of follow-up.

CONCLUSION

We warrant a structural follow-up for all iBP implants, because of the discrepancy between clinical signs and symptoms and radiological loosening, metallosis and consequent progressive bone loss.

ADDITIONAL REMARK

Following the publication of our study, one more recent study on the iBP elbow prosthesis has been published (20). The outcomes of this study were comparable to those of our study, but implant survival rates were inferior. Since that time, the prosthesis has been withdrawn from the market, and no further studies on this type of prosthesis have been published.

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Chapter 3

Mid-term results of the Latitude primary total elbow arthroplasty.

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ABSTRACT

Background: The Latitude total elbow prosthesis is a third-generation implant, developed to restore the natural anatomy of the elbow. Literature on this prosthesis is scarce. Aim of this study is to analyze the mid-term results of the Latitude total elbow prosthesis.

Methods: Sixty-two patients (21M, 41F) were retrospectively evaluated. Mean age at surgery was 65 years (range 28-87). Main indication for surgery was inflammatory arthritis. Outcome measures were complications and re-operations, self-reported physical functioning, pain, satisfaction, objectively measured physical functioning, and radiological signs of loosening. Kaplan-Meier survival analysis was used to determine survival with revision as an endpoint.

Results: Sixty-nine primary Latitudes were placed in 62 patients between 2008 and 2019. Six patients (seven prostheses) died, three elbows were revised, and nine patients were lost to follow-up. Forty-four patients (50 prostheses) were available for follow-up. Mean follow-up was 51 months (range 10-144). Kaplan-Meier survival analysis showed a survival rate of 82% at 10 years after surgery. Main reason for revision was aseptic loosening. Radial head dissociation was seen in eight patients (24%), but none of them had complaints. Self-reported and objectively measured physical functioning yielded good results, although 23 patients (46%) did show radiolucent lines on radiographs.

Conclusion: Latitude TEA is considered a successful procedure with low pain scores, high patient satisfaction, and good physical functioning. Survival rates nonetheless remain low and complication rates high, yet comparable to other elbow arthroplasties. We recommend biomechanical studies to concentrate on specific postoperative loading instructions in order to minimize wear and consequent loosening.

BACKGROUND

Total elbow arthroplasty (TEA) is frequently used in the Netherlands to treat a variety of debilitating elbow pathologies (1). The indication for TEA currently includes rheumatoid arthritis and osteoarthritis, as well as complex fractures of the elbow in elderly patients or in patients with post-traumatic arthritis (2). Unfortunately, survival rates of elbow arthroplasties (10-year survival 80-85%) remain low compared to hip and knee arthroplasties (10-year survival 90-95%) (3-7). The major reason for revision is aseptic loosening (8).

Several new implant designs have been developed over the last decades to improve TEA survival (3, 4, 9, 10). The first designs were fully constrained, but the high force transmission caused early failure. Unlinked designs were developed to avoid this constraint issue. However, these designs caused problems in patients with ligamentous deficiency and instability. The Latitude (Wright Medical, USA) total elbow prosthesis is developed to restore the natural anatomy. It is a convertible device and can be used as either an unlinked or a linked version. The linked version is developed with 7 degrees varus-valgus laxity. The native radial head can either be preserved, resected or replaced by a radial head component, depending on the anatomy of the elbow joint and the surgeon's preference. It has a titanium coating to enhance long-term fixation. Our common practice was to retain the native radial head only if it was in a relatively good condition. Replacement of the native radial head with a prosthesis was performed in cases with severe degeneration or deformation of the radial head with adequate alignment with the capitellum. In all other cases the radial head was resected. The original Latitude was updated in 2013 to the Latitude EV, with changes in humeral design, coating of the humeral and ulnar components, and bending of the ulnar component; besides the prosthetic changes the instrumentation was also simplified, to facilitate the surgical technique.

The Latitude prosthesis has been in clinical use since 2001, but literature on the prosthesis is scarce and survival rates are not always reported. Recently Wagener et al. (11) showed their mid-term results with the Latitude for a mean follow-up of 43 months, but did not analyze survival rates. A major complication in their study was dissociation of the radial head component in 31% of their patients. They did not detect loosening of the prosthesis, which has been described frequently as a long-term complication after TEA (2, 12-14). However, they did see radiolucencies around humeral, ulnar and radial components (4-6%). Cinats et al. (15) published their results with the Latitude prosthesis in a study with a mean follow-up of 4.7 years, but did not report survival rates either. They reported only 9% radial head dissociation. However, radiolucencies were seen in 60% of their patients, which might be a concern in the long term since progressive radiolucencies can result in early prosthetic loosening. Mehta et al. (16) are the only authors to report survival rates of the Latitude with a 95% survival at short-term (2 years) follow-up.

Aim of our study was to analyze the mid-term results of the Latitude elbow prosthesis – more specifically, the survival, complications, pain, satisfaction, physical functioning, and radiological outcomes.

MATERIALS AND METHODS

A retrospective study was conducted at two Dutch hospitals, University Medical Center Groningen (UMCG) and Martini Hospital Groningen. Included were all patients with a primary Latitude elbow prosthesis who were treated between 2008 and 2019: a total of 62 patients (21 male, 41 female) with 69 prostheses. Mean age at time of surgery was 65 years (range 28-87). Forty-three prostheses were left-sided and 26 right-sided. The indication was inflammatory arthritis in 36 cases, osteoarthritis in 6, post-traumatic arthritis in 17, hemophilic arthropathy in 2, acute fracture in 3, instability in 1, Hegeman's disease in 2, pseudoarthrosis in 1, and synovial chondromatosis in 1 (Table 1). The study was reviewed and approved by the Medical Ethical Committee of UMCG (METc2019/532). Local approval was obtained from Martini Hospital (MEC 2020-021).

Surgical technique

All procedures were performed by two senior orthopedic surgeons (2008-2012 ALB at UMCG, from 2013 ALB and CLEG together at both hospitals). In 23 cases a triceps-detaching approach was used, (17) in 46 cases a triceps-sparing approach (18). The ulnar nerve was always located and released. The radial head was excised in 18 cases; a radial head component was placed in 48 cases. In the remaining three cases the radial head was left intact. All components were inserted with cement and all prostheses were linked. In 16 cases a Latitude prosthesis was inserted, in 53 cases a Latitude EV.

For a triceps-detaching approach, the elbow was protected by a removable cast for 4 weeks postoperatively, avoiding active extension. Thereafter, the elbow was mobilized without a brace and active triceps training was allowed. When a triceps-sparing approach was performed, patients were allowed to start functional mobilization immediately and weight bearing after 3 weeks. All patients were advised to limit weight bearing up to 1 kg repetitively and 5 kg incidentally.

Outcome measures

Outcome measures were survival, complications, re-operations, pain, satisfaction, self-reported physical functioning, objectively measured physical functioning, and radiolucent lines on anteroposterior (AP) and lateral radiographs.

Elbow function was measured with the Oxford Elbow Score (OES) (19), which consists of three sub-domains: pain, function, and social-psychological. Total scores vary between 0 and 48, where a lower score represents greater severity. The Dutch-language version is considered reliable and valid (20). Upper limb function was assessed using the Quick Disabilities of Arm Shoulder and Hand (Quick-DASH) (21), which gives a score out of 100 with a higher score indicating greater disability. The questionnaire is available in Dutch and is considered reliable and valid. Health-related quality of life was measured by the EQ5D-5L-VAS score, a widely used and valid generic instrument to measure health-related quality of life that is validated in Dutch (22, 23). Elbow pain was determined using a 10-point Numeric Rating Scale (NRS). Pain level was scored during activities and at rest. Lastly, patients were asked whether they were satisfied with their elbow prosthesis. This item is self-constructed and consists of five answer options: completely agree, agree, neutral, disagree, completely disagree.

Range of motion (ROM) (flexion, extension, pronation, supination) was measured using a goniometer. A systematic review analyzing use of a goniometer in elbow measurements showed high intrarater and interrater reliability of the universal goniometer (24). Elbow stability was stated as intact, < 10° instability or > 10° instability. Motoric and sensory deficits of the ulnar, medial, and radial nerves were tested. The Mayo Elbow Performance Score (MEPS) measures elbow function across four sub-domains: pain, range of motion, stability, and daily functional tasks (25).

All patients had standard AP and lateral radiographs of the elbow. Radiolucent lines around the implants were classified using a system described by Wagener et al. (11) Radiographs were also assessed of prosthetic dislocation/dissociation and periprosthetic fractures. Dissociation is defined as the radial head component being dissociated from the stem in AP or lateral view.

Statistical analysis

Descriptive statistics were used to describe patients' characteristics and clinical outcomes. Kaplan-Meier survival analysis was performed with revision as an endpoint. The Kruskal-Wallis Test for independent samples was used to analyze differences in indication for surgery between the three major groups (inflammatory arthritis, osteoarthritis, post-traumatic arthritis). The Mann-Whitney U-test (data was not normally distributed) was used to analyze differences in outcomes between type of Latitude elbow prosthesis and surgical approach. SPSS statistical software (version 24.0, IBM SPSS, Chicago) was used. P-values < .05 were considered statistically significant.

RESULTS

Mean follow-up was 51 months (10-144). At follow-up six patients (7 prostheses) had died and three prostheses had been revised. This left 53 patients with 59 prostheses in situ, who were invited for a follow-up visit. Nine patients were unable to visit the hospital due to several comorbidities, sometimes combined with Covid-19, so clinical data of 44 patients (50 prostheses) are reported in this study (Fig. 1). There was no significant difference in age or sex between the patients lost to follow-up and those available for follow-up. There was no significant difference in outcome measures between patients > 24 months follow-up and < 24 months follow-up. Therefore, we decided to include all patients regardless of length of follow-up.

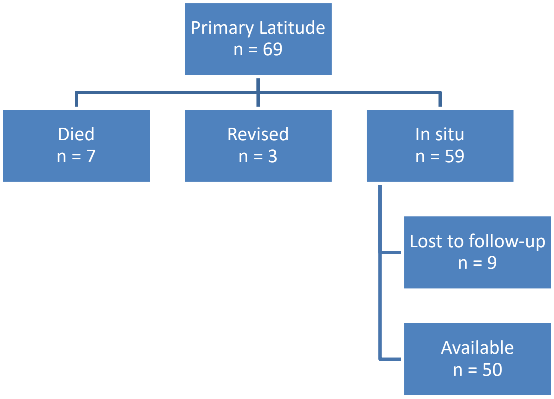

Figure 1. Flow- chart of Latitude elbow prosthesis.

Survival

The Kaplan-Meier survival analysis (Fig. 2) showed survival rates of 91% and 82% at 5 and 10 years after surgery, respectively. All 69 primary Latitudes were included in this analysis. Three elbow prostheses had been revised. Reasons for revision were aseptic loosening in two cases (5 and 7 years after TEA) and infection in one case (4 years after TEA). In addition, one patient died due to sepsis caused by an infected elbow prosthesis (4 years after TEA), so this was also registered as an event. There were no significant differences in survival rates between indication for surgery.

Complications and re-operations

Not including revisions, all complications and re-operations of the total group (62 patients, 69 prostheses) are reported in this section. The most frequently reported complication was ulnar nerve neuropathy in nine patients (13%), three of whom (4%) needed additional surgery. Other neuropathies were seen in two patients (3%): one radial nerve neuropathy, proximally from the elbow joint and treated conservatively, and one neuropathy of the posterior interosseus nerve due to cement leakage, requiring surgical removal of the cement. Loosening of the humeral component was reported in two patients (3%); one of them had loosening of the radial head component too. These two patients were not scheduled for revision surgery, since one was asymptomatic and the other suffered from several comorbidities. There was one radial head dislocation (2%), requiring surgical removal. Three patients (4%) had an infection, one requiring three additional surgical procedures and two requiring two procedures. All three patients retained the primary prosthesis. One patient (1%) had a perioperative fracture of the coronoid and was treated

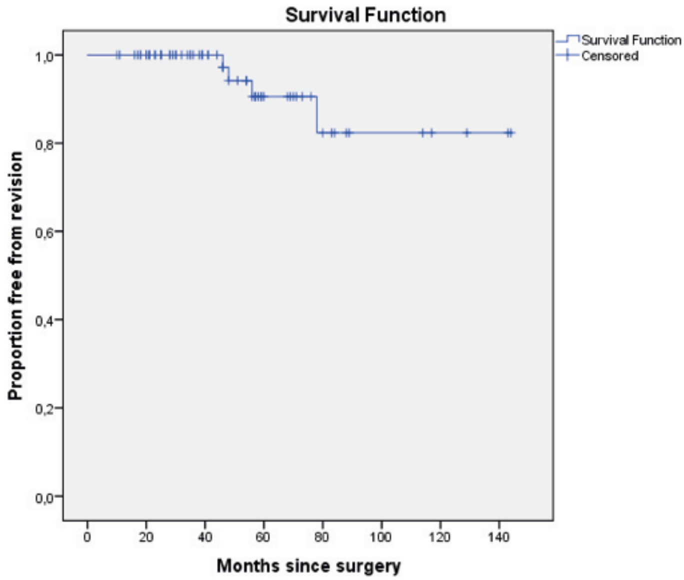

Figure 2. Kaplan-Meier survival analysis curve with revision for any reason as an endpoint. Note number at risk by 5 years = 17, by 10 years = 3.

3

with a wire cerclage. Two additional surgical procedures were performed, one involving removal of an osseous fragment in the olecranon bursa, another involving removal of the cap of the Latitude prosthesis to an unlinked version; this was planned in conformity with the original recommendation, yet soon after the first TEA procedures both the distributor and colleagues advised that this was not necessary.

Self-reported physical functioning

Outcomes of 44 patients (50 prostheses) available for follow-up are reported in this section. Mean OES score was 35 points (2-48, SD 13), mean DASH score 36 points (0-91, SD 27), mean EQ5D-VAS score 66 (10-100, SD 23). Mean NRS pain score was 2 at rest (0-10, SD 3) and 3 during activities (0-10, SD 3), indicating low pain levels. Overall, most patients (79%) were satisfied with their Latitude elbow prosthesis. Five patients (10%) were not satisfied with the result: three suffered from neuropathies, two reported high pain levels. One patient (2%) was no longer satisfied, due to neuropathy and a radial head dislocation requiring revision surgery. Four patients were neutral (8%). There were no significant differences in these self-reported outcomes between surgical technique, type of Latitude and indication for surgery.

Table 1

Patient	Sex	Age at surgery (years)	Indication	Side	Type	Surgical approach	Radial head	Survival (years)	Reason for revision	Complication	Flexion	Extension deficit	OES	QDASH	EQ5D	MEPS	NRS rest	NRS activities	Radial head dissociation
1	F	43	PTA	R		TD	PR	12		CAP	115	25	12	77	40	55	7	9	
2a	M	63	HA	R		TD	PR	11			120	35	45	7	85	95	0	0	
2b		62	HA	L		TD	PR	12			125	35	45	7	85	100	0	0	
3	F	74	PTA	L		TD	RES	10			145	25	32	43	40	85	3	7	
4	F	56	IA	L		TD	PR	10		INF, FRACT	140	15	31	50	30	90	0	1	
5	F	83	PTA	L	EV	TD	PR	7		AL	120	70	18	75	90	35	5	6	
6a	F	54	IA	R	EV	TS	RES	2		ULN	135	25	34	61	50	85	6	6	
6b		53	IA	L	EV	TS	RES	3			140	25	42	46	50	85	0	4	
7a	F	68	IA	R	EV	TS	PR	3			130	75	12	86	50	50	5	7	
7b		68	IA	L	EV	TS	RES	3		RDN	135	60	8	91	25	50	7	9	
8	F	74	PTA	L		TD	RES	7			140	30	48	36	75	95	1	3	
9	M	44	PTA	L	EV	TS	PR	5		AL	110	20	7	75	45	55	10	7	
10	F	50	IA	L	EV	TS	PR	5			120	85	23	57	50	75	1	2	
11	F	46	IA	L	EV	TD	PR	6			145	40	21	48	60	70	4	7	
12	M	28	PTA	R	EV	TS	PR	5			135	40	40	25	50	95	0	3	
13	F	52	PTA	L	EV	TS	RES	2											
14	M	43	PTA	L		TD	RES	7	AL										
15	F	77	PTA	L		TD	PR	2											†
16	F	77	OA	L		TD	PR	4	INF										

Table 1

Patient	Sex	Age at surgery (years)	Indication	Side	Type	Surgical approach	Radial head	Survival (years)	Reason for revision	Complication	Flexion	Extension deficit	OES	QDASH	EQ5D	MEPS	NRS rest	NRS activities	Radial head dissociation	
17a	F	73	PTA	L		TD	PR	2												†
17b	F	73	PTA	R		TD	PR	2												†
18	F	63	IA	L		TD	PR	6		AL										†
19	F	67	IA	L	EV	TS	RES	2												†
20	F	67	IA	L		TD	PR	6		INF										
21	F	85	IA	R	EV	TS	PR	2												†
22	F	64	IA	L	EV	TD	PR	5	AL											
23	M	46	HD	L	EV	TS	PR	5			110	40	21	39	70	80	1	4		
24	F	87	FRA	R	EV	TS	RES	1			100	25				75	0	0		
25	M	78	FRA	R	EV	TS	PR	3		ULN										
26	F	45	INST	L	EV	TD	PR	6					48	2	95		0	0		
27	M	56	PTA	L	EV	TD	PR	5		ULN	120	20	22		70	70	7	7		
28	M	66	PTA	R	EV	TS	PR	4			140	25	48	9	95	100	0	1	Y	
29a	M	71	IA	L	EV	TS	RES	3			100	40	46	0	90	95	1	1		
29b		71	IA	R	EV	TS	PR	3			125	25	46	0	90	100	1	1		
30	F	77	IA	R	EV	TS	PR	1			135	40	48	0	90	95	0	0		
31	M	71	IA	R	EV	TS	PR	5			140	30	47	5	80	100	0	0	Y	
32	M	65	OA	R	EV	TS	PR	1			125	15	47	0	95	100	0	1		
33	F	70	IA	R	EV	TD	PR	6			140	10				100	0	0	Y	

Table 1

Patient	Sex	Age at surgery (years)	Indication	Side	Type	Surgical approach	Radial head	Survival (years)	Reason for revision	Complication	Flexion	Extension deficit	OES	QDASH	EQ5D	MEPS	NRS rest	NRS activities	Radial head dissociation
34	M	81	IA	L	EV	TS	PR	3		ULN	125	15	46	0	90	100	0	0	
35	F	80	PSA	L	EV	TS	PR	5			140	15	48	0	85	100	0	0	
36	F	66	OA	L	EV	TS	PR	5			130	20	29	50	50		7	7	
37	F	70	IA	R	EV	TS	PR	2			125	30	29	41	80	80	3	3	Y
38	F	72	IA	R		TD	PR	7			140	10	48	30	30	95	0	0	Y
39a	M	42	IA	L	EV	TS	PR	5			110	10	28	55	30	75	5	7	
39b		46	IA	R	EV	TS	PR	2			100	30	28	55	30	80	5	7	Y
40	M	46	IA	L	EV	TS	RES	2											
41	F	58	PTA	R	EV	TS	PR	1			110	35	32	25	80	80	3	3	
42	F	75	FRA	L	EV	TS	RES	4		OBF	130	20				100	0	0	
43	F	76	IA	L	EV	TS	PR	5											
44	F	52	IA	L	EV	TS	RES	4		ULN	130	30	36	30	70	95	0	4	
45	M	67	IA	R	EV	TS	RES	2		ULN	120	20	34	46	70	85	3	4	
46	F	32	IA	R	EV	TS	RES	3			135	75	35	23	50	100	0	4	
47	F	71	HD	L	EV	TS	RES	4		ULN	135	35	28	52	60	85	3	3	
48	F	83	IA	R	EV	TS	PR	1			145	10	44	36	75	100	0	0	
49	M	60	SC	L	EV	TS	RET	2		ULN	120	25	42	7	90	95	2	3	
50	F	55	PTA	L	EV	TS	PR	3		PIN, RHD	140	5	2	91	10	30	8	10	
51	F	72	IA	R	EV	TS	RET	4		INF									†

Table 1

Patient	Sex	Age at surgery (years)	Indication	Side	Type	Surgical approach	Radial head	Survival (years)	Reason for revision	Complication	Flexion	Extension deficit	OES	QDASH	EQ5D	MEPS	NRS rest	NRS activities	Radial head dissociation
52	M	69	PTA	L	EV	TS	RES	3			135	0	42	11	100	100	0	0	
53a	M	69	IA	R	EV	TS	PR	4			120	15	46	55	70	100	0	0	Y
53b		69	IA	L	EV	TS	PR	3			135	15	46	55	70	100	0	0	
54	M	72	IA	L	EV	TS	RET	2		INF	140	5	32	46	50	100	2	3	
55	F	66	IA	L	EV	TS	PR	2											
56	M	69	OA	R	EV	TS	PR	3			130	5	42	7	85	100	0	0	
57	F	83	IA	L	EV	TS	PR	4		ULN									
58	F	78	OA	L		TD	PR	7											
59	F	55	IA	L		TD	PR	7			140	10	32	50	60		4	5	
60	F	74	OA	L	EV	TD	PR	6			130	5	40	63	75	85	2	4	
61	M	74	IA	R	EV	TS	PR	5			130	20	48	7	70	100	0	0	Y
62	F	70	PTA	L	EV	TS	RES	3			150	5	39	11	85	100	1	2	
Mean (SD)		65 (13)									129 (12)	27 (19)	35 (13)	36 (27)	66 (23)	86 (18)	2 (3)	3 (3)	

IA = inflammatory arthritis, OA = osteoarthritis, PTA = post-traumatic arthritis, HA = hemophilic arthropathy, INST = instability, HD = Hegeman's disease, FRA = fracture, PSA = pseudoarthrosis, SC = synovial chondromatosis, TS = triceps-sparing, TD = triceps-detaching, PR = prosthesis, RES = resected, RET = retained, AL = aseptic loosening, INF = infection, ULN = ulnar nerve neuropathy, RDN = radial nerve neuropathy, PIN = posterior interosseous nerve neuropathy, RHD = radial head dislocation, CAP = removal of the cap, OBF = olecranon bursa osseus fragment, † = died.

Objectively measured physical functioning

Outcomes of 44 patients (50 prostheses) available for follow-up are reported in this section. Mean flexion was 129º (100º-150º, SD 12), mean extension deficit 27º (0º-85º, SD 19), mean pronation 69º (25º-85º, SD 14), mean supination 68º (10º-90º, SD 19). Stability was intact in the majority of patients. In three patients (5%) the elbow was unstable: two patients diagnosed with loosening of the prosthesis and one patient with an unlinked Latitude. Mean MEPS score was 86 points (30-100, SD 18), indicating good results. There were no statistical differences in these objectively measured physical outcomes between surgical technique and type of Latitude. Indication for surgery did influence postoperative supination. This difference was significant ($p=0.013$) between osteoarthritis (mean supination 83°) and post-traumatic arthritis (mean supination 62°), favoring patients with osteoarthritis.

Figure 3. Radiologic loosening of humeral and radial head components.

Radiological assessment

Outcomes of 44 patients (50 prostheses) available for follow-up are reported in this section. At the clinical assessment, one additional patient showed loosening of both the humeral and the radial head components (Fig.3). Diagnostic testing did not reveal an infection, so one-stage revision was scheduled for a few months later. During revision surgery the humeral spool was also loose.

Radial head dissociation was visible on radiographs in eight patients (24%, total of 34 patients with radial head component in this group), yet none of them had complaints. Further, a total of 23 patients (46%) showed radiolucent lines, especially in zones 1 and 5 of the humeral component (Table 2). Looking back at the already-revised cases, one patient had aseptic loosening of all three components, the other a massive pseudotumor with particle disease and aseptic loosening of the humeral spool.

Table 2

Patient	AP humerus	AP ulna	AP radius	Lat humerus	Lat ulna	Lat radius	Radial head dissociation
1	5			1,2			
2a		3					
2b	2	3					
3							
4	1						
5	1-5			1-5			
6a				1-3			
6b		3					
7a			1-3	1		1-3	
7b	1,5				1,3		
8					3		
9	1,2,4,5	1	1-3	1,2,4,5	3	1-3	
10	1					3	
11							
12		3			1	3	
13							
14							
15							
16							
17a							
17b							
18							

Table 2

Patient	AP humerus	AP ulna	AP radius	Lat humerus	Lat ulna	Lat radius	Radial head dissociation
19							
20							
21							
22							
23	5			1,5	3	1	
24							
25							
26							
27							
28							Y
29a							
29b							
30				4,5			
31							Y
32							
33	1		1-3			1-3	Y
34							
35							
36			1			1	
37							Y
38					1		Y
39a					3		
39b							Y
40							
41							
42							
43							
44							
45							
46							
47							
48							
49	5						
50							
51							

Table 2

Patient	AP humerus	AP ulna	AP radius	Lat humerus	Lat ulna	Lat radius	Radial head dissociation
52	5						
53a							Y
53b							
54							
55							
56	1,5	3		5	3		
57							
58							
59		2,3			1-3	1	
60							
61							Y
62							

AP=anteroposterior, Lat=lateral. Numbers indicate zone of radiolucency.

DISCUSSION

This study shows survival rates of 91% and 82% at 5 and 10 years, respectively, after Latitude TEA. These results are comparable to survival rates of other TEA designs, with rates varying between 82 and 90% at 5- and 10-years follow-up (3).

Reasons for revision in our series were infection in one patient and aseptic loosening in two patients. Aseptic loosening of the humeral component was observed in three other patients in our study (6%), and two of them also had loosening of the radial head component. These results are comparable to previously reported results in a review by Prkic et al. (8), with aseptic loosening as the most common reason for revision, followed by infection.

