Anatomical evaluation of the axillary approach to the axillary and radial nerves for nerve transfer or nerve grafting procedures

A thesis submitted to the Department of Anatomy, School of Medicine, Faculty of Health Sciences, University of Pretoria, in fulfilment of the requirements for the degree of MSc in Anatomy

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UNIVERSITY OF PRETORIA

Declaration

Title: Anatomical evaluation of the axillary approach to the axillary and radial nerves for nerve transfer or nerve grafting procedures

I, *Levó Beytell*, student nr: *12075699* understand what plagiarism is and am aware of the University's policy in this regard. I declare that this thesis is my own original work. Where other people's work has been used (either from a printed source, internet or any other source), this has been properly acknowledged and referenced in accordance with departmental requirements. I have not used work previously produced by another student or any other person to hand in as my own. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as his or her own work. This thesis is being submitted for the degree of MSc in Anatomy at the University of Pretoria. It has not been submitted before for any other degree or examination at this or any other Institution.

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This 31st Day of October 2019

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Anatomical abbreviations

AA: Axillary artery.

AD: Anterior division of the axillary nerve.

AN: Axillary nerve.

AV: Axillary vein.

ETE: End-to-end

ETS: End-to-side

ICBN: Intercostobrachial nerve.

LN: Nerve to the long head of triceps brachii muscle.

LTD: Latissimus dorsi muscle.

MABCN: Medial antebrachial cutaneous nerve.

MBCN: Medial brachial cutaneous nerve.

MN: Median nerve.

NVB: Neurovascular bundle.

PCHA: Posterior circumflex humeral artery.

PCM: Pectoralis major muscle.

PD: Posterior division of the axillary nerve.

QS: Quadrangular space.

RETS: Reverse-end-to-side

RN: Radial nerve.

SA: Subscapular artery.

SM: Subscapular muscle.

TBLM: Long head of the triceps brachii muscle.

TN: Nerve to the teres minor muscle.

UN: Ulnar nerve.

Measurement and observation abbreviations

A-B: The distance from the origin of the axillary nerve to the anteromedial border of latissimus dorsi muscle.

A-D: The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.

B-C: The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.

D-E: The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.

Dia AD: Diameter of the anterior division of the axillary nerve at its origin.

Dia AN: Diameter of the axillary nerve at its origin.

Dia PD: Diameter of the posterior division of the axillary nerve at its origin.

AN-PCHA: Axillary nerve course in relation to the posterior circumflex humeral artery.

AN-RN: Origin of the axillary nerve in relation to the radial nerve.

AN-SA: Axillary nerve course in relation to the subscapular artery.

RN-SA: Radial nerve course in relation to the subscapular artery.

Statistical abbreviations

CI: Confidence interval.

df: degrees of freedom

IQR: Interquartile range.

Max: Maximum.

Min: Minimum.

n: Number of individuals

SD: Standard deviation.

Stat.: Statistic

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To my family that always supported me through each and every obstacle with love, I am eternally indebted. My father that taught me that anything is possible by never giving up and showed me how to be a rock against the crashing waves of life. To my mother who showed me the potential that can be reached when the outmost love and care is given to your family, no matter the circumstances. My big brother that always has my back and sets the forever example to which I can look up to.

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Executive summary

Having detailed anatomical knowledge when performing surgeries, is crucial to ensure a successful outcome. This is especially true when undertaking relatively new procedures. Even though nerve transfers and nerve grafts have been performed on the different parts of the brachial plexus for some time, nerve transfer and grafting procedures involving the axillary and radial nerves using a newly proposed axillary approach has not yet been fully studied. This study provides some enlightenment to the anatomy surrounding the axillary approach, with special regard to the axillary and radial nerves and their branches. The axillae of 51 (26 female and 25 male) formalin fixed cadavers were bilaterally dissected using a simulation of the axillary approach, which has been described to gain access to the brachial plexus in a clinical setting. Following which, various distances between easily identifiable anatomical landmarks and relevant neurovascular structures were measured, and observations regarding the relationship of these structures to the landmarks were recorded. This study found that the axillary nerve and its anterior and posterior divisions, as well as the radial nerve with its nerve to the long head of triceps brachii muscle could be easily identified however, their proximal parts were situated fairly deep and therefore were difficult to expose. Methods such as the musculo-arterial triangle described by Bertelli *et al.*, which was designed to aid in identification on localization of the axillary nerve was also assessed; it was found to be relatively successful, however more consistent landmarks might be considered. In conclusion this study found that the axillary approach may serve as a reliable and safe method to reach the axillary and radial nerves, as well as their branches, allowing for adequate exposure when considering a nerve transfer or graft.

Key words: axillary approach; axilla; axillary nerve; radial nerve; nerve transfer; neurotisation; nerve graft; nerve repair; brachial plexus; latissimus dorsi muscle.

1. Introduction

Having detailed knowledge of anatomical structures, such as the location and relationship of nerves to other anatomical landmarks, is crucial to the success of clinical procedures.[1,2] A number of injuries including those to the cervical spinal cord,[3] as well as iatrogenic injuries such as, adverse effects caused in a patient by medical treatment, to the brachial plexus or its components, specifically those that influence the radial and axillary nerves, can negatively impact the function of the upper extremity.[4,5] During clinical procedures, predefined landmarks are utilised to aid in locating targeted and surrounding nerves or structures, as well as to avoid unnecessary injuries.[1] Iatrogenic injuries to the radial and axillary nerve during shoulder surgeries has been identified as one of the most common causes of injury.[5,6] The landmarks used during surgeries depend on the approach that is chosen for the procedure in the relevant area.[7] For isolated axillary nerve injuries, and repair thereof, through a nerve transfer of one or more branches of the radial nerve, a combination between an anterior (deltopectoral) and posterior approach is typically used.[4] However, it has been suggested by Sedel,[8] that a single inferior or axillary approach could be considered to be an alternative approach.

There are a number of ways to functionally repair the adverse effects from damage to the cervical spinal cord[9] (such as the loss of muscle innervation) and nerves of the brachial plexus, especially the axillary nerve. The most common of these include nerve grafting, where a segment of an unrelated nerve is used to replace or bridge an injured portion of a nerve, as well as nerve transfers (neurotisation), which involves the repair of a distal denervated nerve element by using a proximal foreign nerve as the donor to reinnervate the distal targets.[10] The gold standard of treatment for isolated nerve injuries is nerve grafting.[4] However, some studies show more favourable outcomes towards nerve transfers compared to nerve grafting.[11] Improved results are also seen when a combination between nerve transfers and grafts are performed.[12]

A review, of nerve transfers performed on patients presenting with tetraplegia, a paralysis resulting in the loss of motor, sensory or both innervations of the four limbs and thorax, was done by Cain *et al.*[13] to evaluate the use of nerve transfer procedures and rated it as a promising repair option, it is also mentioned that anatomical studies of possible donor nerves for tetraplegia are essential for clinical application. The study concluded that nerve transfers can serve as an alternative, but only if tendon transfers are not an option. Furthermore, nerve transfers, in isolation, as well as the combination of nerve and tendon transfers in tetraplegic patients show promise as a reconstructive option and should be further studied. The study by Anderson[14] mentioned that patients presenting with tetraplegia desired the recovery of their upper limb function the most.

Although the location of the axillary nerve has been reported in a number of studies, the precise location of the axillary nerve with its branches for nerve repair or transfer surgeries, has not yet been fully defined using the axillary approach.[2,6] There is a segment of the axillary nerve that is not visible through either the anterior (deltopectoral) or posterior approaches even when used in conjunction.[15] The rationale is that the axillary approach allows for better visualisation of the structures in the axilla during the surgery, even though few studies have actually defined the location of the nerve through the axillary approach.[4] The location of the radial nerve however, has been well documented especially in the arm[16], yet iatrogenic injury still remains common with the radial nerve.[5]

Based on the sparsity of anatomical information on these surgical approaches, there is a need for an alternative to the anterior (deltopectoral) and posterior approaches to the axillary content, but before surgeons can consider the axillary approach to the axillary and radial nerves as a safe alternative, more studies on the detailed anatomical description of the position of neurovascular structures in relation to visible musculo-skeletal landmarks or structures are required.

Therefore, this study set out to address the anatomical short comings of the axillary approach by providing a detailed anatomical description of the structures that can be visualised through the axillary approach, with special reference to the location and course of the axillary and radial nerves (as well as their branches) using visible anatomical landmarks.

2. Literature review

2.1 Anatomy

2.1.1 Brachial plexus

The brachial plexus originates from the ventral rami of the spinal nerve roots C5-C8 as well as the first thoracic spinal nerve root T1. In some cases, there are contributions to the brachial plexus from C4 and T2. Typically, the first two ventral rami from C5 and C6 will join to form the superior trunk. The ventral rami of C7 will continue as the middle trunk and the last two ventral rami from C8 and T1 will join to form the inferior trunk. Each trunk then divides into an anterior and posterior division. The anterior divisions from the superior and middle trunk join to form the lateral cord, and the anterior division from the inferior trunk forms the medial cord. All three posterior divisions from the different trunks join to form the posterior cord. The brachial plexus then ends as the terminal branches from the three cords. The musculocutaneous nerve continues from the lateral cord, the ulnar nerve continues from the medial cord and the median nerve receives contributions from both the lateral and medial cord. Finally, the axillary and radial nerves originate from the posterior cord[17] (see Figure 2-1). This study specifically focused on the axillary and radial nerves and their branches.

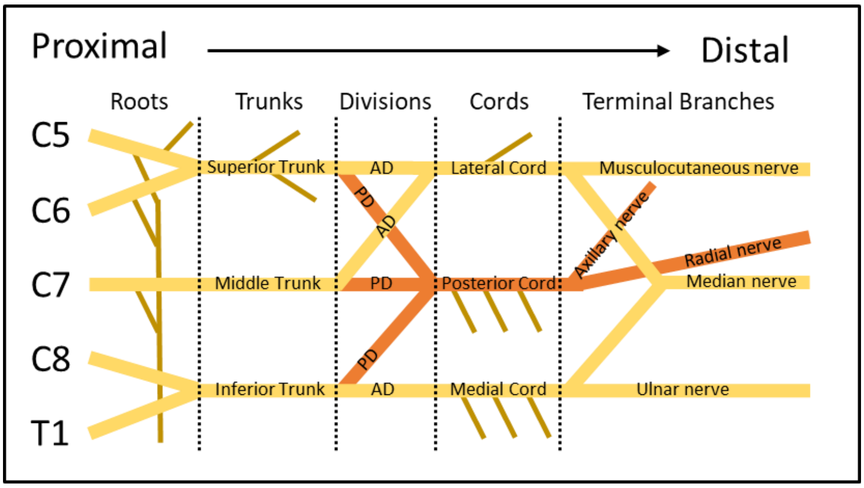

Figure 2-1 Diagram showing the different parts of the brachial plexus (AD= anterior division; PD = posterior division; brown lines = non-terminal branches from the brachial plexus).

2.1.2 Axillary nerve

The axillary nerve receives contributions from the ventral rami of the C5 and C6 spinal nerve roots and originates as a terminal branch of the posterior cord of the brachial plexus.[1,18,19] It has been noted to arise immediately behind the coracoid process of the scapula.[18] The nerve innervates the deltoid muscle, thus injury to the nerve diminishes the abduction function of the upper limb excessively.[20] The nerve then courses inferolaterally on the anterior surface of the subscapularis muscle to the quadrangular space, which is a space between the teres minor muscle superiorly, long head of triceps brachii muscle medially, teres major muscle inferiorly and the surgical neck of the humerus laterally, and typically no branches are given off by this part of the axillary nerve.[2,19] During its course over the subscapularis muscle it passes deep to the subscapular artery[4] and once it enters the quadrangular space, it separates into two main anterior and posterior divisions.[18,19,21] Tubbs *et al*.[22] noted that in a third of cases from their study sample, the axillary nerve separated within the quadrangular space, compared to separating at the posterior aspect of the quadrangular space in two thirds of the cases. The superior lateral brachial cutaneous nerve also originates at this posterior aspect, from the posterior division of the axillary nerve as a cutaneous branch.[18,19,21] Another study by Uz *et al*.[2] noted that the axillary nerve separated during its course on the subscapularis muscle.

The two divisions of the axillary nerve are accompanied by the posterior circumflex humeral artery through the quadrangular space[2,22,23] with the axillary nerve being the most superior structure.[22] The anterior division of the axillary nerve is known to curve around the surgical neck of the humerus on its way to the deltoid muscle.[19,21,23] The anterior division further splits into two to three branches before entering the deltoid muscle[21] at the raphe between the anterior and middle parts of the deltoid muscle.[18] The anterior division of the axillary nerve supplies the deltoid muscle and some studies have found slight differences in which of the certain parts of the muscle specifically. In general, the anterior part of the deltoid muscle is found to be supplied by the anterior division, the middle part by the anterior and posterior divisions and the posterior part by the posterior division with discrepancies on whether the anterior division does indeed supply the posterior part at all.[2,4,23–25] The posterior division of the axillary nerve has consistently been found to give off a nerve to the teres minor muscle,[2,4,19,21–23] the posterior part of the deltoid muscle,[2,4,6,19,21,23] as well as the superior lateral brachial cutaneous nerve.[4]

2.1.3 Radial nerve

The radial nerve receives contributions from the C5 – T1 spinal nerve roots and it is the terminal branch of the posterior cord of the brachial plexus and originates deep to the axillary artery. The nerve courses over the posterior axillary wall towards the triangular interval, which is defined as a space formed by the teres major muscle superiorly, the long head of triceps brachii muscle medially and the humerus laterally.[1,17] It passes anterior to the subscapular artery as it courses over the subscapularis muscle.[4] The radial nerve is accompanied by the deep artery of the arm through the triangular interval.[17] Four branches are given off by the radial nerve, the posterior cutaneous nerve of the arm, as well as branches to the long, medial and lateral heads of the triceps brachii muscle.[17] The nerve to the long head of triceps brachii muscle is the most proximal branch of the radial nerve.[4,20,21] This branch further divides into two or three more branches before entering the muscle. The nerves to the medial and lateral heads of the triceps brachii muscle originate distal to the teres major muscle, with the exception of the medial head that also receives a branch originating proximal to this border.[23] The nerve to the lateral head of the triceps brachii muscle is the more distal branch.[21] The radial nerve terminates as the deep and superficial branches of radial nerve in the forearm at the level of the radial neck.[17]

2.2 Procedures

2.2.1 Nerve transfer

Nerve transfer is a surgical technique that includes transecting a functioning nerve or branches thereof, and transferring it from its original course onto an injured nerve.[26] The goal of these transfers is to use a nerve that has a less important functional role and transferring it onto a more important nerve to restore the structures function, with as little clinical implications, such as local or systemic morbidity, as possible.[27] In order to perform a nerve transfer successfully and safely, adequate visualisation of the targeted nerves and the surrounding anatomical structures is essential,[28] as well as a competently vascularised site[29] with minimal tension on the suture.[26,30] It is also recommended that the donor nerve must restore a single function, as well as be a pure motor or sensory nerve that is the same diameter as the recipient nerve.[26] The advantages of using this surgical technique, include the reduction in the denervation time of motor end plates, as well as increasing the effect of the axonal load on a single high priority function, which in turn improves recovery.[26] For future consideration, the procedure must not compromise any future tendon transfers in the region.[26] Nerve transfers are indicated in cases where nerve grafts or primary nerve repair (repair of an injured nerve within one week of the injury) procedures are unreliable.[27]

There are different types of nerve transfer techniques in which the nerves can be joined together. An end-to-end suture involves cleaving of both the donor and recipient nerve and joining the two ends together as the name suggests.[26] The end-to-side suture is done by joining the transected recipient nerve end to the intact donor nerve, this has however not shown positive results.[31] A technique that has not yet been fully studied, is the reverse end-to-side, in which a donor nerve will be partially transected and joined to the recipient nerve, the expected advantages are the possibility of recovery of the donor nerve and the continuity of the recipient nerve (See Figure 2-2).[32]

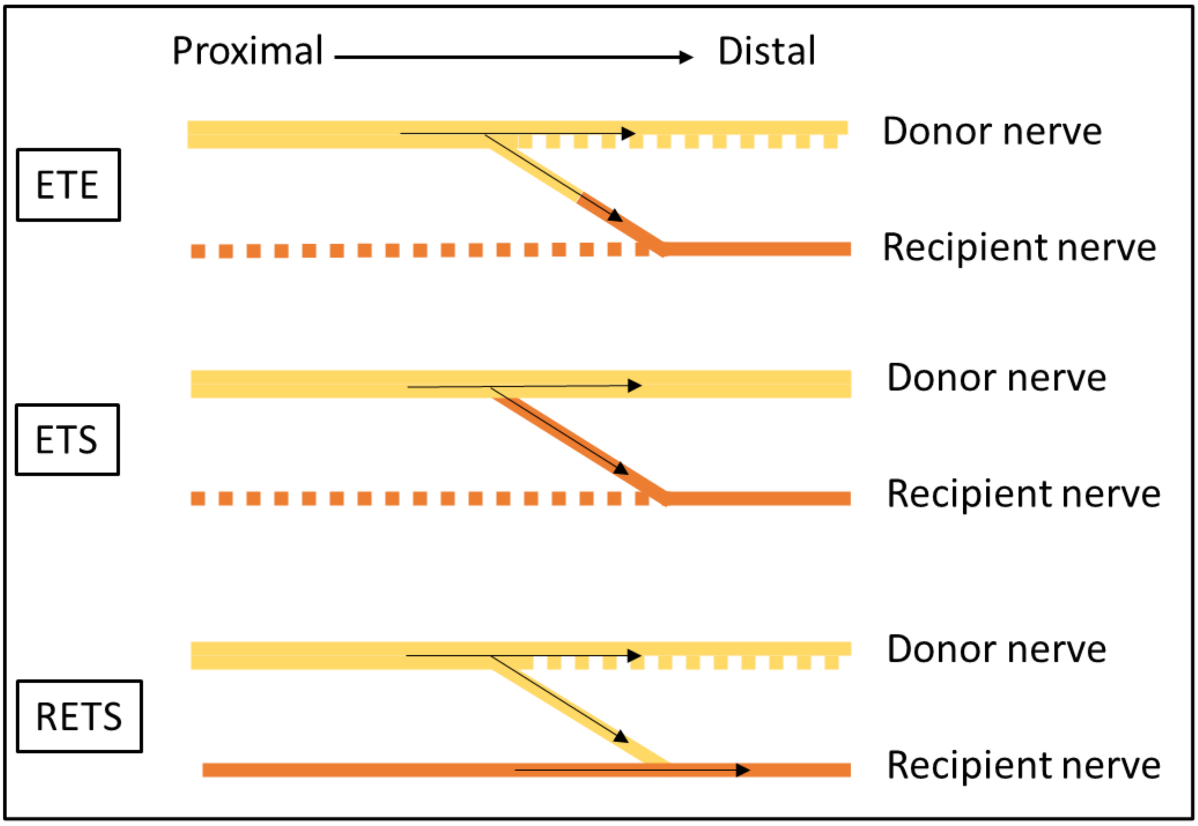

Figure 2-2: Diagram showing the different types of nerve transfers (ETE = end-to-end transfer, ETS = end-to-side transfer, RETS= reverse-end-to-side transfer) (Adapted from Forli *et al*.[26])

Motor donor nerves can be classified based on their location and the type of nerve transfer that will take place. The location can be either intra- or extra-plexus with reference to the brachial plexus and the type of nerve transfer is either terminal or non-terminal depending on whether the nerve will be completely or partially transected.[26]

Radial to axillary nerve transfers have been reported on in a number of studies for repair of axillary nerve injuries.[4,10,33] However, the transfer of axillary to radial nerve injuries are far less common as there are other options available to restore function closer to the motor end plates.

