Thesis

The Paraolecranon Approach for Total Elbow Arthroplasty and Complex Fracture Management: Is the Anconeus Branch Safe?

submitted by

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Declaration of Academic Integrity

I hereby confirm that the present diploma thesis is the result of my own independent scholarly work. I also confirm that in all cases, where material from the work of others (in books, articles, essays, dissertations, and on the internet) is acknowledged, quotations and paraphrases are clearly indicated. No material other than that cited in the reference list has been used. I have read and understood the Medical University's regulations and procedures concerning plagiarism.

Graz, 24.10.2023 Ulrike Schwarz m.p.

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Abbreviations

AM	anconeus muscle
AP1	most lateral edge of the tip of the olecranon
AP2	most lateral edge of the olecranon
D	distal
D1	distance between AP1 and the intersection point of the anconeus nerve in alignment with the POA 1
D2	distance between AP2 and the intersection point of the anconeus nerve in alignment with the POA 2
EW	epicondylar width (defined as the distance between the medial and lateral humeral epicondyles)
HL	humerus length (defined as the distance between the most proximal tip of the greater tubercle and the most distal point of the humeral capitulum)
ICC	intraclass correlation coefficient
L	lateral
M	medial
P	proximal
POA	paraolecranon approach
POA 1	paraolecranon approach 1
POA 2	paraolecranon approach 2
r	Pearson correlation coefficient
RN	radial nerve
RN-O	distance between the separation of the anconeus nerve from the radial nerve and the center of the tip of the olecranon
SD	standard deviation
TD	transverse distance between the most lateral edge of the olecranon (AP2) and the anconeus nerve
TEA	total elbow arthroplasty
TM	triceps muscle
UN	ulnar nerve

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Zusammenfassung

Einführung

Der Paraolekranon-Zugang hat für den prothetischen Ersatz des Ellbogengelenks und die Versorgung distaler Humerusfrakturen zunehmende Bedeutung. Bei posterioren Zugängen zum Ellbogen besteht das Risiko einer iatrogenen Verletzung des Nervenastes, der den Musculus anconeus innerviert. Ziel dieser Studie war es, den Verlauf des Nervs des Musculus anconeus im Musculus triceps brachii in Relation zu zwei Modifikationen des Paraolekranon-Zugangs zu untersuchen und die Stelle einer iatrogenen Verletzung sowie einen sicheren Bereich für den Nerv zu bestimmen.

Methoden

Im Rahmen der Studie wurden 120 obere Extremitäten von 60 Körperspender*innen untersucht. Zwei modifizierte Versionen des Paraolekranon-Zugangs (POA 1 und POA 2) wurden definiert und aufeinander folgend an jeder oberen Extremität durchgeführt. Der Abstand zwischen anatomischen Referenzpunkten am Olekranon und dem Nervus anconeus wurde in der Ausrichtung des jeweiligen Zugangswegs vermessen. Die statistische Analyse erfolgte, um mögliche Unterschiede der Zugänge relativ zum Nervenverlauf zwischen den Zugängen, Seiten, Geschlechtern und Humeruslängen zu ermitteln.

Ergebnisse

Bezüglich des Verlaufs des Nervus anconeus in Bezug auf die beiden Paraolekranon-Zugänge wurde ein Unterschied zwischen den Zugängen festgestellt ($p \leq 0{,}001$). Der Abstand zwischen dem jeweiligen Referenzpunkt und dem Nervenast war bei dem medialer gelegenen POA 1 (Abstand 12,3 cm) größer als bei dem lateraler gelegenen POA 2 (Abstand 5,5 cm). Die Seite hatte keinen Einfluss auf die Ausdehnung des Abstands. Signifikant größere Abstände wurden für männliche Individuen und für längere Humeri erhoben.

Schlussfolgerung

Es wurde ein größerer Abstand zwischen dem Olekranon und dem Nerv bei dem medialer gelegenem Paraolekranon-Zugang (POA 1) gefunden. Daher kann die Anwendung dieses Zugangs das Risiko einer iatrogenen Nervenverletzung während Operationen verringern.

Abstract

Introduction

The paraolecranon approach has become increasingly important for prosthetic replacements of the elbow joint or the treatment of distal humerus fractures. The nerve innervating the anconeus muscle is at risk for iatrogenic injury during posterior surgical approaches to the elbow. The objective of this study was to investigate the course of the anconeus nerve branch through the triceps muscle in relation to two versions of the paraolecranon approach and determine the location of an iatrogenic injury and a safe zone for the nerve.

Methods

120 upper extremities of 60 human adult body donors, that were embalmed using Thiel's method, were investigated during the study. Two modified versions of the paraolecranon approach (POA 1 and POA 2) were defined and carried out sequentially on each upper extremity. The distance between anatomical landmarks on the olecranon and the anconeus nerve was measured in alignment with the approaches. Statistical analysis was performed to determine a possible difference between the approaches and whether side, sex, or humerus length affected the course of the nerve in relation to the approaches.

Results

Regarding the course of the anconeus nerve branch in relation to the two paraolecranon approaches, a significant difference between the approaches was found ($p \leq 0.001$). The distance between the respective landmark and the nerve branch was longer for the more medially located POA 1 (distance 12.3 cm) compared to the more laterally located POA 2 (distance 5.5 cm). The side did not influence the extent of the safe zone. The study showed statistically significant longer distances for male specimens when compared to females and longer distances for longer humerus bones.

Conclusion

The more medially located paraolecranon approach (POA 1) resulted in a wider safe zone for the nerve. Therefore, the use of this approach may reduce the risk of iatrogenic nerve injury.

Declaration of Previous Publications

Parts of the data collected during this thesis were published in:

Plecko M, Schwarz UM, Hohenberger GM, Hammer N, Schwarz AM. Lateral para-olecranon approach: surgical guide and anatomical considerations to the anconeus branch: is there a nerve-free zone? Eur J Trauma Emerg Surg. 2023 Apr;49(2):875-884. doi: 10.1007/s00068-022-02141-4. Epub 2022 Oct 20. PMID: 36266477; PMCID: PMC10175359.

I contributed to the study by performing anatomical dissections and the surgical approaches and taking measurements. Furthermore, I was involved in the acquisition and assembly of data, as well as in the statistical analysis and design of the figures.

1 Introduction

1.1 Anatomical background

1.1.1 The elbow joint

The elbow joint is formed by the distal end of the humerus, and the proximal parts of the radius and ulna. It is classified as a composed joint comprised of three articulations with a continuous synovial cavity: the humero-ulnar joint, the humero-radial joint, and the proximal radio-ulnar joint. The humero-ulnar joint acts as a hinge and allows flexion and extension. The humero-radial joint is involved in movements of the humero-ulnar and proximal radio-ulnar joints and may be classified as a spheroid joint, even though the soft tissue prevents movements in all directions. The proximal radio-ulnar joint acts as a pivot joint and allows axial rotation. The elbow has two degrees of freedom: flexion-extension and supination-pronation (1–3).

1.1.1.1 Osseous components

1.1.1.1.1 Humerus

The distal end of the humerus can be divided into articular and non-articular parts. The articular part consists of the laterally located capitulum and the medially situated trochlea, which are divided by a groove. The convex capitulum articulates with the radial head, while the trochlea articulates with the trochlear notch of the ulna (1,2,4). A part of the radial head is described to articulate with the groove between the trochlea and the capitulum (1,4). The articular surfaces are rotated approximately 30 degrees anteriorly to the long axis of the humerus in the coronal plane (1) and are not set at a right angle to the long axis of the humerus but at an average angle of 82.5 degrees in the coronal plane (5). The trochlea itself is shaped like a pulley with a groove. This groove is not located vertically but winds obliquely in a spiral from the anterior to the posterior surface of the trochlea. The trochlea is asymmetrically formed with a longer medial edge (1,2,4). The non-articular part of the humerus is composed of the medial and lateral epicondyles, the coronoid and radial fossae anteriorly, and the olecranon fossa posteriorly. The medial and lateral epicondyles serve as a point of origin for muscles and the collateral ligament complexes of the elbow (1,2).

1.1.1.1.2 Radius

The articular surfaces on the proximal radius can be found on its head and circumference. The discoid head of the radius articulates with the capitulum of the humerus, while a part of the rim of the radial head articulates with the groove located between the trochlea and the capitulum. The articular surface on the radial head is concave to match the convex capitulum. At the proximal radio-ulnar joint the vertically oriented articular circumference of the radial head articulates with the radial notch of the ulna and the annular ligament (1,2,4).

1.1.1.1.3 Ulna

The proximal end of the ulna is formed by the olecranon dorsally and the coronoid process anteriorly. There are two articular surfaces on the proximal ulna, the trochlear notch and the radial notch (1,2,4). The trochlear notch, also called the greater sigmoid notch, articulates with the trochlea of the humerus at the humero-ulnar joint (1–3). The articular surface is rotated approximately 30 degrees posteriorly to the long axis of the ulna in the coronal plane to match the angulation of the humerus (1). Similar to the articular surfaces of the humerus, the articular surface of the ulna is not set at a right angle to the shaft of the ulna but at an average of 86.5 degrees in the coronal plane (5). A ridge, matched to the groove on the trochlea, separates two facets on the trochlear notch anteriorly: An antero-lateral facet, that articulates with the lateral ridge of the trochlea, and an antero-medial facet, that articulates with the medial ridge. At the posterior part of the trochlear notch formed by the olecranon, there may be a third area located laterally to the two above-mentioned facets. This area abuts the trochlea during extension (1,2,4). The depression located laterally on the coronoid process is known as the radial notch or the lesser sigmoid notch (1,2). The radial notch articulates with the radius at the proximal radio-ulnar joint (1–3).

The angulation of the articular surfaces to the shafts of the humerus and ulna in the coronal plane and the configuration of the trochlear groove cause a so-called “carrying angle” between the longitudinal axes of the humerus and the ulna in full extension and supination (1,2,5,6). This angle varies between individuals but was described to average approximately 169 degrees in males and 165 degrees in females (7).

1.1.1.2 Elbow joint movements

Flexion and extension, and pronation and supination can be achieved at the elbow joint (1–4). During flexion and extension, an arc of approximately 150 degrees may be reached (2). The motion is primarily regarded as a hinge type. Even though the axis has been shown to perform a type of helical motion due to the configuration of the trochlear groove along which the ulna moves, this motion is rather minimal except at the extremes of flexion and extension (1,8). The humero-ulnar joint is thereafter regarded as a uniaxial joint and the axis is described to closely resemble the epicondylar axis and pass through the centre of the arcs of the trochlea and the capitulum of the humerus (4,9). During forearm rotation, an excursion of approximately 180 degrees can be achieved (1,2). When performing pronation and supination, the radial head rotates within the radial notch of the ulna and the annular ligament (2,3). During pronation and supination, however, movements also take place in the distal radio-ulnar joint. The axis for pronation and supination is described to pass through the radial head at the elbow and the fixation of the articular disc at the styloid process at the distal part of the ulna (4,6).

1.1.1.3 Joint capsule

At the humerus, the joint capsule attaches distal to the medial and lateral epicondyle, above the coronoid and radial fossae at the anterior surface but not above the olecranon fossa posteriorly. The synovial membrane covers the coronoid, radial, and olecranon fossae. There usually is a synovial fold between the coronoid and radial fossae separating the humero-ulnar and humero-radial joints. The joint capsule extends to the articular margin of the ulna but leaves the tip of the coronoid process and of the olecranon extraarticularly (2,3,6). Medially and laterally, the capsule blends into the collateral ligaments. Laterally, the capsule blends into the annular ligament (1,2). Distal to the annular ligament, the capsule continues as the joint capsule of the proximal radio-ulnar joint and is forming the sacciform recess (1,2), which attaches to the radial neck (6).

There are fat pads between the fibrous capsule and the synovial membrane in the olecranon, radial, and coronoid fossae, that are pushed in the fossae during the extremes of flexion and extension (2).

The elbow joint is supplied by branches from multiple small anastomoses around the joint forming the rete articulare cubiti. Several branches of the brachial artery anastomose with recurrent branches from the radial and ulnar arteries. The radial collateral artery anastomoses with the radial recurrent artery near the lateral epicondyle. The medial collateral artery anastomoses with the interosseous recurrent artery posteriorly to the elbow. The superior ulnar collateral artery anastomoses with the posterior ulnar recurrent artery and inconstantly with the inferior ulnar collateral artery near the medial epicondyle. The inferior ulnar collateral artery anastomoses with the anterior ulnar recurrent artery (1–4,6).

The joint capsule of the elbow has been described to be innervated by nerve branches of the median, musculocutaneous, ulnar, and radial nerves (4,6,10). Anteriorly, the joint is supplied by the median and musculocutaneous nerves medially, and by the radial nerve laterally (10). Posteriorly, the joint is supplied by the ulnar nerve medially, and by the radial nerve laterally (10). Cavalheiro et al. (11) described the innervation of the joint capsule based on dissection of 30 elbows. According to their results, the nerves do not supply the joint capsule consistently because they found that not every nerve innervates the joint capsule in several specimens.