Several mechanisms causing aseptic loosening have been reported. Marsh et al. (26) ascribe loosening to long-term overloading. Overloading leads to polyethylene (PE) wear, which in turn eventually results in bone and tissue destruction, causing unstable fixation and loosening. In our series, two out of five patients with aseptic loosening performed heavy physical work, despite our postoperative instruction to limit weight bearing to up to 1 kg repetitively and 5 kg incidentally. Overloading might have contributed to early loosening of the prosthesis in these cases.

Besides overloading, the design of the prosthesis might also influence the risk of loosening. It is hypothesized that unlinked TEAs induce less stress and hence reduce wear and loosening. In their cadaveric study, Brownhill et al. (27) investigated humeral loading of the linked and unlinked Latitude elbow prosthesis and concluded that linking the Latitude leads to a nearly-doubled amount of humeral loading in the varus direction. This may have detrimental effects on implant survival, as loading might induce wear and loosening. The authors therefore advised that patients with a linked version of the Latitude should be cautioned to avoid heavier activities as a result of greater stress on the implant. However, to the best of our knowledge no specific postoperative loading instructions for patients following TEA are available. We therefore recommend that future research concentrate on specific postoperative loading instructions in order to minimize wear and consequently loosening. Although in vitro studies show favorable results for unlinked designs, these results are not yet supported by clinical evidence. Welsink et al. (3) concluded in their systematic review that there was no single type of design (e.g. linked/unlinked) that could be supported over another when looking at survival rates and complications following TEA. Similar results are reported in linked and unlinked Latitude prosthesis (11, 15, 16, 28). It is considered an advantage of the Latitude that it offers the possibility to decide whether the prosthesis is placed linked or unlinked. And yet considering the lack of clear evidence for one design over the other, it is hard to make an evidence-based decision. In our series, one removal of the cap of the Latitude prosthesis to an unlinked version was performed. Initially this was scheduled for all patients, but soon after the first TEA procedures both the distributor and colleagues advised that this was not necessary.

Other major findings in our series were radial head dissociation in eight patients (24%) and one radial head dislocation (2%), requiring surgical removal. These numbers are lower than those presented by Wagener et al. (11), who showed 31% dissociation of the radial head, but higher than reported by Cinats et al. (15), who only had 9% radial head dissociation. Although patients in our study did not have complaints of radial head dissociation, the implications of this problem remain unclear. Recently, Wright developed a newer, more modular type of radial head component, possibly preventing this complication. Another possibility is to leave the native radial head in place (11).

Further, ulnar nerve neuropathy was seen in nine patients (13%), three of whom (5%) needed additional surgery. Still, ulnar nerve neuropathy rates appear to vary in literature and it is unclear whether mobilizing the nerve affects the outcomes (12, 15, 16, 29-32). Our routine care therefore remains to locate and release the ulnar nerve during TEA, while leaving the nerve posteriorly if possible or transposing it anteriorly when needed because of tension and pressure.

Another concern is that a total of 23 patients (46%) showed radiolucent lines, especially in zones 1 and 5 of the humeral component. Progression of radiolucent lines can lead to loosening of the prosthesis. We recognize the aspect of asymptomatic radiolucent lines following TEA as described earlier (12, 13), and expected that a more anatomical design would give better fixation and fewer of these radiological signs. Our series do show, however, that also after a TEA with the Latitude prosthesis patients should be followed for asymptomatic loosening. Structural follow-up is therefore warranted to allow for timely intervention, thereby preventing severe bone destruction which also hampers results of revision surgery.

Despite the low survival rates and high complication rates, we consider TEA a successful procedure, since this study and previous studies show that patient satisfaction is high, pain scores are low, and scores on self-reported and objectively measured physical functioning are good.

LIMITATIONS

Our study had a retrospective design, which entailed an important loss of patients. Further, due to the retrospective design we had a wide range in follow-up.

CONCLUSION

Latitude TEA is considered a successful procedure with low pain scores, high patient satisfaction, and good physical functioning. Outcomes were similar for all indications for surgery. Survival rates nonetheless remain low and complication rates high, yet comparable to other elbow arthroplasties. We recommend that biomechanical studies concentrate on specific postoperative loading instructions in order to minimize wear and consequent loosening.

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PART 2: THE PATIENT

Chapter 4

Elbow joint biomechanics focusing on total elbow arthroplasty - a scoping review.

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ABSTRACT

Background: Overloading is hypothesized to be one of the failure mechanisms following total elbow arthroplasty (TEA). Yet, it is unclear whether the current post-operative loading instruction is compliant with reported failure mechanisms. Aim is therefore to evaluate the elbow joint load during activities of daily living (ADL) and consequently compare these loads with reported failure limits from retrieval and finite element studies.

Methods: A scoping review of studies until November 23rd 2021 investigating elbow joint load during ADL were identified searching PubMed/Medline and Web of Science. Eligible studies: (1) report on the elbow joint load in native elbows or elbows with an elbow arthroplasty in adults; (2) full text article available.

Results: Twenty-eight studies with a total of 256 participants were included. Methodological quality was low in 3, moderate in 22 and high in 3 studies. Mean flexion-extension joint load was 17 Nm, mean varus-valgus joint load was 9 Nm, mean pronation-supination joint load was 8 Nm and mean bone-on-bone contact force was 337 N.

Conclusion: The results of our scoping review give a first overview on the current knowledge of elbow joint loads during ADL. Surprisingly, the current literature is not sufficient to formulate a postoperative instruction regarding elbow joint loading, which is compliant with failure limits of the prosthesis. In addition, our current instruction appears to not be evidence-based. Our recommendations offer a starting point in order to assist clinicians in providing informed decisions about post-operative instructions for their patients.

BACKGROUND

Total elbow arthroplasty (TEA) is a viable option for patients with end-staged, symptomatic elbow pathology such as post-traumatic arthritis, post-traumatic deformities, primary osteoarthritis or rheumatoid arthritis (1). Its survival rate is limited by complications (10-40% complication rates) and mechanical failures with aseptic loosening and polyethylene (PE) wear, leading to 10-year survival rates of 80-85% (2-4). These survival rates are low compared to hip and knee arthroplasties (~95%) (5, 6). Understanding the mechanisms of TEA failure may help in formulating implications for clinical practice, in order to improve implant survival rates and lower complication rates.

Based on retrieval studies, several mechanisms have been hypothesized to cause TEA failure. First, overloading of the prosthesis during activities of daily living (ADL) is thought to result in PE wear, with consequently instability of the hinge, asymmetric varus-valgus load transmission and PE particle disease. This cascade finally results in bone and tissue destruction and loosening of the implant. For example, PE wear of the Coonrad Morrey (Zimmer Biomet, USA) elbow prosthesis, retrieved at revision surgery, showed asymmetrical wear with PE bushings deformed to an elliptical shape, which is mainly attributed to varus-valgus and torsional loading of the elbow (7). A second mechanism of failure may be due to inadequate cement fixation (8), where excessive stresses at the bone-(cement)-prosthesis interface leads to micromotion and consequent failure.

Next to retrieval studies, finite element studies examining the stress distribution on the elbow prosthesis have also shed light on the failure mechanisms of TEA. In a study by Lo and Lipman (9), with the Coonrad Morrey (Zimmer Biomet, USA) elbow prosthesis, it was concluded that 5 Nm varus-valgus load at the ulno-humeral joint was sufficiently high to result into stresses exceeding the theoretical yield strength of PE (ultrahigh molecular weight PE; UHMWPE). These stresses led to extrusion and non-reversible PE deformation, eventually causing wear. Similarly, during the evaluation of three different types of TEAs (Coonrad Morrey (Zimmer Biomet, USA), Nexel (Zimmer Biomet, USA) and Discovery (Lima Corporate, Italy)); the calculated moment in the elbow, when holding a 2.3 kg weight in the hand with the shoulder abducted at 45 and 90 degrees, also led to stresses exceeding the yield strength of PE (10).

In conclusion, both retrieval and prosthetic design studies report elbow load values that lead to failure and thus should not be exceeded following TEA. However, the consequences of these findings for clinical practice of patients following TEA remains unknown, since elbow loads actually experienced by a patient during ADL are not well established. Daily tasks can result in high loads and thus stresses on the elbow depending on the amount of load being lifted and the movement being executed (10). Our current clinical practice is to instruct patients to limit weight lifting to 1 kg in general and to 5 kg incidentally. However, depending on the type of movement and how it is executed, similar weights can lead to different loads on the elbow (10). Moreover, several tasks do not involve external weight, but still require load on the elbow, such as rising from a chair or steering a car. Therefore, in the current review we aim to investigate the literature on reported elbow loads during different ADL tasks. It is now unclear whether elbow loads experienced during ADL tasks exceed the reported failure limits of the prosthesis. Additionally, it is unclear whether the experienced loads and failure limits relate to our postoperative instruction. The overview of elbow loads during ADL tasks is expected to create a basis for better clinical practice and guide more informed decisions on which tasks should be avoided following TEA.

Therefore, the main research question of the current review is: what is the elbow joint load (joint reaction force and net joint torque) during different ADL tasks and do these loads exceed the failure limits as reported in retrieval and finite element studies concerning TEA.

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines were followed. The review was registered in an international prospective register of scoping reviews 'Science Framework'. The protocol has been registered online and can be accessed electronically at: https://osf.io/823vt/

Literature search and study selection

With the assistance of a clinical librarian, a systematic literature search was performed on November 23rd 2021 in two online databases (PubMed/Medline and Web of Science). The following terms were used: [Elbow], [Elbow Joint], [Arthroplasty], [TEA], [Biomechanical]. The search was performed using the filters "Dutch" and "English". Full search details are available in Appendix 1.

Identified articles were imported to Endnote (Philadelphia, USA). Duplicates were removed. Based on title and abstract, two independent reviewers (DM and RGAD) identified potentially relevant articles for review of the full text. In case of disagreement, a third author was consulted (AM). Additionally, the reference list of the included articles was manually checked to avoid missing relevant articles. The authors independently selected articles. Studies were not blinded for author, affiliation or source.

Eligibility criteria

Studies were eligible if: (1) report on the elbow joint load in native elbows or elbows with an elbow arthroplasty in adults; (2) full text article was available. A study was excluded if it only contained specific sport analysis. Studies containing patients with neurological comorbidities (i.e. cerebral palsy, stroke, spinal cord injury) were excluded. Animal studies and cadaveric studies were also excluded.

Data extraction

After initial selection, data from eligible studies were extracted based on a predefined extraction template. The following data and baseline parameters were recorded when available: author and publication year, number of participants, participant characteristics (sex, age, indication for TEA, type of TEA, radial head status, ligament status (if applicable)) and methods (tracking system, ADL tasks). The primary objective was to report on elbow joint load along the local axes (i.e. flexion, extension, varus, valgus, pronation and supination). For all axes the largest measured load (peak load) per task was taken. Lastly, load definitions were extracted using the following categories: net joint torque (Nm), interaction torque (Nm) and bone-on-bone contact force (N). An explanation of these definitions can be found in figure 1.

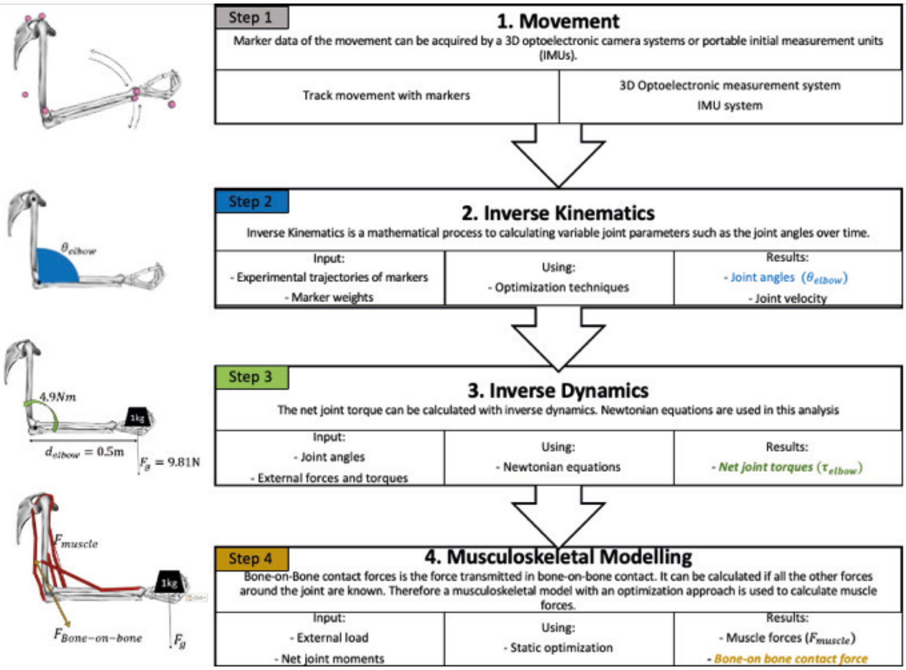

Figure 1 Steps in order to be able to analyze joint torque. θ_{elbow} = elbow joint angle , τ_{elbow} = net joint torque, d_{elbow} = moment arm (distance between force-vector and rotation point (the elbow axis), F_g = gravitational force ($m * g$) and $F_{Bone\text{-}on\text{-}bone}$ = internal bone-on-bone contact force.

Figure 1 describes four steps of increasing detail in the study of joint torque. First, movement can be tracked using markers. Marker data of the movement can be acquired by using a 3D optoelectrical camera system or portable initial measurement unit (IMU) (step 1). Then, a mathematical process called inverse kinematics is used to calculate joint parameters (joint angles and joint velocity), by using marker trajectory data from step 1 (step 2). The net joint torque can be calculated using inverse dynamics. Inverse dynamics methods estimates the torques and forces needed to generate a motion. Position data of the segments (step 1 and 2) are put into a biomechanical model (step 3). The net joint torque can then be calculated by the formula ($\tau_{elbow} = d_{elbow} * F_g$) A larger moment arm ($d_{elbow}$) or a larger gravitational force (F_g) results in a higher net joint torque (τ_{elbow}). So, a 1kg mass in the hand leads to an elbow moment depending on the moment arm (i.e. the type of movement). Therefore, translating a mass to a moment is difficult. Interaction torque only occurs by multi-joints movements. For example, by reaching where both elbow and shoulder joints are active. Generation of the resulted joint-torque is complicated by the presence of interaction torque. The interaction torque is due to initial torque, centripetal torque, and Coriolis torque (11). Bone-on-bone contact force is the force transmitted in bone-on-bone contact (12). It can be calculated if all the other forces (i.e. muscle, external, gravitational) around the joint are known. Therefore, an optimization process needs to be performed to calculate the muscle force, which can be done using a musculoskeletal model (step 4) (13).

Methodological quality assessment

The methodological quality of included studies was evaluated according to an checklist by Heyward et al. (14) (Appendix 2). For each question a score of 1 was given for an 'adequate' or 'yes' response, a score of 0.5 was given for a 'partial' or 'limited' response; and a score of 0 was awarded for a 'no', 'not stated' or 'inadequate' response. A maximum score of 8 was possible. Studies were considered low quality when scoring 0-3.5 points, moderate quality 4-5.5 points and high quality 6-8 points. These ranges are chosen arbitrarily. Methodological quality assessment was assigned by two authors, any differences in scoring were resolved by consensus (DM and RGAD).

RESULTS

Selection of literature

An initial search yielded 3701 potentially relevant studies. After the removal of duplicates, 2675 articles were identified. After evaluation of titles and abstracts, the remaining 106 papers were retrieved for detailed assessment of full text manuscript. Seventy-eight studies were excluded since they did not report elbow joint load. Consequently, a total of 28 articles (10, 15-41) were included (Figure 2).

Quality assessment

Of the articles included, three studies (16, 30, 32) were of low quality, 22 (10, 15, 18-27, 29, 31, 33-39) of moderate quality and three (17, 28, 40) of high quality. Areas of improvement for most studies were description of inclusion and exclusion criteria, and description of validity and reliability of measurement tools. Details of these outcomes can be seen in Appendix 3.

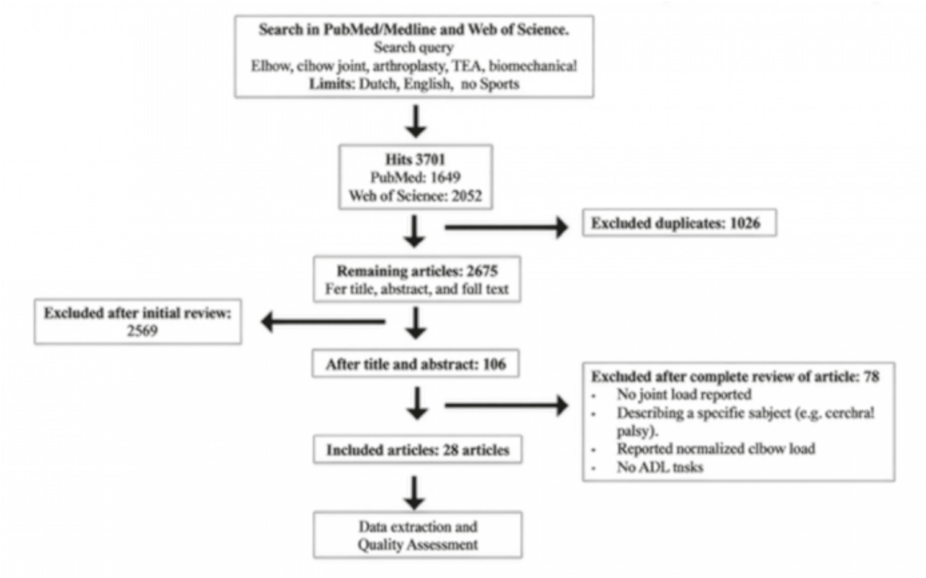

Figure 2 Flow-chart

4

Study characteristics

Overall, a total of 256 participants were included. Age ranged from 17 to 59 years. Table 1 shows an overview of the study characteristics.

Type of ADL Task

Since the type of ADL tasks are heterogeneous, it was decided to divide the ADL tasks into categories: 1) close to the body and 2) further away from the body: tasks are classified as further away if the position of the shoulder was >90 anteflexion and/or >45 abduction. Tasks were then subdivided in: 1) cyclic flexion/extension, 2) push-up, 3) reaching, 4) self-care, 5) work. In some articles, several conditions with external weight were tested. In those cases, the condition with the lowest external weight applied was taken for further analysis, other conditions are reported in table 1.

Elbow joint load

Nineteen studies (10, 15-17, 19, 21-26, 28, 29, 31, 32, 34, 38, 39, 41) report about tasks that are classified as further away, nine (18, 20, 27, 30, 33, 35-37, 40) report about tasks close to the body. These studies are then further classified in six studies about cyclic flexion-extension tasks (10, 15, 18, 20, 27, 40), nine about push-up tasks (16, 21-26, 28, 34), seven about reaching tasks (17, 19, 29, 31, 32, 38, 39), four about self-care tasks (30, 33, 35, 37) and two about a work task (36, 41) (table 1). Twenty-five studies reported net joint torque (10, 15-37, 41), two studies reported interaction torque (39, 40) and one study reported both interaction and net torque (38). In addition, nine studies that reported net joint torque (step 3 figure 1), also reported bone-on-bone contact force (step 4 figure 1) (16, 21-26, 28).

Twenty-five articles (10, 15-22, 24-38, 41) reported the elbow flexion-extension net joint torque (table 1). The mean elbow flexion-extension net joint torque of tasks close to the body was 18 Nm. The mean elbow flexion-extension net joint torque for tasks further away from the body was 19 Nm. More specifically, the mean elbow flexion-extension net joint torque for cyclic tasks was 21 Nm, for pushup tasks 26 Nm, for reaching tasks 11 Nm, for self-care tasks 3 Nm and for work tasks 39 Nm (figure 2). Three articles (38-40) reported the elbow flexion-extension interaction torque. The mean elbow flexion-extension interaction torque was 10 Nm in the close to the body tasks and 16 Nm in the further away tasks.

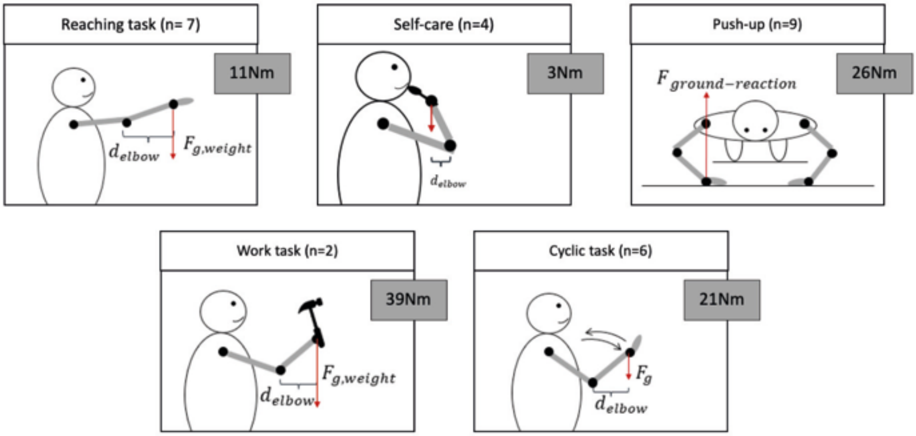

Figure 3 Average net joint moment (flexion-extension), classified per type of task.

Ten articles (17, 21, 22, 24-26, 28, 34, 35, 37) reported the varus-valgus net joint torque (table 1). The mean varus-valgus net joint torque was 1 Nm in tasks close to the body and 11 Nm in tasks further away from the body. More specifically, the mean varus-valgus torque was 1 Nm in selfcare activities, 3 Nm in reaching activities and 12 Nm in pushup tasks.

Eleven articles (10, 17, 21, 22, 24, 26, 28, 33-36) reported about the pronation-supination net joint torque (table 1). The mean pronation-supination net joint torque in tasks close to the body was 18 Nm and 6 Nm in tasks further away from the body. More specifically, the mean pronation-supination torque was 1 Nm in selfcare tasks and reaching tasks, 7 Nm in pushup tasks, 10 Nm in cyclic tasks and 34 Nm in work tasks.

Nine studies (10, 16, 21-26, 28) reported bone-on-bone contact force. Eight (16, 21-26, 28) of them were pushup tasks, with a reported mean bone-on-bone contact force of 337 N. One study (10), a cyclic flexion extension task, reported 450 N bone-on-bone contact force.

DISCUSSION

Aim of the current review is to scope the literature on the reported elbow joint loads during ADL. Consequently, these loads will be compared with published data from retrieval and finite element studies to see if values exceed the failure limits of the prosthesis in the following section. Our current clinical practice is to instruct patients to limit weight lifting to 1 kg in general and to 5 kg incidentally. It is now unclear whether elbow loads experienced during ADL tasks exceed the reported failure limits of the prosthesis. Additionally, it is unclear whether the experienced loads and failure limits relate to our postoperative instruction. The overview of elbow loads during ADL tasks is expected to create a basis for better clinical practice and guide more informed decisions on which tasks should be avoided following TEA. The most important finding of this review is that very little literature on elbow joint loading during ADL is available and that our current postoperative instruction appears to be not evidence-based.

When comparing tasks close to the body with tasks further away from the body; the tasks further away result in higher loads, as can be expected since the longer the moment-arm of the contributing muscles, the bigger the moment. Therefore, it seems to be safer to perform ADL tasks that are close to the body or perform tasks in such a way that the distance away from the body is minimized (elbow flexion and shoulder adduction). The highest elbow flexion-extension net joint load for tasks further away from the body was 19 Nm. In addition, work and push-up tasks resulted in the highest flexion-extension loads (39 Nm and 26 Nm respectively). Unfortunately, there is no literature available that report about failure limits of load on the prosthetic materials for FE movements. Therefore, it is not known if failure limits would be exceeded in these moments and clinical implications remain unknown. Both work and push-up tasks result in loads that exceed our post-operative instruction, to not regularly exceed 1kg and only incidentally 5kg.

Highest varus-valgus loads were reported for tasks further away from the body (11 Nm), more specifically the highest loads were reported for the push-up tasks (12 Nm). It is known from finite element studies that a varus-valgus load of 5 Nm can lead to irreversible PE deformation (9). Comparing our results to available literature, it shows that all push-up tasks, as well as a work task, hammering with a 2 kg hammer in the hand, resulted in moments that led to stresses that exceed the limit of irreversible plastic deformation. Therefore, these activities need to be avoided following TEA. Similar results are reported by King et al. (10), where cyclic flexion-extension with 2.3 kg weight in the hand resulted in a moment in the elbow that led to stresses exceeding the yield strength of PE. This was the case for the condition with 45 and 90 degrees shoulder abduction. The condition with 0 degrees shoulder abduction did not exceed the yield strength of PE. It is therefore important to not only report about the movements or tasks being executed and the amount of external weight applied, but also about the distance of the elbow joint in relation to the body (i.e. shoulder position), since similar movements with similar weights can lead to different loads depending on how the movement is executed.

Highest pronation-supination loads were reported in tasks close to the body (18 Nm), more specifically in work tasks (34 Nm). The mean pronation-supination (PS) loads are lower than flexion-extension loads, as can be expected due to shorter moments arms of contributing muscles. Unfortunately, there is no literature available that report about failure limits of load on the prosthetic materials for PS movements. Therefore, it is not known if failure limits would be exceeded in these moments and clinical implications remain unknown.