2.2.2 Nerve grafting

Nerve grafting is a technique that involves harvesting a nerve from a different part of the body and replacing an injured nerve or bridging a gap in cases where a nerve has been sectioned. Nerve grafting is considered in cases where end-to-end nerve repair is not possible, or when gaps between nerve ends are formed after unhealthy parts of the nerves are excised. The nerve graft serves as a bridge through which new nerve fibres can grow and recover lost functions in muscles.[34]

Different nerve grafting material can be used, which are classified into autogenous nerve grafts, allo-nerve grafts, or conduits. Autogenous nerve grafts are considered to be the gold standard nerve graft and involves using a nerve from a different part of the body of the same patient. Typical nerves used include the: medial and lateral cutaneous nerves of the forearm, dorsal cutaneous branch of the ulnar nerve, superficial and deep fibular nerves, intercostal nerves, the posterior and lateral cutaneous nerves of the thigh, accessory nerve, medial pectoral nerve and, sural nerve.[27,35] The advantage of using an autogenous nerve graft is the lack of an immunogenic response due to the nerve deriving from the same patient, it is an affordable procedure and is more reliable,[36] while some of the disadvantages are secondary incisions to harvest the donor nerve and neuroma formation.[27]

While autogenous nerve grafts involve harvesting nerves from the same patient, allo-nerve grafts use a donor nerve from a different donor. The advantages of using this technique, are the availability of possible nerve donors and the accessibility to the nerves. However, along with a different donor comes the disadvantage of possible immunosuppressive responses leading to failure of the allo-nerve graft.[27]

Another option for nerve grafting is the conduit technique, which is the use of a synthetic or biological nerve conduit. The conduit serves as a guiding tube, along which the two ends of nerves can grow to be connected, whilst being protected from surrounding structures.[37] The advantages of this technique are the availability of conduits, avoidance of donor site morbidity and the possibility of accumulating neurotrophic factors. Some of the disadvantages, however, are the inconsistent outcomes of the technique, the lack of Schwann cells and its restriction to short nerve gaps (see Figure 2-3).[27]

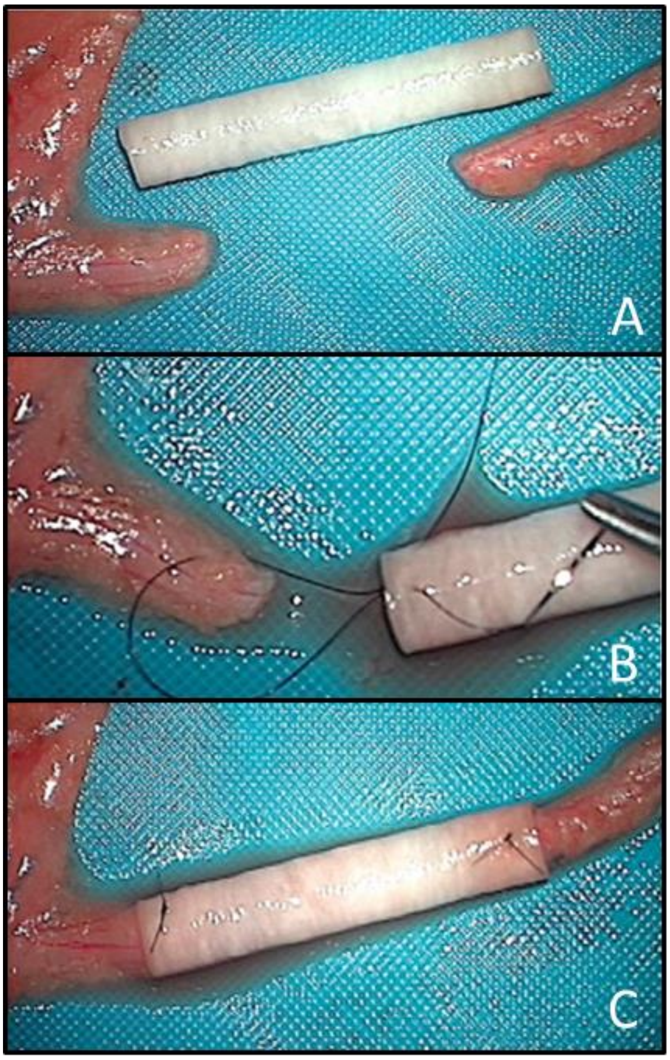

Figure 2-3: Photograph showing the nerve grafting technique using a conduit.[38]

For proximal injuries of the radial nerve, it has been reported to show favourable outcomes when using the combination between nerve or tendon transfers and nerve grafts to restore function to the wrist and fingers, rather than only performing an isolated nerve graft.[39] In the case of axillary nerve grafts, similar recovery results have been reported between long nerve graft and modern nerve transfer procedures,[40] except when dual nerve transfers are performed, in which better outcomes are seen.[11]

2.3 Approaches

There are different approaches that are used to expose the targeted nerves for repair and are selected based on the location and type of injury. The aim of the approach is to achieve adequate visualisation and exposure of the targeted structure, in order to perform repair with as minimal damage to the surrounding structures as possible.[7] For this to be achieved, the knowledge of the location of the targeted and surrounding anatomical structures is crucial.[1,7]

The following approaches are indicated for nerve transfers or nerve grafts involving the axillary or radial nerve to restore functions after brachial plexus or cervical spinal cord injuries:

2.3.1 Anterior (deltopectoral) approach

The patient is placed in the supine position to expose the deltoid and pectoral region. An incision is then made between the deltoid muscle and pectoralis major muscle. Both muscles are then retracted for better exposure of the axillary region. To view the brachial plexus inferior to the clavicle, the pectoralis minor muscle is cut. The axillary artery and lateral cord of the brachial plexus is retracted medially exposing the axillary and radial nerve, as well as the posterior cord. The nerves to the triceps brachii muscle are also visible at this point.[41]

Some of the advantages of this approach are the good visualisation of the proximal brachial plexus, which includes the axillary nerve,[4] the large area that is exposed, the shortened surgery times and the small amounts of bleeding due to the incision being between muscle planes.[42] One of the major disadvantages of this approach is the requirement to section muscles such as the pectoralis minor muscle which, often leads to prolonged healing[33] and the difficulty reaching the nerve to the teres minor muscle from the posterior division of the axillary nerve.[42]

2.3.2 Posterior approach

For this procedure, the patient can either be put in the supine position with the shoulder elevated and the arm in the adducted position, so that the arm is positioned over the ipsilateral side of the chest, or the patient is placed in the prone position with the arms adducted. A vertical incision is made between the lateral and long heads of the triceps brachii muscle, from the posteroinferior border of the deltoid muscle and inferior to the scapular neck until the desired branch (either nerve to lateral, medial or long head of the triceps brachii muscle) of the radial nerve is visible. The incision can then be deepened to expose the axillary nerve within the quadrangular space. [43]

The advantages of the posterior approach lie within accessing the axillary nerve at its termination into the deltoid muscle. Due to the axillary nerve branching into its muscular components close to the deltoid muscle, this approach allows for selective repair of non-functioning branches in axillary nerve injuries, [43] as well as reduced reinnervation distance due to nerve coaptation being close to the deltoid muscle.[44] The disadvantages include the high risk of injury to the posterior division of the axillary nerve due to low visibility,[42] difficulty reaching the nerve to the teres minor muscle[4,41] and the necessity to section muscles.[33]

2.3.3 Axillary approach

Even though the procedure of transferring the fascicles of the branches to the triceps brachii muscle from the radial nerve to the axillary nerve was first described by Lurje,[45] the axillary approach was first proposed by Sedel[8] as a single inferior approach, at a much later time. Due to the combination of the anterior (deltopectoral) and posterior approaches for treatment of isolated axillary nerve injury, being the more commonly used and studied approaches,[4] Bertelli *et al*.[4] set out to study the surgical anatomy of the axillary nerve with the intention of repairing it, by using the radial nerve branches to the triceps brachii muscle through the axillary approach.

The procedure through the axillary approach was described as follows: the patient is placed in the supine position with the arm abducted and externally rotated. An incision is then made from the middle of the axilla to the area over the brachial vessels in the arm. Once the incision is made, the axillary vein is retracted in a cephalad direction as needed. The area from the medial border of the latissimus dorsi muscle to the subscapularis muscle is dissected. The radial nerve with its branches to the triceps brachii muscle are visible at this point. To further expose the quadrangular space and the axillary nerve within it, the latissimus dorsi and teres major muscles are retracted laterally. For further aid in finding the axillary nerve, Bertelli *et al*.[4] described a musculo-arterial triangle, bordered medially by the subscapular artery, laterally by the latissimus dorsi muscle and superiorly by the posterior circumflex humeral artery, in which the axillary nerve could be reliably found (See Figure 2-4).[4]

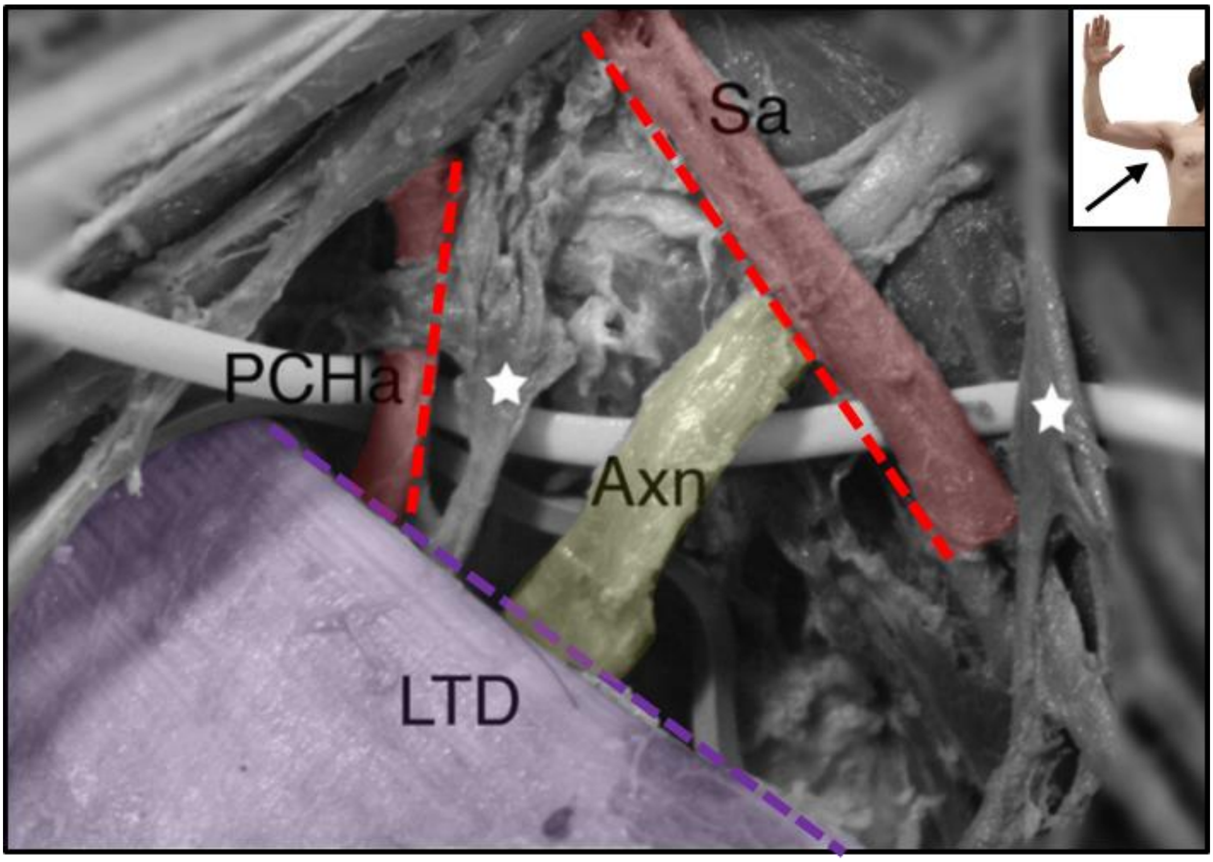

Figure 2-4: Adapted photograph by Bertelli *et al*.[4], showing the axillary nerve found within the musculo-arterial triangle indicated with the dashed lines (Sa = subscapular artery; PCHA = posterior circumflex humeral artery, Axn = axillary nerve; LTD = latissimus dorsi muscle).

The advantages of the axillary approach include, the good visualisation of the distal axillary nerve and its branches, the visualisation of the major blood vessels in the axilla, the fact that there is no need for sectioning of muscles,[33] as well as, that it is a safe[4,33] and reliable technique.[33] A major disadvantage of the axillary approach however, is the limited access to the proximal part of the axillary nerve.[4,41]

3. Aim

The aim of this project was to provide a detailed anatomical description of the structures that can be visualised through the axillary approach, with special reference to the location and course of the axillary and radial nerves, as well as their branches, using visible and easily identifiable anatomical landmarks.

3.1 Research objectives

In order to achieve the aim of this study, the following objectives were established and accomplished after exposing the axillary content using a simulated axillary approach:

- Measure the distance from the medial border of the latissimus dorsi muscle to the origin of the axillary nerve and to the branch of the radial nerve that supplies the long head of the triceps brachii muscle.
- Measure the distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions, as well as measuring the distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.
- Measure the diameter of the axillary nerve, as well as the diameter of its anterior and posterior divisions at their origin.
- Observe the branching pattern of the axillary nerve and observe its division into its anterior and posterior divisions in relation to the borders of the quadrangular space.
- Evaluate the anatomical accuracy of the musculo-arterial triangle described by Bertelli *et al*.,[4] to locate the axillary nerve and its divisions using an axillary approach.
- Create a comprehensive anatomical step-by-step guide to visualise the axilla and its content with special regard to the axillary and radial nerves with their branches, using an axillary approach.

4. Materials and methods

4.1 Setting

All dissections were conducted in the dissection halls of the Department of Anatomy, Faculty of Health Sciences, University of Pretoria.

4.2 Type of study

This study was designed as an observational analytical cross-sectional study collecting quantitative and qualitative data.

4.3 Sample Size

This study included 51 formalin fixed cadavers that were dissected on both the left and right sides when possible, as well as a fresh frozen cadaver that was used for illustrative purposes in the section for the step-by-step guide. The sample was divided into 25 male and 26 female cadavers that were randomly chosen to test for sex-specific differences between the measurements. Only adult (18 years or older) cadavers, that had no observable anatomical abnormalities or notable surgical intervention in the relevant axillary area, were dissected. Cadavers were not excluded based on ancestry or age. Table 4-1 outlines the demographic details of this sample (see Appendix A).

Table 4-1: Demographic details (Min = Minimum; Max = Maximum; SD = Standard Deviation).

	Mean	SD	Min	Max	Range (Max – Min)
Age	69.6	16.3	21	94	73
Height (cm)	167	10	153	190	65
Weight (kg)	57.1	17.6	30.6	110.8	80.2
BMI	20.7	7.2	11.4	44.9	33.6

4.4 Procedure for exposing the axilla

With the cadaver in the supine position, the arm of the cadaver was abducted and externally rotated to expose the axillary fossa as much as possible. This is important as it closely simulates the position of a patient undergoing surgery using the axillary approach. The skin was incised in a cross shaped manner over the axillary fossa instead of along the lateral border of the pectoralis major muscle as described in the typical axillary approach for better exposure of the area. This was due to the skin being more rigid in cadavers when compared to patients undergoing surgery. The skin was then retracted to expose the axillary space (see Figure 4-1). The underlying subcutaneous tissue was cleaned (see Figure 4-2) until the area between the latissimus dorsi muscle, subscapularis muscle and humerus could be identified along with the neurovascular structures that form the content of the axillary space (See Figure 4-3).

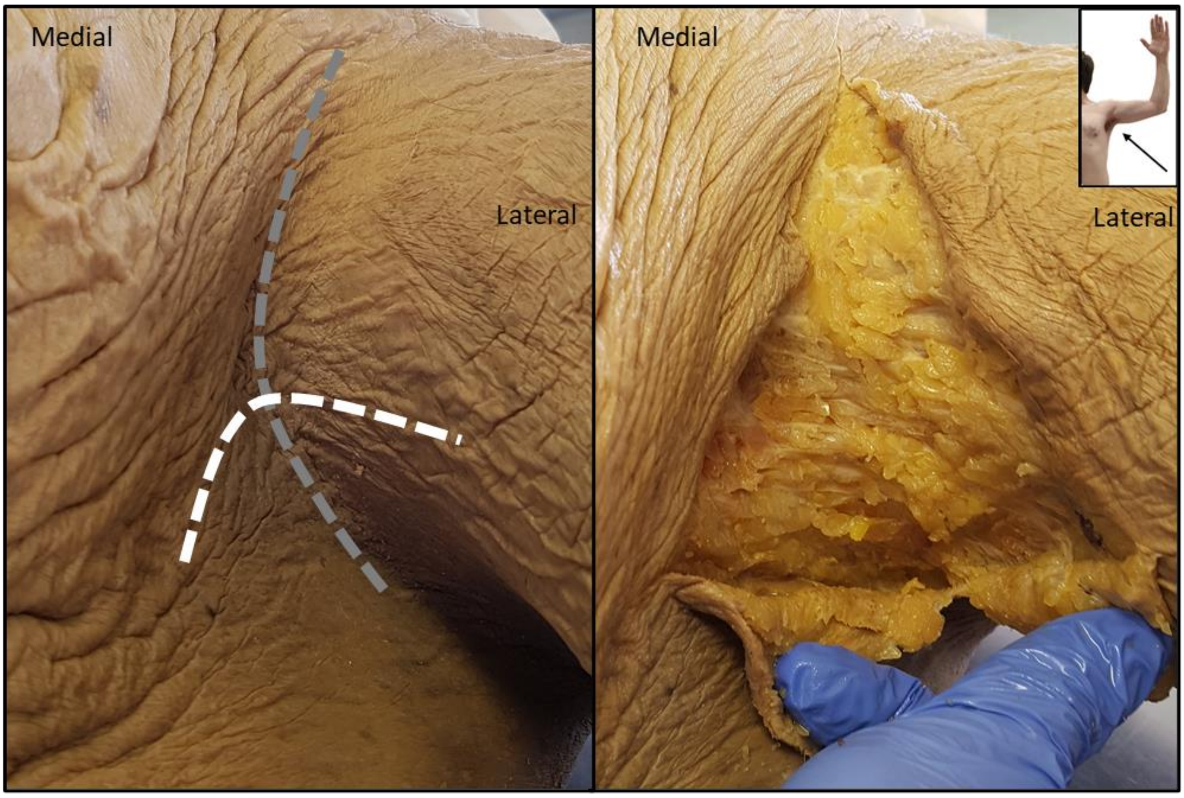

Figure 4-1: Photographs of a cadaver, showing the skin incisions made over the axillary fossa and after it has been reflected (white and grey dashed line = skin incisions).

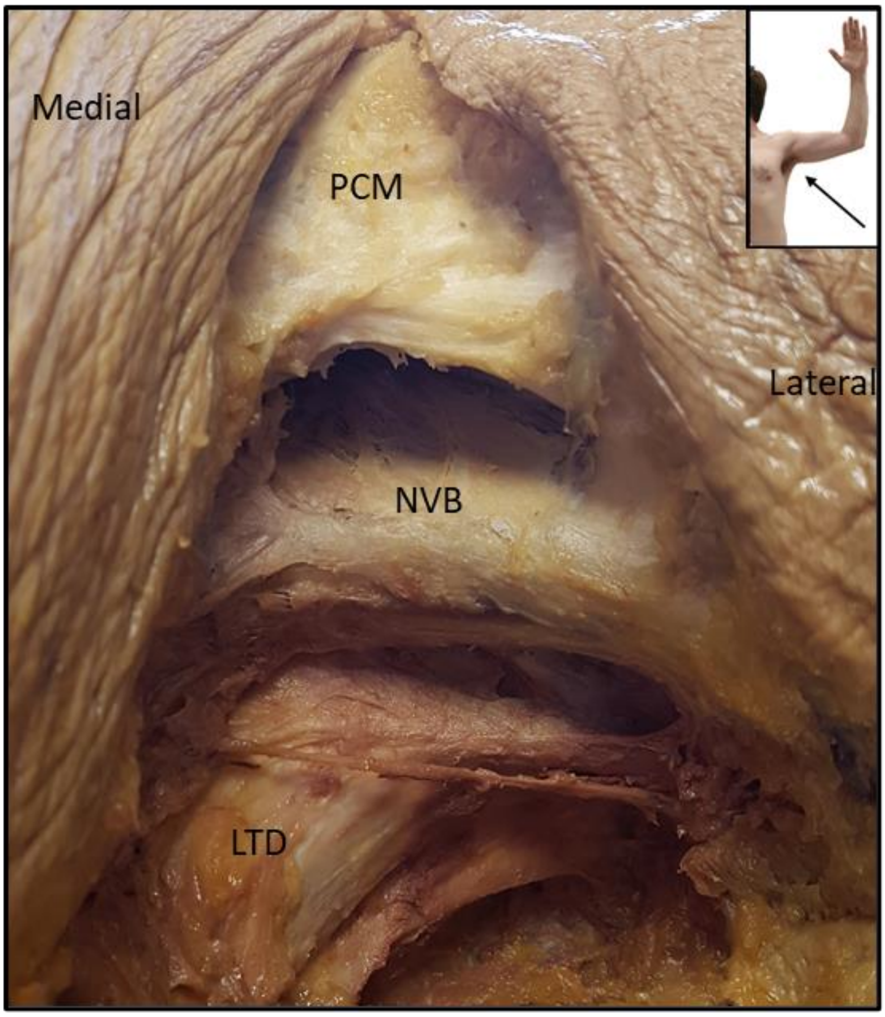

Figure 4-2: Photograph of a dissected cadaver, after subcutaneous tissue was removed, with the axillary neurovascular bundle within the axillary sheath and the tendon of the latissimus dorsi muscle visible (PCM = pectoralis major muscle; NVB = neurovascular bundle; LTD = latissimus dorsi muscle).

As with the clinical procedure, the axillary vein and pectoralis major muscle were retracted as far as necessary in order to further expose the axillary content. In cases where visibility or access was limited, only non-essential muscles or structures (the structures not used as a landmark or in close relation to the target neurovascular structures) were transected / reflected. No muscles or structures described as a landmark for the axillary approach were incised (see Figure 4-3). When required, the skin over the proximal arm was removed for better visualisation of the radial nerve and branches to the triceps brachii muscle. This was in order to allow accurate identification of the nerves and to facilitate the necessary measurements.