1.1.1.4 Stabilizing ligaments of the elbow

The elbow joint has a medial (or ulnar) collateral ligament complex and a lateral (or radial) collateral ligament complex (1,2). The axis of flexion and extension of the elbow joint passes through the origins of both collateral ligament complexes and consequently, a component of both complexes is taut firmly at any position of elbow flexion (1). In addition to the collateral ligament complexes, there is the quadrate ligament. The ligament extends from the radial neck to the supinator fossa of the ulna and lies close to the joint capsule of the proximal radio-ulnar joint. The quadrate ligament acts as a stabilizer during pronation and supination (1,2).

1.1.1.4.1 Medial collateral ligament complex

The medial collateral ligament complex comprises an anterior, posterior, and transverse segment (1,2). The segments are connected by thinner tissue and form a triangular shape (2). The anterior band originates from the humerus antero-inferiorly halfway between the trochlea and the apex of the medial epicondyle and inserts into a tubercle on the medial edge of the coronoid (1,2). Because of the proximity to the axis for flexion and extension of the elbow, the anterior segment is taut throughout the majority of the range of motion and contributes to the stability of the elbow (2). The posterior band originates from the posterior aspect of the medial epicondyle and inserts along the medial portion of the medial edge of the trochlear notch (1,2). The posterior band is taut between 90 degrees and full flexion. The transverse band connects the anterior and posterior bundles between the olecranon and the coronoid processes and is known as the ligament of Cooper (1,2). It contributes insignificantly or not at all to elbow stability (1).

1.1.1.4.2 Lateral collateral ligament complex

The lateral collateral ligament complex consists of the radial collateral ligament, the annular ligament, the lateral ulnar collateral ligament, and the accessory lateral collateral ligament (1). The radial collateral ligament originates from the lateral epicondyle of the humerus anteriorly and inferiorly to the small tubercle and inserts into the annular ligament (1,2). The origin is near the axis for flexion and extension of the elbow and the ligament is, therefore, taut throughout most of the range of flexion and extension (1). The annular ligament originates from the anterior margin of the radial notch of the ulna and inserts into a ridge at the posterior margin of the radial notch, surrounding the circumference of the radial head (1,2,12). The annular ligament is tapered distally, creating a funnel-shaped form (12). The articular surface of the annular ligament is covered with a thin cartilaginous layer (2). The superficial surface of the ligament blends into the radial collateral ligament and into the joint capsule (1,2). The lateral ulnar collateral ligament originates inferiorly to the tubercle from the lateral epicondyle as well but separates from the radial collateral ligament in the course and inserts into the tubercle of the supinator crest of the ulna (1,2). The accessory lateral collateral ligament blends with inferior fibres of the annular ligament proximally and inserts into the tubercle of the supinator crest of the ulna (1).

1.1.1.5 Stability of the elbow

The stability of the elbow joint is provided by osseous and soft-tissue constraints. The articular surfaces at the elbow joint, especially the humero-ulnar joint, are highly congruent, which itself supplies a high degree of stability (1,2). Soft-tissue stabilizers may be divided into static and dynamic structures. Static soft-tissue stabilizers include the anterior and posterior joint capsule and the medial and lateral collateral ligament complexes, while dynamic structures represent the muscles that cross the joint (13).

Morrey and An (14) tried to determine the contribution of ligaments and articular structures by eliminating an element and observing the load for constant displacement. The articulation resists 55% of the varus stress and 30% of the valgus stress in extension, and 75% of the varus stress and 35% of the valgus stress in 90 degrees flexion. The anterior capsule resists approximately a third of the varus and valgus stress in extension but does not contribute during flexion. Regarding valgus stability, the medial collateral ligament complex provides 30% in extension and 55% in flexion. The lateral collateral ligament complex, however, provides 15% of varus stability in extension and 10% of varus stability in 90 degrees of flexion. Regarding osseous constraints, the coronoid has the most significant effect on elbow stability, while the radial head and olecranon play a minor role (15). Morrey and An (15) showed, that in spite of the absence of 50% of the olecranon, the joint stability was not adversely affected. At least 50% of the coronoid, however, are necessary for functional elbow stability. The crucial factors to stability in the coronal plane are the lateral and medial collateral ligament complexes. The medial collateral ligament complex provides resistance to valgus stress, while the lateral collateral ligament complex provides resistance to varus stress (1). Dynamic structures, namely the muscles that cross the elbow joint, enhance and confer further stability (13). Contraction of muscles crossing the joint compresses the joint (13,16). This may support some of the varus and valgus load, thus protecting the static soft-tissue stabilizers (17).

1.1.2 Anconeus muscle

The anconeus is a small muscle, that lies postero-laterally to the elbow joint and has a triangular shape. The muscle's origin forms the top of the triangle and is often referred to as the apex, and the broad insertion forms the base of the triangle. The muscle originates from the posterior surface of the lateral epicondyle of the humerus and attaches to the lateral surface of the olecranon and the posterior surface of the ulnar shaft proximal to the oblique line. (1–3,6,18,19). According to Molinier et al. (20), the origin on the lateral epicondyle covers an area of about 1 cm^2, while Jiménez-Díaz et al. (21) describe an area of approximately 0.85 cm^2. From the origin, a tendon arises, which transitions into an aponeurosis and muscle fibres. The aponeurosis forms approximately 70% of the length of the anterior edge of the muscle and lies parallel and adjacent to the lateral collateral ligament. The muscle fibres fan out from the aponeurosis and tendon and run obliquely in order to attach to the ulna (18,22,23). These muscle fibres have been described to run parallel to those of the medial head of the triceps in extension (20). The anconeus lies in a separate compartment from surrounding forearm muscles, like the extensor carpi ulnaris muscle or the supinator muscle, but lies in direct continuation with the medial head of the triceps muscle (18,20). The muscle is consequently, and because of similar function and innervation, regarded as the "fourth head of the triceps" by some authors (3,6,18,24).

Cadaveric studies have described the size of the muscle with an average length of approximately 8 cm and an average width of approximately 3 cm (21,23,25–27), while Elhassan et al. (28) described an average size of approximately 8 cm x 4 cm. The length was measured as the distance of the insertion on the ulna and the width as the posterior margin of the muscle. The insertion on the ulna extends to approximately one-third the length of the ulna (25–27).

In the course, the muscle adheres closely to the joint capsule of the elbow and the lateral collateral ligament, covering the lateral portion of the annular ligament (1,2,4,20,21,23).

1.1.2.1 Vascular supply

The muscle is supplied by three arteries: the recurrent posterior interosseous artery, the medial collateral artery, and the posterior branch of the radial collateral artery (26,29,30). Schmidt et al. (29) and Hwang et al. (26) dissected human specimens to investigate the vascular supply of anconeus. They found the recurrent posterior interosseous artery to be the dominant artery with an average diameter of approximately 1.1 mm. The artery originates either directly from the ulnar artery or from the posterior interosseous artery, which originates from the ulnar artery. The artery travels retrogradely on the interosseous membrane and radius between the anconeus and the extensor carpi ulnaris muscles to the entry point to the anconeus (26,29). It anastomoses between the olecranon and the lateral epicondyle with the medial collateral artery (3,6). The medial collateral artery had an average diameter of 0.7 mm during the two studies (26,29). The artery originates from the deep brachial artery and is accompanied by the muscular nerve branch of the anconeus. They both travel distally through the triceps muscle. The posterior branch of the radial collateral artery had an average diameter of 0.5 mm (26,29). The artery originates distal to the radial nerve from the deep brachial artery. It travels next to the lateral intermuscular septum and terminates at the lateral epicondyle. Both the recurrent posterior interosseous artery and the medial collateral artery were present in all specimens. The posterior branch of the radial collateral artery, however, was supplying the muscle inconsistently, only entering the muscle in approximately 70% of all cases during these two studies (26,29).

1.1.2.2 Innervation

The anconeus muscle is innervated by the radial nerve. The radial nerve gives off a motor branch to the medial head of the triceps brachii, that terminates as the muscular branch to the anconeus. This branch consists of fibres from the seventh and eighth cervical ventral rami (2,3,6,18,19,31). Occasionally, the branch receives tributaries from the sixth cervical branch (2,19). Foerster (31) described a rare additional innervation of fibres from the first thoracic ventral ramus. According to Maniglio et al. (32), the nerve branch separates from the radial nerve at a mean of 164 mm proximal to the lateral epicondyle. Özer et al. (33) measured a similar mean distance of 168 mm between the branching point from the radial nerve and the medial epicondyle. After separating from the radial nerve, the anconeus nerve lies between the lateral and medial head of the triceps and subsequently enters the medial head of the triceps. Maniglio et al. (32) observed the entry point into to muscle at a mean of 102 mm proximal to the intercondylar line, while Özer et al. (33) described a mean of 84 mm from the horizontal line passing through the lateral epicondyle. The nerve supplies parts of the medial head of the triceps as it travels distally. Since the anconeus muscle frequently lies in direct continuation to the medial head of the triceps without any space in between (18), the nerve may enter the anconeus muscle directly after exiting the medial head of the triceps. However, there may be a gap between the two muscles, which the nerve then passes freely (18). Maniglio et al. (32) describe a short passage on the periosteum of the distal humerus and the dorsolateral aspect of the joint capsule of the elbow after exiting the medial head of the triceps and before entering the anconeus muscle. According to Wilhelm (10), the anconeus nerve innervates most of the lateral aspect of the posterior joint capsule up to the proximal radio-ulnar joint. Cavalheiro et al. (11), however, only inconsistently found fibres of the nerve innervating the posterolateral region of the capsule. In the course, the nerve is accompanied by the medial collateral artery, a branch of the radial collateral artery (2,4,26,29).

Due to the location and course of the nerve through the entire medial head, the nerve is at risk for iatrogenic denervation during posterior surgical approaches to the elbow (1,30,33–36).

In addition to the innervation of the anconeus muscle by the nerve branch innervating the medial head of the triceps, Linell (37) and Morrey et al. (1) described a rare and inconsistent innervation of the anconeus muscle by a branch of the posterior interosseous nerve. However, the authors did not mention the frequency of this innervation. Recently, a cadaveric study by Jiménez-Díaz et al. (21) investigated the nervous supply of the anconeus muscle. They found the nerve branch from the medial head of the triceps to terminate in every of their investigated specimens in the anconeus muscle. They observed an additional innervation of the muscle by a branch of the posterior interosseous nerve in 38 of the 54 dissected elbows (70% of all specimens). Von Lanz and Wachsmuth (6) mention a rare innervation of the anconeus muscle by fibres originating from the ulnar nerve. However, they negate a potential collateral innervation in another chapter in the same book and there is no mention of a possible innervation of the anconeus muscle by the ulnar nerve elsewhere in their book.

1.1.2.3 Function

The detailed function of the anconeus muscle remains ambiguous. Studies have shown controversial results and the contribution to elbow motions, and further purposes have been under yearlong debate.

It seems to be undisputed, that the anconeus functions as an extensor of the elbow besides the triceps brachii (2,3,18,19,38). Electromyography of the anconeus has shown activity during extension of the elbow in multiple studies (39–47). However, the significance of the contribution to the extension remains unclear. Zhang and Nuber (44) quantified the moment distribution among the heads of the triceps and the anconeus muscle during isometric elbow extension using the relationship between electrical stimulation and the corresponding electromyography signal. Their results suggest that the anconeus contributes up to approximately 15% of the extension moment. Miguel-Andres et al. (46) observed the effect of anconeus muscle blocking on elbow kinetics and kinematics using lidocaine. Their results suggest that the anconeus is only a weak extensor, since blocking of the anconeus did not significantly affect the kinematics and kinetics of the elbow. Pauly et al. (40) observed in their electromyographic study that the anconeus initiates extension of the elbow, but becomes less active at higher degrees of extension when the triceps brachii contracts. They concluded that the muscle is responsible for fine control. However, a change in the activity of the muscle during different elbow positions remains in dispute. Currier (48) conducted an electromyographic analysis on the triceps brachii and anconeus muscle during maximal isometric contractions and observed different electrical activity with varying elbow positions in 1972. The author found higher electrical activity with increasing degrees of elbow extension. Le Bozec et al. (43) conducted a similar electromyographic study in 1980 but did not observe any influence of the elbow position on the electrical activity.

Duchenne (38) postulated in 1867 that the anconeus abducts the ulna in addition to its contribution to the extension of the forearm. He stated that the ulna moves laterally during pronation and that the anconeus causes this abduction and therefore supports pronation of the forearm. Ray et al. (49) conducted an experiment in 1951 in order to observe the movement of the ulna during pronation and supination. They inserted pins into the epicondyles to immobilize the humerus and used double-exposure roentgenograms and cinefluorography to visualize the motion of the forearm during pronation and supination. They found the ulna to be relatively stationary during pronation and supination around an axis passing through the radial head and the fifth digit. During movement around an axis passing through the radial head and the second digit, they described abduction or lateral movement of the ulna during pronation and adduction of the ulna during supination. The authors observed a significant action potential in the electromyogram of the anconeus during the whole of pronation and concluded, that contraction of the anconeus can lead to abduction of the ulna. Gleason et al. (50) supported this conclusion of Ray et al. when they conducted an electromyographic study in 1985 to determine whether the anconeus contracts during abduction of the ulna. They observed electric activity of the anconeus muscle during pronation of the forearm around an axis through the radial head and the second digit. Since this movement has been shown to be accompanied by abduction of the ulna, they regarded their observation as prove of the muscle’s function as an abductor of the ulna. Bergin et al. (42) conducted an electromyographic study of the anconeus muscle and other muscles of the elbow in 2013. The authors found regional differences in the activity during extension and forearm pronation between a transverse and longitudinal segment of the anconeus. The longitudinal segment of the muscle was more active during pronation than during supination and the activity during pronation was greatest about the lateral axis passing through the radial head and the second digit, which could support a possible contribution of the longitudinal segment to the abduction of the ulna during pronation as proposed by Ray et al. (49) and Gleason et al. (50). Even the major anatomic textbook “Gray’s Anatomy” (2) stated, that the function of the anconeus may be to control ulnar abduction during pronation, when the motion is carried out without medial translation of the hand and the hand is, thus, not shifting away from its original position.