Highest bone-on-bone contact forces are reported for a cyclic flexion-extension task while holding a 2.3kg weight in the hand (450 N). Bone-on-bone contact forces during push-up tasks range from 275 to 441 N (mean 337 N). Unfortunately, none of the articles reported between which bones the bone-on-bone contact force was calculated. Finite element analyses evaluating three different prosthetic designs (hourglass, concave and cylindrical) showed that by applying 100 N axial load, the stresses of both the hourglass and concave designs remained far below (<50%) the yield strength of PE (42). The cylindrical design, on the contrary, showed the highest stress under these loads, with stresses exceeding the yield strength of PE. Unfortunately, the amount of applied load that would result in the PE yield strength being exceeded in both the hourglass and concave designs, was not specified. So, clinical implications for these types of prostheses remain unknown. So far, it is known that implant design, type of load, type of movement, frequency of movement cycles and fixation methods influence the stress distribution on the prosthesis and thereby influence the risk of loosening of the prosthesis (43-45). Unfortunately, the consequences of these findings for daily practice remain unclear.

Recommendations for future research

The results of our review give a very limited, first overview on elbow joint loads during ADL, given the limited availability of literature on this topic. It is shown that elbow joints loads (both varus-valgus moment and bone-on-bone contact force) in several ADL tasks exceed the reported failure limits of elbow prostheses. Besides, elbow joint loads also exceed our current post-operative instruction. However, current literature is not sufficient to formulate a new post-operative instruction, which is compliant with failure limits of the prosthesis. Therefore, we formulate two recommendations for future research, that should be addressed.

First, clinical studies should focus on a thorough analysis of different ADL tasks, since several relevant conditions (i.e. cycling, driving a car, opening a door, carry groceries) are not yet tested. Therefore, we advise to use a standard set of ADL tasks, which should comprise at least a personal care task, feeding task, housework task and transportation task (46). These clinical studies should be done in both healthy participants and patients following TEA, to be able to analyze differences following surgery.

Second, all prosthetic suppliers should test their prosthesis and report failure limits, since different types of prosthesis may have different failure limits (42). We advise to report flexion-extension moment, varus-valgus moment and pronation-supination moment, as well as bone-on-bone contact forces (e.g. axial compression forces) for both clinical and prosthetic studies. Additionally, we advise to use net joint torque definitions and calculations and bone-on-bone contact force definitions and calculations as described in our methods section in order to be able to compare results (47-49). This will enable clinicians to compare clinical loading with reported failure limits of the prosthesis and thereby guide informed decisions about post-operative instructions for patients, in order to improve survival rates.

Lastly, formulating postoperative instructions might be difficult, since translating a mass into a joint moment is difficult. As mentioned previously, depending on the type of movement and how it is executed, similar weights can lead to different loads on the elbow. Therefore, focus should be more on a balance in load and load capacity and about the execution of the movement (i.e. close to the body, elbow flexion and shoulder adduction vs further away, elbow extension, shoulder abduction), instead of the amount of mass being lifted as is current practice.

LIMITATIONS

The results of this review should be interpreted in light of several limitations, caused by the quality of the included articles. Three studies were of low quality, 22 of moderate quality and three of high quality. In addition, many studies used different measurement systems and different methods to calculate the joint load, frequently without reporting validity and reliability, as presented in the quality assessment. Further, different definitions of joint load are reported. Therefore, comparison of loads is difficult. Lastly, the included studies mostly measured young healthy males, which may not be comparable to joint loading in patients following TEA.

CONCLUSION

The results of our scoping review give a first overview on the current knowledge on elbow joint loads during ADL. Surprisingly, the current literature is not sufficient to formulate a postoperative instruction regarding elbow joint loading, which is compliant with failure limits of the prosthesis. In addition, our current instruction appears to be not evidence-based. Our recommendations offer a starting point in order to assist clinicians in providing informed decisions about post-operative instructions for their patients.

Table 1

First Author	Year	Number of participants (n)	Male (n)	Age (Mean)	Weight (kg)	Close to body/ Further away	Type of Task	Sort torque	Peak F/E load (Nm)	Peak V/V load (Nm)	Peak Pro/Sup load (Nm)	External weight applied (kg)	Bone-bone contact force (N)
Almeida (15)	1995	4	4	32		Further	C	Net	40				
An (16)	1992	9	9			Further	P	Net	23				304
Balendra (17)	2017	10	10	24	81	Further	R	Net	8	3	1	0.45	
									15	7	2	0.9	
Ballaz (18)	2016	12	6	23		Close	C	Net	2			0	
									5			1	
									9			2	
									11			3	
Beer (19)	2004	5	3	59		Further	R	Net	15				
Challis (20)	1994	1	1		65	Close	C	Net	46				
Chou (21)	2001	11	11	26	69	Further	P	Net	22	11	8		353
Chou (22)	2002	8	8	17	69	Further	P	Net	51	20	17		441
Chou (25)	2008	10	10	27	63	Further	P	Net	16	10			304
Chou (23)	2009	15	15	23	68	Further	P	Net					422
Chou/Hsu (26)	2011	14	14	25	66	Further	P	Net	28	7	2		294
Chou/Lou (24)	2011	15	15	20	69	Further	P	Net	24	14	3		275
Dennerlein (27)	2007	6	4			Close	C	Net	4				
Donkers (28)	1993	9	9	20-30	78	Further	P	Net	23	12	3		304

Table 1

First Author	Year	Number of participants (n)	Male (n)	Age (Mean)	Weight (kg)	Close to body/ Further away	Type of Task	Sort torque	Peak F/E load (Nm)	Peak V/V load (Nm)	Peak Pro/Sup load (Nm)	External weight applied (kg)	Bone-bone contact force (N)
Emmatty (41)	2021	30	30	24	67	Further	W	Net	1				
Essers (29)	2013	3	3	31	76	Further	R	Net	3				
Finsen (30)	1997	8	0	46	63	Close	SC	Net	3			2	
Gottlieb (31)	1996	8				Further	R	Net	9				
									13			0.9	
									20			2.2	
									22			3.1	
Hong (32)	1994	6	6			Further	R	Net	10				
									14			0.9	
									20			2.2	
									25			3.1	
Hussain (33)	2020	1	0		66	Close	SC	Net	1		1		
King (10)	2019	1	1			Further	C	Net	12		10	2.3	450
Lou (34)	2001	10	10	26	69	Furter	P	Net	22	10	9		
Murray (35)	2004	10	10	34		Close	SC	Net	6	1	0.03		
Okunribido (36)	1999	8	8	26	74	Close	W	Net	76		34	37	
Ratzlaf (37)	2019	10	6		66	Close	SC	Net	2	1			

Table 1

First Author	Year	Number of participants (n)	Male (n)	Age (Mean)	Weight (kg)	Close to body/ Further away	Type of Task	Sort torque	Peak F/E load (Nm)	Peak V/V load (Nm)	Peak Pro/Sup load (Nm)	External weight applied (kg)	Bone-bone contact force (N)
Sainburg (38)	1995	13	5	28-46		Further	R	Interaction	25			1.2	
								Net	19				
Topka (39)	1198	10		47		Further	R	Interaction	7				
Yamasaki (40)	2009	9	5	22		Close	C	Interaction	10			0,5	
	Total	256	Mean	30	69				17	9	8		337
			St.Dev.	10	5				15	5	9		55

Overview of study characteristics. C=cyclic task, P=push-up task, R=reaching task, SC=selfcare task, W=work.

Appendix 1

(“Elbow”[Mesh] OR elbow*[tiab] OR “Elbow Joint”[Mesh] OR “Arthroplasty, Replacement, Elbow”[Mesh] OR TEA[tiab])

AND

(“Biomechanical Phenomena”[Mesh] OR biomechanic*[tiab] OR kinematic*[tiab] OR kinetic*[tiab] OR (load*[tiab] AND (joint*[tiab] OR distribution*[tiab] OR transmission*[tiab] OR transmit*[tiab] OR carriage*[tiab])) OR mechanical force*[tiab])

AND

(flexion[tiab] OR extension*[tiab] OR varus[tiab] OR valgus[tiab] OR pronation[tiab] OR supination[tiab])

NOT (“Sports”[Mesh] OR “Cerebral Palsy”[Mesh] OR “Stroke”[Mesh] OR “Down Syndrome”[Mesh] OR “Spinal Cord Injuries”[Mesh]) NOT (“animals”[MeSH] NOT “humans”[MeSH])

TS= (elbow* OR tea)

AND

TS= (biomechanic* OR kinematic* OR kinetic*[tiab] OR (load* AND (joint* OR distribution* OR transmission* OR transmit* OR carriage*)) OR “mechanical force*”)

AND

TS=(flexion OR extension* OR varus OR valgus OR pronation OR supination) NOT TI=(sport* OR “cerebral palsy” OR “down syndrome” OR “spinal cord injuries” OR stroke)

Appendix 2

Quality assessment criteria checklist

Questions	Response / decision rule criteria
1. Participant characteristics – are participant demographics adequately described? (include: number, age, gender)	Adequate – all details provided Partial – all details except level of competition or gender Inadequate – missing details
2. Were inclusion/exclusion criteria stated?	Stated - clear list of both given Limited - one or two points only Not stated - not provided
3. Was the design appropriate to the research question?	Yes - well matched to question No
4. Were key-dependent variables measured?	Adequate - all details provided Partial - only some variables measured Inadequate - missing details
5. Psychometric properties - was the reliability of measurement tools reported and adequate?	Adequate - all details provided Partial - only some aspects of reliability reported Inadequate - missing details
6. Psychometric properties —was the validity of measurement tools reported and adequate?	Adequate - all details provided Partial - only some aspects of validity reported Inadequate - missing details
7. Was the external validity of the results discussed?	Yes - generalizability of findings discussed No
8. Were the limitations of the studies described?	Adequate - all limitations discussed Partial - limited description Inadequate - not described

Appendix 3

Study First Author	Year	Are participant demographics adequately described? (include: number, age, gender)	Were inclusion/exclusion criteria stated?	Was the design appropriate to the research question?	Were key-dependent variables measured?	Psychometric properties - was the reliability of measurement tools reported and adequate?	Psychometric properties —was the validity of measurement tools reported and adequate?	Was the external validity of the results discussed?	Were the limitations of the studies described?	Total (max 8)	Category
Almeida (15)	1995	0,5	0	1	1	0,5	0	1	0	4	M
An (16)	1992	0	0	1	0	0	0	0	0	1	L
Balendra (17)	2017	1	1	1	0,5	1	0	1	1	6,5	H
Ballaz (18)	2016	0,5	0,5	1	0,5	1	0	1	1	5,5	M
Beer (19)	2004	0,5	0	1	1	0	0,5	1	0,5	4,5	M
Challis (20)	1994	0,5	0	1	0	0	0,5	1	1	4	M
Chou (21)	2001	1	0	1	0,5	0	0,5	1	0	4	M
Chou (22)	2002	1	0	1	1	0	0,5	1	0,5	5	M
Chou (25)	2008	0,5	0	1	0,5	0	0,5	1	1	4,5	M
Chou (23)	2009	1	0	1	0	0	0,5	1	1	4,5	M
Chou/Hsu (26)	2011	1	0,5	1	1	0	0,5	1	0	5	M
Chou/Lou (24)	2011	1	0,5	1	1	0	0,5	1	0	5	M
Dennerlein (27)	2007	0,5	0	1	1	0	0,5	1	1	5	M
Donkers (28)	1993	1	0,5	1	1	0	0,5	1	1	6	H

Study First Author	Year	Are participant demographics adequately described? (include: number, age, gender)	Were inclusion/exclusion criteria stated?	Was the design appropriate to the research question?	Were key-dependent variables measured?	Psychometric properties - was the reliability of measurement tools reported and adequate?	Psychometric properties —was the validity of measurement tools reported and adequate?	Was the external validity of the results discussed?	Were the limitations of the studies described?	Total (max 8)	Category
Emmatty (41)	2021	1	0.5	1	0.5	1	1	0	0.5	5,5	M
Essers (29)	2013	1	0,5	1	0,5	0	0	1	1	5	M
Finsen (30)	1997	1	0	1	0	0	0	1	0	3	L
Gottlieb (31)	1996	0	0	0,5	1	0	0,5	1	1	4	M
Hong (32)	1994	0	0	1	0,5	0	0,5	1	0	3	L
Hussain (33)	2020	0,5	0	1	0,5	1	1	1	0,5	5,5	M
King (10)	2019	0,5	0	1	1	0,5	0,5	1	1	5,5	M
Lou (34)	2001	1	0	1	0,5	0,5	0,5	1	0	4,5	M
Murray (35)	2004	0.5	0	1	0.5	1	0,5	1	1	4,5	M
Okunribido (36)	1999	1	0	1	0,5	0,5	0,5	1	1	5,5	M
Ratzlaf (37)	2019	0,5	0,5	1	0,5	0	0,5	1	1	5	M
Sainburg (38)	1995	0,5	0	1	0,5	0	0,5	1	1	4,5	M
Topka (39)	1998	0,5	0	1	1	0,5	0,5	1	1	5,5	M
Yamasaki (40)	2009	0,5	0	1	1	1	1	1	1	6,5	H
									Mean	4,7	

Overview of quality assessment. L = low quality, M = moderate quality, H = high quality.

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Chapter 5

Elbow Joint Loads during Simulated Activities of Daily Living: Implications for Formulating Recommendations after Total Elbow Arthroplasty.

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ABSTRACT

Background: Overloading of the elbow joint prosthesis following total elbow arthroplasty can lead to implant failure. Joint moments during daily activities are not well-contextualized for a prosthesis' failure limits and the effect of the current postoperative instruction on elbow joint loading is unclear. This study investigates the difference in elbow joint moments between simulated daily tasks and between flexion-extension, pronation-supination, varus-valgus movement directions. Additionally, the effect of the current postoperative instruction on elbow joint load is examined.

Methods: Nine healthy participants (age 45.8 ± 17 years, 3 males) performed eight tasks; driving a car, opening a door, rising from chair, lifting, sliding, combing hair, drinking, emptying cup, without and with the instruction "not lifting more than 1 kg". Upper limb kinematics and hand contact forces were measured. Elbow joint angles and net moments were analyzed using inverse dynamic analysis, where the net moments are estimated from movement data and external forces.

Results: Peak elbow joint moments differed significantly between tasks ($p < 0.01$) and movement directions ($p < 0.01$). The most and least demanding tasks were, rising from a chair (13.4 Nm extension, 5.0 Nm supination, 15.2 Nm valgus) and sliding (4.3 Nm flexion, 1.7 Nm supination, 2.6 Nm varus). Net moments were significantly reduced after instruction only in the chair task ($p < 0.01$).

Conclusion: This study analyzed elbow joint moments in different directions during daily tasks. The outcomes question whether postoperative instruction can lead to decreasing elbow loads. Future research might focus on reducing elbow loads in the flexion-extension and varus-valgus directions.

INTRODUCTION

Total elbow arthroplasty (TEA) is a surgical procedure that is performed to reduce pain and regain function in patients with a variety of debilitating elbow pathologies, such as inflammatory or post-traumatic arthritis and complex fractures (1). Though the use of TEA is growing, it remains a relatively uncommon orthopedic procedure, with 3,146 TEAs performed over a 5-year period in the USA (2). In the Netherlands, the number of TEAs rose from 67 in 2017 to 73 in 2022 (3). It is performed more often in women than in men (4, 5). Unfortunately, elbow prosthesis survival rates following TEA are low compared to those following hip and knee arthroplasties. The current TEA survival rate in the range of 7.5-14.2 years is 71-87% (1, 6, 7) compared to a 10 year survival rate of 90-95% for hip and knee arthroplasty (8-10).

The most important factor determining poor survival rates of elbow arthroplasty is aseptic loosening of the humeral component (1, 6, 7, 11, 12). Retrieval studies showed that aseptic loosening results from different mechanisms. First, overloading of the prosthesis during activities of daily living (ADL) causes polyethylene (PE) wear (12, 13), bringing loose particles to the proximity of the bone-prosthesis interface, ultimately leading to bone destruction and inflammation (12, 14, 15). Revision surgery becomes necessary as a result of aseptic loosening. A second mechanism of failure may be inadequate cement fixation (16), where excessive stresses at the bone-cement-prosthesis interface leads to micromotion and consequent failure of the implant. Last, joint replacements face greater durability requirements as lifespan lengthens. It has been observed that patients following TEA stay active for a longer period, and are less inclined to restrict their lifestyle to safeguard the prosthesis' lifetime (39). In the long term, this behavior may lead to overloading of the implant during activities of daily living (31).

In vitro tests to analyze elbow joint biomechanics have provided insight into the failure mechanisms of TEA. Lo and Lipman examined retrieved Coonrad Morrey ulnar components, demonstrating that varus-valgus (VV) moments in the ulnohumeral joint as high as 5 Nm would lead to loads exceeding the PE's theoretical yield strength of the Coonrad-Morrey prosthesis and consequently to irreversible plastic deformation (17). Furthermore, elbow joint loading of three different types of TEAs while holding a 2.3-kg weight exceeded the yield strength of PE when the shoulder was abducted at 45° and 90° (18). However, these results are not easily generalizable to ADL tasks, as it isn't known what the specific loads during different ADL tasks are and which tasks could lead to a potential overload of the elbow joint.

To reduce overloading of the elbow, common clinical practice is to instruct patients not to perform daily activities that regularly exceed lifting 1 kg weight and incidentally up to 5 kg (19, 20). However, this guideline lacks specificity since it is unclear which ADL tasks or specific movements would exceed the 1-5-kg limits and should thus be avoided (20).

Depending on the type of movement and how it is executed, similar weights can lead to different loads on the elbow (18, 21). It is therefore crucial to know whether the current clinical instruction brings about a detectable reduction in elbow joint loads.

The low survival rates, combined with the lack of consensus on postoperative management, emphasize the need for biomechanical studies focusing on elbow joint loading during ADL. The aims of the current study are: first, to identify any differences in range of motion and elbow joint moments between eight ADL tasks in a lab setting; second, to identify differences in peak loads between the flexion-extension (FE), pronation-supination (PS), varus-valgus (VV) movement; and last, examine whether the current instruction of “not lifting more than 1 kg” leads to a decrease in elbow joint moments. We hypothesize that joint moments will differ per task and that the instruction will not lead to a decrease in elbow joint load.

MATERIALS AND METHODS

Participants

Nine healthy, able-bodied participants performed eight simulated ADL tasks. Exclusion criteria were 1) mental or physical disability to meet study requirements; 2) insufficient command of the Dutch language; 3) prior surgery in the upper extremity or other pathologies affecting upper extremity function. Participants were informed about the procedures and signed an informed consent. The study was approved by the Medical Ethical Committee of University Medical Center Groningen, The Netherlands (METc2019/624). Anthropometric data are presented in Table I.

Table I: Participant demographics

		N	Mean	SD
Age (years)		9	45.8	17.4
Height (cm)		9	178	7.4
Weight (kg)		9	74.9	5.4
Shoulder width (cm)[a]		9	44.4	2.1
Arm length (cm)[b]		9	65.9	2.8
Gender	Male	3		
	Female	6		
Dominance (%)[c]	Right	8	86.1	12.4
	Left	1	-90	

[a] Measured from acromion- acromion.
[b] Measured from dominant acromion to 3 red MCP of dominant arm.
[c] Handedness was analysed using the Edinburgh inventory (Oldfield et al 1971).

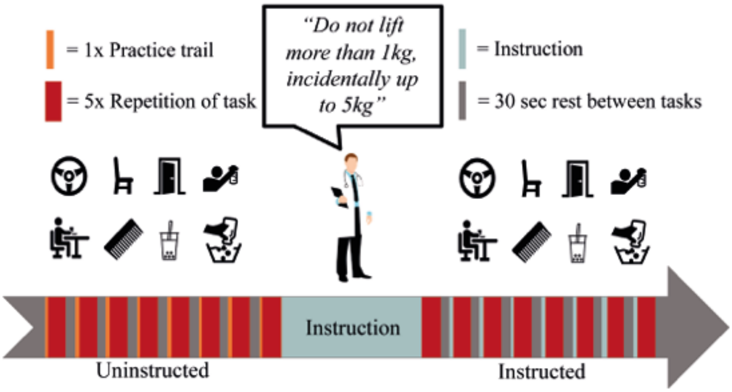

Figure 1: Research protocol. Each symbol illustrates an ADL task. Participants first performed a series of eight ADL tasks. Next, there was the instruction of "not lifting more than 1 kg". Then the second series was performed. The instruction was repeated before each task.

Procedure

Basic anthropometric data (length, weight, arm length, shoulder width) and a maximum voluntary contraction of the biceps and triceps were collected at entrance. After a static calibration trial, participants performed a standardized series of eight ADL tasks in two conditions (Figure 1). All tasks are explained in Table II. After one entire series (uninstructed condition), another series followed with each task performed again (Figure 1), this time with a verbal instruction comprising the recommendation to "not exceed lifting 1-kg weight and only incidentally use up to 5 kg" (instructed condition). In both conditions, the tasks were performed in the same fixed order (Table II).

The tasks were selected based on the expected amount of elbow movement, as well as on patients' frequently asked questions after TEA surgery (22). In the seated tasks, the participant sat on a height-adjustable chair without back support. A 75-cm high table was placed in front of the participant, with a marked starting point. The height of the chair was adjusted so that the elbow was flexed at 90° when the hand was placed on the table, and the upper arm was held in vertical position (Figure 2). For each task, an initial position and aim were defined. After verbal instruction and one test trial, each task was repeated five times. The participant was instructed to move at a comfortable speed throughout the experiment. Between the different tasks, there was a rest period of at least 30 seconds. All tasks were performed consecutively twice, i.e., in two consecutive conditions.

In three ADL tasks (1, 2, 3), a force transducer was used to record generated external reaction forces. During the steering wheel task, a constant force of 15N for the car task and 25N for the door task was applied as resistance (23, 24).

Table II: Description of activities of daily living and order of execution.

	Activity	Initial position	Aim
	1. Steering a car wheel (T-bar horizontal on the table).	Table placed in front of participant, at 1 AL. Chair is lowered, legs stretched. Dominant hand on T-bar, non-dominant hand on the leg.	Turn T-bar, using the handle, from 10 o'clock to 4 o'clock and turn it back to 10 o'clock.
	2. Opening and closing a door (T-bar vertical on the table).	Participant stands in front of the door, with elbow at 90°, hand resting on the handle.	Push T-bar to 90° using the handle. Close the door, back to starting position.
	3. Rising from a chair (T-bar in armrest).	Seated, both hands on armrests.	Rise from the chair using armrests, sit down again.
	4. Lifting 1-kg object	Target X on the platform (SH) placed 1 AL and 1 SW from dominant arm. Hold 1-kg object at SP.	SP, place object at target X, back to SP.
	5. Sliding 1-kg object	Target X at 1 SW on the non-dominant side, 1 AL with the dominant arm. Hold 1-kg object at SP.	SP, slide target to target X, and back to SP.
	6. Combing hair	Rest a hand on SP.	SP, combing hair in the midline back and forth, SP.
	7. Drinking (1 kg)	Hold 1-kg object at SP.	SP, simulate drinking, SP.
	8. Emptying a cup (1 kg)	Target one full AL in front of participant. Hold 1-kg object at SP.	SP, stretch arm toward target, 180° rotation counterclockwise, then back, SP.

Note: AL: arm length, measured from acromion to 3rd MCP of the dominant hand. SW: shoulder width, measured acromion-to-acromion, SH: shoulder height, SP: starting point. The T-bar is an aluminum bar connected to the force transducer. Each activity was repeated 5 times, all within 35 seconds.

Instruments and Data Collection

Body segment position of the upper extremity was collected at 100Hz using a 4-position sensor motion capture system (Optotrak 320, Northern Digital Inc., Waterloo, ON, Canada). Four infrared light-emitting markers were placed on bony landmarks of the upper limb and thorax. Six rigid bodies were placed on the thorax and upper limb segments, which mapped 14 additional virtual markers. Last, one marker was placed on the center of the force transducer and one marker on the 1-kg object. All marker positions are shown in Appendix A. The coordinate system of the marker data was set on the table, with X forward, Z to the right, and Y upward.

Force data were recorded with a force transducer (ME-Messysteme GmbH, Henningsdorf, Germany) with an accuracy of 0.01 N. The force transducer was mounted on an aluminum T-bar and could be set in different positions (Figure 2a/b). Both marker data and force data were recorded with a frequency of 100 Hz. The motion capture system and the force transducer were digitally synced to enable simultaneous recording.

Data Analysis

The force values in the local coordinate systems were converted into a global coordinate system of the motion capture system using a customized MATLAB script (version 20a, MathWorks Inc., Natick, MA, USA). The motion capture data and force data were filtered in MATLAB using a 4th-order Butterworth filter with a 6Hz cut-off frequency. Data gaps were reconstructed using piecewise cubic spline interpolation.

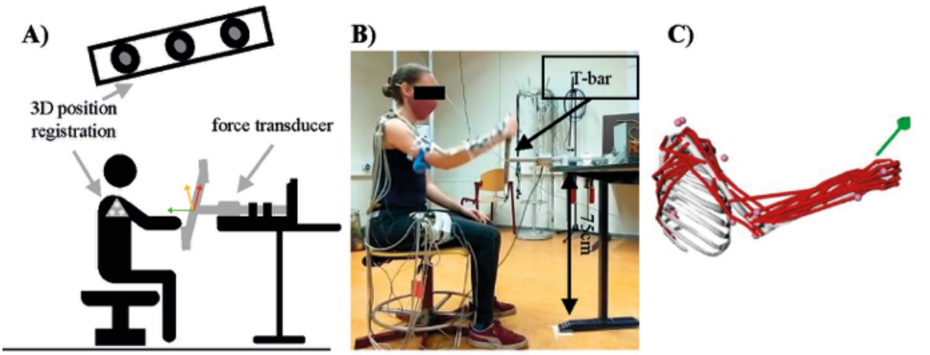

Figure 2: Schematic overview of experimental set-up for car task with the force transducer (15 N resistance force). (A) sagittal view of the lab setting. (B) view of the geometry of the musculoskeletal model. (C) view during the car task. The markers are in pink, the muscles in red, the green arrow represents the external reaction force (force from T-bar to hand).