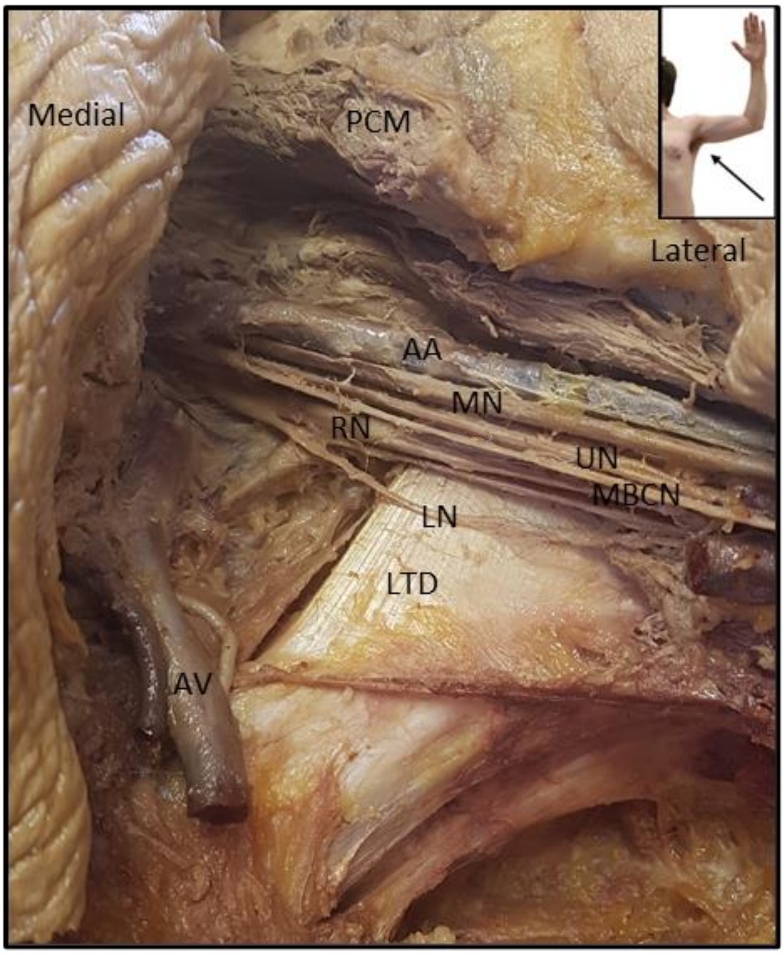

Figure 4-3: Photograph of a dissected cadaver, after the sheath surrounding the neurovascular bundle was removed and the axillary vein and pectoralis major muscle were incised for better exposure of the content within the axilla. (PCM = pectoralis major muscle; AA = axillary artery; MN = median nerve; UN = ulnar nerve; MBCN = medial brachial cutaneous nerve; RN = radial nerve; LN = nerve to the long head of triceps brachii muscle; AV = axillary vein; LTD = latissimus dorsi muscle).

4.5 Measurements and observations

After the axilla was exposed as described in the procedure section, the latissimus dorsi muscle was identified as the most anterolateral muscle in the space. Following the anteromedial border of the muscle superiorly, the terminal branches of the brachial plexus were visualised within the neurovascular sheath. The sheath was then removed for better visualisation of the structures. Continuing from this point, the nerves were traced proximally until the three cords of the brachial plexus (lateral, posterior and medial cords) were identified. The posterior cord was identified as the nerve structure posterior to the axillary vein and artery and that divided into two branches, the radial nerve continuing into the arm, and the axillary nerve that coursed towards the quadrangular space together with the posterior circumflex humeral artery (see Figure 4-4). These two nerves were used to confirm the position of the posterior cord.

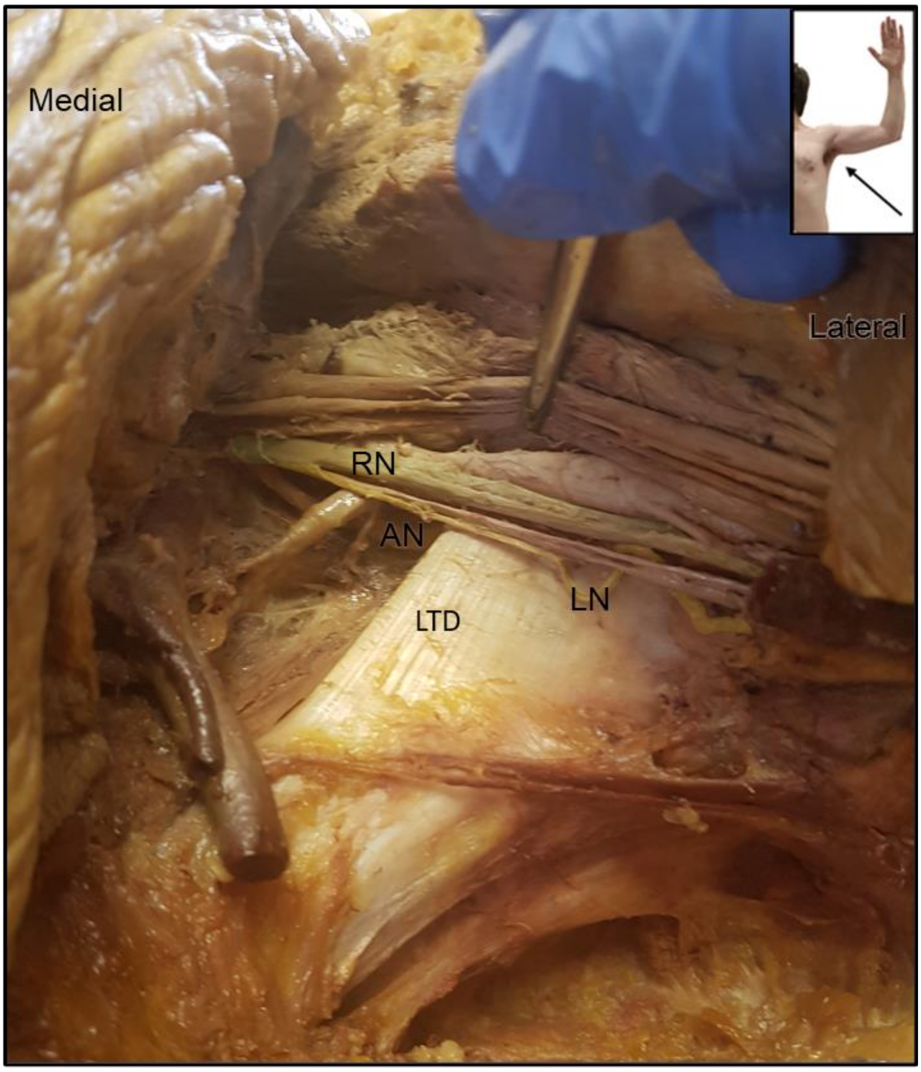

Figure 4-4: Photograph of a dissected cadaver, showing the axillary and radial nerves, as well as the nerve to the long head of triceps brachii muscle from the radial nerve (RN = radial nerve; AN = axillary nerve; LN = nerve to the long head of triceps brachii muscle; LTD = latissimus dorsi muscle).

The first step in organising the data was to separate the quantitative (measurements) and qualitative (observational) data groups from each other. Once this was done each of the two groups were then separated into their male and female data sets, which allowed the researcher to test for sex specific differences. Furthermore, the left and right sides were separated from each other in the female and male groups of the quantitative and qualitative data groups, which allowed the researcher to test for any differences between the two sides.

4.5.1 Quantitative data: measurements

Pins were placed in the structures and landmarks prior to any measurement being taken. A mechanical dial calliper with an accuracy of 0.05mm was used to take the measurement and the results were recorded into raw data sheets in Microsoft Excel (Version 1910, build 12130.20272) [Computer software] as seen in Appendix B. It must be noted that for measurements involving the origin of the nerves, the origin was considered to be in the angle formed between the branch and the continuing trunk (see Figure 4-5).

Figure 4-5: Photograph of a dissected cadaver, showing an example of where a pin would be placed in the angle, formed between the branch and the continuing trunk, which is considered the origin of a nerve for measurements (red arrow = where the pin would have been placed, yellow line = the angle formed between the nerves).

The first two measurements were 1) the distance between the anteromedial border of latissimus dorsi muscle and the origin of the axillary nerve and 2) to the nerve to the long head of triceps brachii muscle. In order to visualise the origin of the axillary nerve and nerve to the long head of triceps brachii muscle, the lateral and medial cords, as well as the axillary artery and vein were retracted to further expose the posterior cord. The point where the posterior cord splits into the radial and axillary nerves was the first pinned point A, which served as the origin of the axillary nerve (Fig 4-6). The radial nerve was then followed distally to the point where it crossed the anteromedial border of the latissimus dorsi muscle. The second pin B was placed in the radial nerve at this point to serve as the anteromedial border of the latissimus dorsi muscle (Fig 4-6). Lastly the radial nerve was followed until the nerve to the long head of the triceps brachii muscle was identified as the most proximal branch. The point where the nerve to the long head of triceps brachii muscle originates from the radial nerve was the point where the third pin C was placed (Fig 4-6). Once all three points (pin A, pin B, and pin C) were pinned, the following measurements were taken from pin A to pin B along the radial nerve, which is the distance of the axillary nerve to the anteromedial border of the latissimus dorsi muscle (A-B). Next the distance from pin B to pin C was measured along the radial nerve, which is the distance of the nerve to the long head of the triceps brachii muscle to the anteromedial border of the latissimus dorsi muscle (B-C). A negative value in the measurement indicated that the nerve to the long head of triceps brachii muscle originates distally to the latissimus dorsi muscle (pin B) (see Figure 4-6).

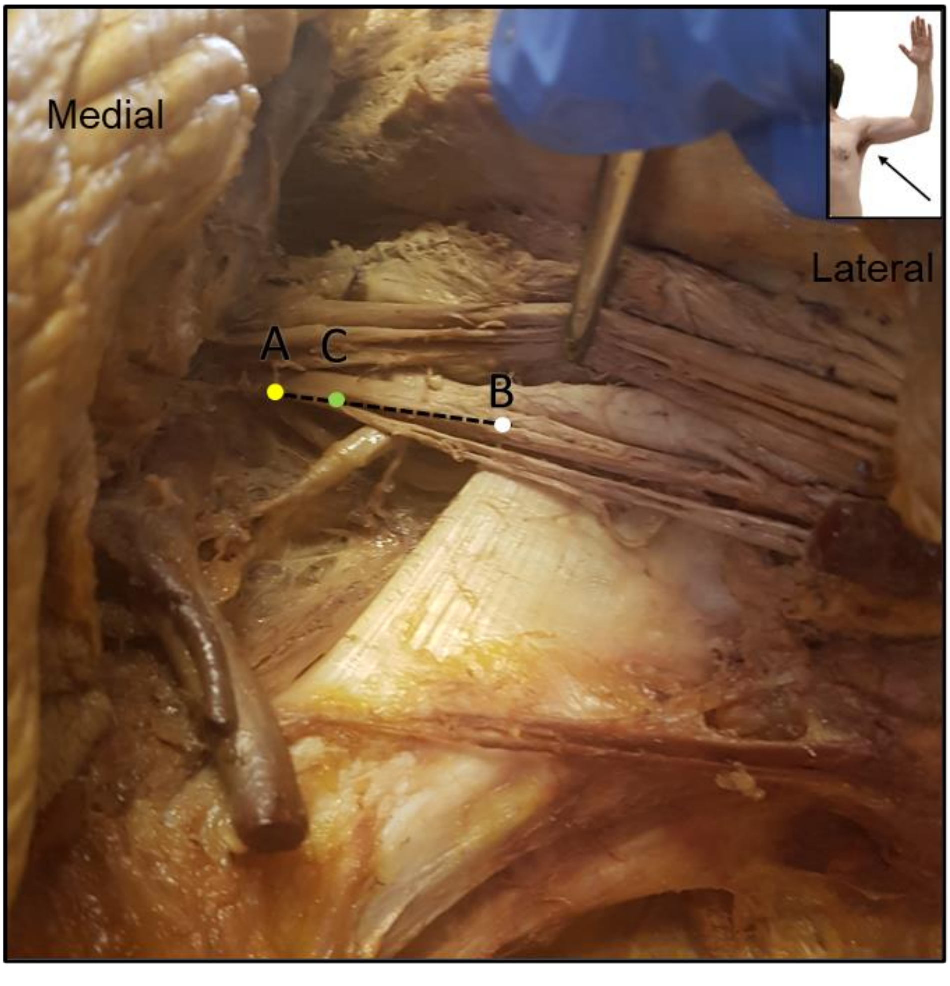

Figure 4-6: Photograph of a dissected cadaver, showing the placement of pins A, B and C for measurements A-B and B-C. (yellow point = pin A origin of the axillary nerve; green point = pin C origin of the nerve to the long head of the triceps brachii muscle; white point = pin B anteromedial border of the latissimus dorsi muscle).

The third measurement was the distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions. The axillary nerve was followed distally from its origin (pin A) to the point where it divides into its anterior and posterior divisions, pin D was placed at this point to mark the dividing point of the axillary nerve. Once both pins were placed, the distance between these pins (pin A and pin D) was measured along the axillary nerve as the length of the axillary nerve (A-D) (see Figure 4-7).

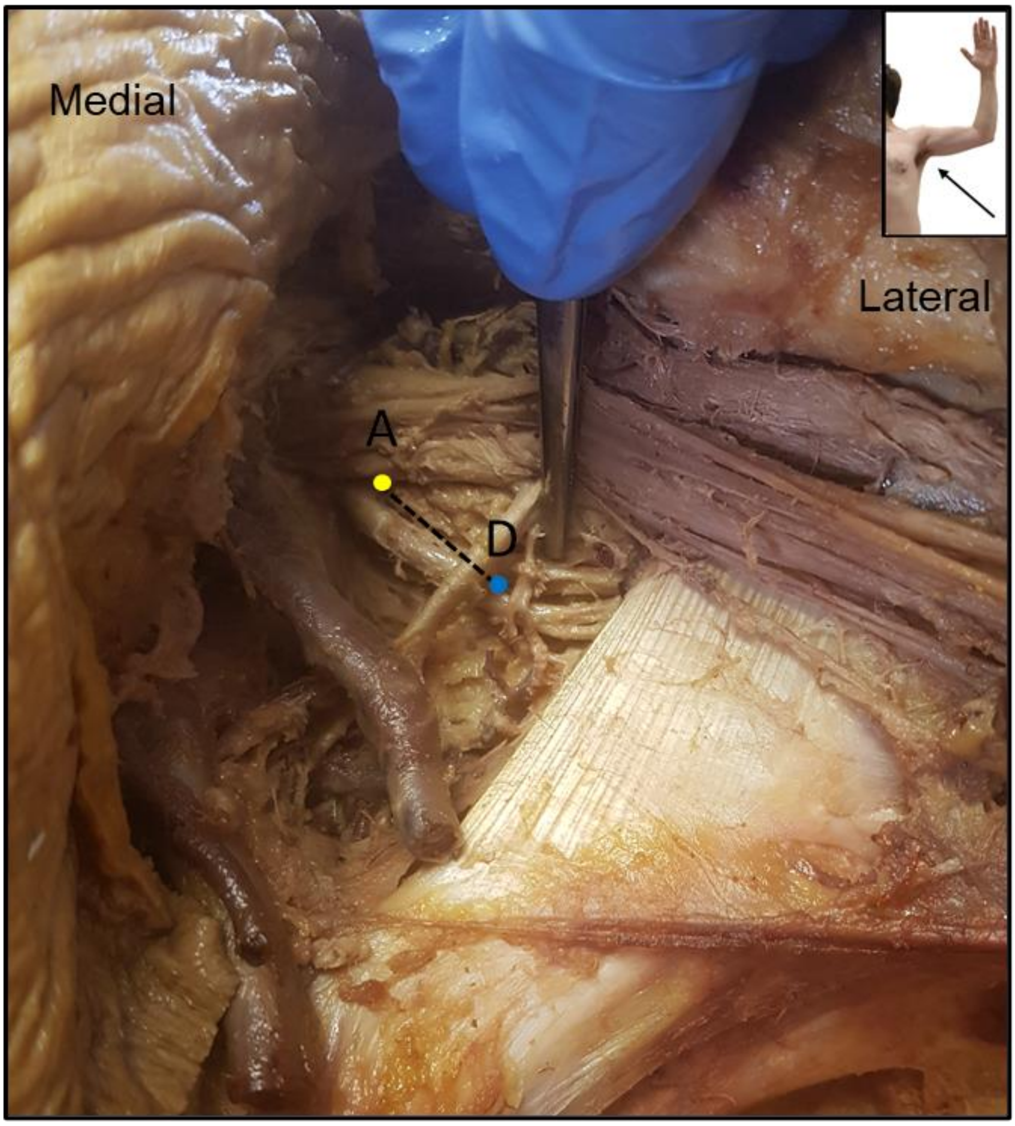

Figure 4-7: Photograph of a dissected cadaver, showing the placement of pins A and D for the measurement A-D (yellow point = pin A origin of the axillary nerve; blue point = pin D division of the axillary nerve into its anterior and posterior divisions).

The fourth measurement was the distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve. The posterior division travels to the posterior part of the deltoid muscle and gives off a nerve to the teres minor muscle, as well as the superior lateral brachial cutaneous nerve. After the identification of the division of the axillary nerve (pin D), the posterior division was followed distally from the division of the axillary nerve to the point where the nerve to the teres minor muscle can be visualised, which is the first branch and courses to the teres minor muscle. Seeing the branch entering the teres minor muscle was used to confirm the identity of the nerve. Its origin at the posterior division was marked by pin E and the distance between the two pins (D–E) was then measured (see Figure 4-8).

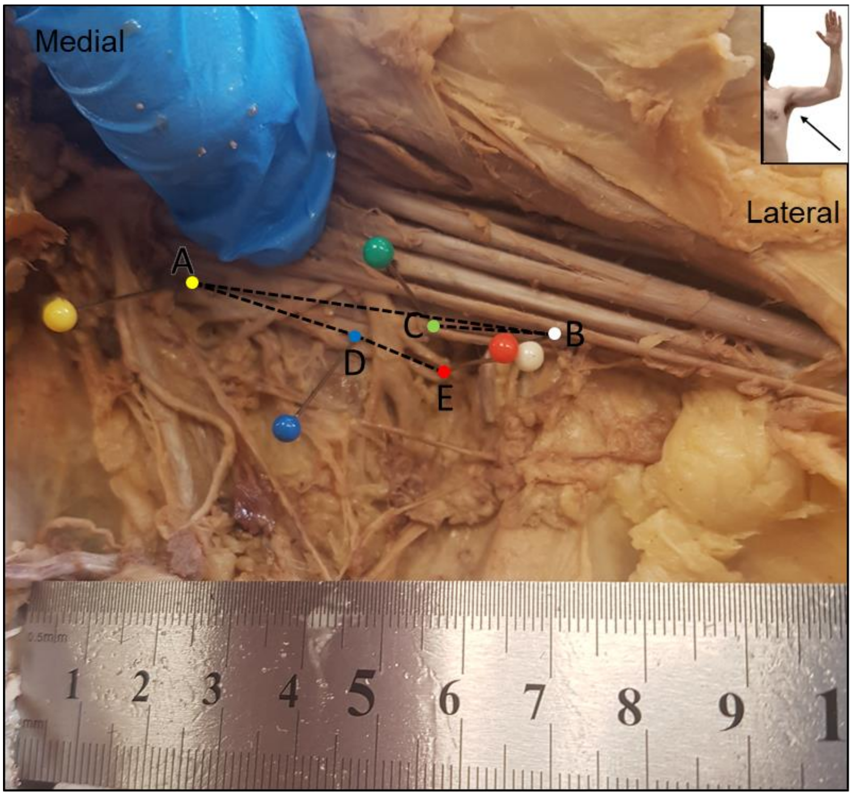

Figure 4-8: Photograph of a dissected cadaver, illustrating an example after all pins have been placed for measurements. (Yellow pin = pin A origin of the axillary nerve; blue pin = pin D division of the axillary nerve into its anterior and posterior divisions; green pin = pin C origin of the nerve to the long head of the triceps brachii muscle; red pin = pin E origin of the nerve to the teres minor muscle; white pin = pin B anteromedial border of the latissimus dorsi muscle).

There was one case where the nerve to the teres minor muscle originated proximal to the origin of the posterior division, instead originating from the axillary nerve. In this case, the measurement was recorded as a negative value (see Figure 4-9).

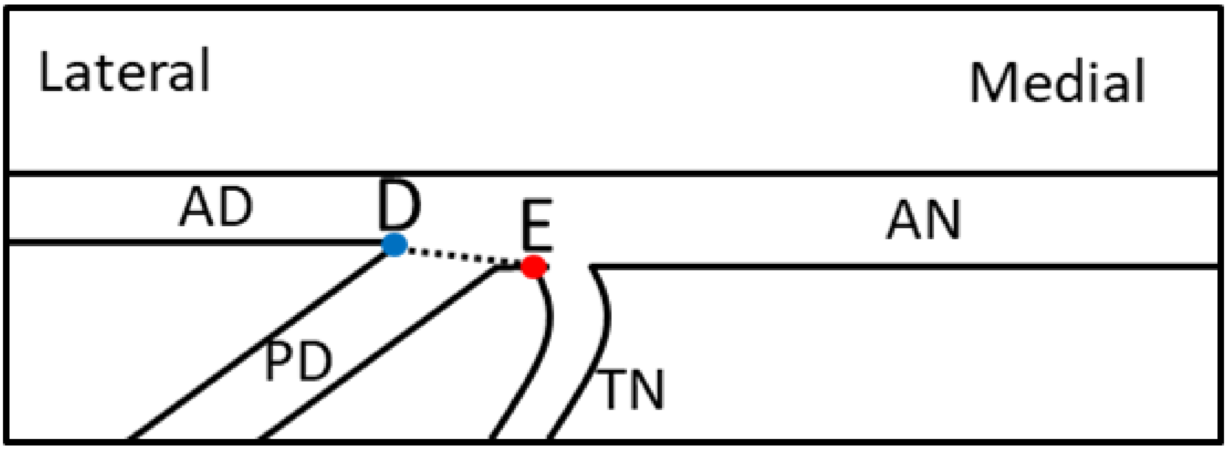

Figure 4-9:Diagram showing the variation in the origin of the nerve to the teres minor muscle, originating proximal to the origin of the posterior division of the axillary nerve. (TN = nerve to the teres minor muscle; AN = axillary nerve; AD = anterior division of axillary nerve; PD = posterior division of axillary nerve; blue point = pin D division of the axillary nerve into its anterior and posterior divisions; red point = pin E origin of the nerve to the teres minor muscle).