However, several electromyographic studies revealed contrary results. Miguel-Andres et al. (46) observed no activity during unresisted pronation and supination, implying that the muscle is not active during pronation. Travill (41) reported activity of the anconeus during both resisted pronation and supination, but he did not find the muscle to be active during free loaded pronation and supination. Even though Basmajian stated in 1967 (51) that his scattered electromyographic studies of the anconeus muscle appear to confirm Duchenne’s theory, he rejected the hypothesis in 1972 with his co-author Griffin (39). They found moderate activity during both pronation and supination through most of the range of elbow motion and suggested that the anconeus could act as a stabilizer of the elbow joint. Pauly et al. (40) observed activity of the muscle during various resisted movements and concluded that the muscle is very active during pronation and less active during supination. They showed activity during extension of the elbow, pronation and supination of the forearm, resisted flexion and extension of the fingers, medial and lateral rotation, abduction and adduction, and flexion of the arm at the shoulder. Funk et al. (47) monitored the electromyographic activity of the anconeus, and other elbow muscles, during resisted movements of the forearm at the elbow joint. After applying varus stress to the elbow joint in 90 degrees of flexion, the authors were able to show activity in the anconeus in all subjects. The studies of Pauly et al. and Funk et al. showed activity in the anconeus in almost all positions and, thus, suggest the role of a dynamic joint stabilizer. Werner et al. (52) recorded the muscle activity of the anconeus, and other muscles, during a baseball pitch. The anconeus was active throughout the pitch despite limited demand for elbow torque during this activity (42), which supports a contribution to elbow stability by compressing the joint. The idea of a contribution to elbow stability has since been further discussed. The parallel course of the aponeurosis of the muscle to the lateral collateral ligament and the proximity to the lateral collateral ligament and the joint capsule of the elbow have been described in anatomic studies (20,23) and suggest a function complementary to the lateral collateral ligament in the stabilization of the elbow during extension. O'Driscoll et al. (53) state that the course and location of the muscle's origin and insertion provide ideal conditions to prevent posterolateral rotational displacement of the elbow. They regard the anconeus as a dynamic stabilizer of the elbow to resist varus stress among the triceps brachii and the brachial muscle. Buchanan et al. (17) developed a model to estimate the contribution to valgus and varus moments of elbow muscles and found the anconeus to be the most significant contributor to valgus moments. An et al. (54) estimated the moment arms of each muscle at the elbow joint by serial cross-sectioning and obtaining several biomechanical parameters of human specimens. They concluded that the anconeus generates valgus moments, and, thus, plays a role in varus stability of the elbow. Bergin et al. (42) observed the electric activity of the anconeus muscle, and other muscles of the elbow, during various gripping tasks. They hypothesized that any activity of the anconeus muscle during a grip supports a role in elbow stability since the anconeus cannot produce force at the fingers but counteracts elbow flexion moment from wrist flexor muscles. The authors did show activation of the anconeus and concluded that their data is consistent with a contribution to dynamic constraint to varus moments and posterolateral stability, as suggested by An et al. (54). Badre et al. (22) hypothesized that the role of the anconeus muscle in the stability of the intact elbow is negligible because the osseous constraints, the medial and lateral collateral ligament complexes, and the dynamic muscle stabilizers confer sufficient stability. However, they demonstrated in a cadaveric study that anconeus tensioning improves the varus stability of a combined lateral collateral ligament and common extensor origin-deficient elbow. A lateral collateral ligament or common extensor origin-deficient elbow as the result of trauma or iatrogenic injury can lead to symptomatic lateral elbow instability. Despite the previous studies, that suggested a possible contribution to elbow stability, this is the first and only study investigating and demonstrating the role of the anconeus muscle as a dynamic soft tissue stabilizer of the elbow joint.

Capdarest-Arest et al. (55) recently proposed the hypothesis that the anconeus muscle has a primary function as a stability augmenter during the period when infants crawl, and plays a more accessory-type role as infants grow.

There is not only the description of the close proximity of the anconeus muscle to the joint capsule of the elbow, but also mention of an additional point of origin on the joint capsule (3). Contraction of the anconeus muscle may prevent impingement of the lateral capsule between the radial head and the capitulum of the humerus during extension (3,33,56).

1.2 Total Elbow Arthroplasty

Total Elbow Arthroplasty (TEA) has gained importance and popularity over the last decades due to greater surgical experience and improvements in implant designs, operative technique, and selection of patients (1,34,57).

1.2.1 Indications

The most common indications for TEA include rheumatoid arthritis, acute comminuted distal humerus fractures in the elderly, primary osteoarthritis, and posttraumatic sequelae such as instability and arthritis (57–60). While TEA is a recognized treatment option for patients with rheumatoid arthritis (61), the indications for TEA after an acute trauma are evolving. In 1997, Cobb and Morrey first described the treatment of 20 patients over the age of 65 years with severe comminuted acute fractures of the distal humerus with TEA as the primary procedure (62). Since then, numerous authors have reported on TEA as a primary treatment option for acute fractures (58,63–65). Regarding distal humerus fractures, elbow replacement surgery is indicated in elderly patients with a pre-existing symptomatic pathology or comminuted distal humerus fractures and osteopenia where a stable osteosynthesis is unlikely, or in fractures when the articular surface and joint anatomy are not salvageable (62,66,67). Primary TEA is not recommended for fractures in which stable internal fixation may be achieved, in open fractures, or in patients involved in high-demand activities (67).

After an elbow replacement, patients are advised not to lift more than 5 kg as a single event or more than 1 kg repeatedly with the affected arm for the rest of their lives (1,67,68). This restriction must be considered before the performance of a TEA and is the reason for the contraindication for patients with high-demand activities.

1.2.2 Implant designs

Prostheses may be distinguished between constrained or linked and non-constrained or unlinked models. The selection of the implant type largely depends on the state of the capsuloligamentous structures surrounding the elbow, the integrity of the musculature, and the bone quality around the elbow (34,68). Constrained prostheses of the first generation with a stiff coupling mechanism are not produced nowadays due to a high loosening rate (57). Modern constrained prostheses of the second and third generation include a coupling mechanism with 7 degrees of rotary and side-to-side laxity ("sloppy-hinge"-principle). Since the coupling only works if the joint stabilization provided by the surrounding soft tissue fails, these prostheses work as non-constrained models up to this situation and are therefore also called semi-constrained elbow prostheses. Most semi-constrained prosthetic implants consist of a polyethylene bushing and titanium humeral and ulnar components. They may be implanted in cases of insufficiency of the stabilizing ligaments and capsule of the joint, atrophic musculature, and severe osseous destructions (34,57,68). Non-constrained prosthetic implants are designed to decrease the stress on the cement-bone interface and therefore depend more heavily on the surrounding soft tissue to provide stability (57). They may be used in cases of stable joint conditions, an intact radial column, and good bone quality. Their implantation is generally more sophisticated since it requires a stable capsule-ligament-musculature apparatus (68).

1.2.3 Diagnostics

The skin status around the elbow joint (scars, consistency of the subcutis, skin lesions, infections, etc.), deformities of the upper extremity, and the respective neurovascular status are evaluated and documented. Especially the course of the ulnar nerve and the condition of the triceps are essential. Additionally, stability tests of the joint should be performed (68). Preoperatively, X-rays of the elbow joint and the upper and lower arm must be taken in two planes. In cases of complex fractures and revisions after failed osteosynthesis, computed tomography is recommended (68).

1.2.4 Surgical procedure

1.2.4.1 Anaesthesia and patient positioning

Surgery is usually performed under general anaesthesia. Most commonly, the patient is positioned supine, and the respective arm is draped free and placed on the thorax of the patient or on an additional device. Alternatively, the patient may be positioned in the lateral decubitus position on the healthy side with the upper arm fixed on an armrest. A tourniquet may be applied on the upper arm (1,68).

1.2.4.2 Approaches

A posterior skin incision is regarded as the universal approach to deep structures of the elbow and is used for elbow arthroplasties (1). The skin incision should be performed medially approximately 10 cm above the elbow, continue just medial to the tip of the olecranon, and then distally over the border of the proximal ulna for 5 to 6 cm (1). A transverse release of the tendon of the triceps at its insertion frequently led to triceps weakness and is therefore not recommended (69). The differences between the posterior approaches mainly concern the mobilization and incision of the triceps. They can be distinguished into triceps-splitting approaches, triceps-reflecting approaches, and triceps-preserving approaches (1,68). While the muscle and the tendon are split longitudinally during a triceps-splitting approach, the triceps mechanism is preserved in continuity and reflected from the olecranon during a triceps-reflecting approach. The tendon is detached from the olecranon in triceps-splitting and triceps-reflecting approaches. During a triceps-preserving approach, however, the triceps is elevated from the intramuscular septa and the humerus while preserving most of the insertion of the tendon on the olecranon (1,70). Another type of posterior approach is a form of olecranon osteotomy, but should be avoided during implantation of a TEA because of an increased risk for pseudoarthrosis due to the ulnar prosthetic component (1,68).

1.2.4.3 Surgical technique

After skin incision, full-thickness medial and lateral fascio-cutaneous flaps should be formed to gain access to all structures and minimize the risk of injury to the local cutaneous nerves. Identification of the ulnar nerve is obligatory during TEA. If transposition of the ulnar nerve is planned, dissection of the nerve is performed between the arcades of Struthers and Osborne before the nerve is displaced anteriorly. The resection of a part of the medial intramuscular septum is then required (68,70,71). Transposition is indicated in patients with pre-existing neural deficits and a compromised course of the nerve following implantation of the prosthesis (57). The distal humerus and the proximal ulna are then visualized by mobilizing the triceps muscle depending on the approach. To allow dislocation of the joint, the attachment of the lateral collateral ligament must be released from the lateral epicondyle. Releasing the attachment of the medial collateral ligament may be necessary for better visualization (71). The midportion of the humeral trochlea is resected to gain access to the medullary canal. The size of the humeral prosthesis component is determined with serial rasps. Then, the medullary canal of the ulna is opened, and the preparation is carried out with serial ulnar rasps. If the respective prosthesis model includes augmentation of the radial head, this bone is addressed next. The trial components are then inserted to test the function and stability of the joint. After removing the trial components, the medullary canals are cleansed with pulsatile jet lavage and dried. A medullary cement restrictor, antibiotic-loaded bone cement, and the components are brought into the medullary canals (1,68). After placement of the components, the refixation of the collateral ligaments, if released, is recommended (71). If the attachment of the triceps on the olecranon has been detached, the next step is to reattach it. Sufficient soft tissue coverage of the prosthesis needs to be granted. After the optional placing of drains, a layered closure of the wound is performed (1,68,71).

1.2.5 Postoperative management

Depending on the prosthesis type and the surgeon's preference, the elbow is immobilized in full extension with an anterior splint or compressive dressing. The arm is elevated for 24 hours with the elbow above shoulder level (1). The drains, if used, and the immobilization are removed after 24 to 72 hours (71). After a triceps-preserving approach, early active elbow flexion and extension are allowed as tolerated (1,70). After a triceps-splitting approach, active extension should be avoided for 6 weeks after surgery (68). The patient must not lift more than 5 kg as a single event or more than 1 kg repeatedly with the operated-on arm for the rest of the live (1,67,68).

1.2.6 Complications

In a systematic review of 64 studies, Voloshin et al. (57) reported an complication rate of 24.3 ± 5.8%. Gschwend et al. (72) previously reported a complication rate of 43.1% in a review of literature from 1986 to 1992. The most common complications include aseptic loosening, instability, deep infection, and intraoperative fracture. Less common complications involve an ulnar nerve deficit or a triceps complication (57).

The Scottish Arthroplasty Project (59) reported a 10-year implant survivorship rate of 90% after investigating the data of 1.146 primary total elbow arthroplasties. Gill and Morrey (61) reported a similar 10-year prosthetic survival rate of 92.4% for patients with rheumatoid arthritis. However, only regarding patients, who had a TEA after distal humeral nonunion following a fracture, Cil et al. (73) reported a 10-year implant survival rate of 65%.