Musculoskeletal model

OpenSim musculoskeletal modeling software (version 3.3, Stanford University, Stanford, CA, USA) was used to run the dynamic Holzbauer model (25, 26). This model consists of 7 bone segments and 50 Hill-type muscle-tendon actuators, representing 32 muscles and muscle compartments (Figure 2c). This model, which only allowed elbow joint moments in the FE and PS direction calculation, was adjusted to include the VV moments. To analyze the VV direction, an extra degree of freedom was computed in the humeroulnar joint. The maximum VV range of motion was set from 11.2° valgus to 6.6° varus (27). The model was scaled in OpenSim to the body dimensions of the participant using data from the static calibration trial. The anatomical locations and the segments' coordinate systems are in accordance with the international society of biomechanics (ISB) recommendations (28). Inverse kinematic analysis was accomplished by using the OpenSim application programming interface in MATLAB (29). Inverse dynamic analysis was performed in OpenSim software interface. The external reaction forces were applied to the model's hand segment at the distal end of the third metacarpal bone of the dominant hand. The gravitational force was applied to the hand on the task where the 1-kg object was lifted. In the task where a 1-kg object was slid across the table, a dynamic friction coefficient of 0.5 for polyethylene-on-polyethylene was applied. Repetition 2, 3 or 4 was normalized over time from the start of the movement to the end.

The data was further processed in MATLAB 20a to extract 1) the ROM in the FE and PS directions, and 2) peak elbow joint moments in three different directions (FE, PS, VV). The standard deviations of the peak elbow joint moments were calculated to quantify intersubject variability.

Statistical analysis
Peak joint moments were used to test the differences in elbow joint moments between direction (FE, VV, PS), tasks (car, door, chair, etc.), and condition (instructed, uninstructed). To analyze the data, IBM SPSS Statistics 29 (IBM Corporation, Armonk, NY, USA) was used for linear mixed-model analysis. Bonferroni correction was used for post hoc tests. Cohen's d was calculated to indicate the effect size of the post hoc tests. A p-value < .01 was considered statically significant. Normality of data distribution was tested to allow parametric testing.

Since the joint moments were not normally distributed, the positively skewed distribution of joint moments was normalized via a square root transformation (Appendix B) so that the linear mixed model could be used.

RESULTS

Kinematic data

The average ROM of all the participants is shown in Figure 3. Chair, door, and cup tasks showed the largest FE-ROM (range 19° to 110°). The hair and drinking task corresponded with the highest extension angles (126°). Large PS-ROM was observed during the cup task (range 38° to –59°). The greatest ROM variability was seen during the hair task.

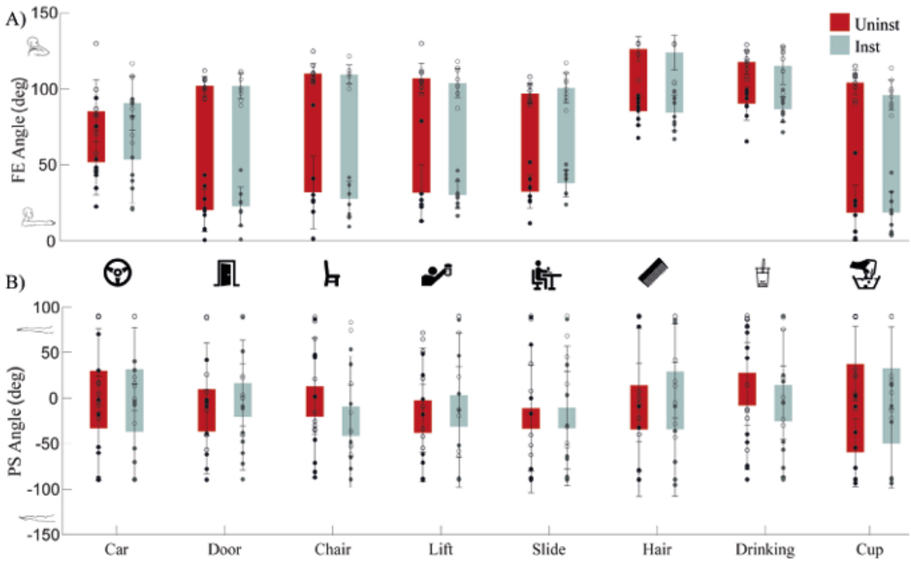

Figure 3: Average (N=9) range of motion in (A) flexion-extension (0° is fully extended) and (B) pronation-supination (90° is fully pronated). direction for eight simulated activities of daily living. Without instruction (red) and with instruction (grey) of not lifting more than 1 kg. Dots represent minimal individual angles (filled) and maximal angles (empty). Angle in degrees. Error bars represent the standard error for the maximum angle (upper end) and minimal angle (lower end).

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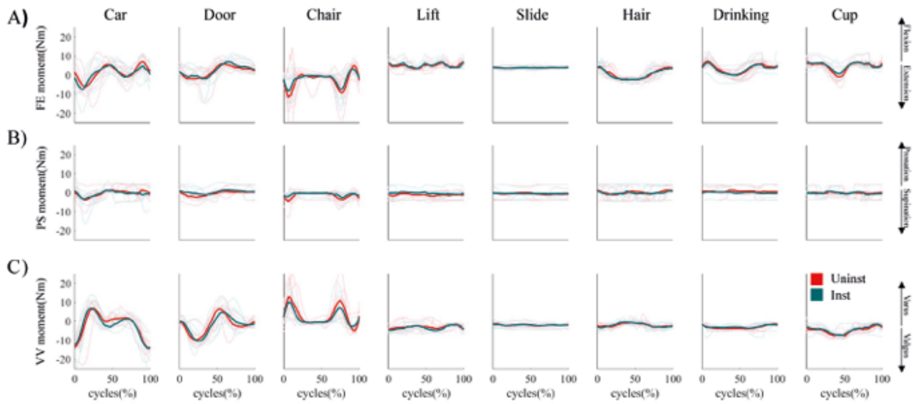

Figure 4: Average (N=9) (dark) and individual (light) normalized elbow joint moment for the selected ADL tasks (one of 5 repetitions). Red: uninstructed condition, blue: instructed condition. (A) Elbow joint FE moment. Negative values indicate extension moment, positive values flexion moment. (B) Elbow joint PS moment. Negative values indicate supination moment, positive values pronation moment. (C) Elbow joint VV moments. Negative values indicate varus, positive values valgus. One of 5 repetitions of every task was normalized over time.

Table III: Peak elbow joint moments (N=9) in an uninstructed and instructed condition for eight simulated activities of daily living

	FE-Moment (Nm)[a]				PS-Moment (Nm)[b]				VV-Moment (Nm)[c]			
	Extension (-)		**Flexion (+)**		**Pronation(+)**		**Supination(-)**		**Varus(+)**		**Valgus(-)**	
Task	Uninst(SD)	Inst(SD)	Uninst(SD)	Inst(SD)	Uninst(SD)	Inst(SD)	Uninst(SD)	Inst(SD)	Uninst(SD)	Inst(SD)	Uninst(SD)	Inst(SD)
1. Steering a car wheel	-8.6(4)	-9.3(4)	9.1(2)	8.5(2)	2.5(2)	3.3(3)	-4.8(3)	-5.4(4)	8.1(3)	8.0(3)	-14.2(4)	-15.2(6)
2. Opening and closing a door	-4.1(4)	-3.7(5)	7.2(2)	8.1(2)	1.8(1)	2.1(2)	-3.1(2)	-1.8(2)	7.7(2)	7.8(2)	-10.2(2)	-11.0(4)
3. Rising from chair	-13.4 (6)	-10.3(7)	6.4(3)	3.1(2)	1.3(1)	0.6(1)	-5.0(3)	-3.4(2)	15.2(10)	11.1(6)	-5.6(3)	-3.0(1)
4. Lifting 1-kg object	-	-	7.5(2)	7.7(2)	2.7(1)	1.1(2)	-0.1(2)	-1.6(2)	-	-	-5.2(1)	-5.3(1)
5. Sliding 1-kg object	-	-	4.2(1)	4.3(1)	0.4(2)	-	-1.7(3)	-1.4(2)	-	-	-2.6(1)	-2.6(1)
6. Combing hair	-3.2(1)	-3.2(1)	5.6(1)	5.2(3)	1.5(2)	1.4(3)	-2.0(3)	-1.6(3)	0.4(1)	0.1(1)	-4.2(1)	-4.2(2)
7. Drinking	-0.3(2)	-0.6(3)	8.4(2)	7.7(3)	1.7(2)	0.9(2)	-0.6(2)	-0.9(2)	-	-	-4.4(1)	-4.3(2)
8. Emptying cup	-1.3(3)	-	8.0(2)	7.7(2)	1.8(2)	1.9(2)	-2.6(2)	-2.6(2)	-	-	-7.8(1)	-7.7(1)

[a] Peak flexion and extension elbow joint moment for instructed and uninstructed task in Nm, negative value indicates extension, positive flexion.

[b] Peak pronation and supination elbow joint moment in Nm for the instructed and uninstructed task. A positive value indicates a pronation moment, a negative value indicates a supination moment.

[c] Peak varus and valgus elbow joint moment in Nm for the instructed and uninstructed task, a positive value indicates a varus moment, a negative value indicates a valgus moment.

Joint Moments

Figure 4 shows the normalized joint moments over time in the FE, PS, and VV directions for the eight ADL tasks. Especially the chair, car, and door tasks show greater intersubject variability. Peak elbow joint moments for the FE, PS, and VV direction are shown in Table III. The overall highest peak moments were observed when rising from a chair (13.4 Nm extension, 5.0 Nm supination, 15.2 Nm varus), followed by steering a car (9.3 Nm extension, 5.4 Nm supination, 15.2 Nm valgus). The slide task required the smallest elbow moment (4.3 Nm flexion, 1.7 Nm supination, 2.6 Nm valgus). Table IV shows an overall ranking of the eight tasks based on the joint moment magnitude and the externally applied force. Greater elbow joint moments, in all directions, were present during those tasks with an external reaction force applied on the hand.

Statistical outcomes are presented in Table V. Peak elbow joint moments were significantly different between the tasks, $F(7,376) = 40.44$, $p < .001$. There was a significant difference in elbow joint loads between the movement directions, $F(2,376) = 170.02$, $p < .001$. Post-hoc test showed that VV moments ($p < .001$, *Cohen's d* = 1.3) and FE moments ($p < .001$, *Cohen's d* = 1.3) were significantly higher than PS moments.

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The instruction did not lead to a significant decrease in elbow joint load $F(1,376) = 2.07$ $p = 0.15$. However, a significant interaction effect of task and condition was found ($p < 0.01$). This evidences that the instruction only had an effect on selected tasks. Follow-up analysis showed that only during the chair task was there a significant decrease in elbow joint load when the instruction was followed ($t(1,376) = 2.58$, $p < 0.01$). During this task, the participants lifted their own body weight using a combination of arm and, possibly, leg movements.

Table IV: Ranking for each tasks based on joint moments and external force
Note: Lower values indicate a higher risk of polyethylene wear.

Task	FE Moments[a]	PS Moments[a]	VV Moments[a]	External load[b]	Overall total
1. Steering a car wheel	2	1	1	2	**6**
3. Rising from chair	1	2	2	1	**6**
2. Opening and closing a door	3	3	3	3	**12**
8. Emptying cup	5	4	4	4	**17**
7. Drinking	4	7	6	4	**21**
4. Lifting 1-kg object	6	6	5	4	**21**
6. Combing hair	7	5	7	8	**27**
5. Sliding 1-kg object	8	8	8	7	**31**

[a] Elbow joint moments in flexion-extension (FE), pronation-supination (PS), and varus-valgus (VV) direction, ranked from high to low, higher joint moments indicate a higher risk of polyethylene wear.
[b] Total external reaction force, calculated with output force transducer or gravitational/friction force. Higher external load indicates a higher risk of PE wear.

Table V: Statistical outcomes of the linear mixed models. Joint moments were compared between different tasks, directions, and conditions

	df	F	P
Tasks	7	40.44	< .001
Direction	2	170.02	< .001
Condition	1	2.07	0.151
Direction * Condition	2	0.08	0.992
Condition * Tasks	7	3.04	< .001
Task * Direction	14	6.29	< .001
Tasks * Direction * Condition	14	0.31	0.993

Note: p-value < .01 was considered as statically significant; df = degrees of freedom.

DISCUSSION

In this study, eight simulated ADL tasks were analyzed on range of motion and peak joint moments in FE, PS, and VV direction, depending on the given verbal instruction of not lifting more than 1 kg. Joint moments did differ between tasks and movement directions. FE moments and VV moments were significantly higher compared to PS moments. The effect of the instruction of 'not lifting more than 1 kg' was dependent of the tasks. Only during the chair rise task did the instruction result in a significant decrease in elbow joint loads. These results confirm our hypothesis that elbow joint moments differ per task, and indicate that the current instruction might be reconsidered to emphasize the load demand per task based on biomechanical evidence.

The tasks performed during this study give a good representation of elbow ROM needed to naturally perform ADL. The findings of the FE-ROM (range 19°–126°) are in line with earlier literature (30). A review of Oosterwijk et al. concluded that an FE-ROM 0°–150° is required for ADL tasks, which is more than the generally used reference of 30°–130° (31, 32). Mainly tasks needed for personal care and feeding needed a flexion angle > 135° (30). FE angles < 30° were observed during the door, cup, and lift tasks. A review of Kincaid and An shows that especially peak bone-on-bone contact forces occur between 7° and 11° flexion (almost fully extended) (33). Muscle activity and therefore bone-on-bone contact forces would be higher early in the flexion cycle due to the poor mechanical advantage of the prime movers: the brachialis, biceps, and brachioradialis muscles (34). The functional PS-ROM of 50° pronation to 88° supination found in our study is higher than the PS-ROM found by Sardelli, who reported a functional ROM between 65° ± 8° pronation and 77° ± 13° supination (32).

In this study we found that overall peak FE moments and VV moments were higher compared to the peak PS moments. Therefore, the focus in preventing overload should probably be on reducing elbow moments, mainly in the FE and VV directions. The high VV-moments found, especially during rising from a chair and steering a car, are likely due to the combination of large external reaction forces and a relatively large moment arm.

Although no other study examined ADL tasks in all three directions, results of previous research on FE and PS moments are comparable to our findings. For instance, the task performed by Murray et al. showed the same order of magnitude as those of our study, although we used a 1-kg object compared to Murray's 0.5-kg object, resulting in higher FE moments (35). To illustrate: during the lifting task, Murray et al. found a maximum FE moment of 5.8 Nm during the lifting of a block (~0.5 kg) to head height, while in our study, where the object was placed at shoulder height, a flexion moment of 6.4 Nm was required. The results of Cheng et al. were comparable to ours, although they found higher moments in tasks where they used a 2-kg object compared to our results, where a 1-kg object was used (36).

For all participants, the highest peak moments, in FE direction, were achieved during the rising phase of the chair task. The lowest elbow joint moments were observed during the slide task. King et al. showed that the amount of shoulder abduction affects the joint loading of the elbow (18). The variation in elbow moment is surprisingly low in the slide task compared to the lifting and cup tasks (which show the same FE-ROM). This may indicate that all participants used the same movement strategy during the slide task, which is initiated from the shoulder. More research is needed to elucidate whether shoulder moments could partially relieve elbow joint loading during selected tasks.

Altogether, the chair, door, and car tasks showed the highest risk of wear because of the higher observed external reaction forces resulting from pushing and pulling. These findings question whether the focus of the instruction should be on lifting an object ("not lifting 1 kg") or on the presence of external reaction force, i.e., the amount of force required for a pulling or pushing movement.

Instruction

No overall main effect of instruction was found; however, the p-value was low ($p = .15$). The results show that the effect of the instruction is dependent on the tasks. During the chair task a significant change was found after the instruction in FE moments (13.4 Nm to 10.3 Nm) and VV moments (15.2 Nm to 11.1 Nm). This was the consequence of less pushing force against the armrest, possibly combined with a greater leg pushing force.

Contrary to our expectations, during the door and lift tasks unexpected higher peak flexion moments were found during the instructed condition, with a change in the minimal FE angle during the door task (figure 3A). However, this kinematic change did not lead to a significant decrease in elbow joint moments. This finding questions whether people can accurately predict which changes in movement will lead to lower loads in the elbow.

Implications for implant failure

Finite element studies indicated that VV moments of 5 Nm at the ulnohumeral joint would possibly exceed the yield strength of PE. Surprisingly, the overall mean of the VV moments found in this study (7.9 Nm) exceeded these failure limits, leading to permanent deformation of the PE material. Moreover, during five (car, door, chair, lift, cup) of the eight tasks, even higher external VV moments were observed (Table III).

Besides the loading, task frequency also plays an essential role in the risk of PE wear. Many repetitions of a movement lead to erosion of the material. The frequency of the FE movement associated with normal ADL is estimated to be 0.5 million cycles/year, while for strenuous ADL with a significant weight in hand the frequency is approximately 7500 cycles/year (37). It is therefore important to remember that there is not one specific limit/threshold on whether a task can be performed, as it is also important to consider the frequency of the task.

Recommendation for clinical practice

So far, it is known that high elbow loads lead to PE wear, which ultimately causes permanent deformation of the prosthetic PE material. Based on the results of the current study, we can now give a better indication of which tasks are more demanding. First, frequent repetition of heavy tasks with a large amount of external load should be avoided or performed differently than before the operation, for example rising from a chair without using the armrest instead of pushing with whole-body weight. Hence external loads are not only the loads resulting from lifting an object (i.e., a heavy book or groceries), but also from the reaction force on the object. Plus, tasks further away from the body with an outstretched arm (e.g., reaching) are more demanding than tasks closer to the body (21).

Limitations and future directions

The musculoskeletal model used in the current study was based on a single cadaver specimen. Individual differences could have led to soft-tissue artifacts or incorrectly-defined joint centers in marker-scaled models, affecting the inverse dynamics results (38). However, the elbow axes and kinematics were defined in accordance with the ISB recommendations (28) and therefore the effect of individual differences is subsequent to the correct anatomical behavior. Future research could further investigate the effect of individual morphological differences on the inverse dynamics estimations.

Second, although healthy participants were examined in this study, it is possible that elbow motions following TEA are changed due to altered motion pathways (i.e., rotation axis), proprioception, and muscle forces (39). Future research should examine the changes in elbow joint moments in TEA patients and incorporate the changes in prosthesis kinematics into the musculoskeletal model. Computed tomography scans, combined with artificial intelligence technology, have already been used to measure muscle elongations for different implants, positions, and patient anatomies, and can therefore be used to personalize the model (40).

Last, we do not know if the observed elbow loads of the current study lead to failure of the material of the elbow prosthesis. So far, we could only compare one feature of the elbow load (VV moments) to the reported failure, i.e. permanent deformation and limits of the PE material of one specific elbow prosthesis. Besides, different types of prostheses may have different failure mechanisms and limits (41). To compare the in vivo elbow load to the loads that exceed the failure limits of the prosthetic material, future research should focus on failure limits and elbow joint load in both elbow joint moments and internal bone-on-bone contact forces [20].

CONCLUSION

Results of the current study provide insight into elbow joint loading during ADL tasks. Tasks that include pushing and pulling result in higher joint loads, especially in the FE and VV direction. Surprisingly, the VV moments found in this study exceeded the failure limits, leading to permanent deformation of the prosthetic material. The current found joint moments could provide a loading range for in-vitro testing of prostheses during the design stage. To avoid overloading the elbow prosthesis, the current postoperative instruction does not appear to be sufficient. The outcomes of this study can be used as a first step in formulating evidence-based and specific instruction. However, bone-on-bone contact forces and elbow joint moments (VV, PS, and FE direction) in both healthy adults and patients following TEA need to be further analyzed to draw more definitive conclusions on elbow joint loading in ADL.

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APPENDIX

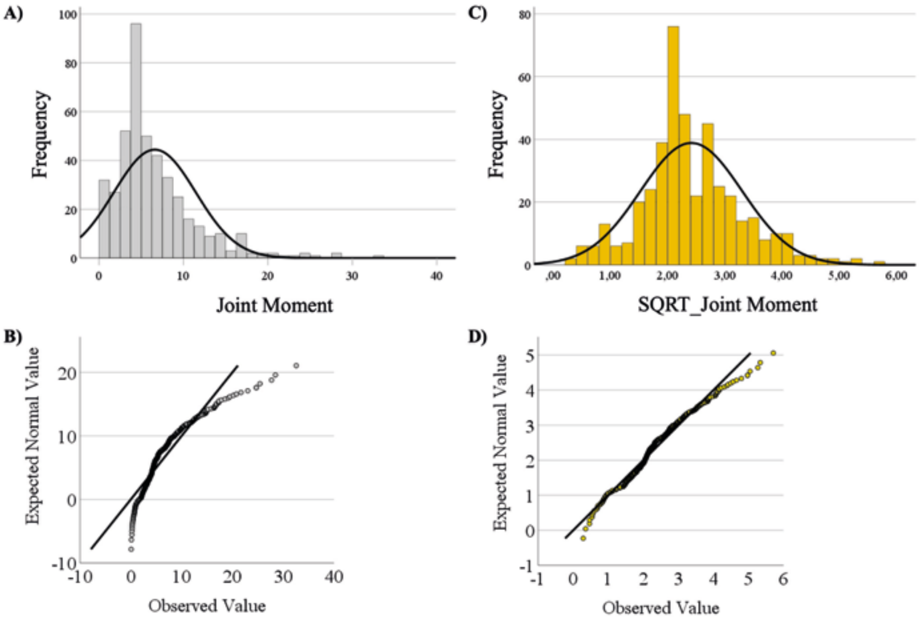
APPENDIX A: Marker position for 3D marker tracking.

Type	Segment	Location on body
Rigid body	Sternum	Jugular incision
Virtual marker	Xiphoid process	Xiphoid process
Virtual marker	Clavicle	Incisura jugularis
Single body + virtual marker	C7 vertebra	Spinal process of C7 vertebra
Single body + virtual marker	Non-dominant shoulder	Acromion
Rigid body	Right upper arm	Lateral upper right arm, 1/4 on the line between acromion and lateral epicondyle of humerus
Virtual marker	Right elbow lateral	Lateral epicondyle of humerus
Virtual marker	Right elbow medial	Medial epicondyle of humerus
Rigid body	Right forearm	Lower lateral surface of right forearm, one finger width proximal of styloid process of the radius and ulna
Single body + virtual marker	Right wrist ulnar	Styloid process of ulna
Single body + virtual marker	Right wrist radial	Styloid process of radius
Rigid body + virtual marker	3^{rd} MCP of finger	3^{rd} MCP of hand
Virtual marker	5^{th} MCP of finger	5^{th} MCP of hand
Rigid body	Sacrum	Sacrum
Virtual marker	Right posterior superior iliac	Right posterior superior spine of ilium
Virtual marker	Left posterior superior iliac	Left posterior superior spine of ilium
Virtual marker	Right anterior superior iliac	Right anterior superior spine of ilium
Virtual marker	Left anterior superior iliac	Left anterior superior spine of ilium
Virtual marker	T10 vertebra	Spinal process of T10 vertebra
Rigid body + virtual marker	Right shoulder	Dominant acromion
Virtual marker	Right shoulder	Acromion angle
Virtual marker	Right shoulder	Inferior angle
Virtual marker	Right shoulder	Trigonum spinae
Virtual marker	Right shoulder	Coracoid process
Virtual marker	Right shoulder	AC most dorsal point
	1-kg object – Force transducer	Center of rotation

5

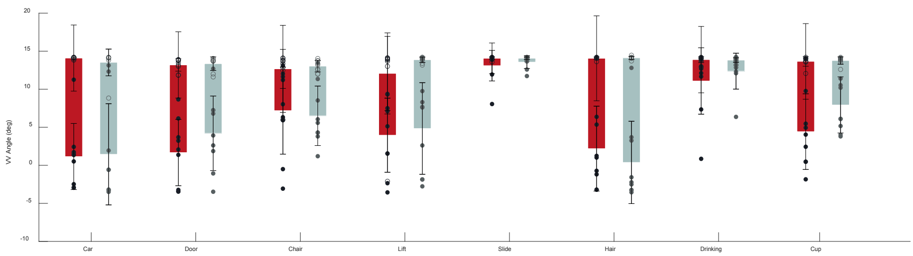
APPENDIX B

Distribution of joint moments before (A and B) and after (C and D) square root transformation. Before the square root transformation, the histogram does not match with the normal curve.



APPENDIX C

Average (N=9) range of motion in varus-valgus direction for eight simulated activities of daily living. Negative angle is in the varus direction and positive angle is in the valgus direction. Without instruction (red) and with instruction (grey) of not lifting more than 1 kg. Dots represent minimal individual angles (filled) and maximal angles (empty). Angle in degrees. Error bars represent the standard error for the maximum angle (upper end) and minimal angle (lower end).