The next group of measurements taken included the diameter of the axillary nerve, as well as the diameter of its anterior and posterior divisions at their origin left *in situ*. After exposing the origin (pin A) and division (pin D) of the axillary nerve and recording of the measurements involving these landmarks were completed, the pins were removed to ensure that they would not obstruct any measurement being taken. Any structures obscuring the origin of the nerves were retracted where necessary.

4.5.2 Qualitative data: observations

The first observation made was to note the branching pattern of the axillary nerve into its anterior and posterior divisions in relation to the quadrangular space, as well as to observe and describe any branches from the axillary nerve. Firstly, once the axillary nerve was identified, it was followed distally from its originating point at the posterior cord (pin A) to the posterior side of the quadrangular space. It was then observed whether the axillary nerve divided into its anterior and posterior divisions (1) before entering the quadrangular space, (2) within the quadrangular space, or (3) only once it has passed through the quadrangular space (see Figure 4-10).

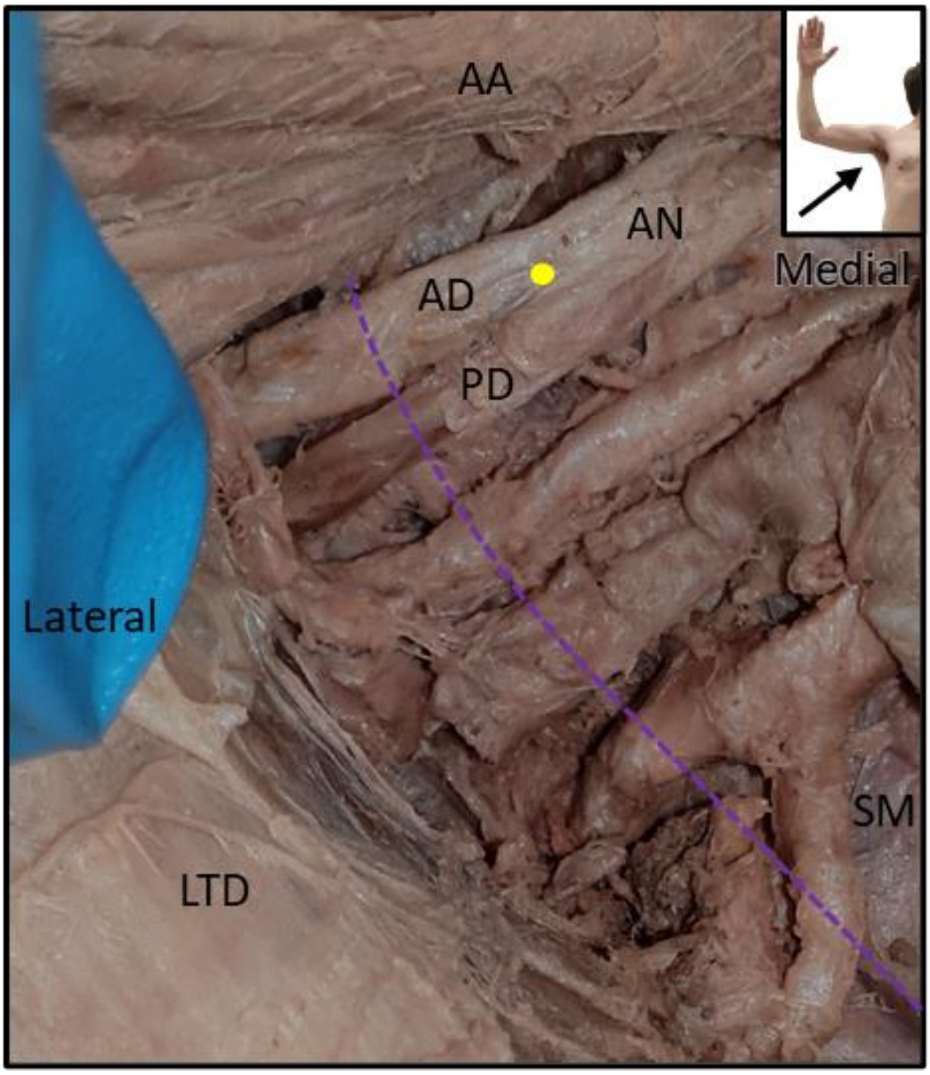

Figure 4-10: Photograph showing the axillary nerve dividing into its anterior and posterior divisions medial to the lateral border of the subscapularis muscle, indicated with the dashed line, which was considered the superior border of the quadrangular space (AA = axillary artery; AN = axillary nerve; AD = anterior division of the axillary nerve; PD = posterior division of the axillary nerve; LTD = latissimus dorsi muscle; yellow point = division of axillary nerve into its anterior and posterior divisions; SM = subscapular muscle; Purple line = lateral border of the subscapularis muscle).

As this study was designed to aid the axillary approach for nerve transfer or grafting procedures, with special regard to the axillary and radial nerves and their branches, the researcher viewed the borders of the quadrangular space from an anterior view as the axillary approach dictates. The quadrangular space was regarded as the continuation of the normal borders of the quadrangular space further anteriorly. The space between the lateral border of the subscapularis muscle, which is anterior to the teres minor muscle (superior border of the quadrangular space), the head of the humerus (lateral border of the quadrangular space), the latissimus dorsi muscle which is anterior to the teres major muscle (inferior border of the quadrangular space) and the long head of the triceps brachii muscle (medial border of the quadrangular space), was regarded as the continuation of the space. Secondly, to further achieve this objective, the number of branches the axillary nerve gave off, from its origin at the posterior cord to its division into its anterior and posterior divisions, were observed and noted.

The next objective was to evaluate the anatomical accuracy of using the musculo-arterial triangle described by Bertelli *et al*.[4] to locate the axillary nerve and its division, using an axillary approach. Bertelli and co-workers identified a triangular space between the subscapular artery (medial border of the triangle), anteromedial border of the latissimus dorsi muscle (lateral border of the triangle), and posterior circumflex humeral artery (superior border of the triangle) within which they stated that the axillary nerve can consistently be found. Each of the borders of the triangle were identified from an axillary approach. If the triangle was indeed formed and found without any anatomical variations obfuscating the triangle, then it was observed whether the axillary nerve was seen as a whole within this triangle or whether only its divisions could be found. As seen in Figure 4-11, the borders were found with the axillary nerve within the space described.

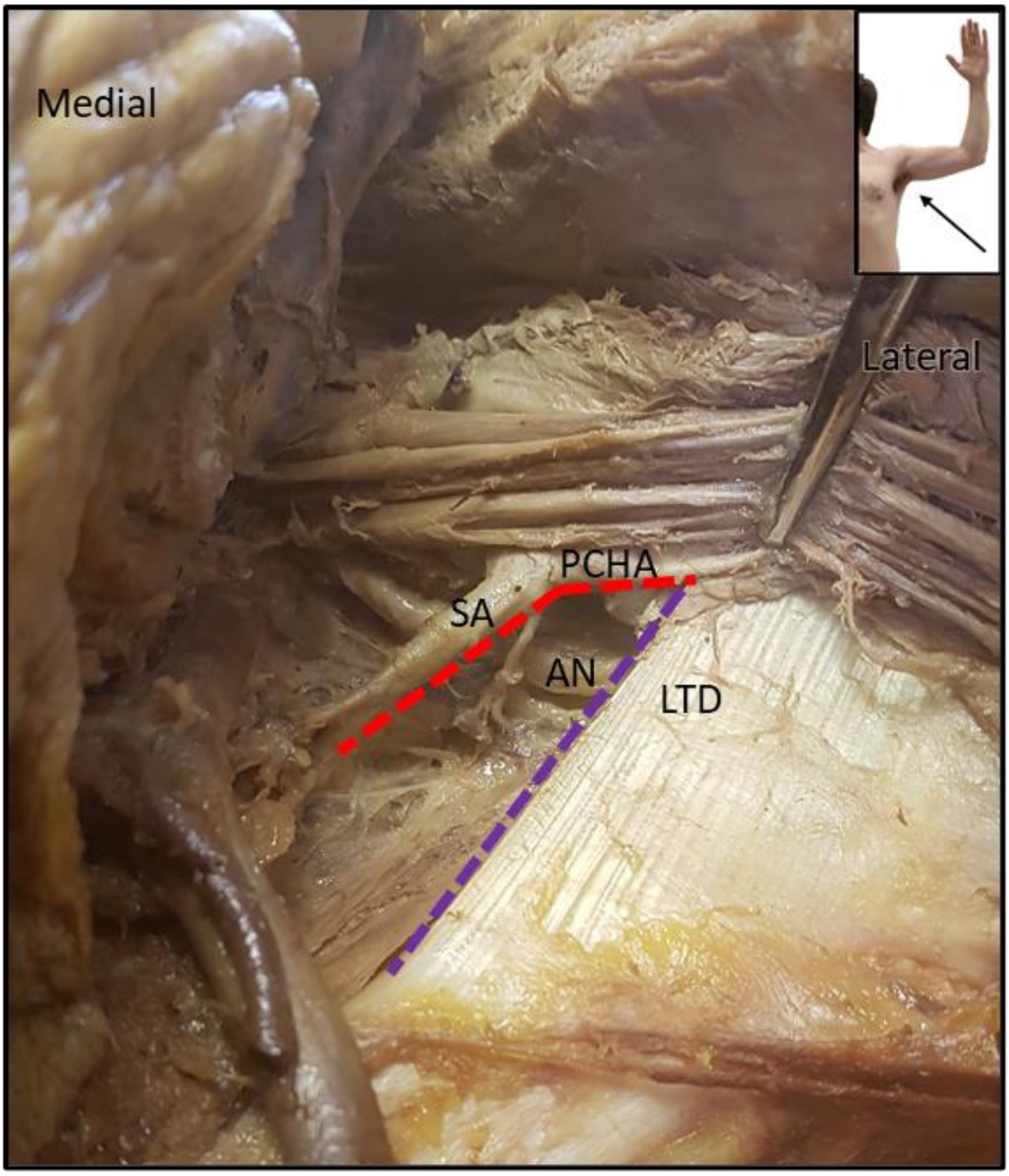

Figure 4-11: Photograph showing the axillary nerve found within the borders of the musculo-arterial "triangle" indicated by the dashed lines as described by Bertelli *et al*.[4] (SA = subscapular artery; LTD = latissimus dorsi muscle/tendon; PCHA = posterior circumflex humeral artery; AN = axillary nerve).

The results of all the measurements and observations were used to compile a comprehensive step-by-step guideline of the anatomy of the axilla and its content via the axillary approach, with special regard to the axillary and radial nerves. The step-by-step process of exposing the axilla and its content was documented by dissecting a fresh frozen axilla. In addition, both the radial and axillary nerves were followed distally from their origin at the posterior cord to the anteromedial border of the latissimus dorsi muscle, the origin of the axillary nerve was observed, whether it originated anterior, posterior, superior, inferior, medial or lateral in relation to the radial nerve. Where the axillary and radial nerve coursed, in relation to the subscapular artery and the relation of the axillary nerve to the posterior circumflex humeral artery, was also observed and recorded.

4.6 Statistical Analysis

All the recorded data in Microsoft Excel (Version 1910, build 12130.20272) [Computer Software] was imported into IBM SPSS statistics (build 1.0.0.1298) [Computer Software] and analysed for further interpretation.

The Shapiro-Wilk test for normality was used to determine if the data were normally distributed or skewed. The standardized values of the skewed quantitative data were then calculated and any outliers more than two standard deviations from the mean were removed. Descriptive statistics were used to describe the data obtained from this sample. This included the mean, median (median is only used if there is a "skewed distribution" of the collected data points), standard deviation, standard error, minimum and maximum of all the measurements and a range with a confidence interval of 95%.

Comparisons between groups/measurements (i.e. left vs right, male vs female) were made using the paired samples t-test for left vs right in males and females (or the Wilcoxon signed rank test if the difference between the paired values was not normally distributed). For the male vs female comparisons an independent samples t-test was used; except that, if the sample variances were unequal, then a Welch test was used. If the data were not normally distributed, then a Mann-Whitney-Wilcoxon rank sum test was used. The critical p-value ("alpha" or Type 1 error) for determining statistical significance was 0.05.

The strength of correlation between the collected measurements and the demographic details (age, height, weight and BMI) was made using a Pearson's correlation test (which determines the correlation coefficient or R). The Pearson's correlation coefficient test determines the strength of the correlation between dependent and independent variables. If the data were not normally distributed, did not exhibit a linear relationship on a scatterplot, or contained extreme outliers, Spearman's rank correlation coefficient, r_s, was estimated instead. In this cadaver study the dependent variables were the nerve measurements, while the independent variables were the sex, height, weight and BMI of the sample. Correlations between the different measurements (dependent variables) and the age, height, weight and BMI (independent variables) of the sample will reveal whether a positive or negative correlation exists. An R-value higher than 0.5 is considered to be a "good" correlation between variables, while a correlation higher than 0.7 is considered "very good". Only in cases where the R-value is 0.7 or higher, will a multilinear regression formula be used to show whether a trend existed between the dependent and independent variables, i.e. whether these distances increased or decreased with changes in the independent variables.

The frequencies of all the observations were determined and a Chi-square test of independence / goodness of fit was used to determine if there were any relationships between the left and right sides of females and males, respectively.

4.6.1 Inter- and intra-observer error tests

The aim of inter- and intra-observer error tests were to test the repeatability and accuracy of the measurement. An external observer performed the inter-observer error determination, without any influence from the primary investigator and tested whether the results can be reproduced by anyone trying to perform the same measurements, hence testing the repeatability. The intra-observer error determination was done by the primary investigator and determines whether, the observer is able to repeat his/her own results with accuracy. This will allow for future addition to the data sets or comparisons with other data sets. For both the inter- and intra-observer assessments, the (graphical) methods of Bland and Altman were used.[46]

4.7 Ethical considerations

The proposal for this project was first reviewed and approved by the MSc committee of the Faculty of Health Sciences, School of Medicine at the University of Pretoria. After approval was obtained, Ethical clearance (reference number: 428/2017) was obtained from the Research Ethics Committee of the Faculty of Health Sciences at the University of Pretoria (Appendix C). All dissections and cadavers were conducted under the rules and regulations given under the South African National Health Act (Act 61 of 2003).

5. Results

The data were divided into quantitative groups for all measurements and qualitative groups for all observations recorded. The quantitative data were separated into a distance group consisting of the lengths of the nerves, as well as the distances of the nerves from landmarks (measurements A-C, B-C, A-D and D-E), to obtain results that will aid in locating and identifying the target nerves for a nerve transfer or grafting procedure, using an axillary approach. The information will also be helpful in determining the length of the nerves that could possibly be transferred or grafted. The second quantitative group of measurements were the diameters of the nerves, which is important for matching size ratios in nerve grafting or transfer procedures.

The results of the qualitative data show the relations of nerves to important landmarks and also assess the accuracy of the musculo-arterial triangle described by Bertelli *et al*.[4] that could be used to aid in locating targeted nerves during nerve transfer or grafting procedures using an axillary approach.

5.1 Quantitative data

The first step in analysing the data of both the distances and diameters, was to test whether the data were distributed normally or skewed, using a Shapiro-Wilk test for normality. The skewed data were then standardized by calculating the Z-score to identify outliers, as the outliers could influence the distribution of the data. Data with a Z score of more than 2.0 or less than -2.0 were two standard deviations away from the mean and were removed.

5.1.1 Distances

A Shapiro-Wilk test for normality was performed on the distance measurements after the outliers were removed and showed that all the data in females and males were normally distributed. (See Table 5-1).

Table 5-1: Shapiro-Wilk test for normality on measurements, after outliers were removed for females and males (Stat. = statistic; df = degrees of freedom).

	Females			Males		
	Stat.	df	p-value	Stat.	df	p-value
Left A-B	.97	21	.73	.94	23	.21
Right A-B	.97	21	.67	.96	23	.41
Left B-C	.96	21	.45	.95	23	.29
Right B-C	.94	21	.23	.92	23	.07
Left A-D	.98	21	.87	.92	23	.07
Right A-D	.95	21	.31	.96	23	.52
Left D-E	.96	21	.59	.93	23	.10
Right D-E	.92	21	.08	.96	23	.52

Key	Description
A-B	The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.
B-C	The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.
A-D	The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.
D-E	The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.

Since all data were normally distributed, a paired samples t-test was used to compare the left and right sides for any significant differences in females and males. The results of the paired samples t-test showed no significant differences for the measurements, which allowed for the combining of the left- and right sided measurements in both male and female groups (See Table 5-2).

Table 5-2: Paired samples t-test on measurements between left and right sides in females and males (Stat. = statistic; df = degrees of freedom).

	Females			Males		
	Stat. t	df	p-value (2-tailed)	Stat. t	df	p-value (2-tailed)
Left vs right A-B	.11	21	.91	.37	24	.72
Left vs right B-C	1.77	20	.09	.32	22	.75
Left vs right A-D	-1.40	21	.18	.99	24	.33
Left vs right D-E	.45	21	.66	-1.41	24	.17

Key	Description
A-B	The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.
B-C	The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.
A-D	The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.
D-E	The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.

Another Shapiro-Wilk test for normality was performed to see the distribution of the combined larger data sets for females and males. The results showed that all distance measurements were still normally distributed.

A Levene's Test for equality of variances was performed between the combined female and male groups to see if equal variances can be assumed. It was found that in all the cases, the null hypothesis of equal variances could be accepted. An independent samples t-test, assuming equal variances, was then performed between the female and male measurements to test for sex specific differences. The results of the independent samples t-test showed that all distance measurements had no significant difference between males and females, except in the measurement of the distance from the division of the axillary nerve, to the point where the nerve to the teres minor muscle originates (measurement D-E) with a p-value of 0.04, which is less than the chosen critical p-value of 0.05 (see Table 5-3). The other three measurements were then combined into a total sample consisting of both female and male measurements.

Table 5-3: Independent samples t-test on measurements, after combining left and right sides in females and males (Stat. = statistic; df = degrees of freedom; Mean diff. = mean difference; Std. error diff. = standard error difference; 95% CI diff. = 95% confidence interval difference).

	Stat. t	**df**	**p-value (2-tailed)**	**Mean diff.**	**Std. error diff.**	**95% CI diff.**	
						Lower	Upper
Female vs male A-B	1.07	96	.29	2.32	2.16	-1.97	6.61
Female vs male B-C	.50	93	.62	.84	1.68	-2.49	4.17
Female vs male A-D	-.54	96	.59	-1.04	1.94	-4.89	2.81
Female vs male D-E	2.09	96	.04	1.22	.58	.06	2.38

Key	Description
A-B	The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.
B-C	The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.
A-D	The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.
D-E	The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.

To see the distribution of the data for the distance measurements that were combined, a Shapiro-Wilk test for normality was performed on each measurement and found that all the data were normally distributed. This allows for comparison with future studies using the means and standard deviations as an accurate description of the data (see Table 5-4).

Table 5-4: Shapiro-Wilk test for normality on measurements after combining males and females (Stat. = statistic; df = Degrees of Freedom).

	Stat.	df	p-value
Total A-B	.98	95	.18
Total B-C	.98	95	.11
Total A-D	.98	95	.20

Key	Description
A-B	The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.
B-C	The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.
A-D	The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.

The descriptive statistics of the final total combined samples for the four distance measurements are shown in Table 5-5. As all data were normally distributed, only the mean and 95% confidence interval are shown as an accurate description of the data and not the median with the interquartile range.

Table 5-5: Descriptive statistics for all combined distance of measurements in mm (n = number of individuals, Stat. = statistic; Std. error = standard error, SD = standard deviation, Min = minimum; Max = maximum; 95% CI = 95% confidence interval).

	n	Mean		SD	Min	Max	Range	95% CI	
		Stat.	Std. error					Lower	Upper
Total A-B	98	62.33	1.08	10.70	31.72	81.90	50.18	59.90	64.28
Total B-C	95	18.68	.84	8.14	-5.98	39.82	45.80	17.02	20.34
Total A-D	98	38.76	.97	9.57	18.64	70.29	51.65	36.95	40.85
Female D-E	48	6.19	.43	3.00	-3.28	13.10	16.38	5.32	7.06
Male D-E	50	7.41	.39	2.78	2.90	15.52	12.62	6.62	8.20

Key	Description
A-B	The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.
B-C	The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.
A-D	The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.
D-E	The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.