1.2.6.1 Loosening

Aseptic loosening can be caused by primary failure of the bone-cement interface or secondary failure of the bone-cement interface after osteolysis due to debris from polyethylene or cement (57). Voloshin et al. (57) did not find a statistically significant difference regarding clinical loosening rates between semi-constrained and non-constrained elbow prostheses. There was, however, a statistically significant difference when regarding clinical and radiographic signs of loosening. They defined radiographic loosening as a shift in component position or a 1 mm or greater lucent line around the component. They found a higher loosening rate of 13.7 ± 6.8% for semi-constrained prostheses compared to a rate of 10.1 ± 4.8% for non-constrained prostheses. Revision surgery is required in cases of symptomatic patients or if imminent prosthesis loosening is radiologically verified (68).

1.2.6.2 Instability

Instability can result in functional deficits and facilitates prosthetic loosening. There is a higher risk of instability and dislocation for non-constrained systems since they are designed to decrease stress at the bone-cement interface and depend more heavily on the soft tissue providing stability (57). Voloshin et al. (57) described a higher rate of dislocation and symptomatic subluxation for non-constrained prostheses compared to semi-constrained designs.

1.2.6.3 Infection

The infection rate following TEA has significantly decreased from 8.1% (72) to 3.3 ± 2.9% (57) . This may be traced back to improved surgical technique, use of antibiotic-loaded bone cement, and postoperative joint immobilization (57). However, when compared to other major joint arthroplasties, the infection rate following TEA is greater. This may result from the spare local subcutaneous tissue and the common immunosuppressive medication used for the treatment of the primary disease such as rheumatoid arthritis (57,68).

1.2.6.4 Ulnar nerve deficit

Because of the location and course of the nerve, the ulnar nerve is at risk for damage during a TEA during exposure, elbow manipulation, component placement, or compression from soft tissue swelling (57). The nerve often is routinely transposed during a TEA. Voloshin et al. (57), however, could not find a statistically significant difference in ulnar nerve deficits after routine transposition compared to procedures without transposition of the nerve.

Most cases of ulnar nerve deficits concern sensory deficits, that are self-limited with resolution of symptoms or patient adaption. An acute motor deficit after TEA, however, requires early exploration (57).

1.2.6.5 Triceps complication

The reported incidence of triceps insufficiency after TEA varies greatly and has been previously described to be as high as 29% (74). Voloshin et al. (57) reported a triceps dehiscence or clinically significant weakness in 2.4 ± 2.4%. Another systematic review reported an overall triceps failure rate of 3%, but an incidence of 11% after detachment of the triceps tendon at its insertion on the olecranon (75). Clinically relevant triceps weakness has been described after the detachment of the tendon in several studies (61,74,76–81). Dachs et al. (35) compared the outcomes after triceps-preserving approaches and triceps-detaching approaches, such as triceps-reflecting or triceps-splitting approaches, and described fewer complications after triceps-preserving approaches.

However, several authors mentioned the poor documentation of the postoperative functional status of the triceps, and consequently, triceps complications may be under-reported (57,70,81,82).

1.3 Complex fracture management

Non-operative treatment of distal humerus fractures has been associated with a very high risk of impaired function due to immobilization. Therefore, non-operative treatment is reserved for patients whose anaesthetic and surgical risk is considered too high due to pre-existing diseases and comorbidity (68,83).

The aim of surgical reconstructive treatment is to restore the anatomical congruence of the joint and create a sufficiently stable fixation of the bone fragments allowing early mobilization (68). Open reduction and internal fixation according to the AO principles is the treatment of choice for distal humerus fractures in most cases (84). However, complex intraarticular distal humerus fractures including comminution represent challenging injuries regarding osteosynthesis. In cases of unreconstructible fractures, good functional results may be achieved with hemiarthroplasty in younger or TEA in elderly, low-demand patients (58,63,83,84).

1.4 The paraolecranon approach

The paraolecranon approach is a modified triceps-splitting approach first described by Studer et al. (70) in 2012. The authors aimed to develop an approach, that preserves most of the attachment of the triceps tendon on the olecranon while allowing adequate visualization of the proximal ulna. Recently, triceps-preserving approaches have become more popular (78,85) because detachment of the triceps tendon has been associated with a higher risk of triceps complications (35,75). However, triceps-preserving approaches are associated with inferior ulna visualization compared to triceps-reflecting and triceps-splitting approaches (85) and a more challenging positioning of the ulna component (86).

The paraolecranon approach has been described to provide excellent exposure to the ulna (1). The approach has led to functional outcomes and strength equal or superior to approaches that demand detachment of the triceps tendon from the olecranon (70). The paraolecranon approach is thought to establish as the exposure of choice for primary elbow replacement (1).

1.4.1 Surgical technique

The posterior skin incision should be approximately 15 cm long. It should begin medially over the triceps, cross the joint just medial to the tip of the olecranon, and pass over the margin of the proximal ulna. Full-thickness medial and lateral fascio-cutaneous flaps are formed, and the ulnar nerve is identified and usually transposed. After the excision of the medial intramuscular septum, a dissection is carried out between the brachialis and the medial head of the triceps. Elevation of the triceps and excision of the joint capsule and fat pad expose the medial supracondylar region (1,70).

The approach exposes the humero-ulnar joint through medial and lateral arthrotomies (70).

Laterally, the incision splits the aponeurosis of the triceps just lateral to the insertion on the olecranon and continues to the lateral aspect of the olecranon. The incision divides the part of the triceps tendon attached to the olecranon from the lateral part, which blends with the anconeus and antebrachial fascia and is known as the lateral cubital retinaculum. Distally, the interval between the ulna and the anconeus muscle is incised, as it is in the Boyd approach (87), but a small cuff of fascia must be left on the ulna for later repair (Figure 1) (70).

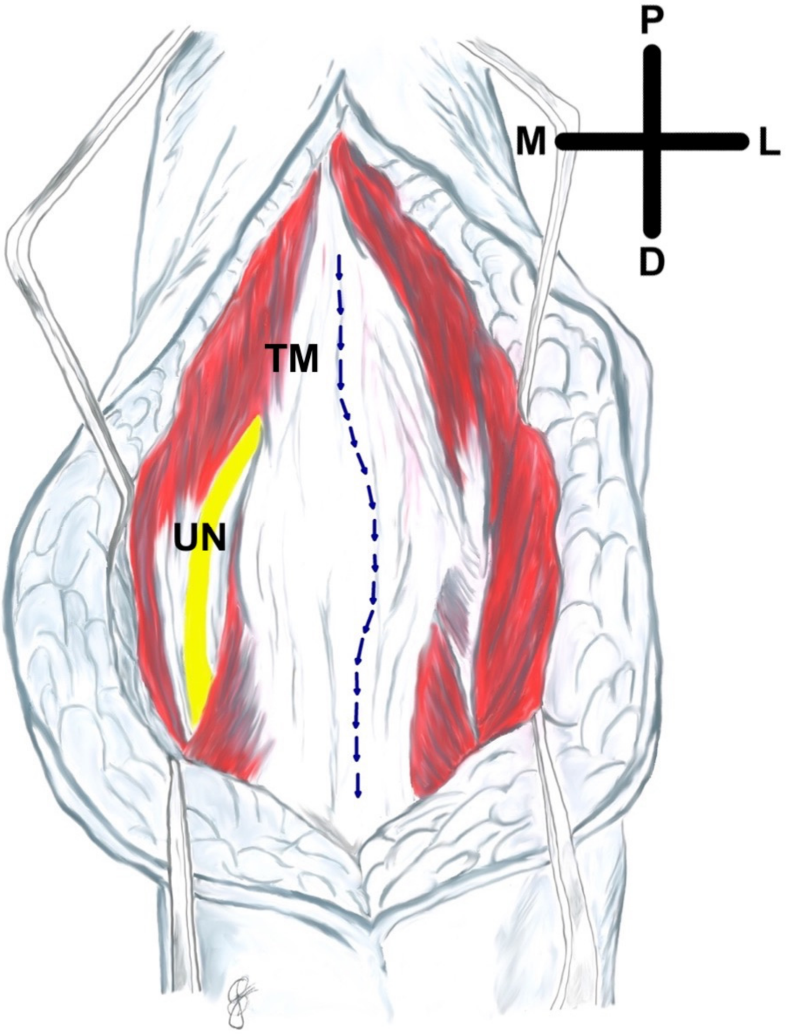

Figure 1: Line of incision for the lateral arthrotomy

The figure shows a right arm in a posterior view after skin incision and formation of a full-thickness flap. The incision through the aponeurosis of the triceps muscle proximally and the interval between the ulna and the triceps muscle distally is depicted.

P: proximal; D: distal; M: medial; L: lateral; TM: triceps muscle; UN: ulnar nerve

The insertion of the anconeus is elevated subperiosteally from the posterior surface of the ulna. The lateral collateral ligament is then detached from the lateral humeral epicondyle. The lateral cubital retinaculum, the lateral part of the triceps tendon, the antebrachial fascia, and the anconeus are reflected laterally (Figure 2) (70).

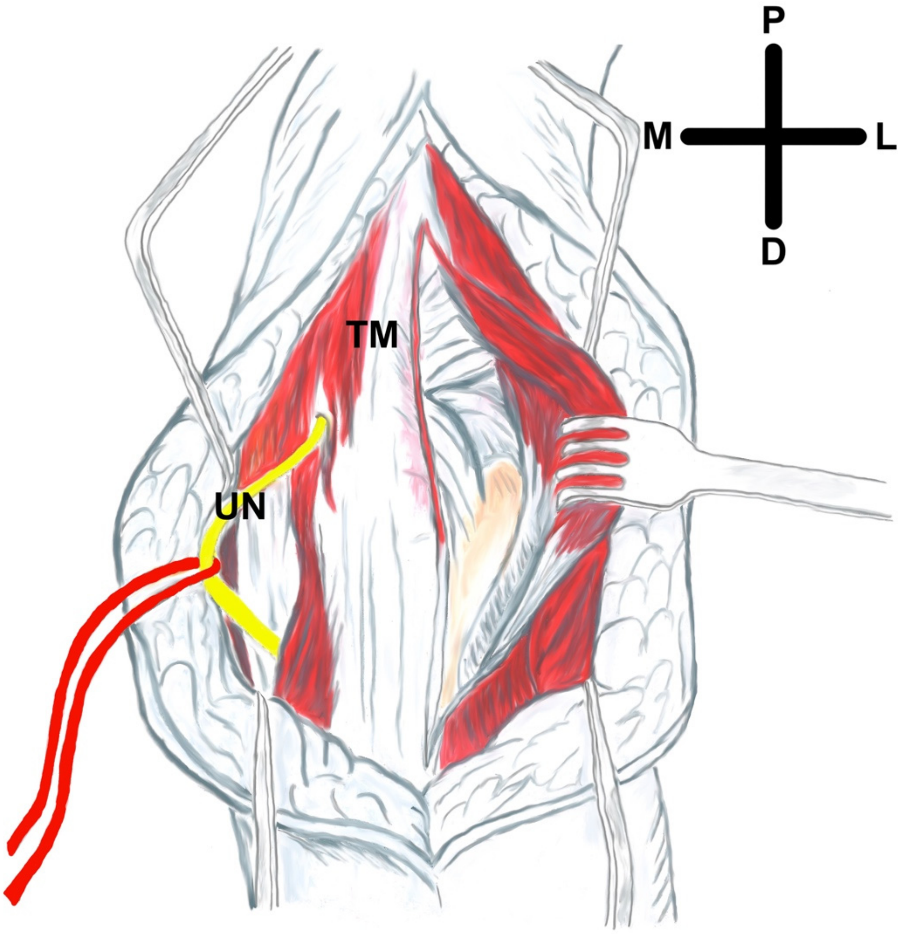

Figure 2: Lateral exposure

The figure shows a right arm posteriorly after a lateral arthrotomy and transposition of the ulnar nerve. The lateral part of the triceps muscle, the cubital retinaculum, the antebrachial fascia, and the anconeus muscle are reflected laterally.

P: proximal; D: distal; M: medial; L: lateral; TM: triceps muscle; UN: ulnar nerve

To perform the medial arthrotomy, the posterior band of the medial collateral ligament is divided, and the anterior band of the medial collateral ligament and the common flexor origin are detached from the medial epicondyle (70). Prior to the joint dislocation, the brachialis muscle and the anterior joint capsule are detached from the anterior portion of the humerus. The distal humerus can be depicted through the medial or lateral arthrotomy. Exposure of the ulna can be maximized by hypersupination of the forearm (70). Following implant insertion, the medial and lateral arthrotomies and the interval between the triceps tendon and the lateral cubital retinaculum are closed. The collateral ligaments and the common flexor origin are reattached, and a layered closure of the wound is performed (70).

1.5 Objective of the study

Despite the growing interest in the paraolecranon approach, the relation between the paraolecranon approach and the nerve to the anconeus muscle has not been studied yet. The objective of this study was to investigate the course of the anconeus nerve branch through the triceps muscle in relation to the two versions of the paraolecranon approach and determine the location of an iatrogenic injury and a safe zone for the nerve. The goal of performing two versions of the paraolecranon approach was to collect additional data and evaluate a possible difference. Moreover, the study aimed to determine whether (A) side, (B) sex, and (C) humerus length affected the course of the nerve in relation to the approaches.