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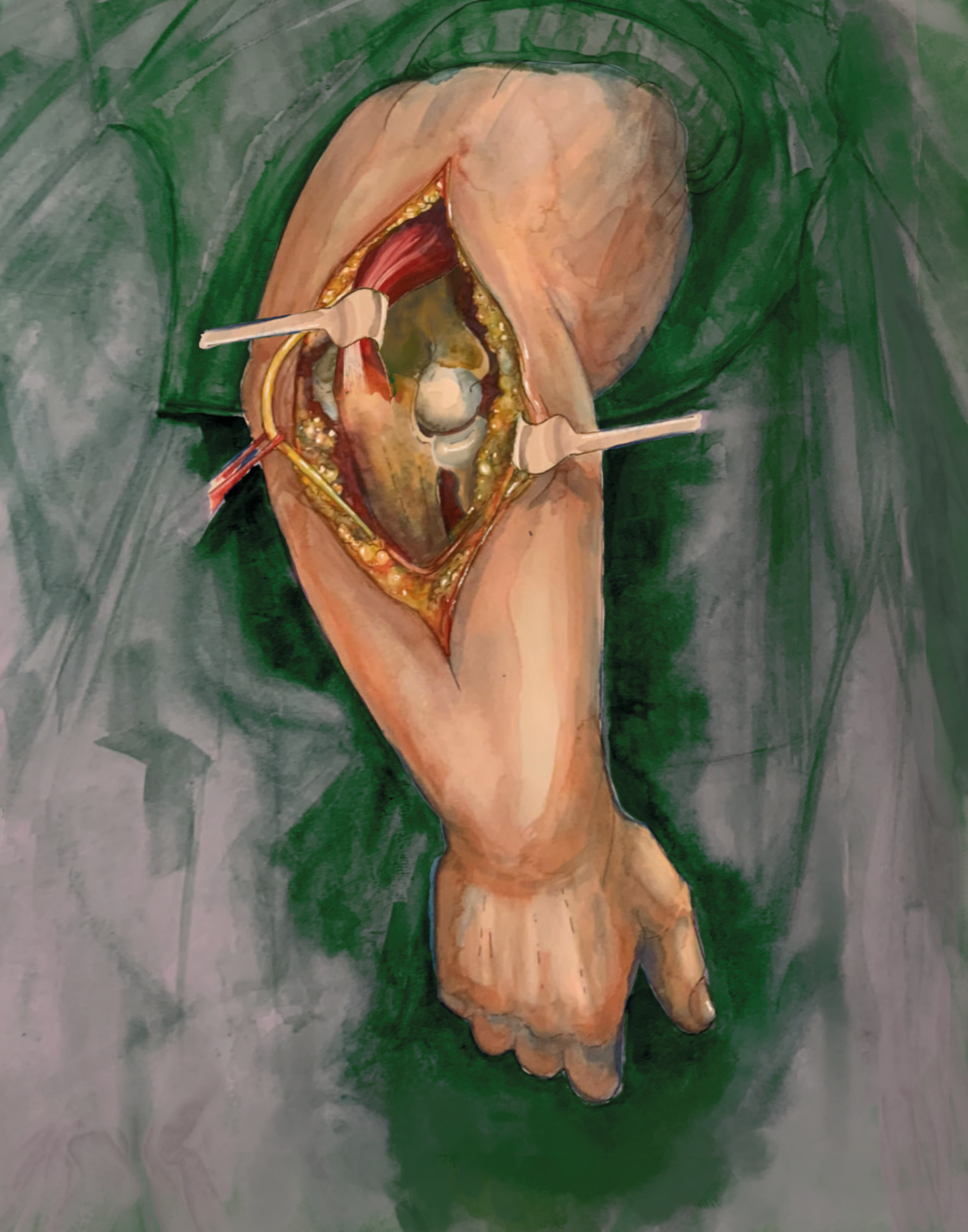
PART 3: THE PROCEDURE



Chapter 6

Triceps insufficiency after total elbow arthroplasty: a systematic review.

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ABSTRACT

Background: Incidence rates of triceps insufficiency after total elbow arthroplasty (TEA) vary in literature, with a lacking consensus on treatment strategy. Aim is to review incidence, risk factors, clinical presentation, diagnosis and treatment of triceps insufficiency after TEA. Based on this information, recommendations for clinical practice will be formulated.

Methods: A systematic review of studies from January 2003 to April 2020 investigating triceps function following TEA were identified by searching PubMed, Cochrane and EMBASE. Eligible studies: (1) reported on triceps function following primary or revision TEA for every indication, regardless of technique (e.g. bone grafts); (2) included at least six adult patients; (3) had the full-text article available; (4) had a minimum follow-up of one year.

Results: Eighty studies with a total of 4825 TEAs were included. Quality was low in 15 studies, moderate in 64 and high in one. Mean incidence of triceps insufficiency was 4.5%. Incidence rates were highest in patients after revision TEA (22%), those with post-traumatic arthritis (PTA) as indication for surgery (10.2%), and after a triceps-reflecting approach (4.9%). Most studies used the Medical Research Council (MRC) scale to score triceps function, although cut-off points and definition differed between studies. Surgical treatment showed favorable results for anconeus tendon transfer and Achilles allograft repair when compared to direct repair.

Conclusion: Incidence rates of triceps insufficiency vary greatly, probably due to a lack of consensus on the definition of the term. We therefore recommend the guidelines as presented in this article for clinical practice. These guidelines assist clinicians in providing the best possible treatment strategy to their patients and help researchers optimize their future study designs in order to compare outcomes.

BACKGROUND

The reported incidence of triceps insufficiency after total elbow arthroplasty (TEA) ranges widely, between 0.4 and 29% (1-5). Triceps insufficiency can cause severe burden, as a functional triceps is required for activities of daily living (ADL) (6). An explanation for the wide range reported in literature is presently lacking, but there are several hypotheses, such as the use of different surgical approaches or different indications for TEA. However, a review by Voloshin et al. (4) found no significant differences in the incidence of triceps insufficiency between surgical approaches. A switch to triceps-sparing approaches has been made nonetheless, as these approaches may minimize the risk of triceps insufficiency (1, 7, 8). Furthermore, patients with rheumatoid arthritis, one of the major indications for TEA, could be at higher risk of developing triceps insufficiency due to poor triceps tendon quality and poor bone quality of the olecranon (8).

Triceps insufficiency can be caused by several mechanisms. First, poor tendon quality or degeneration of the insertion can lead to a deficient attachment. Second, because of devascularization healing may be incomplete due to ischemia, leading to elongation or disruption. Lastly, alterations in moment arms or aggressive rehabilitation can cause triceps insufficiency too. In practice, a combination of factors will be encountered and it is difficult to give a clear, simple reason for failure of the triceps insertion. When facing triceps insufficiency it is important to understand the complex anatomy of the triceps insertion, as described by Barco et al. and Keener et al. (9, 10). The insertion has a broad footprint on the olecranon with a superficial tendinous insertion and a deep muscular insertion. The tendinous superficial insertion originates from the long and lateral heads of the triceps and the deep muscular insertion originates from the medial head. Near the insertion, there is a cleavage plane between the superficial tendinous and the deep muscular insertion. The superficial tendon forms two components as it approaches its insertion area: first a lateral part that is more expansive and relatively thin, continuous to anconeus muscle and fascia, next a medial part of the tendon that is thicker than the lateral aspect and forms the proper triceps tendon inserting directly on the olecranon.

Surgical treatment of triceps insufficiency is possible and the type of reconstruction depends on the cause of the insufficiency. Unfortunately, most surgical reconstructions are challenging procedures with high failure rates (1, 6, 11).

This systematic review has been conducted since incidence rates of triceps insufficiency vary greatly in literature, with lacking consensus on treatment strategy. Primary aim is to analyze the available literature on conditions described as triceps insufficiency. Secondary objective is to analyze risk factors, clinical presentation, diagnosis and treatment of triceps insufficiency. Based on this information, recommendations for clinical practice and future research will be formulated.

METHODS

A systematic review. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed (12).

Literature search and study selection

A systematic literature search was conducted on 30 March 2020 in three online databases (PubMed/Medline, Cochrane database for clinical trials and Embase). The following terms were used: Arthroplasty, Replacement, Elbow, Elbow Joint, Joint prosthesis [Mesh], elbow, replacement, arthroplasty, prosthesis [tiab]. The search was performed using the filters "Dutch", "English", "German" covering the period between January 2003 and April 2020. This time span was chosen because of the evolution of TEA techniques. Full search details are presented in Appendix I.

Identified articles were imported into EndNote X9 (13). Duplicates were removed. Based on title and abstract, two independent reviewers (DM and CLW) identified potentially relevant articles for review of the full text. In case of disagreement, a third author was consulted (MvdB). The reference list of the included articles was manually checked to avoid missing relevant articles. The authors independently selected articles. Studies were not blinded for author, affiliation or source.

Eligibility criteria

Eligible studies: (1) reported on the triceps function following primary or revision TEA for every indication, regardless of technique (e.g. bone grafts); (2) included at least six adult patients; (3) had the full-text article available; (4) had a minimum follow-up of one year. This time span was considered clinically relevant, as it takes postoperative triceps healing into account. Articles that were not original studies were excluded. Expert opinions, surgical technique articles and animal studies were also excluded. Articles thought to have presented data in a previous article were included once; if there was any doubt, the corresponding author was contacted.

Data extraction

After initial assessment, data from eligible studies were extracted based on a predefined extraction form. The following data and baseline parameters were recorded when available: author and publication year, study design, number of patients, sex, age, indication for TEA and follow-up. Primary objective was to report on prevalence of triceps insufficiency, as well as clinical presentation, diagnosis and treatment. Data on surgical approach and definition of triceps insufficiency were collected. Data on surgical approach were then subdivided with a classification system as previously used by Booker et al. (14).

Methodological quality assessment

Level of evidence of the included studies was assessed as previously defined by the Centre for Evidence-Based Medicine (http://www.cebm.net). Methodological quality of the included studies was evaluated according to the methodological index for non-randomized studies (MINORS) criteria (15). The MINORS is a valid instrument used to assess the methodological quality of nonrandomized surgical studies, whether comparative or noncomparative. It consists of eight items, with a maximum score of 16, for noncomparative studies and an additional four items for comparative studies, with a maximum score of 24. As previously described by Khan et al. (16) the scores for noncomparative studies are: 0-4, very low quality; 5-8, low quality; 9-12, moderate quality; and 13-16, high quality. The scores for comparative studies are: 0-6, very low quality; 7-12, low quality; 13-18, moderate quality; and 19-24, high quality. Methodological quality assessment was assigned by two authors (DM, CLW). Any differences in scoring were resolved by consensus.

RESULTS

Selection of literature

An initial search yielded 7136 potentially relevant studies. After removal of duplicates, 4939 articles were identified. 4708 studies were eliminated from consideration after evaluating the titles and abstracts. The remaining 231 papers were retrieved for detailed assessment of the full-text manuscript. Two studies were excluded because there were no full-text articles available. Also, three studies were considered as duplicates because they used the same database for different articles, and 146 articles were excluded since they did not report on triceps function. A total of 80 articles were thus included (Figure 1).

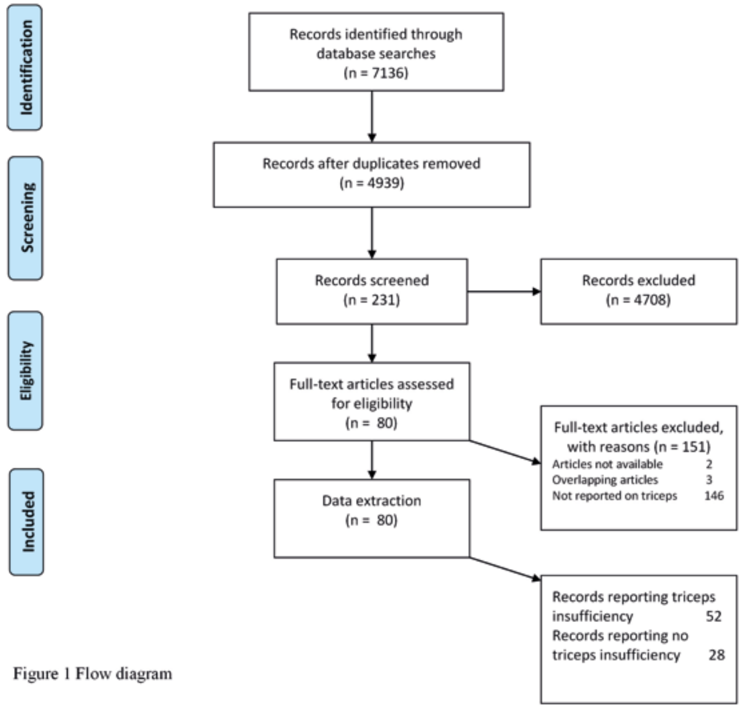

Figure 1 Flow diagram

Quality assessment

Of the articles included, three were prospective comparative (level 3), all other studies were retrospective (level 4). Of these retrospective studies, an additional one was comparative. The others were case series. Fifteen studies were low-quality, 64 moderate-quality and one high-quality. The mean MINORS score for the comparative studies was 16/24 (range 14-18) and for the non-comparative studies 10/16 (range 7-14). Areas of improvement for most studies according to the MINORS were prospective data collection, unbiased assessment of the study endpoint and prospective calculation of the study size. Details of these outcomes are shown in Appendix II.

Study characteristics

A total of 80 studies were included in this review, 52 reporting triceps insufficiency as a complication and 28 reporting no triceps complications. Overall, a total of 4825 TEAs were included. The number of elbows included in the articles ranged from 6 to 887. Age ranged between 23 and 81 years. Follow-up time ranged from 1 to 13.5 years. Table 1 displays an overview of the study characteristics.

Table 1 *Overview of study characteristics*

Number of studies	80
Number of patients	4454
Number of elbows	4825
Mean (weighted) age (years)	62.7
Mean (weighted) follow-up (years)	5.2
Number of triceps insufficiencies	215

Triceps insufficiency: primary vs revision surgery

A total of, 215 cases of triceps insufficiency were reported in 80 articles (1, 3, 6, 8, 17-92). Mean incidence was 4.5% (range, 0-54.8%). Detailed information on primary or revision surgery could be retrieved from 77 articles (1, 3, 8, 17-37, 39-81, 83-92). Missing data on these parameters warranted exclusion from this section. A total of 197 cases of triceps insufficiency were reported in these 77 articles. Mean incidence in this group was 5.1% (range 0-54.8%). Incidence in patients with a primary total elbow prosthesis was 3.5% and in the revision group 22% (Table 2). For revision surgery, some articles reported the number of prior procedures, ranging from one to six. The most common reason for revision was infection, in 125 cases, followed by aseptic loosening in 59 cases. Other reasons for revision were fracture, instability and unknown.

Table 2 *Study outcomes primary and revision TEA*

	Total	Primary TEA	Revision TEA
Number of studies	77	65*	16*
Number of elbows	3841	3509	332
Mean (weighted) age (years)	62.8	62.7	63.6
Mean (weighted) follow-up (years)	5.6	5.6	4.8
Number of triceps insufficiencies (%)	197 (5.1)	124 (3.5)	73 (22)

* Overlap due to studies reporting on both primary and revision TEA

Triceps insufficiency: indication for surgery

Detailed information on indication for surgery could be retrieved from 49 articles (1, 3, 8, 18-20, 23, 25, 27, 28, 30-33, 35-37, 41, 42, 45-51, 54-56, 59-66, 69-71, 74, 76, 79, 80, 82-84, 89, 92), with a total of 49 cases of triceps insufficiency reported. Table 3 shows the distribution of triceps insufficiency between groups. Mean incidence was 2.0% in the rheumatoid arthritis (RA) group, 10.2% in the post-traumatic arthritis (PTA) group, 3.4% in the trauma group, 3.7% in the osteoarthritis (OA) group, and 2.9% in the other group.

Table 3 *Study outcomes per indication for TEA*

	Total*	RA	PTA	Trauma	OA	Other**
Number of studies	49	33	18	27	12	11
Number of elbows	1547	886	128	410	54	69
Mean (weighted) age (years)	63.6					
Mean (weighted) follow-up (years)	5.2					
Number of triceps insufficiencies (%)	49 (3.2)	18 (2.0)	13 (10.2)	14 (3.4)	2 (3.7)	2 (2.9)

RA = rheumatoid arthritis, PTA = post-traumatic arthritis, OA = osteoarthritis
* *O*verlap due to studies reporting on multiple indications
*** Other: hemophiliac arthropathy, idiopathic arthropathy, gouty arthritis, fibrous dysplasia, gunshots, ankylosis, oncology, osteomyelitis, arthritis psoriatic, reactive arthritis.*

Triceps insufficiency: surgical approach

Detailed information about the surgical approach could be retrieved from 57 articles (3, 8, 17-19, 24-28, 30-33, 35-37, 39-45, 47, 49, 50, 52, 55, 56, 58-64, 66, 68-73, 75, 76, 79, 80, 82, 84-89, 91, 92), with a total of 76 cases of triceps insufficiency reported. Mean incidence was 3.3% (range 0-25%). Table 4 shows the distribution of triceps insufficiency between groups. Incidence is 3.1% in the triceps turndown group, 4.9% in the reflecting group, and 1.2% in the splitting group. There were no cases of triceps insufficiency in the osteotomy group or in the triceps-sparing group.

Table 4 *Study outcomes per surgical approach*

	Total *	Triceps turndown	Triceps-reflecting	Triceps-splitting	Olecranon osteotomy	Triceps-sparing
Number of studies	57	15	25	19	5	10
Number of elbows	2293	491	1130	482	41	149
Mean (weighted) age (years)	63.3					
Mean (weighted) follow-up (years)	5.5					
Number of triceps insufficiencies (%)	76 (3.3)	15 (3.1)	55 (4.9)	6 (1.2)	0	0

* Overlap due to studies reporting on multiple surgical approaches

Clinical presentation

Clinical presentation and impact of the triceps insufficiency was reported in nine articles (6, 19, 20, 32, 34, 43, 65, 80, 87, 92) (n=85; 39.5%). One article (87) (n=7; 3.3%) stated that the triceps insufficiency was well-tolerated and patients had almost no complaints. Seven other studies (6, 19, 20, 32, 43, 65, 80, 92) reported complaints about weakness (n=8; 3.7%), inability to extend against gravity (n=19; 8.8%) and pain (n=16; 7.4%). One study (34) reported that 86% of their patients (n=25; 11.6%) complained about interference with ADL, yet more than 50% in that group (n=15; 7.0%) reported better triceps function postoperatively.

Diagnosis

Twenty-four articles (1, 3, 6, 8, 18, 19, 23, 27, 31, 34-36, 42, 47, 55, 59, 62, 63, 68, 71, 73, 76, 81, 84) documented how triceps insufficiency was diagnosed. Sixteen of the 24 articles used the Medical Research Council (MRC) scale. Cut-off values differed between studies. Four studies tested whether patients could extend against gravity and two studies tested whether patients could extend against resistance. Another study compared triceps strength to the contralateral elbow, scoring triceps insufficiency as severe loss of strength exceeding 50%. One study used a force transducer to grade triceps function and calculated a combined flexion and extension score. Two other studies used a force transducer in addition to the MRC score to measure triceps force.

Cottias et al. (31) measured triceps force in flexion and extension, with 4.7 kg mean force in flexion and 1.9 kg in extension. Struder et al. (84) measured extension torque and compared it to the contralateral elbow. Torque range was 13-21 N-m in the operated elbow. Table 5 gives an overview of diagnostic tests by study.

Definition

Sixty-nine studies (1, 17, 20-26, 28-30, 32, 33, 35-58, 60-79, 81-83, 85-92) failed to define the term triceps insufficiency. The remaining 11 studies (3, 6, 8, 18, 19, 27, 31, 34, 59, 80, 84) defined it, but terms and definitions were heterogeneous. Three studies defined a triceps disruption as MRC grade 2 or less (18, 19, 84). Two studies defined triceps weakness as MRC grade 3 or less (3, 59), one of them additionally stating that insufficiency due to a rupture entailed loss of extension strength and inability to extend against gravity (3). Other studies defined triceps insufficiency as loss of active elbow extension (6) or inability to extend against gravity (8, 27, 80). One study defined triceps insufficiency as inability to extend against resistance (31). Lastly, Duquin et al. (34) developed a method to classify triceps insufficiency. Using their method, patients were scored as type I when they had weakness with an intact extensor mechanism and as type II when there was loss of the extensor mechanism. The latter were further classified as having soft-tissue loss (type IIA) if the olecranon was intact on radiograph, but the triceps tendon was absent or avulsed, and having bone loss (type IIB) if the bony insertion of the triceps was absent.

Treatment

Of the 52 articles (1, 6, 19-22, 24, 26, 28, 29, 32, 34, 35, 38-41, 43, 44, 48, 49, 52-54, 57, 58, 63-68, 72-88, 90-92) with triceps complications, 33 reported on treatment (1, 6, 20, 21, 24, 28, 29, 32, 34, 35, 40, 43, 44, 48, 49, 52, 53, 57, 58, 63-67, 72, 74-76, 78, 82, 85, 87, 90). A total of 153 triceps complications were included. Most complications were ruptures and

Table 5 *Diagnostic tests*

Author (year)	No. elbows	Age (years)	Follow-up (years)	MRC scale	Cut-off value	Other
Amirfeyz (2009) (18)	54	69	4.5	Yes	Grade 2 or <	
Baksi (2018) (23)	14		13.5	Yes	Grade 2 or <	
Celli A (2016) (3)	20	63	2.8	Yes	Grade 3 or <	
Celli A (2016) (8)	15	59	3.1	Yes	Grade 3 or <	
Cesar M (2007) (27)	44	56	6.2			Extend against gravity
Cottias (2020)(31)	24	80	2.5			Extend against resistance Force transducer
Gallucci (2016) (36)	23	76	3.3	Yes	Grade 3 or <	
Kalogrianitis (2008) (42)	9	73	3.6	Yes	Grade 3 or <	
Lami (2017) (47)	21	81	3.2			Extend against gravity
Mansat (2013) (55)	87	79	3.1			Extend against resistance
Na (2018) (59)	21	56	5.4	Yes	Grade 3 or <	
Oizumi (2015) (62)	25	69	3.5	Yes	Unknown	
Prasad (2016) (71)	19	68	13	Yes	Grade 3 or <	
Amirfeyz (2011) (19)	11	64	6.3	Yes	Grade 2 or <	
Celli (2005) (6)	887					Extend against gravity
Dachs (2015) (1)	83	60	3.5			Extend against gravity Palpable defect
Duquin (2014) (34)			5.5	Yes	Grade 4 or <	
Fritsche (2015) (35)	46	64	3.2	Yes	Grade 3 or <	
Ovesen (2005) (63)	43	56	6.9			Force transducer
Pham (2018) (68)	54	60	7			Triceps strength compared to contralateral, 50% of cut-off

Table 5 *Diagnostic tests*

Author (year)	No. elbows	Age (years)	Follow-up (years)	MRC scale	Cut-off value	Other
Renfree (2004) (73)	10	58	6.5	Yes	Unknown	
Schneeberger (2007) (76)	23	60	4	Yes	Unknown	
Solarz (2020) (81)	16	72	5.1	Yes	Grade 2 or <	
Studer (2013) (84)	37	68	4.5	Yes	Grade 3 or <	Force transducer Palpable defect

avulsions (n=109), some reported weakness (n=14), others did not define the complication of triceps insufficiency (n=30).

Treatment options were conservative (n=52), surgical (n= 83) and unknown (n= 18). Conservative treatment was not specified. Surgical interventions consisted of: direct bone suture repair (n=29), Achilles tendon grafts (n=7), anconeus rotational flap (n=7), triceps imbrication (n=1), triceps plication (n=1), and not specified (n=38).

A total of five articles also reported on the outcomes following their intervention. Dachs et al. (1) performed four direct suture repairs; all of them failed. Ovesen et al. (63) performed two suture repairs, one was successful. Large et al. (49) performed one anconeus flap with a graft, which was technically successful. Celli et al. (6) published their results on the treatment of triceps insufficiency following TEA and developed a treatment algorithm. They mainly performed bone suture repair, which was successful in 73% of cases. Their success rates were 80% for Achilles tendon graft and 100% for anconeus rotational flap. Duquin et al. (34) performed 14 direct suture repairs with a 36% success rate. In seven cases they used a bone graft combined with five direct repairs, one with an anconeus tendon transfer and one with Achilles allograft. Only one direct repair was successful. The anconeus tendon transfer and Achilles allograft were both successful.

DISCUSSION

In this systematic review, 80 studies on triceps insufficiency following TEA were included and reviewed for incidence, risk factors, clinical presentation, diagnosis, definition and treatment of triceps insufficiency. Main findings are lack of a uniform definition of the term triceps insufficiency and of a uniform diagnostic test including cut-off values. Hence decision-making on optimal surgical approach and treatment strategies remains challenging. The results should be interpreted in light of several limitations, as this review is mainly based on retrospective, non-comparative data and is therefore limited by the quality of the available studies. Fifteen studies were low-quality, 64 moderate-quality and one high-quality. All quality levels were included in this systematic review in order to provide a thorough overview of published literature. In addition, the description of factors associated with triceps insufficiency is not reflected in the MINORs score (e.g. low-quality studies may have given good descriptions of factors associated with triceps insufficiency). Because of heterogeneity and low quality of several study aspects (e.g. small sample size), no meta-analysis could be performed.

Incidence and risk factors

Incidence rates are 0-54.8% in the studies included in this review, with a mean of 4.5%. Patients with numerous prior surgical procedures and those following revision surgery seem to be at a higher risk for developing triceps insufficiency. The highest incidence is reported by Duquin et al. (34), on outcomes of 93 patients following revision TEA for infection with a 54.8% incidence of triceps insufficiency (scored as MRC grade 4 or less). They also stated that the more procedures performed, the more weakness patients showed. However, only a limited number of studies quantified the prior procedures and none mentioned the previously performed surgical approaches, thereby precluding an adequate analysis.

Although it was hypothesized that patients with rheumatoid arthritis are more at risk of developing triceps insufficiency due to poor tendon and bone quality (8), incidence rates in the post-traumatic arthritis group are actually higher. Possible explanation for these higher rates could be the several prior procedures and the more extensive surgery performed (e.g. bone grafts) (19, 35, 76), or insufficiency due to a triceps damaged by fracture fragments.