Due to the data being normally distributed, a Pearson's correlation coefficient test was used to test the strength of correlation between the dependent variables (A-B, B-C, A-D and female D-E and male D-E) and the independent variables (age, height, weight and BMI). An R-value higher than 0.5 was considered to be a "good" correlation between variables, while a correlation higher than 0.7 was considered "very good". However, Pearson's correlation coefficient test revealed no correlations of note between the dependent and independent variables.

5.1.2 Diameters

A Shapiro-Wilk test for normality was performed on the diameter measurements after the outliers were removed and showed that all the data in females and males were normally distributed. Except for the measurement of the diameter of the anterior division of the axillary nerve on the right side in females (Right Dia AD) with a p-value of 0.03 (see Table 5-6).

Table 5-6: Shapiro-Wilk test for normality on diameters after outliers were removed for females and males (Stat. = statistic; df = degrees of freedom).

	Females			**Males**		
	Stat.	df	p-value	Stat.	df	p-value
Left Dia AN	.97	19	.81	.98	23	.90
Right Dia AN	.95	19	.35	.95	23	.27
Left Dia AD	.93	19	.18	.94	23	.14
Right Dia AD	.89	19	.03	.95	23	.24
Left Dia PD	.93	19	.20	.94	23	.15
Right Dia PD	.94	19	.23	.98	23	.93

Key	Description
Dia AN	Diameter of the axillary nerve at its origin.
Dia AD	Diameter of the anterior division of the axillary nerve at its origin.
Dia PD	Diameter of the posterior division of the axillary nerve at its origin.

The left and right sides of the females and males were compared using a paired samples t-test for the normally distributed data (see Table 5-7). For the skewed data, a Wilcoxon Signed Rank test was used to compare the left and right diameters of the anterior division of the axillary nerve in females, which shows the negative, positive and tied ranks associated between the two measurement. The results showed no significant differences in most of the measurements, except for the comparisons of the left and right sided measurements of the diameter of the axillary nerve in females (left vs right Dia AN) with a p value of 0.04. The Wilcoxon Signed Rank test revealed a significant difference between the left and right sided measurements of the diameter of the anterior division of the axillary nerve (left vs right Dia AD) in females, with a p-value of 0.02. The data that were not significantly different, were combined into total female and total male samples, consisting of the combined left and right sides.

Table 5-7: Paired samples t-test on diameters between left and right sides in females and males (Stat. = statistic; df = degrees of freedom).

	Females			Males		
	Stat. t	df	p-value	Stat. t	df	p-value
Left vs right Dia AN	-2.26	21	.04	-1.06	22	.30
Left vs right Dia AD				.26	24	.80
Left vs right Dia PD	1.09	18	.29	1.97	24	.06

Key	Description
Dia AN	Diameter of the axillary nerve at its origin.
Dia AD	Diameter of the anterior division of the axillary nerve at its origin.
Dia PD	Diameter of the posterior division of the axillary nerve at its origin.

A Shapiro-Wilk test for normality was performed to see the distribution of the combined larger data sets. The results showed that all diameter measurements were normally distributed, except for the measurement of the diameter of the axillary nerve in males (male DIA AN). (See Table 5-8).

Table 5-8: Shapiro-Wilk test for normality on diameters after combining left and right sides in females and males (Stat. = statistic; df = degrees of freedom).

	Stat.	df	p-Value
Female Dia PD	.96	45	.09
Male Dia AN	.93	48	.01
Male Dia AD	.97	48	.36
Male Dia PD	.98	48	.40

Key	Description
Dia AN	Diameter of the axillary nerve at its origin.
Dia AD	Diameter of the anterior division of the axillary nerve at its origin.
Dia PD	Diameter of the posterior division of the axillary nerve at its origin.

Levene’s Test for equality of variances was performed for the measurements of the female and male diameter of the posterior division of the axillary nerve to see if equal variances can be assumed. It was found that the null hypothesis of equal variances could be accepted. An independent samples t-test assuming equal variances was then performed between the female and male measurement of the diameter of the posterior division of the axillary nerve, to test for sex specific differences and found there to be no significant difference with a p-value of 0.22. The data were then combined into a total sample consisting of both male and female measurements.

To see the distribution for the combined data of the measurement of the diameter of the posterior division of the axillary nerve, a Shapiro-Wilk test for normality was performed and found that the data were normally distributed. This allows for comparison to future studies using the means and standard deviations as an accurate description of the data.

The descriptive statistics of the final total combined samples for the different diameter measurements are shown in Table 5-9. In cases where the data were normally distributed the mean and 95% confidence interval are shown, whereas for the skewed data the median with the interquartile range are given, as accurate descriptions of the data in this sample.

Table 5-9: Descriptive statistics for all combined diameters (n = number of individuals, Stat. = statistic; Std. error = standard error, SD = standard deviation, Min = minimum; Max = maximum; IQR = Interquartile range, 95% CI = 95% confidence interval).

	n	Mean		SD	Min	Max	Range	Median	IQR	95% CI	
		Stat.	Std. error							Lower	Upper
Female left Dia AN	24	3.67	.16	.79	2.18	5.12	2.94			3.20	3.89
Female right Dia AN	24	4.05	.18	.89	2.29	5.60	3.31			3.57	4.51
Female left Dia AD	24	2.76	.12	.61	1.85	3.82	1.97			2.42	2.99
Female right Dia AD	24			.74	2.28	5.10	2.82	2.86	1.09		
Male Dia AN	48			.85	2.82	7.15	4.33	4.23	0.95		
Male Dia AD	50	2.90	.11	.81	1.48	4.84	3.36			2.66	3.13
Total Dia PD	95	2.59	.07	.67	1.18	4.18	3.00			2.46	2.72

Key	Description
Dia AN	Diameter of the axillary nerve at its origin.
Dia AD	Diameter of the anterior division of the axillary nerve at its origin.
Dia PD	Diameter of the posterior division of the axillary nerve at its origin.

The Pearson's correlation coefficient test revealed no correlations of note between the dependent and independent variables for the normally distributed data. Similarly, the Spearman's rank correlation coefficient, r_s, was estimated for all skewed data and also revealed no correlations of note.

5.2 Qualitative data

A Chi square test of independence / goodness of fit was performed between the left and right sides in females and males for all observations. All left and right sides were found to be associated with each other ($p > 0.05$) and therefore were combined into total female and male groups. The same test was performed between females and males for all observations and found that only the observations between female and male number of lower and upper subscapular branches were significantly different, with a p value of 0.02.

Table 5-10 outlines the combined female and male observed frequencies of the axillary nerve dividing into its anterior and posterior divisions in relation to the quadrangular space either before, within or after the quadrangular space.

Table 5-10: Frequency table of the dividing location of the axillary nerve in relation to the quadrangular space (QS = Quadrangular Space).

	Frequency	Percent
Before QS	47	48.0
Inside QS	51	52.0
After QS	0	0.0
Total	98	100.0

Table 5-11 outlines the combined observed frequencies of the number of branches, originating from the axillary nerve, between its origin and division into the anterior and posterior divisions. The articular branch/es were classified as one or more branches coursing superiorly to the shoulder joint. Usually the lower and upper subscapular nerves would branch from the posterior cord and travel towards, amongst others, the subscapular muscle.[17] Variation of this branching pattern could result in either the lower subscapular nerve or both the lower and upper subscapular nerves to branch from the axillary nerve. If present, this variable branching patterns were observed and noted.

Table 5-11: Frequency table of the number of branches from the axillary nerves' origin to its division.

	Articular branches		**Lower and upper subscapular nerves**			
			Female		Male	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
0 Branches	32	32.7	21	43.8	11	22.0
1 Branch	65	66.3	19	39.6	19	38.0
2 Branches	1	1.0	8	16.7	20	40.0
Total	98	100.0	48	100.0	50	100.0

Table 5-12 outlines the combined female and male observed frequencies of the axillary nerve in relation to the musculo-arterial triangle described by Bertelli *et al*.[4] when viewed from an axillary approach. Observations included: the axillary nerve and/or both its anterior and posterior divisions being found within the triangle, this included cases where the borders were not found in a specific triangular shape, but the axillary nerve was still visible within them. The axillary nerve was found within the triangle in most of the cases (59 of 98 axillae - 60.2%). Further observations were made when neither the axillary nerve nor its anterior and posterior divisions were found within the triangle as seen in 18 of 98 axillae (18.4%), as well as when either the anterior or posterior division of the axillary nerve was found within the triangle as seen in 7 of 98 axillae (7.1%). Finally, “No triangle” indicates the musculo-arterial triangle did not form properly due to one of the borders being mispositioned. This was due to variation in the origin of the subscapular artery being proximal at the axillary artery or the posterior circumflex humeral artery originating from the subscapular artery, which in total was seen in 14 of 98 axillae (14.3%).

Table 5-12: Frequency table of the axillary nerve found within the musculo-arterial triangle as described by Bertelli *et al*.[4] (AN = Axillary nerve).

	Frequency	Percent
AN in triangle	59	60.2
AN not in triangle	18	18.4
Either division in triangle	7	7.1
No triangle	14	14.3
Total	98	100.0

Table 5-13 outlines the combined female and male observational frequencies of the axillary nerve, radial nerve, subscapular artery and posterior circumflex humeral artery in relation to each other. AN-RN indicates where the axillary nerve originated in relation to the radial nerve. AN-SA and RN-SA shows where the axillary and radial nerves were found in relation to the subscapular artery during their course over the subscapularis muscle. AN-PNCHA shows the relation of the axillary nerve to the posterior circumflex humeral artery.

Table 5-13: Frequency table of the relations observed between the axillary and radial nerves and the subscapular and posterior circumflex humeral arteries. (AN-RN = relation of the axillary nerves' origin to the radial nerve, AN-SA = relation of the axillary nerve to the subscapular artery, RN-SA = relation of the radial nerve to the subscapular artery, AN-PCHA = relation of the axillary nerve to the posterior circumflex humeral artery).

	AN-RN		**AN-SA**		**RN-SA**		**AN-PCHA**	
	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Anterior	2	2.2	0	0	64	65.3	0	0
Posterior	29	32.6	79	80.6	30	30.6	0	0
Superior	42	47.2	18	18.4	4	4.1	12	12.2
Inferior	16	18.0	0	0	0	0	61	62.2
Medial	0	0	1	1.0	0	0	25	25.6
Lateral	0	0	0	0	0	0	0	0
Total	89	100	98	100	98	100	98	100

Key	**Description**
AN-RN	**Origin of the axillary nerve in relation to the radial nerve.**
AN-SA	**Axillary nerve course in relation to the subscapular artery.**
RN-SA	**Radial nerve course in relation to the subscapular artery.**
AN-PCHA	**Axillary nerve course in relation to the posterior circumflex humeral artery**

5.3 Inter- and intra-observer tests

Table 5-14 outlines the statistics that were used to perform the Bland and Altman's graphical method to test the inter-observer repeatability. Most of the mean differences for the different measurements were very close to zero, indicating there is a small difference between the results of this studies' investigator and that of another investigator, proving good repeatability of the results. Even when comparing the mean differences to the overall range of the means the differences are not large enough to have any significant clinical impact. The graphs used for the inter-observer tests are shown in Appendix D.1.

Table 5-14: Showing the summary of the Bland and Altman statistics used for the inter-observer tests for the different measurements (Stat. = statistic; std. error = standard error; 95% CI = 95% confidence interval; SD = standard deviation; Min = minimum; Max = maximum).

	Differences							Mean	
	Mean		95% CI for mean		SD	Limit of Agreement		Range	
	Stat.	Std. error	Lower	Upper		Lower	Upper	Min	Max
DIFF. A-B	0,36	2,69	-5,72	6,43	8,50	-16,30	17,01	53,35	72,64
DIFF.B-C	-1,24	1,65	-4,96	2,49	5,21	-11,45	8,98	10,35	33,53
DIFF.A-D	-0,22	1,04	-2,56	2,13	3,28	-6,64	6,21	31,66	57,50
DIFF.D-E	-1,90	0,93	-4,01	0,22	2,95	-7,68	3,89	4,17	8,81
DIA AN	0,41	0,18	0,00	0,83	0,58	-0,72	1,55	1,94	3,58
DIA AD	0,46	0,20	0,00	0,92	0,64	-0,80	1,72	1,72	3,52
DIA PD	0,13	0,22	-0,37	0,64	0,71	-1,25	1,52	2,55	5,72

Key	Description
A-B	The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.
B-C	The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.
A-D	The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.
D-E	The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.
Dia AN	Diameter of the axillary nerve at its origin.
Dia AD	Diameter of the anterior division of the axillary nerve at its origin.
Dia PD	Diameter of the posterior division of the axillary nerve at its origin.

Table 5-15 outlines the same statistics, which were used to perform the Bland and Altman's graphical method but this time to test for the intra-observer repeatability. Most of the mean differences for the different measurements were very close to zero (mean measurements less than 1mm), indicating there is only a small difference between the results of this studies' investigator and the same investigator at a later stage. This is an indication of good accuracy of the measurements. The graphs used for the intra-observer tests are shown in Appendix D.2.

Table 5-15: Showing the summary of the Bland and Altman statistics used for the intra-observer tests for the different measurements (Stat. = statistic; std. error = standard error; 95% CI = 95% confidence interval; SD = standard deviation; Min = minimum; Max = maximum).

	Differences								**Mean**	
	Mean		**95% CI for mean**		**SD**	**Limit of Agreement**			**Range**	
	Stat.	Std. error	Lower	Upper		Lower	Upper		Min	Max
DIFF A-B	-0,72	0,62	-2,12	0,68	1,95	-4,55	3,11		53,10	72,63
DIFF. B-C	0,37	2,06	-4,30	5,04	6,52	-12,42	13,16		11,07	35,47
DIFF. A-D	0,10	0,54	-1,13	1,33	1,72	-3,27	3,47		30,42	56,78
DIFF. D-E	-2,10	0,79	-3,89	-0,31	2,50	-7,01	2,80		4,61	9,21
DIA AN	-0,42	0,40	-1,33	0,49	1,27	-2,91	2,08		2,82	6,00
DIA AD	0,24	0,17	-0,15	0,64	0,55	-0,84	1,32		2,12	4,00
DIA PD	0,18	0,34	-0,59	0,96	1,08	-1,94	2,30		1,48	4,36

Key	Description
A-B	The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.
B-C	The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.
A-D	The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.
D-E	The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.
Dia AN	Diameter of the axillary nerve at its origin.
Dia AD	Diameter of the anterior division of the axillary nerve at its origin.
Dia PD	Diameter of the posterior division of the axillary nerve at its origin.

In both cases (inter- and intra-observer error tests) the distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle (measurement D-E) was seen to be less repeatable or accurate than the other measurements. The measurement differed on average by 1.9mm (range between 4.2mm and 8.8mm) for the inter-observer error test and 2.1mm (range between 4.6mm and 9.2mm) for the intra-observer error test.

A possible reason for this result could be the fact that embalmed cadavers were used in this study and the rigidity of the muscles affected access to this nerve specifically. Even though the exact distance of the measurement has a lower reliability or accuracy score compared to the other measurements, the overall small distance of this measurement would not affect the primary goal of this study, which was to evaluate the feasibility of using the axillary approach to successfully visualise and isolate the target nerves. Despite the variability of the measurement between the division of the axillary nerve and the origin of the nerve to the teres minor muscle (measurement D-E), it could still be reliably found using this approach. For future consideration the nerve to the teres minor muscle could be examined in a sample of fresh frozen cadavers, which would simulate a living patient more accurately and make the measurement of the distance between the division of the axillary nerve and the origin of the nerve to the teres minor muscle easier – and therefore more repeatable and accurate. Another alternative method of accurately measuring this distance could be to transect the latissimus dorsi muscle in formalin fixed cadavers for better visualisation of the nerve to the teres minor muscle from its origin to its termination in the teres minor muscle. This however was not considered for this study as it would have meant sacrificing an important landmark used to identify the target nerves when using the axillary approach.

6. Discussion

6.1 Anatomical Findings

There is a need for anatomical descriptions related to surgical procedures, since a solid and specific knowledge of the anatomy often form the basis for performing these procedures successfully and with the least amount of complications as possible.[47] Even though numerous studies describe the axillary nerve in relation to sets of predefined landmarks,[6] the landmarks chosen are not necessarily relevant to the axillary approach. This study was therefore designed to aid in locating and identifying the axillary and radial nerves, with their branches, using the axillary approach. Various measurements were recorded in this study, including the lengths, diameters and the distances from landmarks to target nerves. Observations were also recorded to help describe the position or course of these nerves in relation to other anatomical structures. The results could aid surgeons during nerve transfer or grafting procedures using these nerves.

For nerve transfer or grafting surgeries using the axillary approach, the anteromedial border of the latissimus dorsi muscle is one of the first large structures that are palpable and visible in close relation to the axillary and radial nerves. This means that the latissimus dorsi muscle could be used as a suitable landmark for the identification of the axillary and radial nerves, as well as their branches. This study found that the origin of the axillary nerve was around 62.3±10.7mm (mean±SD) from the anteromedial border of the latissimus dorsi muscle. However, this measurement demonstrated a wide range for the study sample, ranging between 31.7mm and 81.9mm. In the study conducted by Bertelli *et al*.[4], the authors found the same measurement to be approximately 49.6mm (mean) with a similar wide range from 28.2mm to 70mm. The difference in these studies, albeit small, could be due to Bertelli *et al*.[4] only dissecting 20 axillae of unknown sex, compared to 98 axillae (from both females and males) used in the current study. Even though the proximal part of the axillary nerve is difficult to reach through the axillary approach, this distance can still be helpful for surgeons making decisions involving the tension on the suture between nerves, which plays a critical role in recovery,[26] or the length of the nerve that can be used in nerve transfer or grafting procedures. Considering Bertelli *et al*.[4] recommended using a combined anterior (deltopectoral) and axillary approach instead of a posterior approach, for nerve injuries repaired through nerve grafting, makes knowledge of the proximal part of the axillary nerve more relevant when a combined approach is used.

The nerve branching from the radial nerve to the long head of triceps brachii muscle was found to originate about 18.7±8.1mm from the anteromedial border of the latissimus dorsi muscle and showed an exceptionally wide range of between 6.0mm (distal to latissimus dorsi muscle) and 39.8mm (medial to latissimus dorsi muscle). The study by Bertelli *et al*.[48] reliably found the nerve to the long head of triceps brachii muscle from the radial nerve within the axilla, and the authors reported a length of 31.6mm with a significantly smaller range of between 21mm and 38mm from the distal border of the teres major muscle to its termination in the triceps brachii muscle if compared to the range reported in the current study. Witoonchart *et al*.[21] reported the length of the nerve to the long head of triceps brachii muscle from its origin at the radial nerve to its termination into the triceps brachii muscle to be 68.5mm with a range between 30mm and 110mm. The differences between the results of these studies can be assigned to the measurements being taken from different landmarks. Each of these measurements add a different variable to the knowledge pool surrounding the nerve, with this study focusing on aiding in finding the nerve to the long head of triceps brachii muscle using an axillary approach and using the latissimus dorsi muscle as landmark. In a diagram shown by Bertelli *et al*.[4], it is clear that the nerve transfer they performed, between the nerve to the long head of triceps brachii muscle to the anterior, middle and teres minor branches of the axillary nerve, is performed in close relation to the latissimus dorsi muscle (see Figure 6-1). The current study reliably found the nerve to the long head of triceps brachii muscle in close proximity to the latissimus dorsi muscle, allowing for it to be readily accessible through the axillary approach, which supports its selection as a possible donor or recipient nerve, in nerve transfer or grafting procedures utilizing the axillary approach. This is in support of the conclusions made by Bertelli and co-workers.[48]

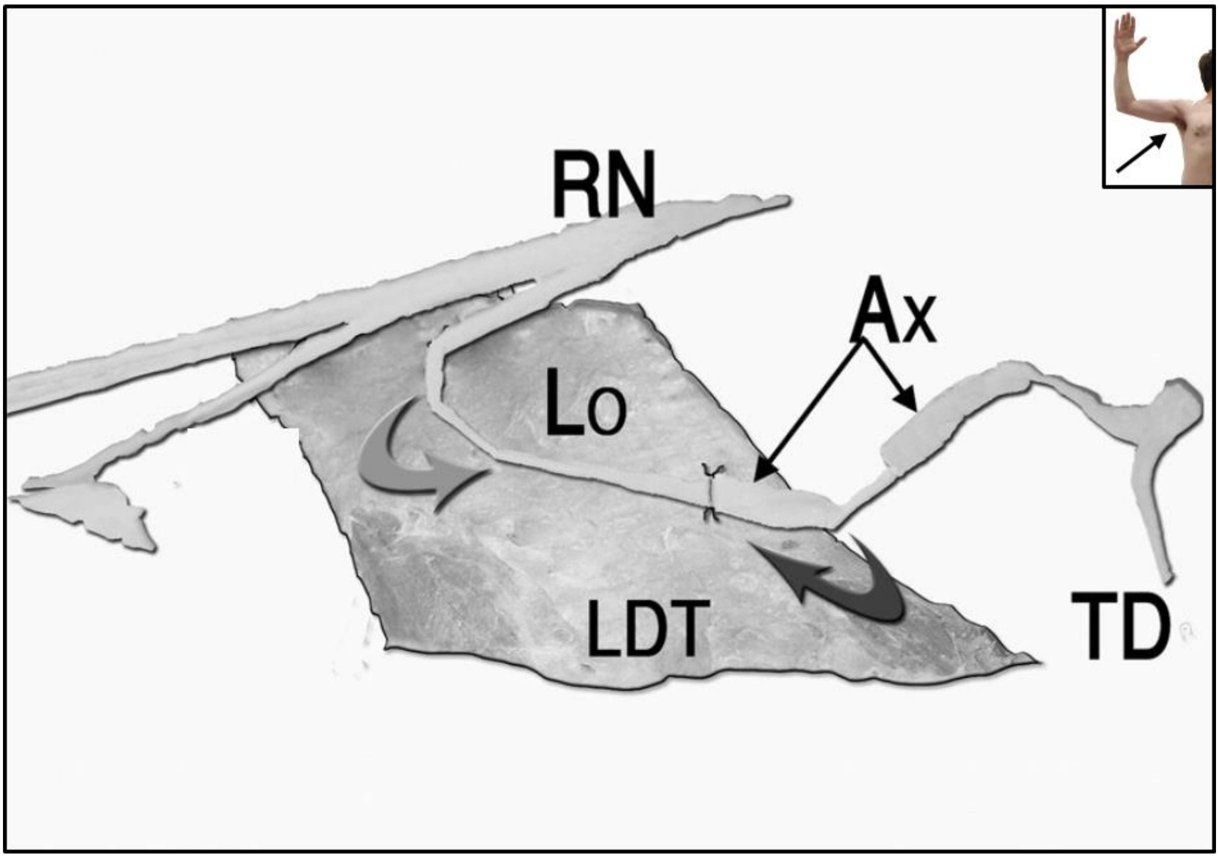

Figure 6-1: Drawing by Bertelli *et al*.[4] of the transfer of the nerve to the long head of triceps brachii muscle to the anterior and middle deltoid branches and to the teres minor branch. The posterior division of the axillary nerve is left in continuity.[4] (RN = radial nerve; Lo = nerve to the long head of triceps brachii muscle; Ax = axillary nerve; TD = thoracodorsal nerve; LDT = latissimus dorsi muscle).