2 Methods

2.1 Specimens

126 upper extremities of human adult body donors were originally included in the study sample. Exclusion criteria were defined as signs of trauma or severe deformities, obvious instability of the elbow, or visual evidence indicating previous surgery, injuries, or pathologies of the elbow or surrounding structures. One specimen had to be excluded due to a severe deformity and two specimens were excluded because of previous surgeries. This resulted in a study sample of 120 upper extremities of 60 cadavers. The gender distribution within the study sample was balanced (28 females, 32 males). The average age was 79 years (SD: 10.8 years; range: 46–95 years; median: 80 years). The mean body mass index was 24 kg/m^2 (SD: 3.6 kg/m^2; range: 17.2–36.0 kg/m^2; median: 23.4 kg/m^2).

The specimens were embalmed using Thiel's method, which is known for well preserving the colour, consistency, and transparency of the tissue (88,89). All investigated specimens were donated to the Division of Macroscopic and Clinical Anatomy at the Medical University of Graz. The study was approved by the ethics committee of the Medical University of Graz (1548/2021) and was performed in accordance with the Declaration of Helsinki.

2.2 Study design

Two modified versions of the paraolecranon approach (POA) were investigated during this study. Both approaches were carried out sequentially on each upper extremity. The specimens were randomized to decide which approach was carried out first. After the incision of the triceps using the respective approach and dissection of the anconeus nerve, the distance between anatomical landmarks and the nerve was measured in alignment with the approach and defined as the intersection point. To gain further information, further measurements were taken. The measurements were taken twice by two individuals. The measurements were taken independently and in separate sessions.

Statistical analysis was performed to determine a possible difference between the approaches and whether side, sex, or humerus length affected the course of the nerve in relation to the approaches.

2.3 Approaches

The versions of the paraolecranon approach were defined based on anatomical landmarks and differed in the origin from the olecranon (Figure 3). A more medially located paraolecranon approach (POA 1) and a more laterally located paraolecranon approach (POA 2) were used (Figure 4):

- Paraolecranon approach 1 (POA 1)

  The incision was carried out in a line between the most lateral edge of the tip of the olecranon (AP1) and the proximal gap between the medial and lateral head of the triceps. This gap was defined to be 2 cm distal and posterior to the insertion of the deltoid muscle. The incision was placed parallel to the axis of the humeral shaft.
- Paraolecranon approach 2 (POA 2)

  The incision was carried out from the most lateral edge of the olecranon (AP2) parallel to the direction of the fibres of the aponeurosis of the triceps.

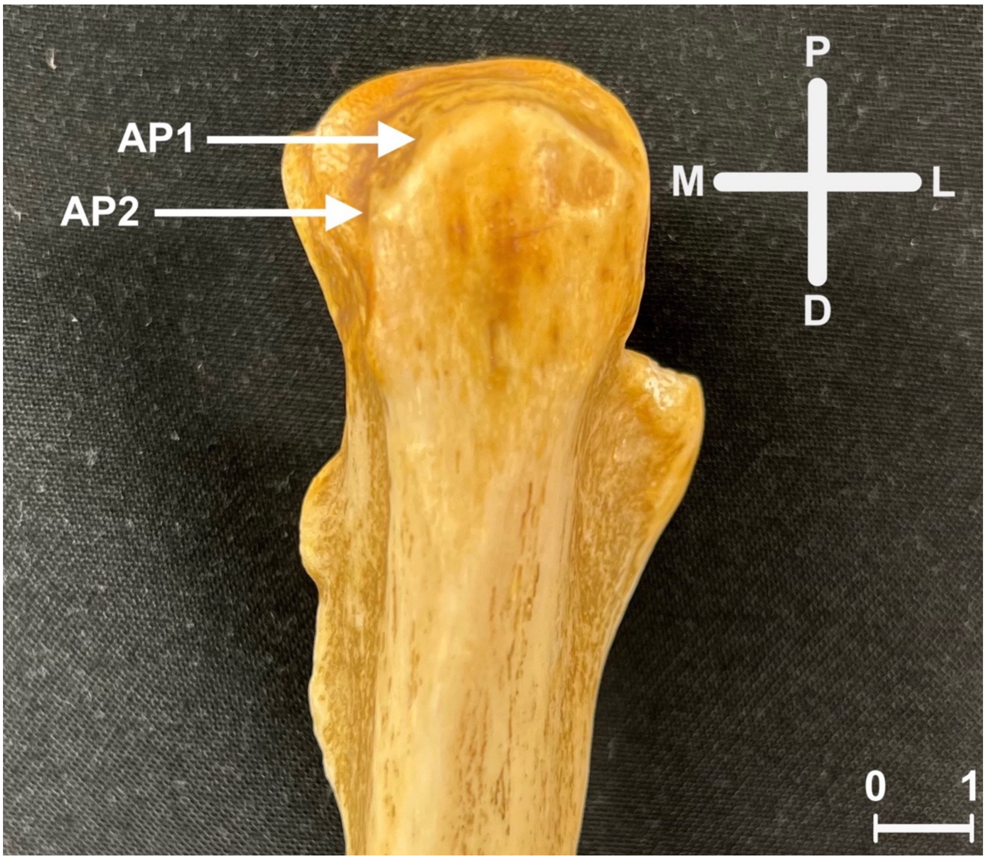

Figure 3: Bony anatomical landmarks on the olecranon

The figure shows the dorsal, proximal aspect of a right ulna. The anatomical landmarks of the point of origin for the respective paraolecranon approaches are depicted. Dimensions are in cm.

P: proximal; D: distal; M: medial; L: lateral

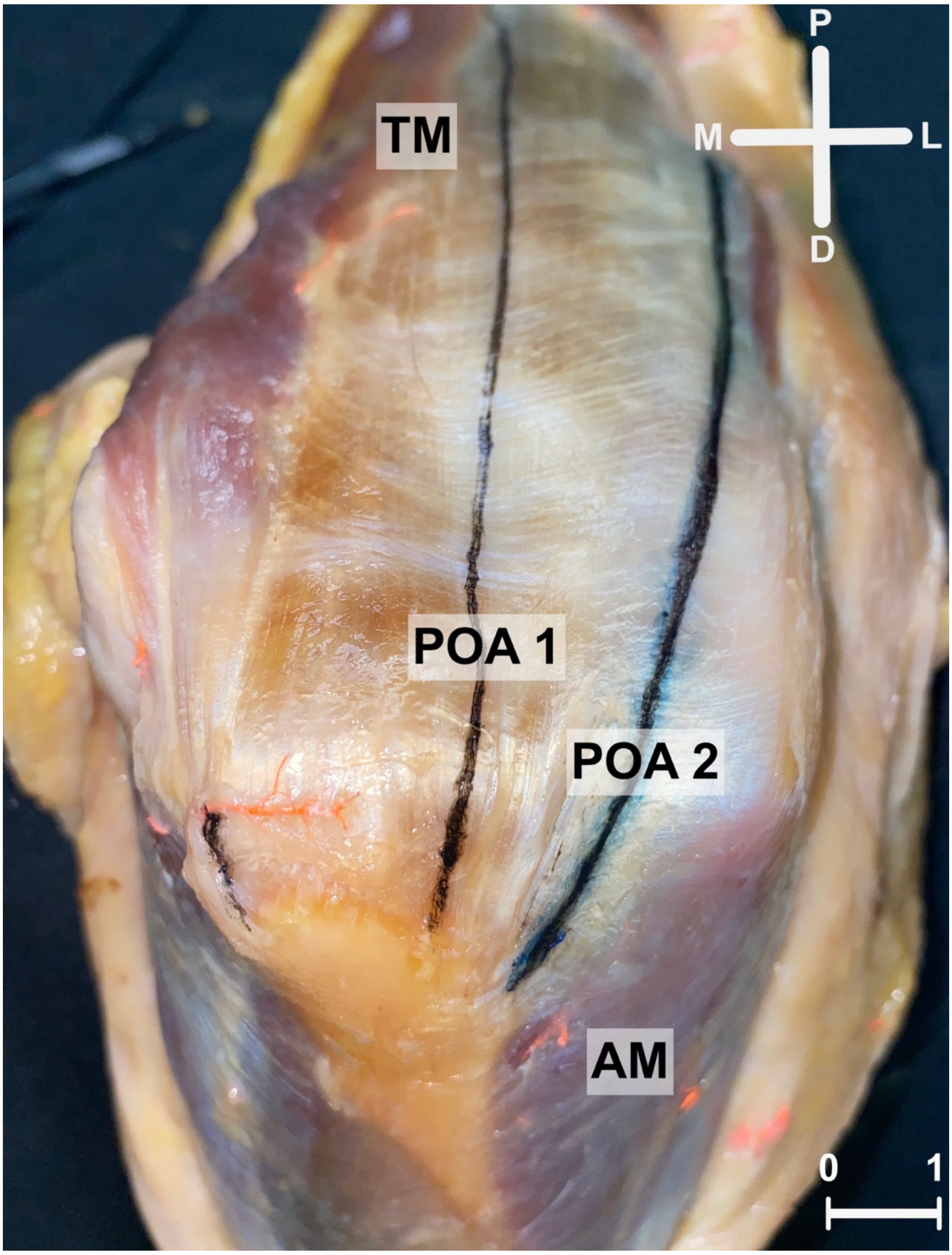

Figure 4: Defined versions of the paraolecranon approach

The figure shows a right arm in a posterior view after subcutaneous dissection and marking of the respective approaches. Dimensions are in cm.

P: proximal; D: distal; M: medial; L: lateral; AM: anconeus muscle; TM: triceps muscle; POA 1: paraolecranon approach 1; POA 2: paraolecranon approach 2

2.4 Dissection

The specimens were placed in prone position. The upper arm was positioned in 90 degrees of shoulder abduction and the elbow was positioned in 90 degrees flexion with the forearm in neutral alignment. Following a longitudinal, posterior skin incision, the subcutaneous tissue of the upper arm and proximal forearm was dissected by forming a medial and lateral full-thickness flap. The triceps was visualized while preserving its fascia. Subsequently, the respective approaches were marked on the specimen. Depending on the result of the

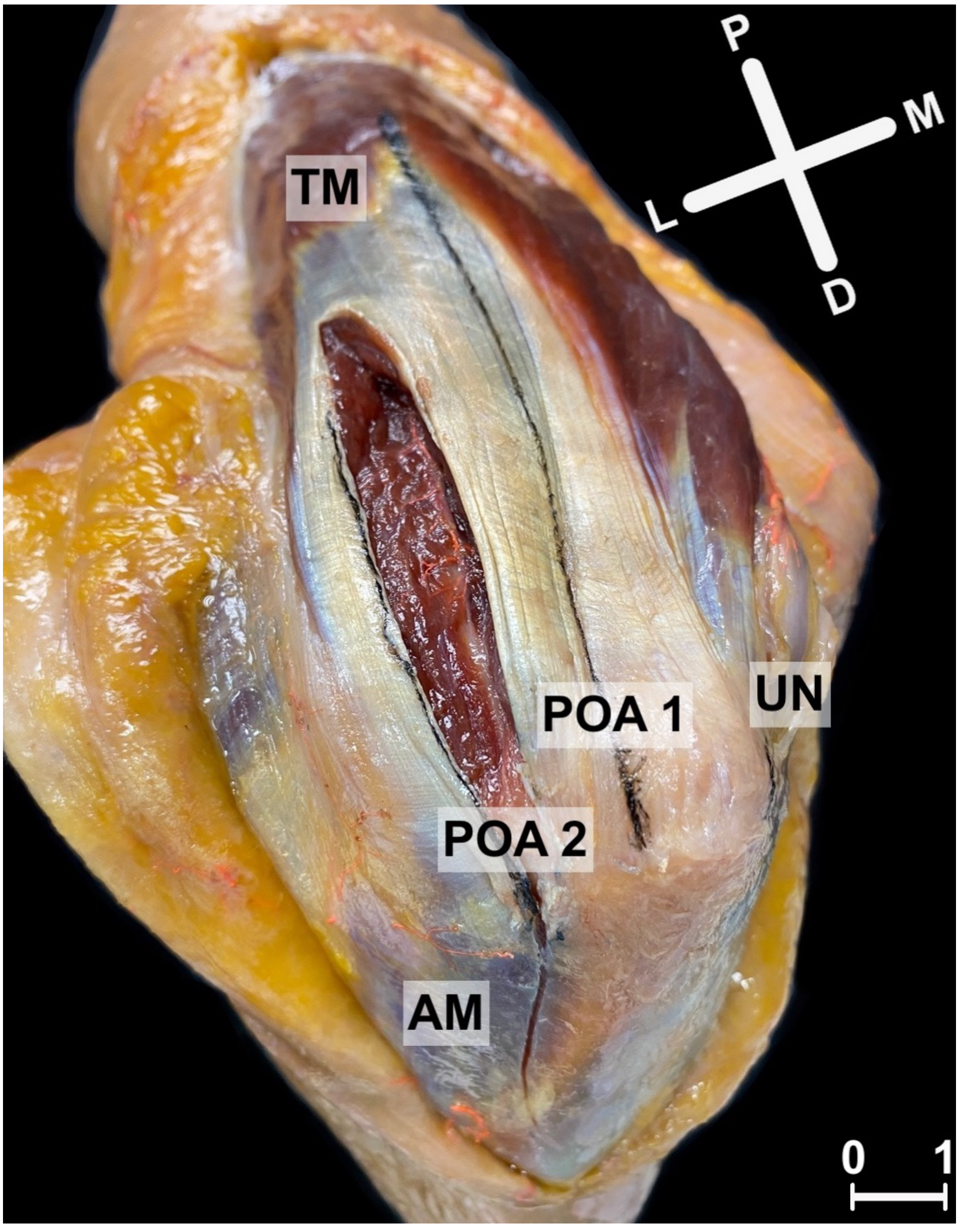

Figure 5: Incision after performance of the POA 2

The figure shows a left arm in the posterior view after marking of the respective approaches. The incision using the POA 2 was carried out. Dimensions are in cm.