The surgical approach also seems to influence triceps function, with favorable results for triceps-sparing approaches (0% triceps insufficiency) and worse results for triceps-reflecting approaches (4.9% triceps insufficiency). These numbers are inconsistent with results reported by Gueroudj et al. (93), whose in vitro study compared triceps strength following triceps-reflecting, -splitting and -turndown approaches, with favorable results for the triceps-reflecting approach. Possible explanations for this discrepancy are that active and passive triceps function are not comparable, so an intact triceps during passive (in vitro) testing could already be dysfunctional during active (physical) testing; or that since a reflecting approach is the most frequently used, less experienced surgeons also perform this technique, with fewer satisfying results (94). In 1988, Morrey et al. (95) already showed that surgical approaches that minimize damage to the triceps result in greater triceps strength. Triceps anatomy has proven to be complex (9, 10), therefore it is hard to determine the best surgical approach. A switch to triceps-sparing approaches is taking place. However, the numbers of patients undergoing triceps-sparing approaches are relatively low compared to triceps-detaching approaches, so further research should focus on prospective comparative studies on this topic.

The reported numbers on the incidence of triceps insufficiency should be interpreted with caution, as several authors already stated that they are well aware of the poor documentation on postoperative triceps function; the complication may thus be underreported (1, 6). In addition, triceps insufficiency can be overlooked if it is not actively assessed at follow-up, since gravity-assisted extension may conceal a weak or absent extensor mechanism (1).

Finally, biomechanical factors may likewise play an important role in triceps function and strength. Inadequate positioning of the prosthesis causes changes in joint axis and muscle length. These changes lead to different moment arms, possibly causing weakness in extension (95, 96). None of the articles included in this review reported on prosthetic positioning, so no conclusions on this aspect can be drawn.

Clinical presentation, diagnosis and definition

Only a limited number of studies report on clinical presentation, diagnosis and definition. Triceps insufficiency can result in pain and interference with ADL, but can also be well tolerated. Most studies used the MRC scale to score triceps function and some used a force transducer to measure triceps strength. However, none of the articles reported on preoperative values, and cut-off values were frequently not stated or varied between studies (Table 5). Definitions of triceps insufficiency were heterogeneous: most authors agreed there is triceps function insufficiency when a patient cannot actively extend against gravity (MRC grade 2 or less), yet others defined it at MRC grade 4 or less (34). There is no current consensus on the definition of triceps insufficiency, and there is no recommended diagnostic test to detect it.

Treatment

Overall results of surgical treatment were disappointing, with high failure rates. Achilles tendon grafts and anconeus rotation flap showed the best results when adequately used in selected cases. These results are comparable to those of Petre et al. (11), who showed in their cadaveric study that augmented repair was nearly twice as strong as direct repair.

When facing triceps ruptures, a treatment algorithm to guide decision-making, developed by Celli et al. (6), could be used. They advise direct bone sutures in cases with good tissue quality and a preserved olecranon. When tissue quality is good but the olecranon is not preserved, a bone graft should be used. If tissue quality is inadequate but the olecranon is preserved, an anconeus rotational flap should be used. If the anconeus is not available, an Achilles tendon graft should be used instead. Conservative treatment was not specified in any of the studies and results were not reported.

RECOMMENDATIONS FOR CLINICAL PRACTICE

Insufficiency is an inability to perform normal function, taking into consideration the preoperative condition but also the recommendation for usage after TEA. Our first recommendation is therefore to take preoperative MRC scores for triceps function. We would advise considering MRC grade 3 or less as an insufficiency of the triceps. Postoperative MRC scores should be taken at six months and one year, when in the event of triceps insufficiency we recommended defining it based on weakness of the muscle with an intact extensor mechanism (e.g. malpositioning (8, 97) or stretching of the fibers due to the surgical approach (93)), or on whether it is due to a loss of the extensor mechanism (avulsion or rupture). This distinction will help decide on the best treatment. Plain radiographs and ultrasound examination are advised to help identify the cause of the insufficiency. Results of these MRC measurements and causes of the triceps insufficiency should then be reported in articles. There are no clinical studies reporting on triceps force pre- and post-TEA, therefore we are not able to formulate recommendations on this topic. When using a force transducer, we do recommend using the set-up as described by Prkic et al. (98), to create uniform measurements for future analysis.

Surgical reattachment is recommended in case of loss of the extensor mechanism. We advise using the algorithm as described by Celli et al. (6), since they are the only authors to provide such treatment algorithm. Conservative treatment should be used in patients with triceps weakness but with an intact extensor mechanism. Conservative treatment could also be opted for severe comorbidities, little functional disability or in low-maintenance patients.

CONCLUSION

This review shows that incidence rates of triceps insufficiency vary greatly, probably due to a lack of attention or consensus on the definition. Furthermore, with high failure rates the results of surgical treatment were disappointing, which stresses the importance of preventing this devastating complication. For clinical practice we recommend the guidelines as presented in this article; they assist clinicians in providing the best possible treatment strategy for their patients and help researchers optimize their future study designs in order to compare outcomes. Prospective comparative studies with larger sample sizes should be used in the future, to improve the quality of available literature.

APPENDIX I

Pubmed:

("Arthroplasty, Replacement, Elbow"[Mesh] OR "Elbow"[Mesh] OR "Elbow Joint"[Mesh] OR elbow*[tiab])

AND

("Arthroplasty, Replacement"[Mesh] OR "Joint Prosthesis"[Mesh] OR replacement*[tiab] OR arthroplast*[tiab] OR prosthe*[tiab])

Embase:

('elbow replacement'/exp OR 'elbow'/exp OR elbow*:ab,ti)

AND

('replacement arthroplasty'/exp OR 'joint prosthesis'/exp OR replacement*:ab,ti OR arthroplast*:ab,ti OR prosthe*:ab,ti)

Cochrane:

Elbow*

AND

(replacement* OR arthroplast* OR prosthe*)

Filters:

Language: Dutch, English, German

Date: 01 January 2003 to 01 March 2020

APPENDIX II

Study	Year	Number of elbows	Level of evidence	Clearly stated aim	Inclusion of consecutive patients	Prospective collection of data	Endpoints appropriate to aim	Unbiased assessment of endpoint	Follow-up period appropriate	Loss to FU less than 5%	Prospective calculation of study size	Adequate control group	Contemporary groups	Baseline equivalence of groups	Adequate statistical analysis	Total	Quality group*
Ikavalko M	2004	158	4	2	2	0	2	0	1	2	0					9	3
Kelly EW	2004	18	4	2	2	0	2	0	2	2	0					10	3
Renfree	2004	10	4	2	2	0	2	0	2	2	0					10	3
Willems K	2004	36	4	1	2	2	2	0	1	0	0					8	2
Athwal	2005	20	4	2	2	0	2	0	1	0	0					7	2
Blaine	2005	12	4	2	2	0	0	0	2	0	0					6	2
Celli A	2005	887	4	2	2	0	1	0	0	2	0					7	2
Khatri M	2005	47	4	2	2	0	2	2	2	2	0					12	3
Lee KT	2005	8	4	1	2	0	1	0	2	2	0					8	2
Loebenberg	2005	12	4	2	2	0	2	0	2	2	0					10	3
Ovesen	2005	43	4	2	2	2	2	0	2	2	0					12	3
Sneftrup	2005	24	4	2	2	2	2	0	2	0	0					10	3
Athwal	2006	27	4	2	2	0	2	0	2	2	0					10	3
Rauhaniemi J	2006	28	4	2	2	2	2	0	2	2	0					12	3
Cesar M	2007	44	4	2	2	0	2	2	2	0	0					10	3
Cheung E	2007	10	4	2	1	0	2	0	0	2	0					7	2

Study	Year	Number of elbows	Level of evidence	Clearly stated aim	Inclusion of consecutive patients	Prospective collection of data	Endpoints appropriate to aim	Unbiased assessment of endpoint	Follow-up period appropriate	Loss to FU less than 5%	Prospective calculation of study size	Adequate control group	Contemporary groups	Baseline equivalence of groups	Adequate statistical analysis	Total	Quality group*
Schneeberger	2007	23	4	1	2	2	1	0	2	0	0					8	2
Shi LL	2007	67	4	2	2	0	2	0	2	0	0					8	2
Cil A	2008	92	4	2	2	0	2	1	2	2	0					11	3
DeGreef	2008	12	4	1	2	0	1	0	1	2	0					7	2
Demiralp	2008	7	4	2	2	0	2	0	2	2	0					10	3
Kalogrianitis S	2008	9	4	1	2	0	1	0	2	2	0					8	2
LaPorte	2008	12	4	2	2	0	2	0	2	2	0					10	3
Peden	2008	13	4	2	2	2	2	0	2	2	0					12	3
Amirfeyz R	2009	54	4	2	2	0	2	2	2	0	0					10	3
Patil N	2009	13	4	2	2	2	2	0	2	0	0					10	3
Weber	2009	12	4	1	2	2	1	0	0	2	0					8	2
Throckmorton T	2010	69	4	2	2	0	2	0	2	0	0					8	2
Amirfeyz R	2011	11	4	2	2	0	2	0	2	2	0					10	3
Becker	2011	25	4	2	2	0	1	0	1	0	0					6	2
Sorbie	2011	51	4	2	2	2	2	0	2	0	0					10	3
Ishii K	2012	35	4	2	2	0	2	0	2	2	0					10	3

Study	Year	Number of elbows	Level of evidence	Clearly stated aim	Inclusion of consecutive patients	Prospective collection of data	Endpoints appropriate to aim	Unbiased assessment of endpoint	Follow-up period appropriate	Loss to FU less than 5%	Prospective calculation of study size	Adequate control group	Contemporary groups	Baseline equivalence of groups	Adequate statistical analysis	Total	Quality group*
Wang	2012	6	4	2	2	2	2	0	2	2	0					12	3
Kumar	2013	11	4	1	2	0	1	0	1	2	0					7	2
Mansat P JSES Bonne	2013	78	4	2	2	2	2	0	2	2	0					12	3
Mansat P OTSR Nouaille	2013	87	4	2	2	0	2	0	1	2	0					9	3
Morrey	2013	25	4	2	2	0	2	0	2	2	0					10	3
Studer	2013	37	3	2	2	2	2	2	2	2	0	1	0	1	2	18	3
Baghdadi Y	2014	723	4	2	2	0	1	0	2	0	0					7	2
Duquin	2014	93	4	2	2	0	2	0	2	0	0					8	2
Giannicola G	2014	24	4	2	2	2	2	0	2	2	0					12	3
Hastings H	2014	46	4	2	2	2	2	0	2	2	0					12	3
Large R	2014	51	4	2	2	2	2	0	2	0	0					10	3
Linn	2014	7	4	2	2	0	1	0	0	0	0					5	2
Dachs RP	2015	83	4	2	2	0	2	0	2	0	0					8	2
Fritsche	2015	46	4	2	2	0	2	0	2	0	0					8	2
Marinello	2015	30	4	2	2	0	0	0	1	2	0					7	2
Mukka S	2015	25	4	2	2	2	1	2	2	0	0					11	3
Ogino	2015	27	3	2	2	0	2	0	2	0	0	1	1	1	2	13	3

Study	Year	Number of elbows	Level of evidence	Clearly stated aim	Inclusion of consecutive patients	Prospective collection of data	Endpoints appropriate to aim	Unbiased assessment of endpoint	Follow-up period appropriate	Loss to FU less than 5%	Prospective calculation of study size	Adequate control group	Contemporary groups	Baseline equivalence of groups	Adequate statistical analysis	Total	Quality group*
Oizumi	2015	25	4	2	2	0	2	0	2	2	0					10	3
Park	2015	23	4	2	2	2	2	0	2	2	0					12	3
Pogliacomi	2015	20	4	2	2	0	2	0	2	2	0					10	3
Tian	2015	8	4	2	2	2	2	0	0	2	0					10	3
Wagener ML	2015	69	4	2	2	2	2	2	1	0	0					11	3
Aleem	2016	12	4	2	2	0	2	1	0	0	0					7	2
Bigsby	2016	29	4	2	2	0	0	0	2	0	0					6	2
Celli A	2016	20	4	2	2	0	2	0	2	2	0					10	3
Celli A	2016	15	4	2	2	0	2	0	2	2	0					10	3
Gallucci	2016	23	4	2	2	0	2	0	2	2	0					10	3
Pogliacomi	2016	20	4	2	2	0	2	0	2	2	0					10	3
Prasad	2016	19	4	2	2	0	2	0	2	0	0					8	2
Sanchez-Sotelo	2016	461	4	2	2	2	2	2	2	0	0					12	3
Ibrahim	2017	21	4	1	2	0	2	0	2	2	0					9	3
Lami	2017	21	4	0	2	0	0	0	2	0	0					4	1
Perretta	2017	102	4	2	2	0	2	0	2	2	0					10	3

Study	Year	Number of elbows	Level of evidence	Clearly stated aim	Inclusion of consecutive patients	Prospective collection of data	Endpoints appropriate to aim	Unbiased assessment of endpoint	Follow-up period appropriate	Loss to FU less than 5%	Prospective calculation of study size	Adequate control group	Contemporary groups	Baseline equivalence of groups	Adequate statistical analysis	Total	Quality group*
Schoch	2017	11	4	2	2	2	2	0	1	2	0					11	3
Toulemonde	2017	100	4	2	2	2	2	0	2	2	0					12	3
Viveen	2017	19	4	2	2	2	2	0	2	2	0					12	3
Baksi	2018	14	4	2	1	0	1	0	2	0	0					6	2
Kondo	2018	75	4	2	2	0	1	0	2	2	0					9	3
Na	2018	21	4	2	2	0	2	0	2	2	0					10	3
Nishida	2018	87	4	2	2	0	2	0	2	0	0					8	2
Pham	2018	54	4	2	2	0	2	0	2	2	0					10	3
Rudge	2018	19	4	1	2	2	1	0	0	2	0					8	2
Cinats	2019	20	4	2	2	0	2	0	2	0	0					8	2
Strelzow	2019	82	4	2	2	2	2	0	2	0	0					10	3
Cottias	2020	24	4	2	2	0	2	0	1	0	0					7	2
Logli	2020	88	3	2	2	0	2	0	2	2	0	2	1	0	2	15	3
Siala	2020	19	4	2	2	0	2	0	2	0	0					8	2
Solarz	2020	16	4	2	2	2	2	0	2	0	0	0	0	1	2	13	3

*Quality group 1 = very low quality; 2 = low quality; 3 = moderate quality; and 4 = high quality

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6

Chapter 7

A prospective cohort study comparing a triceps-sparing and triceps-detaching approach in total elbow arthroplasty: a protocol.

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ABSTRACT

Background: New surgical approaches have been developed to optimise elbow function after total elbow arthroplasty (TEA). Currently there is no consensus on the best surgical approach. This study aims to investigate the functional outcomes, prosthetic component position and complication rates after a triceps-sparing and a triceps-detaching approach in TEA.

Methods and analysis: A multicentre prospective comparative cohort study will be conducted. All patients with an indication for primary TEA will enrol in either the triceps-sparing or the triceps-detaching cohort. Primary outcome measure is elbow function, specified as fixed flexion deformity (FFD). Secondary outcome parameters are self-reported and objectively measured physical functioning, including triceps force, prosthetic component position in standard radiographs and complications.

Discussion: The successful completion of this study will clarify which surgical approach yields better functional outcomes, better prosthetic component position and lower complication rates in patients with a TEA.

Ethics and dissemination: The Medical Ethics Review Board of University Medical Center Groningen reviewed the study and concluded that it is not clinical research with human subjects as meant in the Medical Research Involving Human Subjects Act (WMO), therefore WMO approval is not needed (METc2019/544).

Strengths and limitations of this study

- This is the first prospective cohort study to compare functional outcomes, prosthetic component position and complication rates following triceps-sparing and triceps-detaching approaches in TEA.
- The hospitals participating in this study represent the vast majority (over ±70%) of the TEAs annually performed in the Netherlands.
- A limitation of the study is that it is non-blinded and non-randomised.

BACKGROUND

New surgical approaches have been developed in recent decades to optimise elbow function and reduce complication rates following total elbow arthroplasty (TEA). Several surgical options exist, including a triceps-sparing approach and a triceps-detaching approach. To date, there are no prospective studies comparing triceps-sparing and triceps-detaching approaches, and full insight into the benefits and drawbacks of the two approaches is lacking.

Functional outcomes following TEA can severely deteriorate due to postoperative complications such as triceps insufficiency or long-term complications like aseptic loosening of the prosthesis (1,2). Lenoir et al. showed that functional outcomes are also affected by prosthetic component positioning (3). A triceps sparing approach has recently been advocated because of triceps insufficiency as a complication following triceps-detaching approaches. Another drawback of a triceps-detaching approach is the need to immobilise in a cast, which might impede postoperative elbow function. A triceps-sparing approach makes direct functional treatment is possible, with potentially better functional outcomes.

Several studies already tried to shed light into which surgical approach yields better functional outcomes. In 2015 Dachs et al. (4) conducted a retrospective analysis to compare triceps-sparing and triceps-detaching approaches. They concluded that elbow function, more specifically fixed flexion deformity (FFD), was better in patients following a triceps-sparing approach. They also concluded that triceps-related complications were absent in triceps-sparing approaches. Other authors (5-7) presented similar studies with comparable results, favoring a triceps-sparing approach.

These authors, however, did not analyse prosthetic component position on radiographs. Considering the fact that the triceps-sparing approach results in less exposure of the articular surface (8), prosthetic component position might be compromised. King et al. (9) already showed that a triceps-sparing approach might lead to a more flexed position of the ulnar component. It is also known that implant malalignment increases loading patterns (10), which might cause polyethylene wear and early loosening of the prosthesis (11).

Hence, there is no consensus on the best surgical approach in TEA. Based on retrospective studies it can be hypothesised that a triceps-sparing approach gives favorable results in terms of functional outcomes and a lower risk of triceps insufficiency. Due to the limited visibility, prosthetic component position may be compromised though.

Aim of this study is therefore to investigate the functional outcomes, prosthetic component position in standard radiographs and complication rates following a triceps-sparing and a triceps-detaching approach in TEA.

METHODS

Study design

A multicentre prospective cohort study will be conducted at University Medical Center Groningen, Martini Hospital Groningen, Amphia Hospital Breda, OLVG Amsterdam and Sint Maartenskliniek Nijmegen. The hospitals participating in this study represent the vast majority (over ±70%) of the TEAs annually performed in the Netherlands. In total 102 patients will be included. The first cohort of 51 patients will be assigned to the triceps-sparing group, the second cohort of 51 patients to the triceps-detaching group. This strategy will provide continuity in the surgical approach for surgeons and avoid surgeon-based inclusion bias.

Recruitment and consent

All adult patients with an indication for primary TEA will be asked to participate in the study. The treating surgeon or a member of the study staff will introduce and explain the study to the patient and answer any questions the patient might have. Patients will receive written information document, and after giving informed consent they will be added to the study database.

Study population

Inclusion criteria: age ≥ 18 years, primary total elbow prosthesis, and ability to participate during the entire follow-up schedule. Exclusion criteria: active infection, total elbow prosthesis surgery in the past (at the ipsilateral side) i.e. revision surgery, previous elbow surgery that influences function of the triceps muscle, other upper extremity injuries to the ipsilateral limb that would compromise postoperative rehabilitation, inability to follow postoperative rehabilitation (due to head injury, dementia, mental illness, etc.), insufficient command of the Dutch language, and conversion of surgical technique during the operation.

Intervention

Patients will be placed in the lateral decubitus position. Tranexamic acid 1gr and cefazolin 2gr will be administered. A dorsal skin incision is made. The incision is curved to pass lateral to the olecranon tip. Full-thickness subcutaneous flaps are developed. The ulnar nerve is located and released. Then depending on the cohort, the specific surgical technique will be performed and prosthetic components will be placed. A tourniquet is inflated only during cementing. All patients will receive a linked type Latitude TEA, without radial head replacement. The radial head will not be resected unless severely damaged.

Once the tourniquet is deflated and range of motion is assessed, the ulnar nerve is returned to its preoperative position or transposed anteriorly in case of tension to the nerve. Refixation of collateral ligaments will be performed whenever possible, and the wound is closed with sutures or staples.

Cefazolin 1gr will be given 8 and 16 hours after initial dose, tranexamic acid 1gr 8 hours after initial dose.

Triceps sparing – cohort 1
After full-thickness skin flaps are developed, medial and lateral windows along the edge of the triceps are created. The triceps attachment remains intact to the olecranon, and after release of the collateral ligaments and opening of the joint capsule the joint can be dislocated (12).

Active flexion, extension, pronation and supination are commenced on the first postoperative day. After three weeks patients are allowed to lift 1kg repetitively and 5kg occasionally.

Triceps detaching – cohort 2
A triceps detaching technique as described by Van Gorder et al. (13) will be used. This approach reflects the aponeurosis of the m. triceps downwards, with the base on the olecranon. The underlying muscle is longitudinally split in the midline and elevated.

Postoperatively the elbow will be protected by a removable cast in 30° flexion for four weeks, avoiding active extension. This time span was chosen arbitrary, to take the post-operative healing of the triceps into account. Unfortunately, evidence for the best aftertreatment following a triceps-detaching approach is unavailable and therefore this protocol is historically rooted in our daily practice. Exercises with active flexion and passive extension are allowed, 3 times a day. Thereafter, the elbow will be mobilised without a brace and active triceps training is allowed. After three weeks, patients are allowed to lift 1kg repetitively and 5kg occasionally.

Outcome measures

Demographics
Age, sex, hand dominance, indication for surgery and previous surgery will be registered.

Primary outcome

The primary outcome measure is elbow function, described as fixed flexion deformity (FFD), measured in degrees of flexion using a goniometer.

Secondary outcomes

Secondary outcomes are self-reported physical functioning, objectively measured physical functioning, prosthetic component position on AP and lateral radiographs and complications.

Self-reported physical functioning

- Elbow function will be measured with the Oxford Elbow Score (OES) (14). The OES consists of three domains; pain, function and social-psychological. Each domain comprises four questions with five response options per question. Each response is scored 0 to 4, with 0 representing greater severity. Scores for each domain are calculated as the sum of each individual item scored within that domain. These scores are then converted to a metric score between 0 and 48, where a lower score represents greater severity. The Dutch language version is considered reliable and valid (15).
- Upper limb function will be assessed using the Quick Disabilities of Arm Shoulder and Hand (Quick-DASH) (16). The DASH gives a score out of 100, where a higher score indicates greater disability. The questionnaire is available in Dutch and is considered reliable and valid (16).
- Health-related quality of life will be measured by the EQ5D-5L (17), a widely used and valid generic instrument to measure health-related quality of life that is validated in the Dutch language (18,19). EQ5D-5L has five dimensions: mobility, self-care, usual activities, pain/discomfort and anxiety/depression. Each dimension is divided into five degrees of severity: no problems, slight problems, moderate problems, severe problems and extreme problems or unable to do. Current quality of life must also be identified on the EQ5D-5L Visual Analogue Scale.
- Elbow pain; level will be determined using a 10-point Numeric Rating Scale (NRS). Pain level will be scored during activities and rest.
- Satisfaction; patients are asked whether they are satisfied with their elbow procedure and whether they would recommend it to others. These items are self-constructed and consist of five answer options (Completely agree, Agree, Neutral, Disagree, Completely disagree). In addition, patients in the triceps-detaching cohort are asked about their satisfaction with the removable cast.

Objectively measured physical functioning

- Active and passive range of motion (ROM) (flexion, extension, pronation, supination) will be measured using a goniometer. A systematic review analysing use of a goniometer in elbow measurements showed high intra-rater and interrater reliability of the universal goniometer (20).
- Triceps brachii force will be measured with a MicroFET and expressed in Newtons. Measurements will be with the elbow in 30° flexion as described by Prkic et al. (21). In case of a flexion contracture >30°, measurement will be done in 60° flexion. In case of an acute fracture, preoperative force will be measured contralateral. The results of the study by Prkic et al. (21) will then be used to calculate the triceps brachii force on the operated elbow.
- Triceps brachii function will be measured using the Medical Research Council (MRC) scale.
- Elbow stability will be stated as intact, <10° instability or >10° instability.

- Neurovascular function; motoric and sensory deficits of the ulnar, medial and radial nerves will be tested. Neurovascular function will be stated as “intact”, “sensory deficit”, “motoric deficit”, “both sensory and motoric deficit”.
- Paraesthesia of the ulnar nerve will be measured using the Tinel Test.
- Carrying angle; expressed in varus/valgus degrees and measured using a goniometer.
- Swelling of the elbow; stated as none, minimal, some, excessive.
- Pain during palpation will be testing by locating the position of the pain.

Prosthetic component positioning

- Positioning of the prosthesis will be analysed on anteroposterior and lateral radiographs at six weeks and one year follow-up. Flexion, extension, varus and valgus positioning of both the humeral and ulnar components will be measured in degrees, as described by Lenoir et al. (22).

Complications

- Number of complications and type of complication will be registered.