Bertelli *et al*.[4] performed nerve transfers from the nerve to the long head of triceps brachii muscle to the deltoid branches from the axillary nerve and the nerve to the teres minor muscle. The current study found the axillary nerve length, from its origin at the posterior cord to the point where it branches into its anterior and posterior divisions to be 38.8±9.6mm. Another study by Stecco *et al*.[19] found the same measurement to be 44.9±10.8mm. When looking at the total length of the axillary nerve, compared to the difference in the means between this study and that of Stecco *et al*.[19], the two means only differ by 6mm. Following the posterior division distally, it was found in this study that in females the nerve to the teres minor muscle originates

6.2±3.0mm from the division of the axillary nerve. This measurement ranged between 3.3mm proximal to the origin of the axillary nerve and 13.1mm distal to it. In males, it was found to be 7.4±2.8mm with a range between 2.9mm and 15.5mm. The difference between females and males could possibly be due to differences in the musculature between sexes. Even though the difference is roughly only one millimetre, it remains unclear as to why exactly this difference between females and males exists. The study by Stecco *et al*.[19] divided the same measurement into two groups, the one group consisted of the nerve to the teres minor muscle originating from the axillary nerve, which was reported as 17.5±7.8mm and the second group where the nerve to the teres minor muscle originated from the posterior division of the axillary nerve, which was reported as 19.1±4.3mm. Bertelli *et al*.[4] also reported on the same measurement and found the mean distance to be 12.7mm with a range between 9.7mm and 23.5mm. The difference in the current study's results and that done by Stecco *et al*.[19] could be due to the different procedures used to perform the measurements. In the current study all nerves were left *in situ* to the furthest possible extent and a direct measurement was taken from the origin of the teres minor to the division of the axillary nerve, not accounting for the turn or angle the nerve undergoes during its course, but rather the direct distance between the origin and division. Whereas Stecco *et al*.[19] first detached the deltoid muscle and along with it the axillary nerve, allowing them to straighten the nerve before taking the measurement. Although this would increase the accuracy of the measurement, the goal of the current study was to maintain the integrity of the axillary approach as much as possible by not disrupting the *in situ* position of the structures. Other possible explanations for the differences in the measurements between this study and both the study done by Stecco *et al*.[19] and Bertelli *et al*.[4] could be the increased sample size, as well as the use of embalmed, versus unembalmed, cadavers.

Various studies have found different branching patterns of the axillary nerve however, the nerve to the teres minor muscle was most commonly found as the first branch from the posterior division of the axillary nerve.[4,19,49] Similarly, this study also found the nerve to the teres minor muscle within a short distance from the origin of posterior division of the axillary nerve, with the exception of one variation where the nerve to the teres minor muscle originated more proximal, from the axillary nerve. The study by Stecco *et al*.[19] found this variation of the origin of the nerve to the teres minor muscle in 6 of the 16 (37.5%) axillae they dissected. This confirms that if the axillary nerve can be located, together with its branching into anterior and posterior divisions, the nerve to the teres minor muscle could be readily identified and accessed using an axillary approach as it can be located originating from the posterior division (normal) or originating directly from the axillary nerve (variation). In both cases, the origin of the nerve to the teres minor muscle is adequately visible from the axillary approach and lies in close relation to the division of the axillary nerve.

Using optimal size ratios between donor and recipient nerves is key to performing successful nerve transfers.[26] Although some studies reported on axonal counts in individual nerves as a measure of ratio,[21,43] this study did not perform any axonal counts, but rather measured the diameters of nerves to aid in providing an estimate of the size of donor and recipient nerves. Significant differences were found between the left and right sides, as well as between females and males, thus not all data could be combined into totals. This study found the diameter of the axillary nerve in females to be 3.7±0.8mm and 4.1±0.9mm, on the left and rights sides respectively and 4.2mm (median) with an interquartile range of 0.95mm in males at the origin of the nerve. Stecco *et al*.[19] found the diameter of the axillary nerve to be 5.7±4.4mm. Firstly, the difference between studies could be due to a difference in where the diameter of the axillary nerve was measured, as Stecco *et al*.[19] did not mention the point at which the diameter of the axillary nerve was measured. Secondly the difference could be due to the difference in cadavers used. In their study they used 16 unembalmed cadaver axillae for their measurements, whilst this study used 96 embalmed cadaver axillae consisting of both females and males.

The diameter of the anterior division of the axillary nerve was found to be 2.8±0.6mm, ranging between 1.9mm and 3.8mm on the left side and 2.9mm (median) with an interquartile range of 1.1mm, as well as a normal range between 2.3mm and 5.1mm on the right side in females. In males the diameter was found to be 2.9±0.8mm, with a range between 1.5mm and 4.8mm. Three other studies also reported on this measurement, Stecco *et al*.[19] reported a diameter of 4.0±3.3mm while both Bertelli *et al*.[4] and Witoonchart *et al*.[21] found the anterior division of the axillary nerve to be much closer to the current study's mean. The former reported it as 2.9mm, with a range between 1.7mm and 3.5mm, while the latter found it to be 2.2mm with a range of 1.8mm to 2.5mm. The difference between this study and the one by Stecco *et al*.[19] could once again be due to the reasons explained above with regard to cadaver type.

The last diameter in this study that was measured was the posterior division of the axillary nerve, which was found to be 2.6±0.7mm, with a range of 1.2mm and 4.2mm. This measurement was very similar to that of Stecco *et al*.[19] who reported it to be 2.4±2.3mm. Bertelli *et al*.[4] measured the posterior division of the axillary nerve after the nerve to the teres minor muscle was given off, which is a slightly different measurement than the one in this study. They found the nerve to the teres minor muscle to be 2.2mm, ranging between 1.2mm and 4.0mm, while the continuing trunk was 2.1mm, with a range between 0.8mm and 3.5mm.

These diameters play a role when surgeons choose to perform nerve transfer or grafting procedures, involving the axillary nerve, its anterior and posterior divisions or the nerve to the teres minor muscle, as they can be individually repaired or used to repair other nerves.

The observations reported in this study would possibly aid or serve as guidelines to locate and identify the axillary and radial nerve, as well as their branches, when using an axillary approach. When using the axillary approach, the quadrangular space is a pertinent landmark used to accurately identify the axillary nerve and its branches. For suitability this study regarded the quadrangular space lateral to the subscapular muscle, as discussed previously, as the space was viewed from an anterosuperior view similar to the axillary approach. This study found that the axillary nerve branches into its anterior and posterior divisions before it reached the quadrangular space or lateral border of the subscapularis muscle in 47 of the 98 axillae (48%) while in 51 of the 98 axillae (52%) after the axillary nerve already entered the quadrangular space before branching. In none of the cases was it found that the axillary nerve branched after the nerve passed through the quadrangular space to the posterior aspect. Bertelli *et al*.[4] found that the anterior and posterior divisions of the axillary nerve could be easily separated through blunt dissection at the entrance of the quadrangular space or the lateral border of the subscapularis muscle. Witoonchart *et al*.[21] found that the anterior and posterior divisions of the axillary nerve had already divided into its terminal muscular branches at the level of the quadrangular space using a posterior approach. Similarly, the study by Kuppasad *et al*.[50] found that the axillary nerve divided into its muscular branches within the quadrangular space in 44 of 50 axillae (88%) and in 6 of 50 axillae (12%) after exiting the quadrangular space. They however did not report where the axillary nerve divided into the anterior and posterior divisions. They also defined the quadrangular space, as the space between the subscapularis muscle and the long head of the triceps brachii muscle and used a posterior approach to the axillary nerve. In contradiction, Tubbs and co-workers[22] found that the axillary nerve divided into its muscular branches to the deltoid muscle within the quadrangular space in 10 of 30 axillae (33%) and in the majority of cases (66%), at the posterior aspect of the quadrangular space. As the quadrangular space is an important landmark in locating and identifying the axillary nerve using the axillary approach, the location of branching of the axillary nerve in relation to the quadrangular space is relevant, when surgeons are palpating or visibly locating the axillary nerve or its branches.

Several non-terminal branches were seen to originate from the axillary nerve prior to its division into the anterior and posterior divisions (i.e. during its course over the subscapularis muscles). They were divided into two groups, a group of branches that course superiorly and a group that courses inferiorly from the axillary nerve. In the group that coursed superiorly, it was seen that the branch/es coursed to the shoulder joint capsule as articular branches. This study found that in 32 of 98 axillae (32.7%), no articular branches were seen originating directly from the axillary nerve, in 65 of 98 axillae (66.3%) one branch was observed and in 1 of 98 axilla (1%) two branches were observed coursing superiorly to the shoulder joint capsule from the axillary nerve. Uz *et al*.[2] found no articular branch in 6 of 30 axilla (20.0%) and an articular branch that originated from the axillary nerve in 9 of 30 axilla (30%), in 10 of 30 axilla (33.3%) the articular branch originated from the posterior division of the axillary nerve and in 5 of

30 axilla (16.7%) the branch originated at the anterior division of the axillary nerve. In the current study, no attempt was made to find the articular branch/es if they did not originate directly from the axillary nerve. Bertelli *et al*.[4] reliably found the same articular branch originating laterally from the axillary nerve and terminating over the inferior parts of the anterior joint capsule. Zhao *et al*.[49] found that in the case of a second articular branch, it usually originates from the anterior division of the axillary nerve. During nerve transfer or grafting procedures using an axillary approach, the surgeon must be vigilant of the articular branch to avoid any injury to this structure. The variation in origin must also be considered when deciding to use the posterior or anterior divisions of the axillary nerve for nerve transfer or grafting procedures.

The second group of branches that were observed, originated from the axillary nerve and coursed inferiorly. In this study the branches were observed to course over the subscapularis muscle as the lower and upper subscapular nerves. These nerves usually originate from the posterior cord of the brachial plexus.[17] However, in this study the lower and upper subscapular nerves originated proximal from the axillary nerve in some cases. This study found a significant difference in the number of branches between females and males. In females it was found that in 21 of 48 axillae (43.0%), and in males only 11 of 50 axillae (22.0%) had no branches originating from the axillary nerve before it divided into its anterior and posterior divisions. The second category was more similar between the sexes, a singular lower subscapular nerve was found to originate from the axillary nerve in 19 of 48 axillae (39.6%) in females and 19 of 50 axillae (38.0%) in males. Both the lower and upper subscapular nerves were found to originate from the axillary nerve in 8 of 48 axillae (16.7%) in females and 20 of 50 axillae (40.0%) in males. A study by Muthoka *et al*.[51] that investigated the variations of the posterior cord of the brachial plexus in a Kenyan population, found similar variations in the origins of the lower and upper subscapular nerves. They found the lower subscapular nerve originated from the axillary nerve in 43 of 75 axillae (57.3%) and the upper subscapular nerve originating from the axillary nerve 8 of 75 axillae (in 10.7%) they dissected. In their study 35 female and 33 male embalmed cadavers were used, they however did not state whether there were any significant sex specific differences that could lead to differences between their study and this one. In the study by Muthoka *et al*.[51], they did an in-depth investigation into the origin and course of the lower and upper subscapular nerves, including observing whether these nerves originate from a common trunk. This was not done in the current study and in these cases, the observation would have been classified under a singular branch from the axillary nerve. Even with the differences between these two studies, it is clearly seen that variations do occur, and that the lower and upper subscapular nerves originate from the axillary nerve in some cases. Even though the lower and upper subscapular nerves originated proximal from axillary nerve in this study, it is still relevant, as it will affect the diameter of the axillary nerve at its origin. It will also affect the movement allowed and length of axillary nerve that can be utilised when undertaking nerve transfer or grafting procedures using an axillary approach. The variations in the upper and lower subscapular nerves could also open up more possibilities to other nerve transfers within the axilla using the axillary approach, as the lower subscapular nerve innervates the teres major muscle via muscular branches to the teres major muscle.

Bertelli *et al*.[4] described a musculo-arterial triangle, bordered medially by the subscapularis artery, laterally by the latissimus dorsi muscle and superiorly by the posterior circumflex humeral artery. This triangle was described to aid in locating the axillary nerve, using an axillary approach. It was found in this study that in 59 of 98 axillae (60.2%) the axillary nerve was found within the triangle. In total, this study did not find the axillary nerve within this triangle in 39 of 98 axillae (39.8%), of these 39 axillae, neither the axillary nerve nor its divisions could be found within the triangle in 18 cases while only one of the division of the axillary nerve could be found within the triangle in 7 cases. However, this study also found that variations of the blood vessels could obfuscate or distort the borders of the triangle itself. The presence of this reported musculo-arterial triangle is largely dependent on the anatomy of the subscapular and posterior circumflex humeral artery. It was observed that variation in the origins of the posterior circumflex humeral artery and subscapular artery resulted in the musculo-arterial triangle not forming as described. This therefore resulted in the axillary nerve not being found within the triangle in 14 cases.

In actual fact, it was often found that the shape of the triangle was more in the shape of an inverted U, with subscapular artery mainly seen travelling parallel to the latissimus dorsi muscle and eventually terminating as the circumflex scapular and thoracodorsal artery (see Figure 4-11). If present within the borders of these three structures, the axillary nerve was found to lie in close relationship to the posterior circumflex humeral artery. The study by Bertelli *et al*.[4] found that the axillary nerve was reliably found within this triangle, however they do include that variations do occur regarding the origin of the posterior circumflex humeral artery. The difference between this study and the study by Bertelli *et al.*[4] could be partially due to sample size resulting in a possible type 2 error (missed detection). The frequency of the axillary nerve being found within this triangle is important as surgeons may encounter variations during surgery and must be able to adapt to different circumstances. Although there might not always be a clearly defined “triangle”, the results of this study would suggest that the axillary nerve does course between the three musculo-arterial landmarks more often than not and they can be used as a reliable indicator of the position of the axillary nerve.

The axillary nerve has been reported to be the most superior structure within the quadrangular space, even superior to the posterior circumflex humeral artery.[22] This could have possible implications on the accuracy of the musculo-arterial triangle described by Bertelli *et al*.[4] However the arm was not necessarily abducted and externally rotated when these observations were made, which does have an influence on the position of the axillary nerve. In this study the axillary nerve was found superior to the posterior circumflex humeral artery in 12 of 98 axillae (12.2%), medial to the artery in 25 of 98 axillae (25.6%) and inferior to the artery in 61 of 98 axillae (62.2%).

6.2 Anatomical guide to the axillary approach

The following anatomical guide was created in a step-by-step process after dissection of a fresh frozen axilla. The description below can serve as a guideline to locate and identify the contents of the axilla using an axillary approach, with special reference to the axillary and radial nerves, as well as their branches. The landmarks used to identify these nerves are portrayed, as well as the musculo-arterial triangle described by Bertelli *et al*.[4], to locate the axillary and radial nerves.

The first step in the axillary approach, was to place the cadaver in a supine position with the arm abducted and externally rotated to expose the axillary fossa (see Figure 6-2).

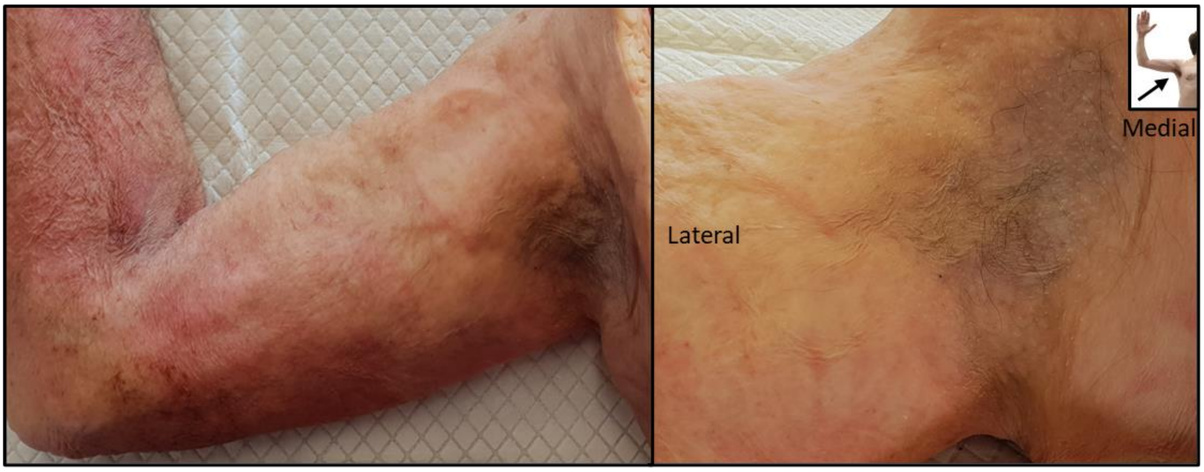

Figure 6-2: Photographs of a fresh frozen cadaver showing the arm in the abducted and externally rotated position exposing the axillary fossa for an axillary approach.

An incision was then made in the axillary fossa, care was taken when dissecting through the subcutaneous tissue to avoid damage to the intercostobrachial nerve found within the tissue. The dissection was progressed until the latissimus dorsi muscle could be palpated and was visible, following the muscle superior led to visualising the neurovascular sheath surrounding the terminal brachial plexus and axillary vessels with their branches (see Figure 6-3).

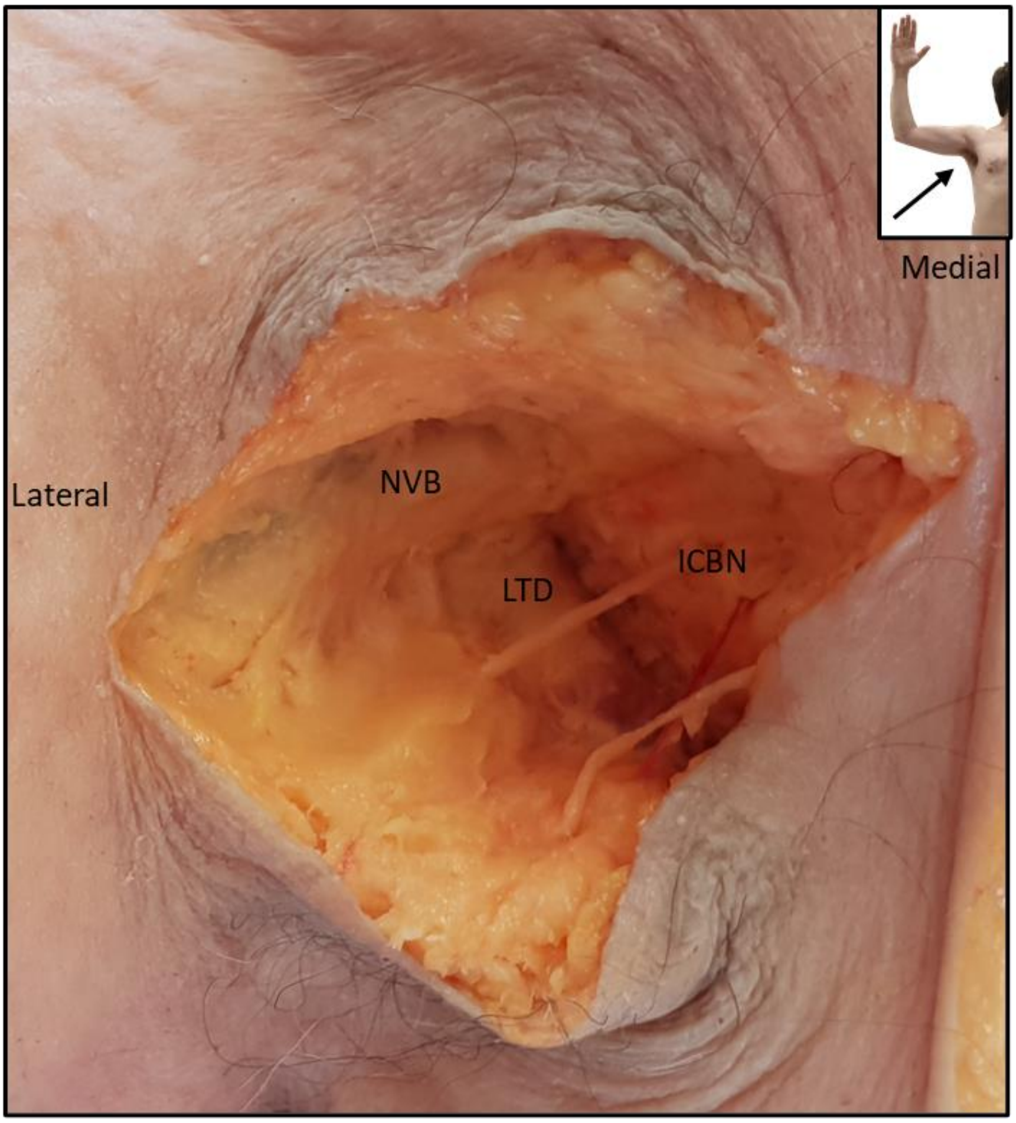

Figure 6-3: Photograph of a dissection of a fresh frozen cadaver showing the axillary space after clearing subcutaneous tissue, with the neurovascular bundle visible superior to the latissimus dorsi muscle (NVB = neurovascular bundle covered by a sheath; LTD = latissimus dorsi muscle; ICBN = intercostobrachial nerve).