P: proximal; D: distal; M: medial; L: lateral; AM: anconeus muscle; TM: triceps muscle; UN: ulnar nerve; POA 1: paraolecranon approach 1; POA 2: paraolecranon approach 2 randomization, the two approaches were performed consecutively through the splitting of the triceps alongside the above-defined line (Figures 5 and 6).

The anconeus nerve was identified and followed distally and closely studied until it reached the anconeus muscle. The anconeus nerve was also followed proximally to the separation from the radial nerve. Special care was taken to avoid manipulation of the course and topography of the nerve during dissection.

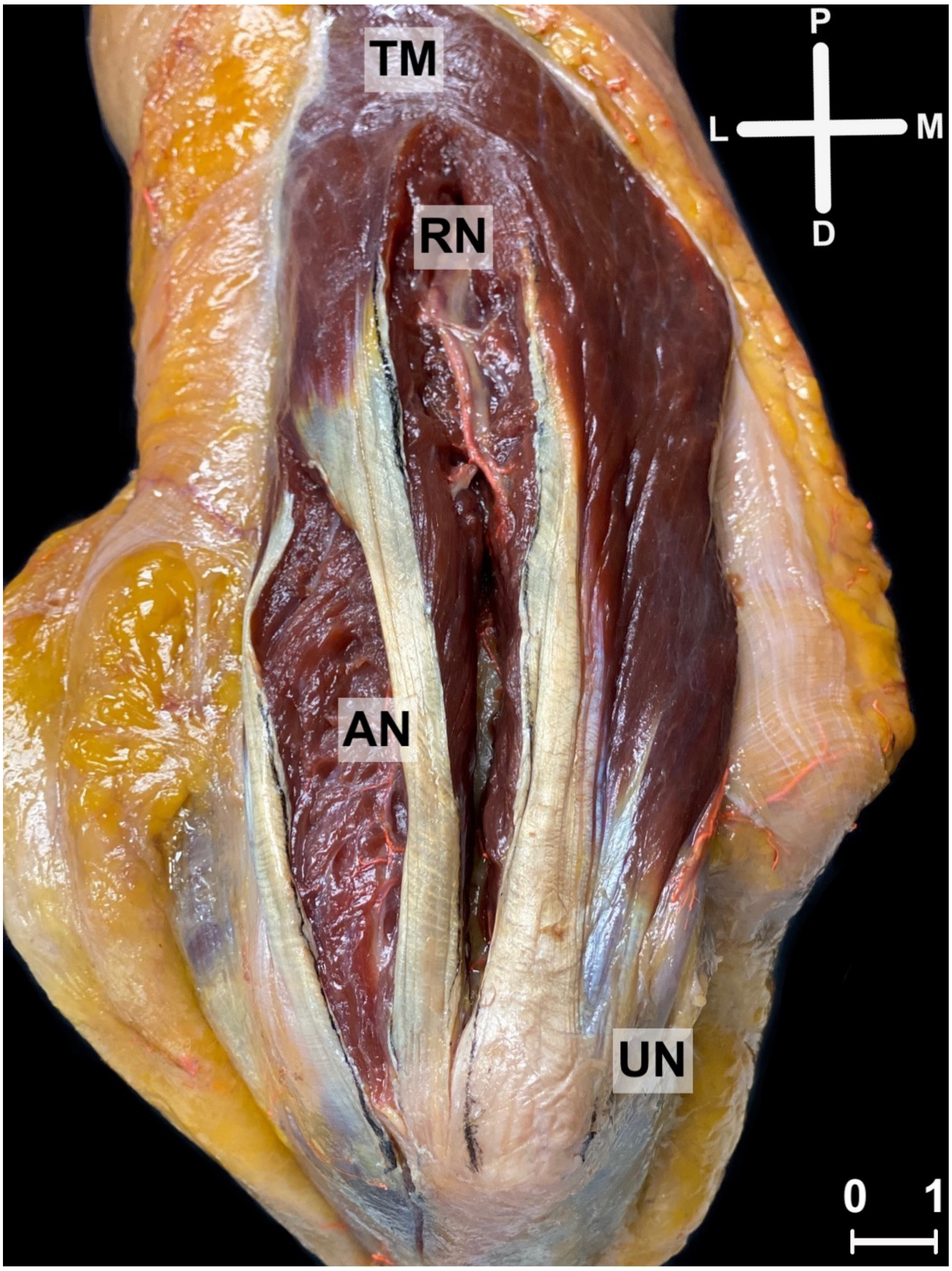

Figure 6: Incisions after performance of the POA 1 and the POA 2

The figure shows a left arm in the posterior view after performance of the respective approaches. Dimensions are in cm.

P: proximal; D: distal; M: medial; L: lateral; TM: triceps muscle; AN: anconeus nerve with accompanying medial collateral artery; RN: radial nerve; UN: ulnar nerve

2.5 Measurements

The length of the humerus and the width of the distal humerus were measured. The humerus length (HL) was characterized as the distance between the most proximal tip of the greater tubercle and the most distal point of the humeral capitulum. The epicondylar width (EW) was characterized as the distance between the medial and lateral humeral epicondyles. The longitudinal distance between AP1 for the paraolecranon approach 1 respectively between AP2 for the paraolecranon approach 2 and the intersection point with the anconeus nerve was measured (Figure 7). Additionally, a transverse and a longitudinal distance from the olecranon to the anconeus nerve were defined to assess the topography of the nerve. The longitudinal distance from the separation of the anconeus nerve from the radial nerve to the centre of the tip of the olecranon was measured (defined as RN-O, Figure 7). Moreover, the transverse distance (TD, Figure 7) from the most lateral edge of the olecranon (AP2) and the anconeus nerve was measured. The transverse distance was oriented parallel to the axis of flexion and extension of the elbow joint.

A standard calliper was used for all measurements (Emil Lux GmbH & Co. KG, Germany; Art. No. 572587).

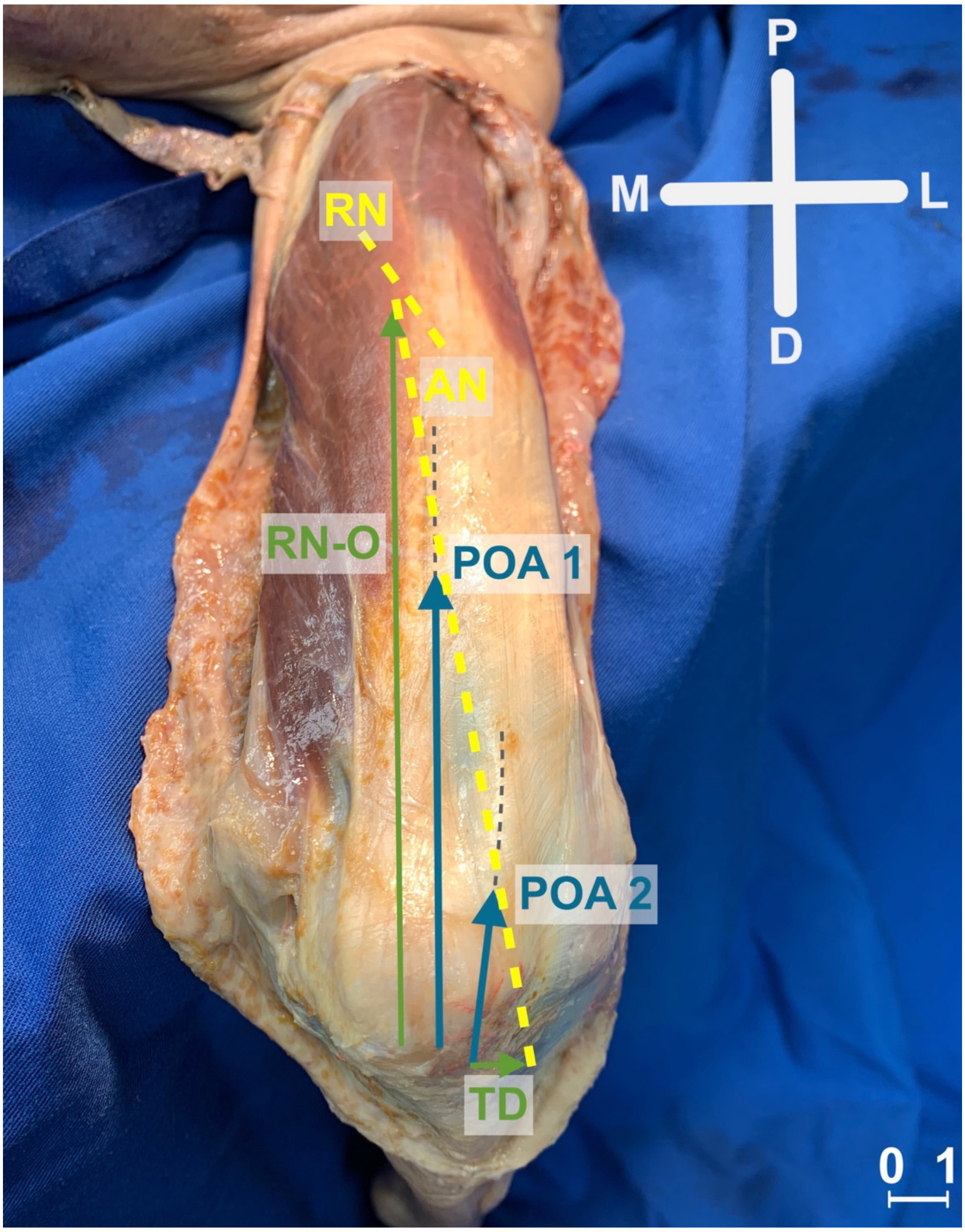

Figure 7: Schematic pattern of the measurements

The figure shows a right arm in the posterior view after subcutaneous dissection. The taken measurements are shown schematically. The radial nerve (RN) and the anconeus nerve (AN) are depicted dashed in yellow. The POA 1 and POA 2 are depicted dashed in grey. The distance between the respective landmarks on the olecranon and the intersection point of the approaches and the anconeus nerve are depicted in blue. Additional measurements from the olecranon to the anconeus nerve are depicted in green. Dimensions are in cm.

P: proximal; D: distal; M: medial; L: lateral; RN: radial nerve; POA 1: paraolecranon approach 1; POA 2: paraolecranon approach 1; RN-O: distance from the center of the tip of the olecranon to the separation of the anconeus nerve from the radial nerve; TD: distance from AP2 to the anconeus nerve

2.6 Statistical analysis

The statistical analysis was performed using IBM SPSS Statistics (90). The data were presented as mean, median, standard deviation (SD), and range. The criteria for normal distribution were met, which was determined Shapiro-Wilk test. A randomizer software (91) was used to randomize the sequence in which the two approaches were carried out. To test the interobserver reliability of the measured data obtained by the two individuals, the intraclass correlation coefficient (ICC) (92) was determined. An ICC with > 0.90 was defined as excellent, from 0.80 – 0.89 as good, and between 0.70 – 0.79 as an acceptable result. An analysis of possible differences between the approaches was performed with a Levene test and independent t-test. Analyses of the influence of (A) side, (B) sex, and (C) humerus length on the course of the nerve in relation to the approaches were performed with an independent t-test and a Levene test for each group. The Pearson correlation coefficient (r) was determined to measure the correlation of the humerus length. The relation between the randomized order of the approaches and longitudinal distance from the olecranon to the anconeus nerve in alignment with the respective approaches was tested with an independent t-test and a Levene test. A significance level was defined at $p \leq 0.05$.

3 Results

3.1 Course

The anconeus muscle and the anconeus nerve branch were present in every specimen. The branch separated from the radial nerve as a direct branch. The anconeus nerve was located between the lateral and medial head of the triceps, entered the medial head, and travelled through the triceps muscle distally (Figure 8). The nerve was accompanied by the medial collateral artery in each specimen.