Study procedures

Clinical assessment will be performed at baseline, six months and one year after TEA (fig 1). At each follow-up visit the surgeon will conduct a physical examination and capture complications, as described previously. Patients will fill out the questionnaires at baseline and at six months and one year follow-up. At six weeks and one year follow-up, anteroposterior and lateral radiographs of the elbow will be taken to analyse component position. Results of questionnaires and radiological analysis will be stored digitally in the Research Electronic Data Capture system (Redcap). Physical examination and

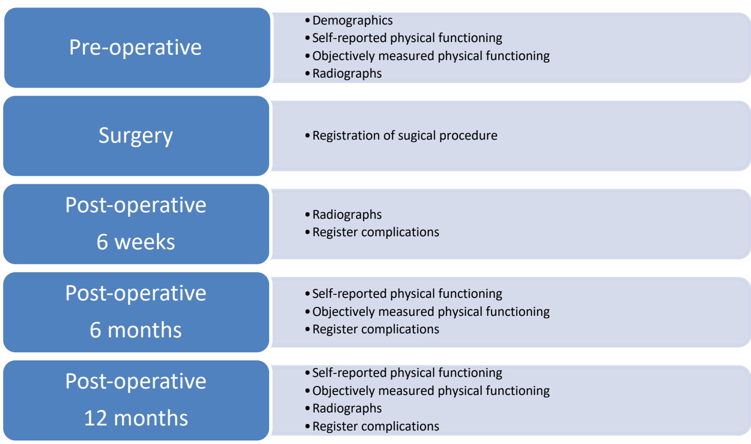

Figure 1. Study procedures

complications will be documented in medical records, then transported to Redcap. Data analysis will be done by an independent researcher.

Sample size calculation

To calculate the sample size, FFD is used as primary outcome measure. To detect 12° difference in elbow function, described as FFD, at one year follow-up, a total of 102 patients are needed in this study. This power is based on earlier research by Dachs et al. that describes FFD after triceps-sparing and triceps-detaching surgical approaches in TEA (4). In this study the difference in FFD was 12° (SD19.6), which was considered clinically relevant, since a functional arc of motion in daily life is described as flexion-extension = 120-30-0 (23). Based on this, a two-sided test with $\alpha = 0{,}05$ and a power of 80%, a sample size of 84 patients is needed. Taking into account a 20% loss of subjects, a total of 102 patients (51 in each group) is needed.

Statistical analysis

Descriptive statistics are used to describe patients' characteristics, clinical outcomes and scores on the questionnaires. Means and standard deviations (SDs) will be used for continuous variables, or percentages for categorical variables. Primary outcome of the study is FFD at one year follow-up. Three measurements will be collected, preoperatively and at six months and one year follow-up. The dependency of FFD between the triceps-sparing group and the triceps-detaching group at one year follow-up is our focal interest. To take into account the dependencies (the nesting structure of the three measurements nested within patients), a longitudinal multilevel model will be used to analyse the data. This model has a level 1 (measurement) and a level 2 (patient). Relevant covariates such as age, gender and indication for surgery will be controlled for. Under the assumption of missing data being missing at random, the missing data will be imputed. The results will be considered statistically significant if $p < 0.05$. SPSS statistical software (version 24.0, IBM SPSS, Chicago) will be used.

Ethics and dissemination

The Medical Ethics Review Board of University Medical Center Groningen reviewed the study and concluded that it is not clinical research with human subjects as meant in the Medical Research Involving Human Subjects Act (WMO); therefore WMO approval is not needed (METc2019/544). Eligible patients will be informed about the study and will sign an informed consent form in order to participate. All informed consent forms will be stored in a locked research office and no personal data will be stored digitally in the Redcap system or revealed in any publication or scientific journal.

Considering current evidence, no clear preference exists for either one of the treatment protocols in this study. Both protocols are regularly applied and all surgeons participating in this study are familiar with the two surgical approaches. Management will not differ between patients, except for the surgical approach. Patients will be exposed to radiation from radiographs, but this is part of routine clinical care. No additional radiographs will be taken as part of this study. Patients may be inconvenienced by filling out questionnaires, which takes approximately 15-20 minutes at three different time points, but in most hospitals this too is part of routine clinical care.

Patient and public involvement

Patients and public were not directly involved in the development of the research question or in the design of the study.

DISCUSSION

To date, there are no prospective studies comparing triceps-sparing and triceps-detaching approaches in TEA. Based on retrospective studies it is hypothesised that triceps-sparing approaches may lead to better elbow function and a lower risk of triceps insufficiency. However, these studies did not analyse prosthetic component position. Considering the technical nature of the triceps-sparing approach, it may carry a higher risk of component malposition, which can cause excessive loads and could lead to polyethylene wear and early loosening of the prosthesis (11). Both triceps-sparing and triceps-detaching approaches are currently being used (2,24), and persistently high complication rates following TEA are reported (1,2). This stresses the need for a prospective comparative study on the best surgical approach, in order to optimise elbow function and reduce complication rates.

The decision to perform a prospective cohort study, instead of a randomized controlled trial (RCT), has been made due to two main reasons. First, we aim to include all Dutch patients requiring a total elbow prosthesis, since numbers of TEAs performed in the Netherlands are low. However our past experience is that a substantial part of the patients is not willing to participate in a RCT. For that we decided to run a cohort study in which in fact usual care is evaluated. By using this design our experience is that more patients are willing to participate. Which is important because the number of TEAs is already quite low. Second, a frequent switch of surgical technique is not desirable, as would be the case in a RCT. Therefore, our study design will provide continuity in the surgical approach for surgeons and for the paramedical care providers (i.e. physiotherapist, nurse) during a certain period.

In recent decades, studies have reported an increasing number of TEAs performed globally (25). This is partly due to the changing trend in indications for TEA, from primary and rheumatoid arthritis to acute trauma and posttraumatic deformities (25) and partly due to an aging population. As the incidence of falls and fall-related injury increases with age, a further rise in the numbers of TEAs is expected.

In conclusion, currently there is no consensus on the best surgical approach in TEA and full insight into the benefits and drawbacks of the two approaches is lacking. The successful completion of this study will shed light into which surgical approach, triceps-sparing or a triceps-detaching, results in better functional outcomes, better prosthetic component position and lower complication rates.

Patient enrolment started in March 2020 and we expect to enrol 50 patients per year. Considering a one-year follow-up, publication of data is expected in 2023.

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7

Chapter 8

Triceps-sparing approach results in better elbow function compared to triceps-detaching approach in total elbow arthroplasty: A multicenter prospective cohort study.

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Chapter 9

General discussion

The overall aim of this thesis is “optimizing total elbow arthroplasty”. The elbow is a complex joint that performs an essential role in daily life, as it is responsible for positioning the hand in space. Replacing the elbow joint with a total elbow prosthesis is a relatively rare and technically challenging procedure, partly due to the complex anatomy of the elbow. Unfortunately, outcomes of total elbow arthroplasty (TEA) are unsatisfying, with low survival and high complication rates. Although numbers of TEA performed are low—in 2024 there were 152 primary TEAs and 82 revision TEAs, compared to over 40,000 total hip (THA) and knee arthroplasties (TKA) in the Netherlands (1)—the unsatisfying outcomes urge research into the underlying failure mechanisms, but more importantly into ways to improve survival rates and reduce complication rates. Therefore, the studies in this thesis are all focused on optimizing TEA. To this end, the thesis examines prosthetic design, patient factors and surgical procedure as interdependent factors that together determine the outcome after TEA. The studies can be divided into three topics. **Part 1** aims to gain insight into functioning of current prostheses to describe the existing problems. **Part 2** focuses on optimizing patient factors during elbow joint loading following TEA, since overloading is hypothesized to be a major cause of failure. **Part 3** emphasizes optimization of surgical procedure, as the surgical approach might influence complications.

This chapter discusses the main findings of the thesis, based on which four key themes are addressed. The key themes are focused on prosthetic design, patient factors during elbow joint loading, surgical procedure and complications, and patient satisfaction. Clinical relevance is emphasized with recommendations for daily practice, and suggestions for future research are made.

Main findings

Part 1 focused on gaining insight into the functioning of two commonly used types of elbow prostheses. In both **Chapter 2**, analyzing the instrumented Bone Preserving (iBP) elbow prosthesis (Zimmer Biomet, Warsaw, Indiana, USA), and **Chapter 3**, analyzing the Latitude (Stryker, Portage, Michigan, USA), the main findings were that 10-year survival rates following TEA remained low, at 80-85%. Main reason for revision was aseptic loosening of the implant. We noted in **Chapter 3** that in 24% of cases the radial head component showed signs of disengagement, which mostly lacked clinical significance. **Chapter 2** revealed a discrepancy between patient-reported outcomes and radiological findings: while patients were generally satisfied, radiographs already showed signs of osteolysis and loosening of the prosthesis with bone loss.

The focus of **Part 2** was optimization of patient factors during elbow joint loading following TEA, since a probable cause of prosthetic failure is overloading the elbow joint. In **Chapter 4**, we conducted a review that provided insight into existing literature on elbow joint loading during activities of daily living (ADL). The main findings were that tasks performed close to the body were less demanding than tasks further away from the body.

More specifically, tasks with elbow flexion and shoulder adduction were less straining for the elbow joint than tasks with elbow extension and shoulder abduction. In **Chapter 5**, we examined elbow loading during eight ADL tasks in healthy individuals and analyzed whether current postoperative instructions, as given to patients, led to a reduction in elbow joint loading. In seven out of eight tasks, we found that the instructions did not result in a change in elbow loading, indicating that the current instructions are insufficient toward reducing loading of the elbow. Only during the chair-rise task did the instruction result in a significant decrease in elbow joint loads. This finding raises the question of whether people can accurately predict which changes in movement will lead to lower loads in the elbow. In addition, this instruction may be rather general since it does not address specific postural advice that is known to influence elbow load, as described in **Chapter 4**. We also found that many ADL tasks exceeded the prosthesis' loading limits, raising concerns about long-term prosthetic survival.

Part 3 focused on optimizing surgical procedure to reduce complication rates. In **Chapter 6**, we conducted a review on triceps insufficiency, a common complication that causes significant morbidity following TEA. The main findings were an incidence of triceps insufficiency of 4–5%, with patients undergoing multiple surgeries being at higher risk. Surgical indication and approach also played a role, with triceps-sparing techniques having a lower risk compared to triceps-detaching techniques. Unfortunately, the results of this review were clouded by a lack of clear definition of triceps insufficiency, poor reporting, and inadequate examination of the triceps without using clear thresholds. Therefore, in **Chapter 7** we presented a study protocol comparing two commonly used surgical techniques—triceps-sparing and triceps-detaching—focusing on postoperative elbow function, triceps function, implant positioning on radiographs and complications, with the aim of recommending the ideal surgical technique for TEA. In **Chapter 8** it was concluded that a triceps-sparing approach results in significantly better extension (fixed flexion deformity, FFD) and range of motion (ROM) than a triceps-detaching approach, with similar patient-reported outcomes, triceps function, prosthetic component positioning on radiographs and complication rates.

Prosthetic design

The focus of this topic will be prosthetic design in relation to survival rates. Types of prostheses will be discussed first, followed by design and prosthetic materials.

<u>Key message</u>*: The ideal prosthesis does not exist yet, but further improvements are within reach.*

Types of prostheses

Over the past decades, several types of elbow prostheses have been developed. In general, prostheses can be categorized as linked or unlinked. In this thesis, both linked and unlinked designs were analyzed. In **Chapter 2**, the unlinked iBP prosthesis had a 10-year survival rate of 81%, which is comparable to literature, but it showed a late drop in survival after 10 years. This late drop is remarkable, since it is hypothesized that unlinked designs result in early failure due to instability but in the long term are expected to result in less aseptic loosening due to lower joint loads and lower stresses on the bone-cement interface (2-5). This theoretical advantage of an unlinked prosthesis has also been proven in laboratory testing, where linking the implant resulted in a doubled amount of humeral loading (2), ultimately resulting in prosthetic failure due to component loosening. Although some research suggests theoretical advantages of unlinked prostheses for long-term survival, several studies on clinical long-term outcomes showed no differences in survival rates when comparing linked to unlinked prostheses, so in general it remains unclear whether a linked or unlinked type of prosthesis is favorable (6-8).

In **Chapter 3**, both patients with a Latitude and a Latitude EV prosthesis were analyzed. The Latitude prosthesis is designed to better recreate the natural anatomy and can be implanted either linked or unlinked. All the prostheses we used were linked. The Latitude also has the option to include a radial head component. There is no current consensus on optimal management of the radial head in TEA. Options include retaining the native radial head, excision or replacement with a prosthesis. It is known that, from a biomechanical perspective, the radial head is an important stabilizer and transfers over half of the amount of load, so resecting it seems to be less favorable (9-11). In our study, replacing the radial head with a prosthesis showed disengagement in 24% of patients. This complication percentage was also present in other studies, with 9% and 31% disengagement reported (12, 13). A newer type of radial head component has now been developed, and future studies need to show whether this problem has been solved. Therefore, our current management is to retain the native radial head unless it is severely damaged.

Prosthetic design

Prosthetic design also plays an essential role in restoring elbow joint motion, ensuring stability and minimizing the risk of complications. The Latitude, used in **Chapter 3**, offers 7° of varus valgus laxity when linked. Considering its design, it has been labeled as a concave cylinder. Other frequently used prostheses have different designs, such as the Coonrad-Morrey (Zimmer-Biomet, Warsaw, Indiana, USA), which is cylindrical, and the Discovery (Zimmer-Biomet, Warsaw, Indiana, USA), labeled as hourglass. These three designs were compared using in vitro testing (14). The Latitude showed superior results in both varus-valgus torque testing and axial compression testing, suggesting possible superior results in long-term survival, since lower loads and stresses may lead to decrease in wear and lower risk of loosening (15). It should be noted though that all implant designs resulted in high torques once the end of the varus-valgus laxity was reached. In the case of a malpositioned stem, this varus-valgus laxity is already partially used, resulting in elevated torques at an earlier stage. Further, although in vitro studies show superior results for the Latitude design, long-term clinical outcomes still fail to yield superior survival rates and aseptic loosening remains the main reason for revision (7, 8). It is therefore important that future studies focus on analyzing in vivo elbow joint loading and relate loading conditions in patients to failure limits of prosthetic designs, so that patient-specific postoperative instructions can be formulated to minimize wear, loosening and revision. In the absence of detailed knowledge of in vivo loading conditions and corresponding failure limits, the theoretical advantages of advanced prosthetic designs remain largely unexploited in clinical practice.

Prosthetic materials - Polyethylene

The original Latitude prosthesis became available in 2001. Since initial problems with fixation and ulnar pistoning were reported, it was updated in 2013 to the Latitude EV prosthesis, with changes in the humeral design, coating of the humeral and ulnar components with a titanium plasma spray on the cobalt chrome stem to enhance cement fixation, and bending of the ulnar component (16). Remarkably, no comparable progress has been made in its polyethylene (PE) bearings. The current implant still relies on ultra-high molecular weight polyethylene (UHMWPE), a material introduced in the 1960s. Since that time, several developments in PE processing have led to the introduction of highly cross-linked polyethylene (HXLPE) and, more recently, annealing and vitamin E-blended HXLPE. Both HXLPE and vitamin E-blended PE have demonstrated improved wear rates in laboratory and clinical studies (17).

When considering implant longevity, TEA continues to trail behind THA and TKA, with 10-year survival rates of approximately 80–85% in TEA compared to 90–95% in THA and TKA (18, 19). Several factors may contribute to these lower numbers, yet an important observation is that the vast majority of hip and knee prostheses consist of HXLPE bearings, whereas most TEA systems still utilize traditional UHMWPE. Among current elbow prostheses, only the Discovery prosthesis incorporates HXLPE. The limited adoption of HXLPE in TEA may be caused by the higher production costs of HXLPE compared to UHMWPE, the less stringent material requirements for a non-weight-bearing joint, and the relatively small TEA market, which reduces commercial incentives for manufacturers to introduce more advanced PE technologies. Future improvements in the Latitude prosthesis could therefore potentially benefit from an upgrade to HXLPE or other next-generation PE formulations to enhance implant longevity. However, realizing such material advancements requires active collaboration from industrial partners. Given the relatively low financial return from elbow prostheses, industrial partners have unfortunately been discouraged from prioritizing these innovations.

Patient factors during elbow joint loading

The focus of this topic will be elbow joint loading. Analyzing elbow joint load and musculoskeletal modeling will first be discussed, then prosthetic failure limits and rehabilitation protocols.

<u>Key message</u>: *Evidence-based postoperative instructions and rehabilitation protocols to enhance prosthetic survival cannot be formulated yet. Patient-specific models to analyze joint load and prosthesis failure limits should be investigated first.*

Analyzing elbow joint load using musculoskeletal modeling

To improve long-term survival, it is essential to create more insight into elbow-loading patterns and prosthetic failure limits so an evidence-based rehabilitation protocol can be created. So far it is known that type of load, type of movement and frequency of movement cycles influence the stress distribution on the prosthesis, thereby affecting the risk of prosthetic loosening (20, 21). In **Chapters 4 and 5** insight was gained into elbow joint loads during ADL in healthy participants, showing that tasks with elbow flexion and shoulder adduction were less straining for the elbow joint than tasks with elbow extension and shoulder abduction. In the years following the studies included in this thesis, additional research has been conducted on this topic. Post-TEA patients were studied as well, revealing that although they were physically capable of greater elbow extension, they tended to perform activities using less extension (22). There could be several explanations, such as altered anatomy, lower proprioception following surgery, less triceps force, or habituation to use a compensatory movement strategy because of preoperative pain with elbow extension. Remarkably, although activities were performed with less extension, the elbow joint load was not lower in patients than in healthy participants—as would have been expected from the results of previous research in healthy participants (i.e. lower loads with less extension). This unexpected finding could have been caused by altered movement speeds, although the impact of movement speed on joint load isn't clear yet. Another explanation could be that TEA patients adopt different postures during ADL tasks compared to healthy participants. These altered postures could result in relatively higher loads, thereby offsetting the expected reduction in load attributable to less elbow extension. A recent study examined not only joint loading but also bone-on-bone contact forces (i.e. axial compression) (23). Consistent with previous findings, this study emphasized that higher forces were encountered with elbow extension and over 90° shoulder abduction. It should be mentioned though that the musculoskeletal model used to calculate these joint loads and forces was based on the anatomic properties of a cadaver of a healthy male and not of a patient with a total elbow prosthesis. Hence calculation of joint load and contact forces might deviate from real forces. Nevertheless, this is so far the best way to calculate forces in patients.

It is my opinion that future studies should focus on optimizing musculoskeletal models and adjust the current model into a personalized patient model, taking sex and age into account (24, 25). Other factors that should be considered are implementing a radiohumeral joint, since current models only use an ulnohumeral elbow joint. From a biomechanical perspective it is already known that the radial head plays an important role in load transfer and stability (10, 11, 26, 27). In addition, future models should reveal differences between linked and unlinked prostheses, since it is known that linking the ulnohumeral prosthesis leads to a doubled amount of humeral loading. Models should also include ligament reattachments, since reattaching ligaments lowers the humeral load due to "off-loading" of the prosthesis (2). Last, models should offer the option to place the prosthesis in such a way that it corresponds with the actual positioning in the patient, since prosthetic malpositioning will also alter elbow loading (28).

Prosthetic failure limits

Insight into actual elbow joint loading is insufficient to come up with specific postoperative instructions and rehabilitation protocols. Modes of failure and failure limits of prosthetic materials are an essential step toward optimizing survival. Studies have already evidenced that PE wear of the Coonrad Morrey elbow prosthesis retrieved at revision surgery shows asymmetrical wear with PE bushings deformed to an elliptical shape, which is mainly attributed to varus-valgus and torsional loading of the elbow (29). In addition, 5 Nm varus-valgus load at the ulnohumeral joint was sufficiently high to result in stresses exceeding the theoretical yield strength of UHMWPE in this type of prosthesis (30). Several ADL tasks in this thesis exceed those limits. Unfortunately, these limits are not known for all prostheses types and movement directions (i.e. flexion-extension, pronation-supination and varus-valgus). Therefore, we reiterate the importance of analyzing loading limits for all prostheses types using finite element modeling so that evidence-based postoperative guidelines can be formulated. To this end, collaborating with industrial partners would be highly beneficial, for example using their computer-based prosthetic models to perform finite-element analysis. Regrettably, industrial partners can be reluctant to collaborate or provide financial support unless they retain the ability to influence or veto the outcomes, which limits the potential for advancing independent research to drive meaningful improvements.

Rehabilitation protocols

In **Chapter 5**, we showed that current postoperative instructions, as given to patients, did not lead to a reduction in elbow joint loading, indicating that the current instructions are insufficient toward reducing loading of the elbow. In addition, this instruction is rather nonspecific and does not explicitly address relevant postural influences on elbow load, as described in **Chapter 4**. We also found that many ADL tasks exceeded the prosthesis' loading limits, raising concerns about long-term prosthetic survival. The consequences of these findings for daily practice remain unclear. A first step toward evidence-based rehabilitation programs is comparison of actual elbow joint load and prosthetic failure limits. Muscle exercise programs should be studied as well, as it is known that muscles may have a stabilizing function in helping offload the prosthetic materials but also have contracting properties which may cause overloading (31, 32). An ideal balance between those functions should be sought.

Some orthopedic surgeons advocate for allowing patients to resume daily activities without substantial restrictions, since the aim of TEA is to lower pain and improve function.

However, in my opinion patients require adequate information to be able to understand the consequences of their choices. It is the responsibility of healthcare professionals to create evidence-based postoperative rehabilitation protocols to prevent overloading first. Ideally, those rehabilitation protocols will be available in a virtual reality (VR) environment to cope with long-existing movement habits and offer the possibility to alter movement strategies and postural habits. If possible, prosthetic optimizations should be made to enhance survival as well. Ultimately, it is up to patients to make an informed decision on their activities.

Surgical procedure

The focus of this topic will be surgical approach in relation to outcomes and complications.

Key message: A triceps-sparing approach is advocated in TEA. However, complication rates remain high and several knowledge gaps persist.

In **Chapter 7** it was shown that a triceps-sparing approach yields better FFD and ROM, compared to a triceps-detaching approach with similar patient-reported outcomes, complications and prosthetic component positioning in radiographs. Considering the better FFD in the triceps-sparing approach, it remains unclear whether the reduced FFD in the triceps-detaching approach is a result of the surgical approach itself or whether it is caused by the after-treatment in a cast. Following a triceps-sparing approach, it is common to start early mobilization post-surgery. In triceps-detaching approaches, most surgeons apply a cast. These after-treatments are not evidence-based and vary between orthopedic surgeons (33). Recent studies advocate a functional after-treatment following triceps-detaching approaches as well, although caution should be taken to avoid triceps insufficiency (34).

It should further be mentioned that several types of triceps-sparing approaches exist. This study focused specifically on the paratricipital approach, so other triceps-sparing approaches such as a lateral paraolecranon approach were not taken into consideration. Previous retrospective research showed that the lateral paraolecranon approach yields more exposure than the paratricipital approach, with comparable results on functional outcomes and triceps-related complications (35). Clinical consequences of this better exposure remain unclear and future prospective comparative studies could probably answer that question.

Complications

Reported complication rates in **Chapter 8** were high, with overall rates around 45% but comparable between the triceps-sparing and triceps-detaching approaches. A remarkable finding was the high number of ulnar fractures in the triceps-sparing approach, possibly caused by using a bell saw in combination with extensive grating followed by an active after-treatment, causing avulsion or insufficiency fractures of the olecranon in a fragile population. Damage to the vascularization could also play a role, although exact vascularity patterns aren't known. We therefore recommended future studies focus on vascularity patterns around the elbow. Our group is currently conducting a cadaveric study evaluating triceps vascularization and perfusion and the consequences of triceps-sparing and triceps-detaching approaches on triceps vascularization. A clearer understanding of these vascular patterns could also guide postoperative rehabilitation programs, as compromised vascularization of the triceps muscle or the olecranon may warrant a more tailored, triceps-specific postoperative management.

Another remarkable finding was the high number of malpositioned prosthetic components. Although clear cut-off points on prosthetic component positioning do not exist, research on implant positioning errors shows malalignment resulting in greater loading and stresses with a risk of early loosening (2, 36, 37). Future studies should shed light on optimal prosthetic component positioning and on how to prevent positioning errors. 3D planning or CT-guided elbow replacement could be of benefit in the future. However, optimal component positioning should be determined first and improvements on 3D planning should then be made as well (38, 39).

A clear explanation for the high complication rates, apart from the prospective and thorough data collection, remains difficult to pinpoint. Several contributing factors may be considered. First, the overall number of TEAs performed annually is substantially lower than for THA and TKA, resulting in limited exposure and experience. Second, the absence of centralization of TEA results in even lower annual TEA rates per surgeon, which is relevant since TEA is considered a technically demanding procedure, with outcomes known to be influenced by surgical expertise (40). Third, the scarcity of research on TEA compared to other joint arthroplasties yields less available knowledge, possibly hindering further optimization of surgical technique and perioperative management. Last, the smaller market for TEA likely results in lower investments from companies in terms of testing and optimization processes, which may result in slower innovation cycles.

Centralizing TEA in experienced, high-volume hospitals could potentially improve survival rates and reduce complication rates. Recent studies indeed demonstrate that complication and revision rates are related to experience and volume, supporting centralization with a minimum cut-off of 10 TEAs per year (40-42). However, in our study all orthopedic surgeons were dedicated elbow surgeons from relatively high-volume centers (>10 TEA procedures per year), making it unlikely that limited experience or low surgical volume confounded our results.

Patient satisfaction

The focus of this topic will be the patients' perspective.

Key message: Optimizing TEA should not stop but move forward!