The sheath was then removed revealing the axillary vein, ulnar nerve and medial brachial cutaneous nerve as the first visible structures. The axillary vein was then retracted superiorly and the nerves inferiorly, to expose the radial nerve and its nerve to the long head of triceps brachii muscle as a clearly separate branch, posterior to these structures and in close relation to the latissimus dorsi muscle (see Figure 6-4).

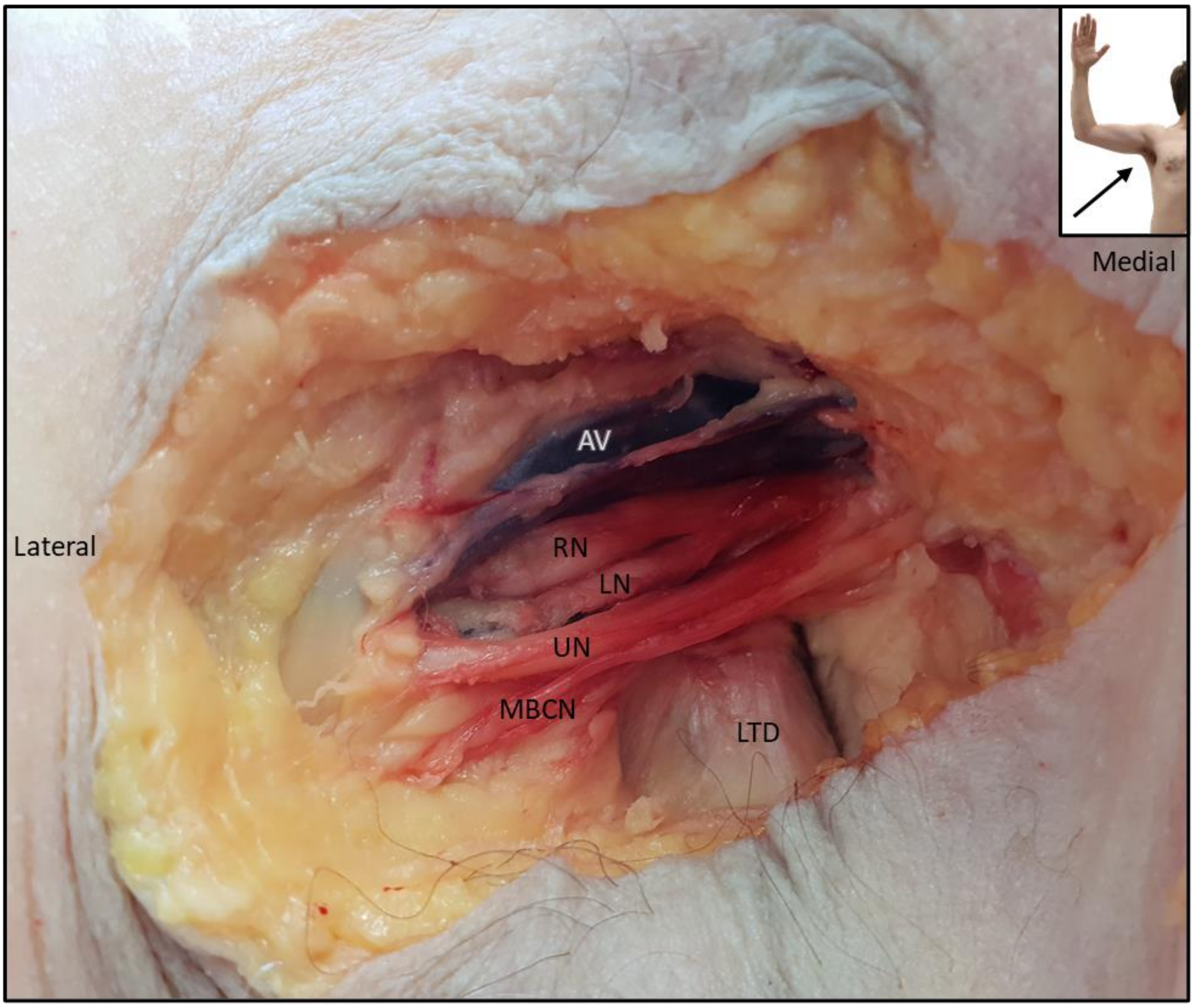

Figure 6-4: Photograph of a dissection of a fresh frozen cadaver showing the radial nerve and nerve to the long head of triceps brachii muscle, posterior to branches of the brachial plexus and the axillary vein, after the neurovascular sheath is removed (AV = axillary vein; RN = radial nerve; LN = nerve to the long head of triceps brachii muscle; UN = ulnar nerve; MBCN = medial brachial cutaneous nerve; LTD = latissimus dorsi muscle).

Slightly retracting the axillary vein, ulnar nerve and medial brachial cutaneous nerve inferiorly, exposed the medial antebrachial cutaneous nerve, axillary artery and median nerve in that order from inferior to superior. The medial antebrachial cutaneous nerve was found between the axillary artery and vein (see Figure 6-5).

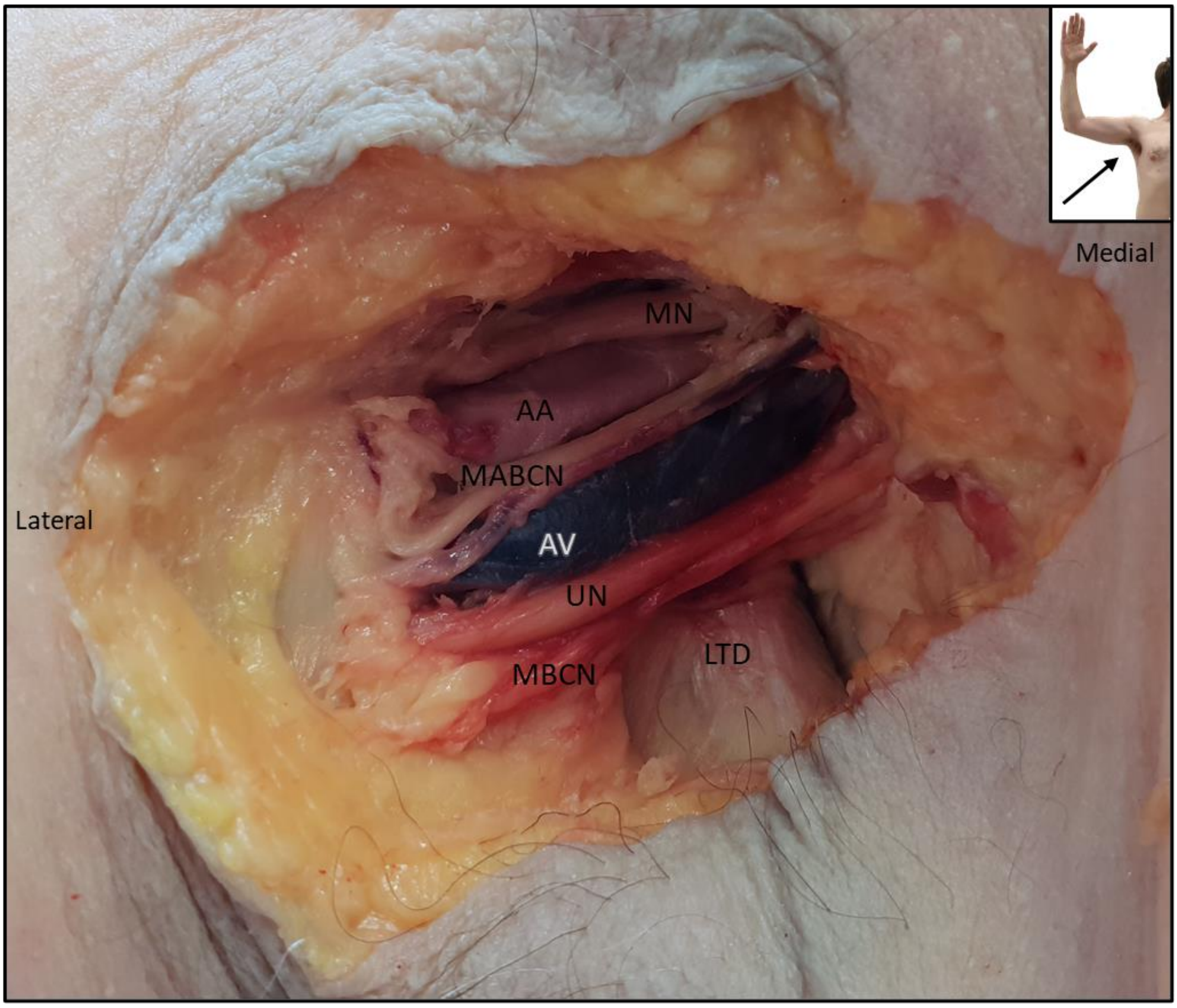

Figure 6-5: Photograph of a dissection of a fresh frozen cadaver showing the axillary artery within the axillary space after slightly retracting the axillary vein and branches of the brachial plexus (MN = median nerve; AA = axillary artery; MABCN = medial antebrachial cutaneous nerve; AV = axillary vein; UN = ulnar nerve; MBCN = medial brachial cutaneous nerve; LTD = latissimus dorsi muscle).

Further retraction of the axillary vein, ulnar nerve, medial brachial and antebrachial cutaneous nerves, once again exposed the radial nerve posteriorly (see Figure 6-6).

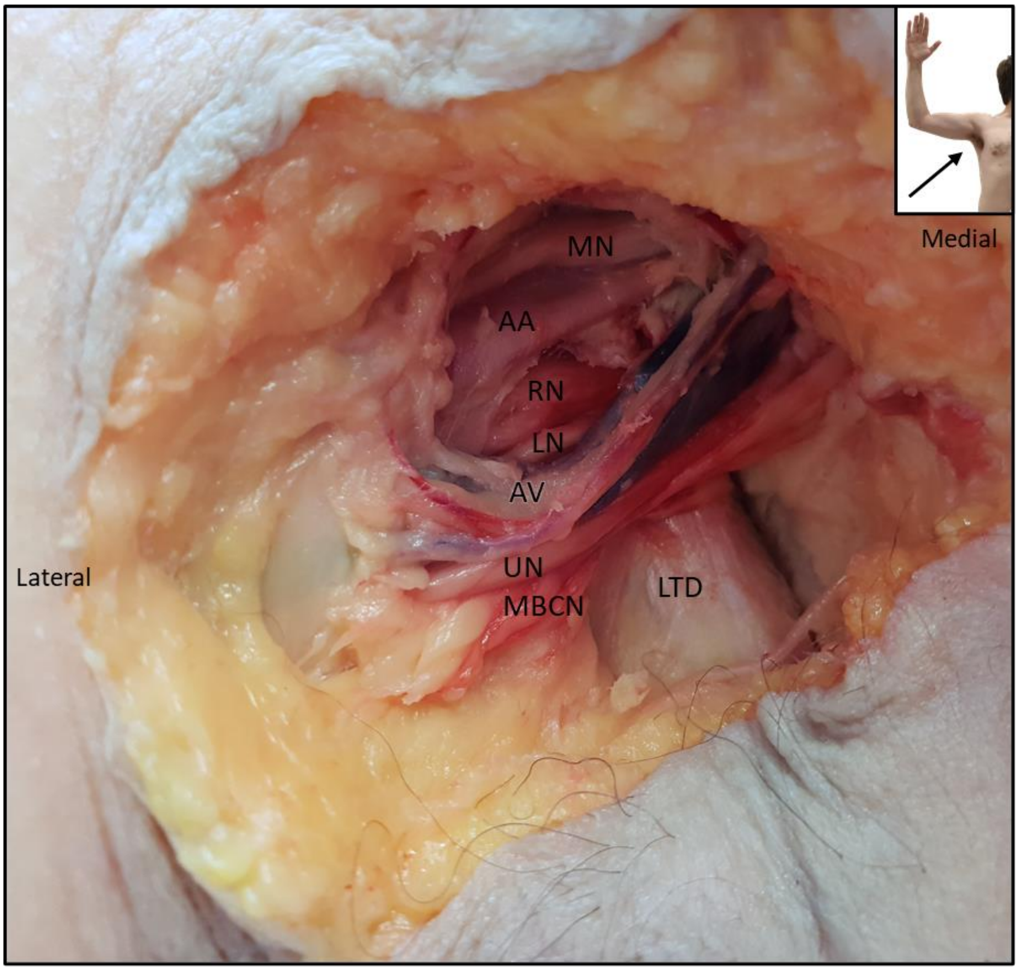

Figure 6-6: Photograph of a dissection of a fresh frozen cadaver showing the radial nerve posterior to axillary artery and vein after slightly retracting the axillary vein and some branches of the brachial plexus inferiorly (MN = median nerve; AA = axillary artery; RN = radial nerve; LN = nerve to the long head of triceps brachii muscle; AV = axillary vein; UN = ulnar nerve; MBCN = medial brachial cutaneous nerve; LTD = latissimus dorsi muscle).

The axillary artery was then followed proximally, and the remaining structures of the brachial plexus were retracted superiorly, which allowed the subscapular and posterior circumflex humeral artery, originating from the axillary artery, to be visualised. Using the musculo-arterial triangle described by Bertelli *et al*.[4] (posterior circumflex humeral artery superiorly, subscapular artery medially and the latissimus dorsi muscle laterally) revealed the axillary nerve within its borders (see Figure 6-7). The anterior and posterior divisions of the axillary nerve could be identified at this point upon further blunt dissection. Depending on the nerve transfer or graft that will take place, further dissection might be required to obtain adequate lengths of the anterior and posterior division in order to perform the repair of the chosen nerve closer to the motor endplate or for selective branch repair.

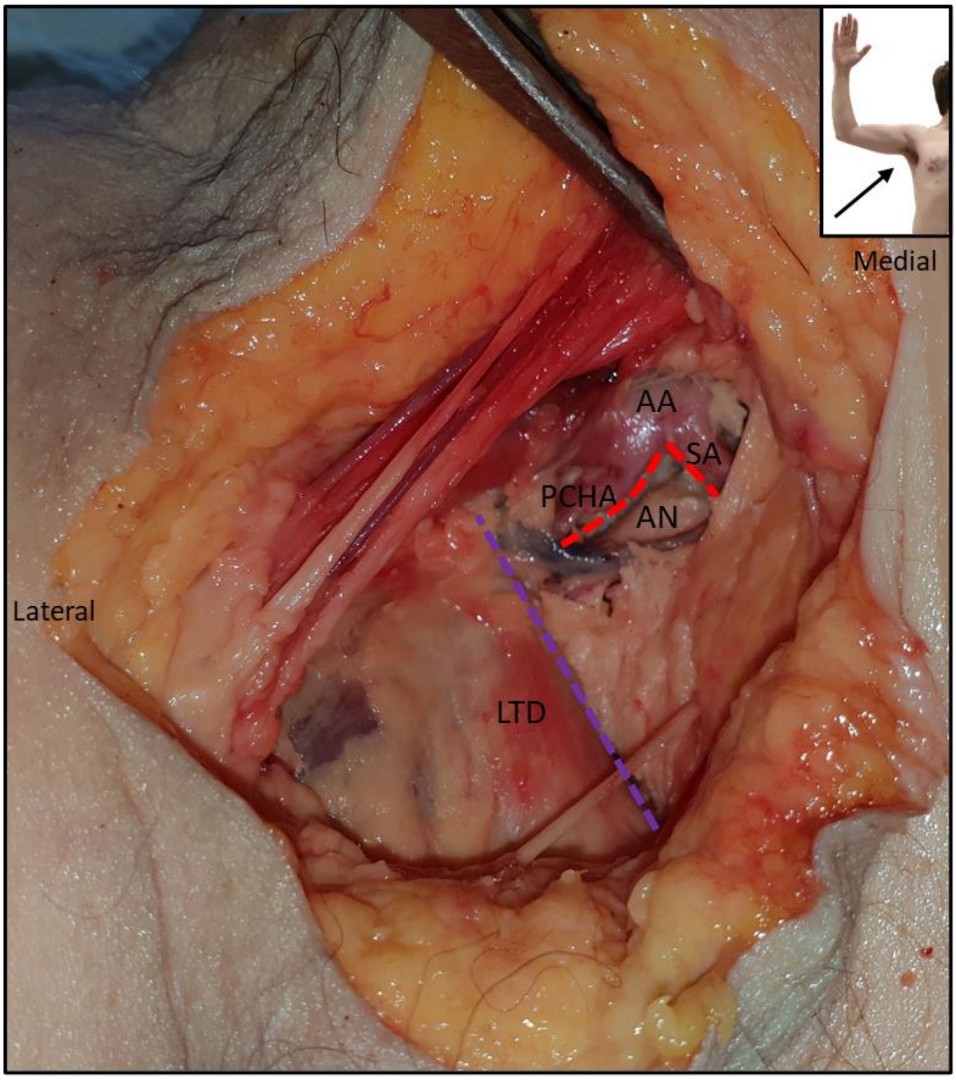

Figure 6-7: Photograph of a dissection of a fresh frozen cadaver showing the axillary nerve found within the musculo-arterial triangle described by Bertelli *et al*.[4] (AA = axillary artery; SA = subscapular artery; PCHA = posterior circumflex humeral artery; AN = axillary nerve; LTD = latissimus dorsi muscle).

For better visualisation of the axillary fossa and its content, the initial dissected area was enlarged and reflected. Retracting the axillary vein and branches of the brachial plexus superiorly showed both the axillary and radial nerves in relation to the latissimus dorsi muscle and subscapular artery (see Figure 6-8).

Figure 6-8: Photograph of a dissection of a fresh frozen cadaver, after the exposure area of an axillary approach is enlarged for better visualisation of the relation of the axillary and radial nerves to the subscapular artery and latissimus dorsi muscle (AA = axillary artery; SA = subscapular artery; RN = radial nerve; AN = axillary nerve; LN = nerve to the long head of triceps brachii muscle ; LTD = latissimus dorsi muscle).

This study found that the axillary nerve generally originates superior to the radial nerve as seen in 42 of 89 axillae (47.2%), posterior to it in 29 of 89 axillae (32.6%), inferior to it in 16 of 89 axillae (18.0%) and anterior to it in 2 of 89 axillae (2.2%). Even though the relation of the origins of these nerves do not necessarily continue throughout their course, the knowledge could still aid in locating the nerves in relation to each other distally or especially when following the nerves proximally.

During the course of the axillary nerve over the subscapularis muscle, it was seen to pass in most cases (79 of 98 axillae - 80.6%) posterior to the subscapular artery, in 18 of 98 axillae (18.4%) it was seen to pass anterior and in one case was it seen medial to the subscapular artery, as the subscapular artery originated extremely distal at the axillary artery. The radial nerve however was generally seen passing anterior to the subscapular artery in 64 of 98 axillae (65.3%), posterior to the subscapular artery in 30 of 98 axillae (30.6%) and in 4 of 98 axillae (4.1%), superior to the subscapular artery.

Lastly, the latissimus dorsi muscle was transected for better visualisation of the axillary nerve, its anterior and posterior divisions, the nerve to the teres minor muscle and their distance from the radial nerve with its nerve to the long head of triceps brachii muscle. Depending on whether one of the divisions of the axillary nerve is used for a nerve transfer or graft between the nerve to the long head of triceps brachii muscle, adequate length can be seen to reach each other (see Figure 6-9).