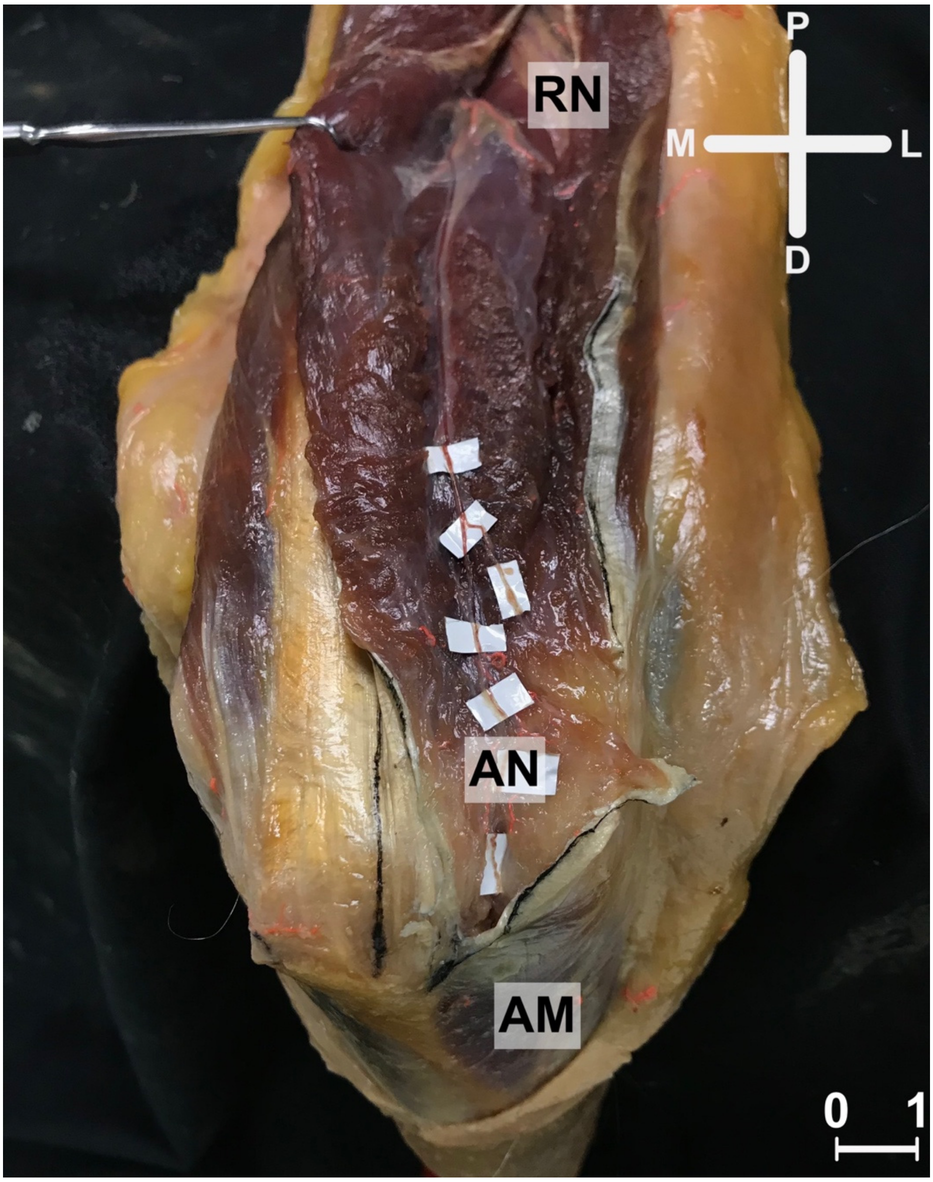

Figure 8: Course of the anconeus nerve

The figure shows a right arm in the posterior view after performance of the POA 2. The anconeus nerve is depicted from the separation of the radial nerve to the anconeus muscle. Dimensions are in cm.

P: proximal; D: distal; M: medial; L: lateral; AM: anconeus muscle; AN: anconeus nerve; RN: radial nerve

The nerve reached the anconeus muscle lateral to the olecranon, where it was located close to the joint capsule (Figure 9).

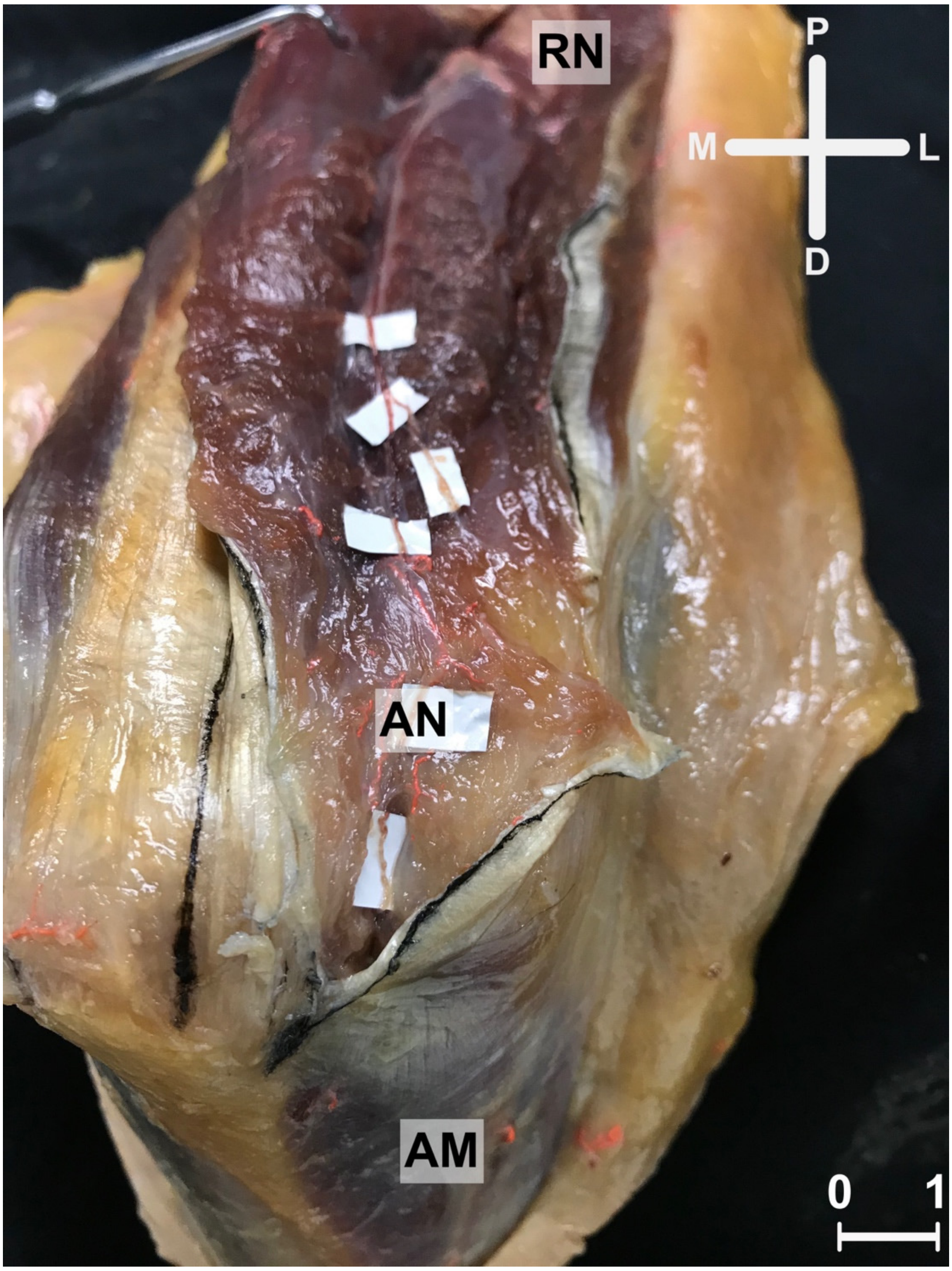

Figure 9: Course of the anconeus nerve near the elbow joint

The figure shows a right arm in the posterior view after performance of the POA 2. Dimensions are in cm.

P: proximal; D: distal; M: medial; L: lateral; AM: anconeus muscle; AN: anconeus nerve; RN: radial nerve

3.2 Results of the statistical analysis

Assessing the interrater reliability showed an excellent result as the ICC was determined 0.902 (range: 0.860–0.921). There was no systematic difference between the measured data obtained by the two individuals (p=0.860).

The mean distance between the medial and lateral epicondyle (EW) was 6.3 cm (SD: 0.5 cm; range: 5.6-7.1; median: 6.4).

The humerus length (HL) was at a mean of 30.0 cm (SD: 2.3 cm; range: 26.1-36.9 cm; median: 29.6 cm) (Figure 10).

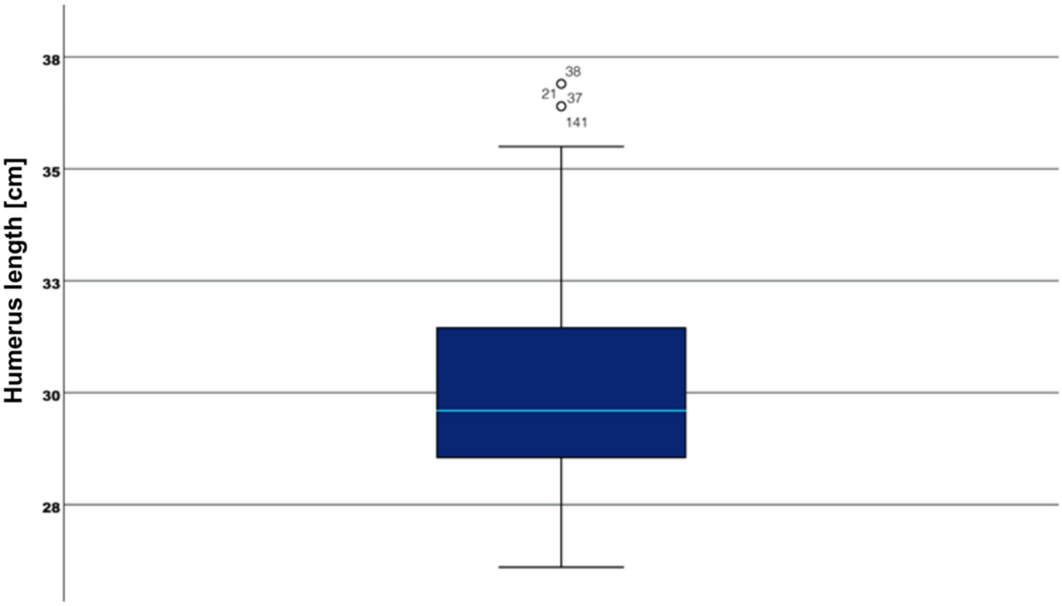

Figure 10: Boxplot illustrating values for humerus length

The mean distance between the centre of the tip of the olecranon and the separation of the anconeus nerve from the radial nerve (RN-O) measured 17.7 cm (SD: 1.0 cm; range: 16.1-19.4 cm; median: 17.6 cm).

The transverse distance (TD) between the most lateral edge of the olecranon (AP2) and the anconeus nerve branch was at a mean of 1.1 cm (SD: 0.3 cm; range: 0.4-1.9 cm; median: 1.0 cm) (Figure 11).

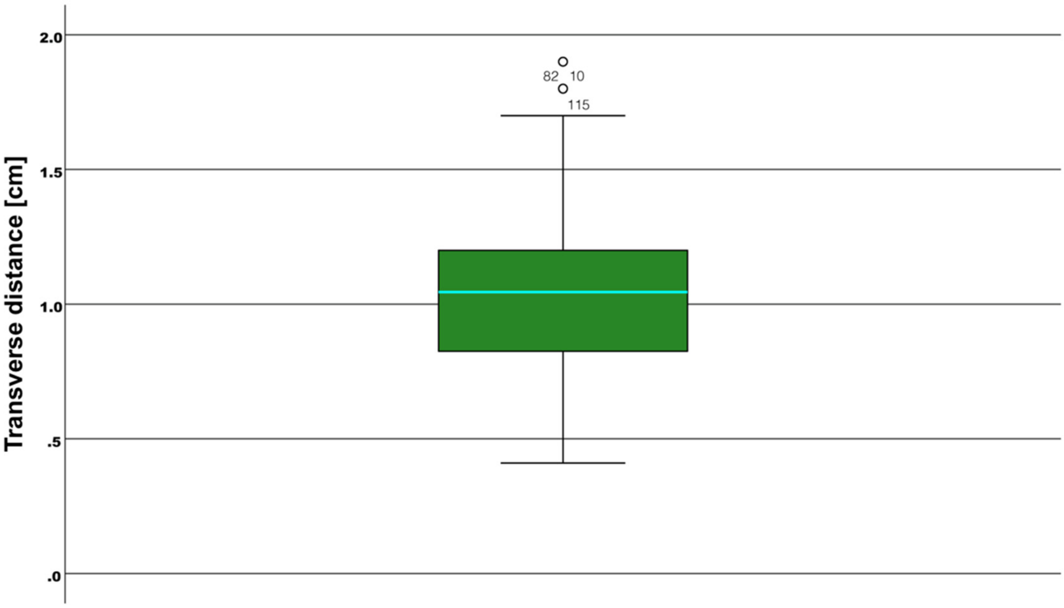

Figure 11: Boxplot illustrating values for transverse distance between AP2 and the anconeus branch

3.2.1 Differences in the paraolecranon approaches

Regarding the POA 1, the average distance between AP1 and the intersection point of the anconeus branch was 12.3 cm (SD: 1.8 cm; range: 8.2-16.8 cm; median 12.5 cm). Regarding the POA 2, the average distance between AP2 and the intersection point of the anconeus branch was 5.5 cm (SD: 1.4 cm; range: 3.0-9.2 cm; median: 5.5 cm) (Figure 12).

There was a statistically significant difference between the approaches (p≤0.001).