The most remarkable finding of this thesis is that, although complication rates following TEA remain high and survival rates remain low, TEA is still considered a successful procedure since patient scores on satisfaction are high, pain scores are low, and scores of self-reported and objectively measured physical functioning are acceptable-to-good. This discrepancy raises the question of whether the TEA-related problems are "patient problems" or "doctor problems", and whether it's necessary to focus on optimizing TEA since patients are already satisfied with the current situation. However, patient satisfaction alone does not adequately reflect implant performance. and long-term outcomes and several points warrant consideration. First, when preoperative function is severely impaired, even modest improvement can lead to substantial benefit even if complications occur. Second, I believe healthcare professionals should continuously strive for the best result. Although financial considerations often pose barriers to future optimization, it is important to realize that re-operations and revisions are associated with high costs as well, with total costs of primary TEA around €19,000 in the Netherlands and revisions twice that amount (43). Third, satisfaction is considered high in TEA, with satisfaction rates at 80-85% in this thesis. And yet in other joint arthroplasties such as TKA, this satisfaction rate is considered low. Last, the main indication for TEA initially was rheumatoid arthritis, but nowadays a shift toward post-traumatic arthritis is seen (44). This shift may be due to improved medical treatment for rheumatoid arthritis (45, 46), postponing severe degeneration and, by extension, prosthetic replacement. And yet the mentioned shift in indications toward post-traumatic arthritis results in a younger patient category that has already shown to be less satisfied and more physically demanding. The higher physical demand might result in higher complication and revision rates too (47). Therefore, optimizing TEA should not stop but move forward!

Clinical implications

- Long-term, structural follow-up of patients following TEA is essential, as studies demonstrated a discrepancy between clinical symptoms and radiological outcomes.
- Current postoperative instructions of not lifting more than 1kg are insufficient to reduce overloading. Focus should be on postural advice to perform ADL close to the body (i.e. elbow flexion, shoulder adduction).
- A triceps-sparing approach results in a significantly and clinically relevant better elbow function than a triceps-detaching approach, with similar patient-reported outcomes, triceps function, prosthetic component positioning on radiographs and complication rates, and is therefore advocated in TEA.

- Total elbow arthroplasty care should be optimized. A first step could involve centralization of care in high-volume, specialized hospitals with dedicated elbow surgeons.

Future recommendations

- To improve prosthetic survival there should be a focus on postoperative elbow joint loading, calculated based on personalized musculoskeletal models. Failure limits of every type of prosthesis in every movement direction should be known, for example using finite element modelling. Comparing elbow joint loads with failure limits should lead to an evidence-based postoperative instruction and rehabilitation protocol. Ideally, those rehabilitation protocols will be available using virtual reality (VR), helping to cope with long-existing movement and postural habits and offering possibilities to modify these movement strategies.
- Improvements in prosthetic design may be necessary to enhance survival rates. A first step could be improvement in type of PE, as UHMWPE is still used yet newer types (HXLPE, vitamin E-blended HXLPE) with reduced wear rates are available. Although newer types of prostheses (i.e. Kaufmann) are being tested, investments from industrial partners to optimize their current models are needed.
- To reduce complication rates, the focus should lie on thorough knowledge of vascularity patterns around the elbow. This knowledge could guide in optimizing surgical procedures and will also help develop rehabilitation protocols focusing on improving postoperative triceps function and preventing triceps-related complications.
- Future studies should shed light on optimal prosthetic component positioning. Next, improvements on how to prevent positioning errors should be made. For example, 3D planning or CT-guided total elbow replacements hold potential benefit.

Conclusion

This thesis aimed to optimize TEA by acknowledging that no single solution exists. Outcomes following TEA are determined by the complex interaction between prosthetic design, patient anatomy, patient-specific factors, activity patterns and surgical procedure. This thesis presented several novel insights and identified important remaining knowledge gaps that need to be addressed in order to further improve outcomes. Last, effort should be made to delay or avoid joint replacement and preserve the native elbow joint whenever feasible, reserving total elbow arthroplasty for carefully selected patients for whom conservative and joint-preserving surgical options have been exhausted.

The most remarkable finding is that, despite persistently high complication rates and relatively low survival rates, TEA is still considered a successful procedure since patient scores on satisfaction are high. This thesis highlights the importance of continued optimization for patients, doctors and society. From a patient perspective, instructions to optimize posture during ADL to reduce joint load have been formulated. Future research should focus on analyzing failure limits of the prosthesis so that evidence-based rehabilitation protocols can be developed. From a doctor perspective, the best surgical procedure is identified. Despite this, complication rates remain high and warrant orthopedic surgeons adequately informing patients about these risks. Moreover, several important knowledge gaps persist, as highlighted throughout this thesis. From a societal perspective, the rising number of TEAs performed and the shifting indications also underscore the importance of continued optimization.

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Appendices

SUMMARY

The elbow is a complex joint that performs an essential role in daily, high-complexity tasks. Difficulties in elbow motion or elbow pain can cause severe disabilities in daily functioning and can have a high impact on patients' quality of life. Patients with rheumatoid arthritis or osteoarthritis, for example following a complex elbow fracture, can develop severe elbow joint degeneration. When these patients reach end-stage elbow degeneration, a total elbow prosthesis can be an appropriate solution.

Replacing the elbow joint with a prosthesis is a relatively rare procedure. Unfortunately, the outcomes of total elbow arthroplasty (TEA) are disappointing. Postoperative complications are frequent and prosthetic survival low. Therefore, the studies in this thesis focus on optimizing TEA.

This thesis examines prosthetic design, patient factors and surgical procedure, all elements that together determine outcomes after TEA. **Part 1** focuses on gaining insight into functioning of current protheses, **Part 2** focuses on optimizing elbow joint load in patients and **Part 3** focuses on optimizing the surgical procedure.

The focus in **Part 1** was on gaining insight into the current functioning of two commonly used types of elbow prostheses. In **Chapter 2** the iBP prosthesis, an unlinked elbow prosthesis, was analyzed in a retrospective cohort. The study showed that the 10-year survival rate of this prosthesis was approximately 81%, with implant loosening as main reason for revision. It also revealed a discrepancy between patient-reported outcomes and radiological findings. While patients were generally satisfied, radiographs already showed signs of osteolysis and prosthetic loosening with bone loss. This discrepancy led to the implementation of long-term, structural follow-up of patients at UMCG instead of the advice for a follow-up visit in case of complaints. In **Chapter 3** we analyzed a newer type of elbow prosthesis, the Latitude. This prosthesis is designed to better recreate the natural anatomy and can be implanted either linked or unlinked. It also has the option to include a radial head component. We found the 10-year survival rate of this prosthesis, around 82%, to be similar to other types. Additionally, we noted that in over 30% of cases the radial head component showed signs of disengagement. A newer type of radial head component has now been developed, and future studies need to show whether this problem has been solved.

Part 2 focused on optimization of patient-related factors, more specifically joint loading, since a probable cause of prosthetic failure is overloading. In **Chapter 4** we conducted a review that provided insight into elbow joint loading during activities of daily living (ADL). Tasks performed close to the body (i.e. elbow flexion and shoulder adduction) were found to be less demanding. We also discovered that certain ADL tasks exceeded the loading limits of the prosthesis. Unfortunately, these limits are not known for all prosthesis

types and directions (i.e. flexion-extension, pronation-supination and varus-valgus). Based on this study, we recommended that clinical studies provide a broader understanding of elbow loading during ADL and that prosthesis manufacturers disclose their loading limits in order to develop patient-specific guidelines to prevent overloading. Therefore, in **Chapter 5** we examined elbow loading during eight ADL tasks in healthy individuals and analyzed whether current postoperative instructions, as given to patients, led to a reduction in loading. In seven out of eight tasks, the instructions did not result in a change in elbow loading, indicating that the current instructions are insufficient in reducing (over)loading of the elbow. We likewise found that many ADL tasks exceeded the prosthesis' loading limits, raising concerns about long-term prosthetic survival. We recommended repeating this study in patients with an elbow prosthesis to determine whether the outcomes are similar, reiterating the importance of analyzing loading limits for all prosthesis types to formulate effective postoperative guidelines.

Part 3 focused on optimizing the surgical procedure. In **Chapter 6** we conducted a review on triceps insufficiency, a common complication that causes significant morbidity following TEA. We found an incidence of 4–5%, with patients undergoing multiple surgeries being at higher risk. The surgical indication and approach also played a role, with triceps-sparing techniques involving lower risk compared to triceps-detaching techniques. Unfortunately, the results of this review were clouded by a lack of a clear definition of triceps insufficiency, poor reporting, and inadequate examination of the triceps without using clear thresholds. We recommended that triceps insufficiency be analyzed in prospective studies to draw more robust conclusions. Therefore, in **Chapter 7** we presented a study protocol comparing two commonly used surgical techniques—triceps-sparing and triceps-detaching—focusing on postoperative elbow function, triceps function, implant positioning on radiographs, and complications, with the aim of recommending the optimal surgical technique for TEA. In **Chapter 8** we presented the results of this study, concluding that a triceps-sparing approach results in significant better elbow function compared to a triceps-detaching approach, with similar patient-reported outcomes, triceps function, prosthetic component positioning on radiographs and complication rates.

Chapter 9 ends the thesis by discussing the main findings, providing a general discussion of the aforementioned studies and formulating suggestions for future research. In conclusion, several insights have been shown to optimize TEA. First, the prosthetic design might be optimized by using a newer type of polyethylene, which has reduced wear rates. Second, patients might benefit from optimizing posture during ADL in order to reduce joint load and prevent overloading, to enhance prosthetic survival. It was also suggested that prosthetic failure limits should be analyzed so that evidence-based postoperative instructions and rehabilitation protocols can be formulated. Third, triceps-sparing approaches yield better functional outcomes compared to triceps-flap approaches. Additional recommendations were to gain insight into vascular patterns of the triceps to reduce triceps-related complications and to analyze optimal component position. Last, the

most remarkable finding of this thesis is that, though complication rates following TEA remain high and survival rates low, TEA is still considered a successful procedure given that patient scores on satisfaction are high.

SAMENVATTING

De elleboog is een complex gewricht en vervult een essentiële rol in het uitvoeren van alledaagse, hoog-complexe taken. Problemen met elleboogfunctie of pijn van de elleboog kunnen lijden tot ernstig functieverlies en dat kan een grote impact hebben op de kwaliteit van leven van patiënten. Dit kan het geval zijn bij patiënten met reumatoïde artritis of patiënten die artrose hebben, bijvoorbeeld na een complexe botbreuk rond de elleboog. Op het moment dat er sprake is van vergevorderde slijtage van de elleboog kan een elleboogprothese een goede oplossing zijn.

Het vervangen van een ellebooggewricht door een prothese is een relatief zeldzame ingreep. Helaas vallen de resultaten van de elleboogprothese vaak tegen. Complicaties na een operatie treden vaak op en de levensduur van de prothese is relatief kort. Daarom richten de studies in dit proefschrift zich op het optimaliseren van de totale elleboogartroplastiek (TEA).

In dit proefschrift worden prothese ontwerp, patiënt factoren en chirurgische procedure onderzocht, allemaal factoren die bijdragen aan de uitkomsten na een TEA. Het proefschrift is opgedeeld in drie delen. **Deel 1** richt zich op het verkrijgen van inzicht in het functioneren van huidige type protheses. **Deel 2** richt zich op het optimaliseren van de belasting van de elleboog van de patiënt. **Deel 3** richt zich op het optimaliseren van de chirurgische procedure.

In **deel 1** ligt de focus op het inzicht krijgen in het huidige functioneren van twee veelgebruikte type elleboogprotheses. In **hoofdstuk 2** wordt de iBP prothese, een niet-gelinkte prothese, geanalyseerd in een retrospectief cohort. Deze studie toonde aan dat de overleving van de prothese op 10 jaar ongeveer 81% was en dat de voornaamste reden voor revisie loslating van de prothese was. Ook toonde de studie aan dat er een discrepantie was tussen de patiënt gerapporteerde uitkomsten en de radiologische uitkomsten. De patiënten waren over het algemeen tevreden, maar de röntgenfoto's toonden in sommige gevallen toch al ernstige (voor)tekenen van loslating van de prothese met botverlies. Deze discrepantie heeft ertoe geleid dat patiënten van het UMCG structureel worden vervolgd op de lange-termijn, in plaats van het advies alleen te komen bij klachten. Vervolgens analyseren we in **hoofdstuk 3** een nieuw type elleboogprothese, de Latitude. Deze prothese is ontworpen om de natuurlijke anatomie beter te benaderen en kan gelinkt of niet-gelinkt worden geplaatst. Tevens heeft het de optie om een radiuskopcomponent te plaatsen. We ontdekten dat de 10-jaars overleving van deze prothese ongeveer gelijk was aan die van andere type elleboogprotheses, zo rond de 82%. Verder constateerden we dat de radiuskopprothese in ruim 30% van de gevallen tekenen van dissociatie liet zien, waarbij de kop van de steel losraakte. Momenteel is er een nieuwe versie van de radiuskopprothese ontworpen en toekomstige studies zullen moeten uitwijzen of het huidige probleem daarmee verholpen is.

Vervolgens concentreren we ons in **deel 2** op patiënt gerelateerde factoren, in het bijzonder op de optimalisatie van elleboogbelasting, aangezien overbelasting een van de oorzaken van het falen van de prothese is. In **hoofdstuk 4** verrichten we een review waarbij we inzicht geven in de belasting van de elleboog tijdens activiteiten van het dagelijks leven (ADL). We constateerden dat taken dichtbij het lichaam minder belastend waren voor de elleboog dan taken verder weg van het lichaam. Verder ontdekten we dat bepaalde ADL taken ertoe leidden dat de belasting limiet van de prothese overschreden werd. Echter, deze limiet is helaas niet voor alle type protheses in alle richtingen (flexie-extensie, pronatie-supinatie en varus-valgus) bekend. Op basis van de uitkomsten van deze studie deden we twee aanbevelingen. De eerste aanbeveling was dat klinische studies een breder zicht op elleboogbelasting tijdens ADL taken zouden moeten geven en de tweede dat prothese leveranciers hun belasting limieten bekend zouden moeten maken. Alleen met die gegevens kunnen specifieke instructies worden gegeven aan patiënten met als doel overbelasting van de elleboog te voorkomen. Daarom onderzoeken we vervolgens in **hoofdstuk 5** de elleboogbelasting tijdens acht ADL taken in gezonde proefpersonen en analyseren we of de huidige postoperatieve instructie, zoals gegeven aan patiënten, leidt tot een afname in belasting van de elleboog. In zeven van de acht taken leidde de instructie niet tot een verandering in de belasting van de elleboog, wat betekent dat de instructie onvoldoende effect heeft op het reduceren van (over)belasting. Verder ontdekten we dat de elleboog belasting tijdens veel van de ADL taken de prothese limiet overschrijdt, wat zorgwekkend is voor de overleving van de prothese op de lange termijn. Onze aanbeveling was de studie ook bij patiënten met een elleboogprothese uit te voeren, om te zien of de uitkomsten vergelijkbaar zijn met die van gezonde proefpersonen en uiteraard bleef de aanbeveling van kracht om van alle type protheses alle belasting limieten te analyseren, om zodoende postoperatieve instructies te kunnen formuleren.

Tot slot staat in **deel 3** de optimalisatie van de chirurgische procedure centraal. In **hoofdstuk 6** verrichten we een review naar triceps insufficiëntie, een veel voorkomende complicatie na een TEA die veel morbiditeit met zich meebrengt. We toonden aan dat de incidentie gemiddeld 4-5% is, waarbij patiënten die meerdere ingrepen ondergaan een hoger risico hebben. Ook indicatie en chirurgische benadering hadden een effect, waarbij triceps-sparende ingrepen een kleiner risico hadden dan triceps-flap en -split technieken. Helaas werden de resultaten van deze review vertroebeld door een gebrek aan een goede definitie van triceps insufficiëntie, goede rapportage en het goed onderzoeken van de triceps functie met duidelijke afkapwaarden. We adviseerden om triceps insufficiëntie in prospectieve studies te analyseren om zo betere conclusies te kunnen trekken. Daarom presenteren we in **hoofdstuk 7** een studieprotocol om twee veelgebruikte chirurgische benaderingen, triceps-sparend en triceps-flap, met elkaar te vergelijken. Hierbij waren we vooral geïnteresseerd in postoperatieve elleboogfunctie, triceps functie, positie van de prothese op röntgenfoto's en complicaties om zodoende een aanbeveling te kunnen doen voor de beste chirurgische benadering voor het plaatsen van een elleboogprothese. In **hoofdstuk 8** presenteren we vervolgens de resultaten van deze studie waarbij we concludeerden dat een triceps-sparende benadering resulteerde in betere elleboogfunctie dan een triceps-flap benadering, met vergelijkbare patiënt-gerapporteerde uitkomsten, triceps functie, protheses positie op röntgenfoto's en complicaties.

Uiteindelijk wordt in **hoofdstuk 9,** in de algemene discussie, een overzicht van de belangrijkste bevindingen gegeven, gevolgd door een beschouwing over de bovengenoemde studies en worden suggesties voor toekomstig onderzoek gedaan. Concluderend tonen de resultaten van dit proefschrift verschillende inzichten om de uitkomsten na een TEA te verbeteren. Allereerst kan het design van de prothese wellicht verbeterd worden door ander polyethyleen te gebruiken, waarvan bekend is dat deze slijtvaster is. Ten tweede kan de belasting van de elleboog afnemen door een verbeterde houding tijdens ADL taken, om zodoende overbelasting te voorkomen en de levensduur van de prothese te verlengen. Verder werd geadviseerd om de prothese limieten te analyseren, om zodoende wetenschappelijk onderbouwde revalidatie protocollen te kunnen ontwikkelen. Ten derde werd aangetoond dat een triceps-sparende benadering resulteerde in een betere elleboogfunctie dan een triceps-flap benadering. We adviseerden om meer inzicht te verkrijgen in de doorbloeding van de triceps om zodoende triceps-gerelateerde complicaties te verminderen. Verder adviseerden we om de optimale positie van prothese componenten te analyseren. Tot slot is de meest opmerkelijke bevinding in dit proefschrift dat de TEA op basis van patiënt tevredenheid als een succesvolle procedure wordt beschouwd, ondanks de hoge aantallen complicaties en de lage overleving van de prothese.

CONTRIBUTIONS OF THE PHD CANDIDATE

The contributions of the PhD candidate D. Meijering to this thesis are detailed below for each chapter, using the Contributor Role Taxonomy (CRediT). Contributions are listed according to role definitions as established by the CRediT system.

Chapter 1	Conceptualization, visualization, writing- original draft.
Chapter 2	Conceptualization, data curation, methodology, formal analysis, investigation, writing- original draft.
Chapter 3	Conceptualization, data curation, methodology, formal analysis, investigation, writing- original draft.
Chapter 4	Conceptualization, data curation, methodology, formal analysis, investigation, writing- original draft.
Chapter 5	Conceptualization, investigation, data curation, formal analysis, investigation, writing- review & editing.
Chapter 6	Conceptualization, data curation, methodology, formal analysis, investigation, writing- original draft.
Chapter 7	Conceptualization, data curation, methodology, project administration, resources, formal analysis, investigation, writing- original draft.
Chapter 8	Conceptualization, data curation, methodology, project administration, resources, formal analysis, investigation, writing- original draft.
Chapter 9	Conceptualization, visualization, writing- original draft.

LIST OF PUBLICATIONS

1. van Dam W, Meijering D, Boerboom AL, Eygendaal D, Stevens M. Reliability of radiologic assessment following total elbow arthroplasty: a varying observer agreement. J Shoulder Elbow Surg. 2025;34(9):2196-204.
2. Duijn RGA, Meijering D, Vegter RJK, Boerboom AL, Eygendaal D, Stevens M, et al. Difference in daily tasks execution and elbow joint load: a comparison between patients after total elbow arthroplasty and healthy controls. JSES Int. 2025;9(2):580-9.
3. Duijn RGA, Meijering D, Boerboom AL, Eygendaal D, Stevens M, Lamoth CJC, et al. Shoulder elevation and arm extension influence elbow joint loading during door-opening in total elbow arthroplasty: a musculoskeletal modelling study. J Biomech. 2025;195:113113.
4. Duijn RGA, Meijering D, Vegter RJK, Albers F, Boerboom AL, Eygendaal D, et al. Elbow joint loads during simulated activities of daily living: implications for formulating recommendations after total elbow arthroplasty. J Shoulder Elbow Surg. 2024;33(1):145-55.
5. Meijering D, Duijn RG, Murgia A, Boerboom AL, Eygendaal D, van den Bekerom MP, et al. Elbow joint biomechanics during ADL focusing on total elbow arthroplasty - a scoping review. BMC Musculoskelet Disord. 2023;24(1):42.
6. Meijering D, Boerboom AL, Gerritsma CLE, de Vries AJ, Vegter RJK, Bulstra SK, et al. Mid-term results of the Latitude primary total elbow arthroplasty. J Shoulder Elbow Surg. 2022;31(2):382-90.
7. Dam WV, Meijering D, Stevens M, Boerboom AL, Eygendaal D. Postoperative management of total elbow arthroplasty: Results of a European survey among orthopedic surgeons. PLoS One. 2022;17(11):e0277662.
8. Meijering D, Welsink CL, Boerboom AL, Bulstra SK, Vegter RJK, Stevens M, et al. Triceps Insufficiency After Total Elbow Arthroplasty: A Systematic Review. JBJS Rev. 2021;9(7).
9. Meijering D, Boerboom AL, Gerritsma CLE, The B, van den Bekerom MPJ, van der Pluijm M, et al. Prospective cohort study comparing a triceps-sparing and triceps-detaching approach in total elbow arthroplasty: a protocol. BMJ Open. 2021;11(5):e046098.
10. Meijering D, Boerboom AL, Breukelman F, Eygendaal D, Bulstra SK, Stevens M. Long-term results of the iBP elbow prosthesis: beware of destructive metallosis! BMC Musculoskelet Disord. 2019;20(1):415.
11. Meijering D, Harsevoort GJ, Janus AJM, van Helden SH. Supracondylar femur fracture repair using IlluminOss in a patient with Osteogenesis Imperfecta type 4. J Orthop. 2018;15(2):663-5.

PHD PORTFOLIO

Description	EC
Courses	
Research Data Management, UMCG	0.1
Managing your PhD, UMCG	2
Ethics of Research and Scientific Integrity, UMCG	2.5
BROK (basic course rules and organization for clinical researchers,)UMCG	1.5
Publishing in English, UMCG	3
ATLS (Advanced trauma life support), Tilburg	
SBMS (systematic approach medical emergency situations), Zwolle	
AO Basic Principles of fracture treatment, Tilburg	
Communication course, Wenkebach institute UMCG	
CASH, basic course general surgery	
Dissection course “upper and lower extremities”, UMCG	
Arhtroscopy Knee Course, Utrecht	
Hip arthroplasty Course, Nijmegen	
Teach the Teacher, Groningen	
CCOC (centrale cursus orthopedische chirurgie), Utrecht	
Radiation hygiene for medical specialists, Zwolle	
Distal Humerus Fracture Course, Nijmegen	
Arthroscopy Elbow, Utrecht	
Knee arthroplasty Course, Amsterdam	
Presentations	1.5
Human movement sciences	
PHR meeting	
GOSSIE meeting	
Invited speaker Regiodag UMCG	
Podium presentation EFORT Barcelona	
E-poster ICSES Buenos Aires	
Podium presentation ICSES Rome	
Podium presentation “Botmetastasen” Nijmegen	
Podium presentation IACES Madrid	
Invited speaker upper extremity course Groningen	

Description	EC
Lecturing and Teaching	
Student Assistant (tutor) RUG	
Invited speaker and teacher Groninger Dissection Course	
Supervising	2
Supervising Master Student Human Movement Sciences Friederike	
Supervising Master Student Medicine Willemijn	
Supervising Master Student Human Movement Sciences Reslin	
Supervising Master Student Human Movement Sciences Roos	
Supervising multiple Bachelor Students Human Movement Sciences	
Supervising Master Student Human Movement Sciences Senya	
Supervising Physician Assistant in training Suzanne	
Supervising Bachelor Student Medicine Zain	
Grants	
AGIKO Grant	
De Boerfonds Grant	
Memberships	
Socrates Honours Program	
NOV (Dutch Orthopedic Association)	
* Member workgroup shoulder and elbow	
Conferences	
Organization AMSTEL Course	1.5
Other	
Review manuscripts	1

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ABOUT THE AUTHOR

Danielle Meijering was born on 31 October 1992 in Stadskanaal, the Netherlands. After completing her Gymnasium education at Ubbo Emmius in Stadskanaal, she started to study Medicine at the University of Groningen in 2011. During her medical training, she completed an internship at the Department of Orthopedic Surgery at the University Medical Center Groningen (UMCG), where she developed a strong interest in orthopedic surgery. Inspired by this experience, she initiated research on total elbow arthroplasty under the supervision of Drs. A.L. Boerboom and Dr. M. Stevens. Subsequent clinical internships further strengthened her ambition to pursue a career as an orthopedic surgeon.

Upon graduating in 2017, she began working as a resident not in training, initially at the Department of General Surgery in Deventer, followed by a position at the Department of Orthopedic Surgery at UMCG. In 2019, she was awarded an AGIKO grant, enabling her to combine clinical training with PhD research. She started this dual trajectory in 2020, during the COVID-19 pandemic.

In 2021, she started her surgical residency (Vooropleiding) at Isala Hospital in Zwolle under the supervision of Dr. Nieuwenhuijs. She then returned to the Department of Orthopedic Surgery at UMCG to start her orthopedic residency under the supervision of Dr. Ploegmakers.

In 2025, she resumed her PhD research, aiming to complete the AGIKO trajectory and to apply for the Mandema Stipend. Currently, she is continuing her orthopedic training in Deventer under the supervision of Dr. Bolink. She will complete her orthopedic training at Martini Hospital in Groningen in 2029.

Danielle aims to further develop her research line and pursue an academic career by obtaining a Mandema Stipend, which would allow her to dedicate time to supervise several other (PhD) students.

Outside of her professional life, Danielle is a passionate athlete who enjoys cycling and mountain biking. She is a two-time Dutch Champion in cyclocross and she won the Drenthe 200 mountain bike marathon in 2017. In August 2025, she and her husband, Allard Neijmeijer, welcomed their son Milan. Together, they live in Zwolle.