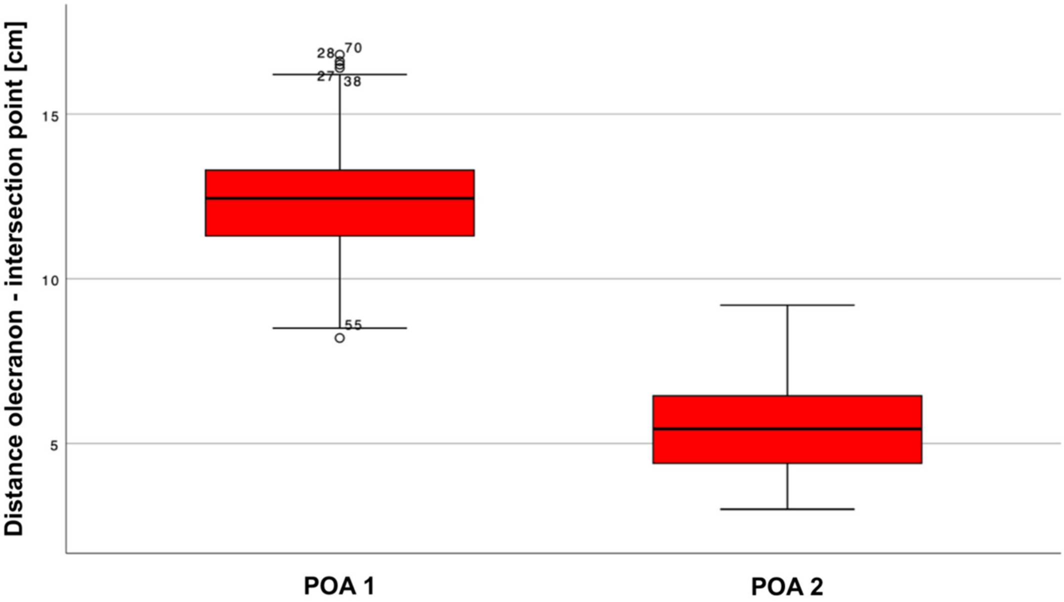

Figure 12: Boxplot illustrating values for the distance between the olecranon and the intersection point of the POA 1 respective the POA 2 and the anconeus branch

The randomized sequence of the approaches did not yield a significant difference. The average distance was 12.4 cm (SD: 1.8 cm; range: 8.2–16.8 cm; median: 12.5 cm) compared to 12.1 cm (SD: 1.6 cm; range: 8.3–16.6 cm; median: 12.2 cm) for the POA 1 (p=0.324). The average distance was 5.5 cm (SD: 1.2 cm; range: 3.0–8,7 cm; median: 5.6 cm) compared to 5.6 cm (SD: 1.3 cm; range: 3.3–9.2 cm; median: 5.7 cm) for the POA 2 (p=0.685).

3.2.2 Influence of side, sex, and humerus length

All evaluated data listed per side are shown in Table 1. There were no statistically significant differences between the sides.

Measurements analysed per gender are depicted in Table 2. The data showed statistically significant longer distances for male specimens when compared to females.

Table 3 shows data analysed per humerus length. Depending on the length in relation to the median, the data were divided into a group with long and a group with short humeri. Statistically significant differences were observed in longer bones. A correlation between the humerus length and the distance from the olecranon to the intersection point of the nerve with the respective approach was shown in the Pearson correlation for both approaches (POA 1: r = 0.550, p≤0.001; POA 2: r = 0.669, p≤0.001).

Table 1: Data analysed per side

(D1 = distance between AP1 and the intersection point of the anconeus nerve; D2 = distance between AP2 and the intersection point of the anconeus nerve; RN-O = distance between the separation of the anconeus nerve from the radial nerve to the centre of the tip of the olecranon; TD = transverse distance between the most lateral edge of the olecranon (AP2) and the anconeus nerve; EW = epicondylar width; HL = humerus length; SD = standard deviation)

Parameter	Side	Mean (cm)	SD (cm)	Range (cm)	p-value
D1	right	12.3	1.8	8.2-16.5	0.710
	left	12.2	1.9	8.6-16.8	
D2	right	5.7	1.3	3.2-9.2	0.104
	left	5.3	1.4	3.0-8.9	
RN-O	right	17.7	1.1	16.1-19.3	0.824
	left	17.8	0.9	16.6-19.4	
TD	right	1.0	0.2	0.6-1.8	0.274
	left	1.0	0.3	0.4-1.9	
EW	right	6.3	0.5	5.8-7.0	0.925
	left	6.3	0.5	5.6-7.1	
HL	right	30.1	2.4	26.1-36.9	0.719
	left	30.0	2.3	26.2-36.7	

Table 2: Data analysed per sex

(D1 = distance between AP1 and the intersection point of the anconeus nerve; D2 = distance between AP2 and the intersection point of the anconeus nerve; RN-O = distance between the separation of the anconeus nerve from the radial nerve to the centre of the tip of the olecranon; TD = transverse distance between the most lateral edge of the olecranon (AP2) and the anconeus nerve; EW = epicondylar width; HL = humerus length; SD = standard deviation)

Parameter	Side	Mean (cm)	SD (cm)	Range (cm)	p-value
D1	male	12.7	2.0	10.6-16.8	0.002
	female	11.7	1.5	8.2-13.7	
D2	male	5.9	1.4	4.5-9.2	≤0.001
	female	5.0	1.2	3.0-7.6	
RN-O	male	18.6	0.6	17.5-19.4	0.002
	female	17.1	0.6	16.1-18.3	
TD	male	1.1	0.2	0.4-1.2	0.002
	female	1.0	0.3	0.7-1.9	
EW	male	6.8	0.2	6.4-7.1	0.001
	female	5.9	0.2	5.6-6.1	
HL	male	31.1	2.3	29.3-36.9	≤0.001
	female	28.8	1.6	26.1-29.9	

Table 3: Data analysed per humerus length

(D1 = distance between AP1 and the intersection point of the anconeus nerve; D2 = distance between AP2 and the intersection point of the anconeus nerve; RN-O = distance between the separation of the anconeus nerve from the radial nerve to the centre of the tip of the olecranon; TD = transverse distance between the most lateral edge of the olecranon (AP2) and the anconeus nerve; EW = epicondylar width; HL = humerus length; SD = standard deviation)

Parameter	Side	Mean (cm)	SD (cm)	Range (cm)	p-value
D1	long	13.0	1.6	9.1-16.8	≤0.001
	short	11.5	1.7	8.2-14.5	
D2	long	6.0	1.3	3.6-9.2	≤0.001
	short	5.0	1.2	3.0-7.7	
RN-O	long	18.3	0.9	17.6-19.4	0.008
	short	17.2	0.7	16.1-18.7	
TD	long	1.1	0.3	0.7-1.8	0.024
	short	1.0	0.4	0.4-1.9	
EW	long	6.6	0.4	5.9-7.1	0.010
	short	6.0	0.4	5.6-6.9	
HL	long	31.8	1.8	29.7-36.9	≤0.001
	short	28.2	1.3	26.1-29.6	

4 Discussion

4.1 Results and comparison with previous studies

The objective of this study was to investigate the course of the anconeus nerve branch in relation to the two versions of the paraolecranon approach and determine the location of an iatrogenic injury and a safe zone for the nerve. Moreover, the study aimed to determine whether side, sex, and humerus length affected the course of the nerve in relation to the approaches.

Regarding the course of the anconeus nerve branch through the triceps muscle in relation to the two versions of the paraolecranon approach, a significant difference between the approaches was found. The distance between the respective landmark on the olecranon and the nerve branch was longer for the more medially located POA 1 (average distance of 12.3 cm) compared to the more laterally located POA 2 (average distance of 5.5 cm).

The data of the POA 1 showed, that the extent of the safe zone for the nerve can be maximized by using a standardized paraolecranon approach. A minimal distance from the olecranon to the nerve of 8.2 cm was found regarding the POA 1. This showed, that use of the POA 1 can reduce the risk of iatrogenic nerve injury.

Moreover, the study did not prove any influence of the side on the extent of the safe zone. Regarding sex and humerus length, however, a correlation for both approaches was found. The study showed statistically significant longer distances for male specimens when compared to females. Longer humerus bones correlated with a longer distance to the nerve.

While the relation of the anconeus nerve and the paraolecranon approach has not been investigated priorly, the topography of the nerve has been described. Maniglio et al. (32) described the topography of the nerve in reference to anatomical landmarks after dissection and investigation of 15 cadaveric specimens. The authors measured the distance from the separation of the anconeus nerve from the radial nerve to the lateral epicondyle and described an average distance of 16.4 cm. Özer et al. (33) described the course of the anconeus nerve after the dissection of 14 specimens and described a mean distance from the separation of the radial nerve to the medial epicondyle of 16.8 cm. During this study, the distance from the separation of the radial nerve to the centre of the tip of the olecranon was measured. The average distance was 17.7 cm, which is a comparable result considering different, but closely situated anatomical landmarks were used.

The transverse distance between the lateral tip of the olecranon and the anconeus nerve branch observed during this study was at a mean of 1.1 cm. However, previously published measurements cannot be fully compared to this finding. Maniglio et al. (32) described the nerve to pass the distance between the olecranon and the lateral epicondyle at a mean of 57% measured from the olecranon. Jiménez-Díaz et al. (21) reported a mean distance of 1.7 cm between a longitudinal axis passing through the lateral epicondyle and the anconeus nerve.
Özer et al. (33) also took measurements of the longitudinal distance between the medial respectively lateral aspects of the olecranon and the anconeus nerve. The authors described a mean distance of 14.2 cm from the medial aspect of the olecranon and 4.7 cm from the lateral aspect of the olecranon. The distances measured by Özer et al. resemble the distances of this study between the respective landmark on the olecranon and the nerve branch using the versions of the paraolecranon approach with 12.3 cm for the POA 1 and 5.5 cm for the POA 2.
Regarding the length of the humerus, other published results were 29.5 cm (33) regarding the distance from the lateral epicondyle to the lateral tip of the acromion or distances of 29.2 cm (93) and 31.0 cm (94) for the distance between the tip of the greater tubercle and the lateral epicondyle. This study found a comparable average humerus length of 30.0 cm.
The mean epicondylar width of the humerus has previously been described as 6.6 cm in males and 5.8 cm in females (95). This study found a comparable result with 6.8 cm in males and 5.9 cm in females.

4.2 Limitations

All in all, the results of this study are comparable to previously published data. However, this study has some limitations.
Both versions of the paraolecranon approach were carried out in each specimen. Even though utmost care was taken during dissection not to manipulate the course and topography of the nerve, a measuring error cannot be excluded. Nevertheless, the randomized sequence of the approaches did not yield a significant difference. The results of both approaches showed similar values (p>0.05) and no difference in the extent of the safe zone.
Since the specimens were taken from elderly subjects of Caucasian descent, an age or population bias cannot be ruled out. Anatomical variations in different human populations are possible. The specimens were embalmed using Thiel's method, which is known for well

preserving the consistency and transparency of the tissue (88,89). However, since all specimens were embalmed using the same method, a comparison with other embalming methods was impossible. Denaturation and degreasing or other embalming-related effects cannot be excluded. It is important to emphasize, that since cadavers are without muscle tone and tension, the dissection might not have fully represented physiologic in vivo conditions. Therefore, the results cannot be directly applied to the living organism. Differences between a traumatic setting and the elective setting in an anatomic environment of this study are possible. A fracture that requires treatment using the paraolecranon approach may cause changes in the topography of the anconeus nerve. Therefore, the results of this study may not always be fully applicable to clinical practice. Nevertheless, it can be assumed that the observed anatomical conditions are a good guide to clinical conditions.

One advantage of this study is the, compared to previous studies of the anconeus muscle with 30 or fewer specimens (20,23,32,33,96), large number of investigated human cadavers. This large sample size has the potential to compensate for individual variations among the specimens.

4.3 Is the anconeus nerve branch worthy of preservation?

The nerve innervating the anconeus muscle is at risk for iatrogenic injury during posterior surgical approaches to the elbow (1,30,33–36). For this reason, among others, O'Driscoll (30) developed an approach during which the nerve can be preserved.

The anconeus muscle is an extensor of the elbow joint. The primary function of the anconeus is most likely that of a dynamic stabilizer, as suggested in several studies (1,17,20,39,52–54). Although some studies have reported low risk of morbidity after anconeus sacrificing surgery (26,28,29,36,97–99), a recent study suggested possible consequences in elbow stability and function, such as difficulty in pronation (42). However, studies have not yet shown distinct conclusions and further investigations are necessary to end the debate about the function of the muscle. Given the inconclusive literature regarding the functional role of the anconeus muscle, preserving the nerve supplying the muscle during a surgical approach seems favourable.

Additionally, there have been several studies regarding the use of the anconeus muscle as a pedicled or even a free flap to cover soft tissue defects (26,28,29,97,98,100). The flap of the anconeus muscle has also been used in the treatment of chronic lateral epicondylitis

(99,101,102). Moreover, the use of the nerve branch to the anconeus as a nerve graft has been described (103–105). The preservation of the nerve during a surgical approach keeps these additional usages possible.

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