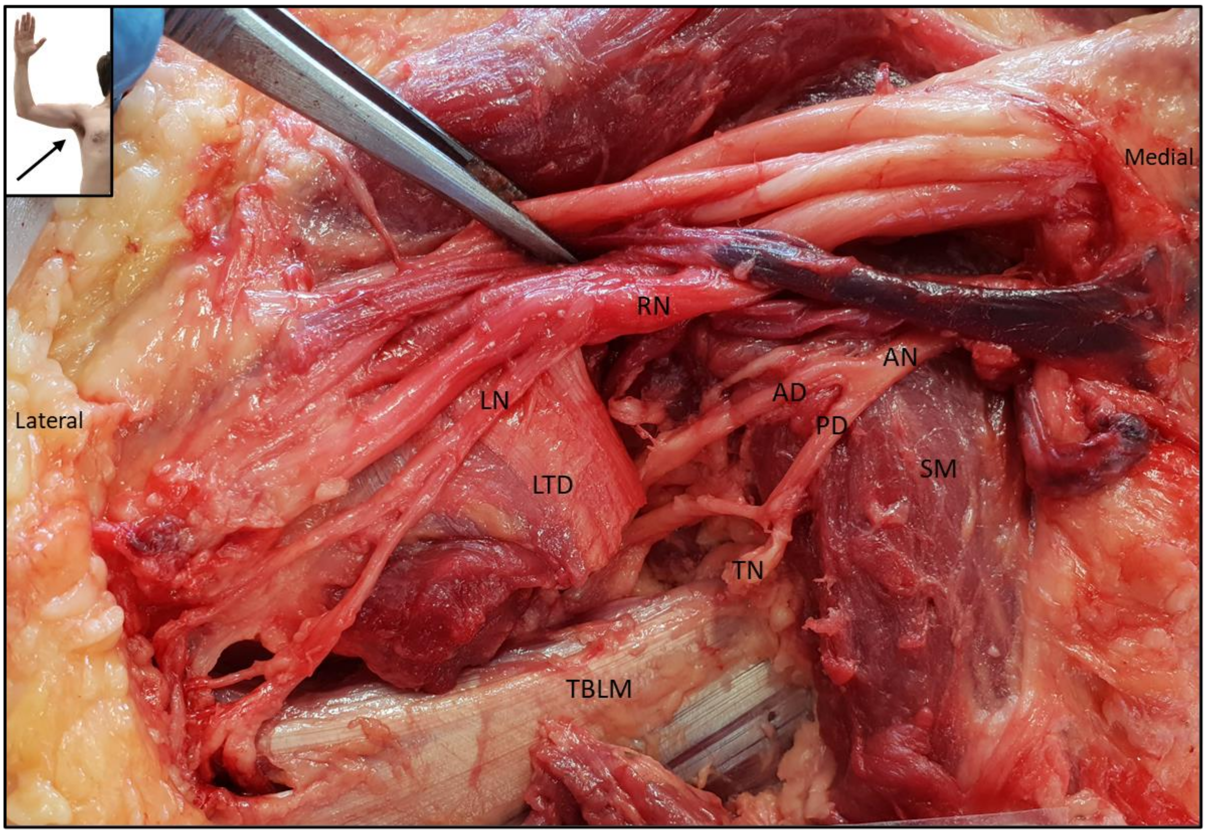

Figure 6-9: Photograph of a dissection of a fresh frozen cadaver, after the latissimus dorsi muscle was transected for better visualisation of the axillary nerve with its branches in relation to the radial nerve and its branch to the long head of triceps brachii muscle. (RN = radial nerve; LN = nerve to the long head of triceps brachii muscle; AN = axillary nerve; AD= anterior division of axillary nerve; PD = posterior division of axillary nerve; TN = nerve to the teres minor muscle; LTD = latissimus dorsi muscle; SM = subscapular muscle; TBLM = long head of triceps brachii muscle)

6.3 Strengths and limitations

The main limitation of this study was the use of formalin fixed cadavers, the rigidness caused from the embalming process did not allow the limbs to have full range of motion and made placing the arm in the abducted and externally rotated position difficult. This could have influenced the position of important structures within the axilla.

Some of the strengths of this study include: (1) the successful use of cadaveric material to evaluate the anatomical feasibility of accessing target nerves using a newly proposed surgical approach, which was further supported by simulating the axillary approach on an axilla of a fresh frozen cadaver. (2) It was found that in a large sample that the musculo-arterial triangle described by Bertelli *et al*.[4] may not be as reliable as initially described using a smaller sample size. (3) The latissimus dorsi muscle proved to be a consistent and reliable landmark when navigating the content of the axilla. (4) Variations in the arterial system could significantly impact access to the target nerves and clinicians need to be cognisant of the anatomy of the axilla when attempting to use the axillary approach. (5) All target nerves could successfully be visualised and accessed using the axillary approach.

Conclusion

In conclusion, using the axillary approach both the axillary and radial nerves are readily accessible, especially at their branching locations of the axillary nerve into the anterior and posterior divisions and the radial nerve with its nerve to the long head of triceps brachii muscle. It is difficult to reach their points of origin at the posterior cord, yet it is not necessarily always the case. Using the musculo-arterial triangle proposed by Bertelli *et al*.[4] is a relatively successful method in locating the axillary nerve, however, variations in the origin of the arterial components of the triangle should be considered. Landmarks such as the latissimus dorsi muscle and subscapular muscle was found to be in close relation to the axillary and radial nerves and could therefore make for an additional or alternate landmark when identifying these nerves. The anterior aspect of the quadrangular space was also found to be an invaluable landmark when tracing the course of the axillary nerve.

Both the axillary and radial nerves have multiple branches that can also be accessed via the axillary approach. These branches can be considered for use in nerve transfers or nerve grafts, depending on the repair taking place, making the nerves or their branches prime choices during such procedures. However, the terminal muscular branches of the divisions of the axillary nerve were not as easily accessed through the axillary approach in this sample, which could lead to a complication when trying to use selective branches for nerve transfer or grafting procedures. Although the majority of the course of the axillary nerve was visible, the origin of the nerve, proximal within the axilla, were sometimes difficult to visualise without manipulation of the extremity, which was difficult in an embalmed cadaver sample. Depending on what is indicated, it might therefore be necessary to use the posterior or anterior (deltopectoral) approach in combination with the axillary approach.

The axillary approach, even though daunting because of the presence of major blood vessels, is suitable to gain access to the target nerves used for nerve transfer or grafting procedures from an anatomical perspective, because the anatomical structures can be visualised at all times throughout the procedure. As seen, the axillary and radial nerves are suitable targets for nerve transfer or grafting procedures, but further investigation into other possible donor or recipient nerves accessible through the axillary approach is recommended. The combination of the axillary approach with other approaches should also be further studied, as the combination might allow for better suited nerve transfer or grafting options. A pitfall that was encountered was the variable or vague methods used by other authors when studying these nerves, it was difficult to make comparisons between the results of this study and the results of numerous other studies for the exact same measurement. Standardising the method in which measurements are taken – especially using the axillary approach – is recommended and should be considered as a possible future study.

When nerve transfers or nerve grafts are planned, possible donor and recipient nerve options and their pitfalls must be kept in mind. From the anatomical perspective of this study, the nerve to the teres minor muscle is a viable option as a donor or recipient nerve for nerve transfer or grafting procedures using an axillary approach, as it is readily accessible, is a pure motor nerve, and has a single function. The concern however is the variations seen in the nerve’s origin and the limited length of the nerve to the teres minor muscle. The variation seen in the origin of the lower and upper subscapular nerves originating from the axillary nerve, could lead to possible other repair options through nerve transfer or grafting procedures using the axillary approach. The option of a possible donor or recipient branch from the lower subscapular nerve such as the nerve to the teres major muscle, must be further studied and possibly considered when performing nerve repair procedures through the axillary approach.

Due to a functioning nerve being used during nerve transfer or grafting procedures, generally means that its original function is lost when moved and a new function is gained. This loss and gain of function must be carefully considered when planning what is to be repaired. As the function of the posterior part of the deltoid muscle is mainly extension of the arm and is innervated by the posterior division of the axillary nerve, compared to the anterior and middle parts of the deltoid muscle, which are more important in abduction and flexion of the arm and is innervated by mostly the anterior division of the axillary nerve, Therefore the choice of nerve (or branch thereof) should be carefully considered based on the function that the surgeon wishes to restore. In patients with tetraplegia the nerve transfer or graft between the axillary and radial nerves could possibly restore function to the forearm or hand, depending on the spinal nerve level at which the function is lost.

Regardless of the end goal of the procedure that requires access to the content of the axilla, this study showed that the axillary approach can provide adequate exposure of the axillary and radial nerves when they, or their branches, are chosen for nerve transfer or nerve grafting.

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Appendices

Appendix A: Demographic details

Nr.	Age	Race	Sex	Height	Weight
1	74	1	1	1.74	48.2
2	79	1	0	1.60	44.8
3	79	1	0	1.56	35.6
4	73	1	0	1.74	62.2
5	92	1	0	1.65	55.6
6	64	0	1	1.63	58.0
7	84	1	0	1.65	60.8
8	66	1	1	1.83	47.8
9	54	1	0	1.70	72.6
10	69	1	1	1.82	93.3
11	38	1	0	1.53	34.4
12	72	1	1	1.76	75.8
13	?	?	?	?	?
14	72	1	0	1.78	72.2
15	?	0	1	1.90	63.0
16	75	1	0	1.25	70.2
17	76	1	1	1.87	65.0
18	77	1	0	1.58	34.8
19	59	1	1	1.74	63.2
20	21	0	1	1.75	43.6
21	85	1	0	1.64	30.6
22	82	1	1	1.73	54.2
23	75	1	0	1.64	92.5
24	79	1	0	1.61	64.8
25	61	0	1	1.66	48.6
26	78	1	0	1.57	58.4
27	75	1	1	1.77	63.2
28	69	1	0	1.66	65.2
29	70	1	1	1.74	48.2
30	84	1	0	1.57	62.2
31	28	0	1	1.69	41.4
32	81	1	1	1.77	60.2
33	68	1	0	1.59	42.4
34	32	0	1	1.76	47.0
35	94	1	0	1.59	40.8
36	80	1	1	1.84	84.4
37	58	1	0	1.66	38.8
38	89	1	1	1.78	50.8
39	77	0	0	1.55	35.4
40	43	0	1	1.78	46.6
41	65	1	1	1.78	63.8
42	86	1	0	1.60	50.2
43	72	1	1	1.78	64.4
44	85	1	0	1.67	110.8
45	74	1	0	1.60	105.8
46	78	1	?	1.57	58.4
47	51	1	1	1.58	44.4
48	89	1	0	1.56	40
49	56	1	1	1.35	60.8
50	65	1	0	1.6	45.2
51	?	0	1	1.69	41.6

Key	Race	Sex
0	**Black**	**Female**
1	**White**	**Male**

Appendix B: Raw data

Appendix B.1: Distance Measurements

The raw data of each of the four different distance measurements (A-B; B-C; A-D; D-E) are shown in the table below as. it was captured during dissections.

	Distance A-B (mm)		Distance B-C (mm)		Distance A-D (mm)		Distance D-E (mm)	
Nr.	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
1	45.10	69.63	19.93	45.56	22.50	34.54	9.74	9.00
2	45.69	?	19.52	?	33.70	?	5.30	?
3	31.72	?	12.42	?	25.60	?	6.30	?
4	72.28	68.81	11.00	8.80	46.76	45.82	5.68	5.33
5	65.54	56.13	23.12	3.91	44.67	37.08	7.18	6.58
6	81.90	72.08	15.83	18.60	70.29	55.68	6.54	3.95
7	56.76	61.98	9.68	22.92	34.48	41.92	6.00	5.66
8	43.26	62.50	19.10	39.82	25.91	33.07	7.59	11.35
9	67.38	50.04	19.74	25.18	23.32	18.64	11.33	5.27
10	78.3	69.61	22.16	28.63	46.80	38.59	6.48	5.78
11	56.66	78.24	19.42	17.34	37.70	51.10	3.36	6.00
12	59.60	77.39	12.00	19.61	43.25	52.36	6.55	7.35
13	62.04	72.51	19.47	22.38	50.15	43.85	3.96	5.12
14	73.20	77.31	30.05	40.86	48.69	44.29	7.62	6.70
15	76.03	80.59	19.61	18.12	44.39	52.67	8.06	3.05
16	54.93	59.65	36.32	8.80	37.42	43.9	-3.28	3.24
17	46.42	32.86	11.60	6.20	30.04	19.96	11.72	9.65
18	62.72	61.64	17.65	12.74	39.66	48.37	12.20	6.93
19	73.53	72.35	23.44	20.67	40.04	46.47	6.55	5.77
20	68.70	67.73	10.89	21.88	39.43	33.38	7.97	15.52
21	68.86	67.47	16.22	11.50	40.92	34.60	6.16	12.84
22	47.30	56.41	9.92	8.50	25.59	26.05	5.38	10.20
23	65.34	68.15	11.62	16.03	40.03	53.47	9.30	4.37
24	51.98	55.24	-5.98	10.41	31.74	41.48	3.80	2.12
25	74.06	63.33	22.30	11.60	44.79	27.26	7.35	12.81
26	64.67	64.08	22.52	12.98	33.88	45.68	4.90	7.59
27	81.31	56.70	17.38	8.52	41.12	33.86	12.68	11.28
28	53.47	50.00	26.52	14.84	22.87	35.7	8.68	3.34
29	59.56	44.44	14.85	10.30	27.63	23.09	9.02	7.81
30	54.13	70.05	8.60	22.35	31.62	37.73	13.10	4.68
31	54.84	57.78	9.35	36.08	32.25	41.75	3.94	6.46
32	72.10	67.32	27.48	28.36	48.16	42.00	8.29	6.76
33	75.81	67.53	32.04	9.40	50.86	44.78	7.05	6.75
34	58.33	56.36	19.68	10.60	27.81	28.18	8.02	2.90
35	69.69	64.90	17.80	23.10	46.40	46.58	8.80	2.84
36	71.65	62.15	30.29	46.60	44.21	24.27	3.83	7.81
37	41.73	40.41	23.46	12.48	25.16	27.42	3.68	3.86
38	75.70	81.42	27.32	23.72	50.06	54.38	6.36	6.56
39	61.25	63.70	23.80	14.34	46.66	43.66	6.18	7.19
40	53.18	60.78	26.27	11.62	32.90	39.46	9.55	10.43

	Distance A-B (mm)		Distance B-C (mm)		Distance A-D (mm)		Distance D-E (mm)	
Nr.	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
41	62.19	59.46	28.74	17.30	38.74	45.45	5.61	5.39
42	66.08	60.23	17.78	22.14	42.77	35.69	1.94	7.88
43	72.82	56.30	13.33	11.61	46.49	21.70	4.18	10.78
44	50.03	50.09	30.27	20.33	27.39	31.95	7.70	11.42
45	?	60.36	?	29.88	?	40.87	?	5.14
46	?	71.91	?	19.05	?	46.36	?	8.37
47	54.06	54.18	10.89	11.86	32.10	42.98	4.04	7.40
48	62.34	69.60	30.02	22.56	32.64	47.46	3.98	3.94
49	71.50	68.18	33.60	10.86	40.24	39.21	4.10	5.27
50	70.02	55.10	30.60	12.91	55.88	40.46	5.22	7.02
51	53.74	53.74	26.35	28.11	36.83	30.54	6.18	8.41

Key	Description
A-B	**The distance from the origin of the axillary nerve to the anteromedial border of the latissimus dorsi muscle.**
B-C	**The distance from the nerve to the long head of triceps brachii muscle to the latissimus dorsi muscle.**
A-D	**The distance from the origin of the axillary nerve to where it divides into its anterior and posterior divisions.**
D-E	**The distance from the division of the axillary nerve to the origin of the nerve to the teres minor muscle from the posterior division of the axillary nerve.**

Appendix B.2: Diameter measurements

The raw data of each of the three different diameter measurements (Dia AN; Dia AD; Dia PD) are shown in the table below as. it was captured during dissections.

	Dia AN (mm)		Dia AD (mm)		Dia PD (mm)	
Nr.	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
1	3.14	2.85	2.09	2.45	2.32	3.01
2	4.09	?	3.42	?	2.35	?
3	5.12	?	2.26	?	3.75	?
4	4.42	3.66	2.96	2.66	3.04	1.91
5	3.03	4.22	1.85	2.43	2.98	2.25
6	4.39	3.44	3.92	1.92	3.6	2.2
7	3.74	3.6	3.68	3.75	2.38	2.8
8	4.7	4.9	3.68	1.69	2.12	2.76
9	2.48	3.57	2.54	4.76	1.83	1.75
10	4.4	3.68	3.74	3.39	3.13	1.66
11	2.8	3.35	3.82	2.84	3.08	1.76
12	4.07	4.73	2.96	1.62	3.2	2.36
13	3.57	5.15	3	4.14	2.25	3.76
14	3.32	2.29	2.2	2.59	2.08	1.72
15	3.85	4.58	2.08	3.23	3.14	1.66
16	3.35	3.39	2.76	2.43	2.32	2.09
17	4.34	4.44	2.84	3.28	1.72	1.46
18	3.95	4.34	3.48	2.84	1.6	1.62
19	4.04	4.38	3.75	2.03	3.25	1.18
20	4.01	4.4	2.04	2.32	3.28	2.74
21	3.15	4.98	2.3	2.86	3.3	2.32
22	6.15	4.4	3.6	3.72	3.24	3.17

	DIA AN (MM)		DIA AD (MM)		DIA PD (MM)	
Nr.	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
23	3.08	4.18	2.07	3.21	4.7	2.64
24	2.98	3.58	2.47	3.66	2.39	2.8
25	3.96	4.9	2.94	1.48	3.38	2.32
26	3.9	5.6	2.34	3.93	3.85	2.39
27	3.56	4.05	1.72	2.55	3.7	2.8
28	4.7	2.86	1.88	4.04	1.77	1.7
29	4.82	3.9	2.17	3.42	2.16	2.75
30	4.1	4.41	2.36	3.59	1.96	2.57
31	5.34	5.22	2.19	2.52	2.74	1.98
32	6.5	7.15	3.91	2.71	4.18	3.69
33	5.12	4.58	3.54	3.76	4.73	2.56
34	3.5	3.03	1.84	4.48	2.21	2.28
35	4.5	5.48	2.96	5.1	2.32	2.96
36	4.76	6.78	3.96	4.84	3.1	2.52
37	2.85	5.56	2.71	3.41	2.08	2.34
38	3.48	4.03	3.12	3.1	3.23	1.41
39	3.79	5.17	2.74	3.38	3.36	2.88
40	3.86	4.46	2.96	2.82	4.04	2.38
41	3.82	4.5	2.74	2.27	2.08	2.06
42	3.75	3.1	3.6	2.8	2.38	2.08
43	2.82	4.98	2.82	3.03	1.98	2.52
44	3.39	4.58	3.53	3.78	3.33	4.44
45	?	3.62	?	2.28	?	3.25
46	?	3.49	?	3.06	?	2.48
47	4.23	3.76	2.86	2.08	1.47	3.34
48	4.34	4.5	2.56	2.72	3.17	3.61
49	4.22	3.92	3.64	4.3	3.08	3.27
50	2.18	3.14	2.24	2.46	1.91	2.9
51	5.46	3.27	2.57	2.27	3.2	2.52

Key	Description
Dia AN	**Diameter of the axillary nerve at its origin.**
Dia AD	**Diameter of the anterior division of the axillary nerve at its origin.**
Dia PD	**Diameter of the posterior division of the axillary nerve at its origin.**

Appendix B.3: Observations (branches from the axillary nerve and the axillary nerve in relation to the quadrangular space)

The raw data recorded for observations made regarding the articular branches from the axillary nerve noted as the sup. in the table, as well as the lower and upper subscapular branches recorded as inf. branches and the relation of the axillary nerves' division to the quadrangular space is also recorded in the table below.

	AN nr. of branches				AN dividing location	
	Left		Right			
Nr.	Sup.	Inf.	Sup.	Inf.	Left	Right
1	0	0	0	0	0	0
2	0	0	?	?	1	?
3	0	0	?	?	0	?
4	1	0	2	0	0	0
5	0	0	0	0	1	0
6	0	2	1	2	1	1
7	1	0	0	1	1	1
8	0	1	1	2	0	0
9	1	1	1	0	0	0
10	1	2	0	1	0	0
11	0	0	0	0	0	0
12	1	2	0	2	1	1
13	0	2	1	1	1	1
14	0	0	0	0	1	1
15	1	1	1	2	0	0
16	1	1	1	2	1	1
17	1	0	1	0	1	1
18	1	1	0	0	1	1
19	0	1	0	2	0	1
20	1	2	1	2	0	0
21	1	1	1	2	0	0
22	1	2	1	1	1	0
23	1	1	0	1	0	1
24	0	1	1	0	1	1
25	1	2	1	1	0	0
26	1	2	1	2	0	1
27	1	2	1	1	0	1
28	1	0	1	1	0	1
29	1	2	1	1	0	1
30	1	1	1	2	0	0
31	1	1	1	2	1	1
32	1	2	1	1	1	1
33	0	2	1	1	1	1
34	1	0	1	1	0	0
35	0	1	1	1	1	1
36	1	1	1	0	0	0
37	1	1	1	2	1	1
38	1	1	1	1	0	0
39	0	2	0	1	1	1
40	1	0	1	2	1	0
41	1	0	1	1	0	1
42	1	1	0	1	0	1
43	1	1	0	2	1	0

	AN nr. of branches				AN dividing location	
	Left		**Right**			
Nr.	**Sup.**	**Inf.**	**Sup.**	**Inf.**	**Left**	**Right**
44	1	0	1	0	0	0
45	?	?	1	0	?	1
46	?	?	1	0	?	1
47	1	2	0	1	1	1
48	1	0	0	1	0	0
49	1	0	1	0	0	0
50	0	1	0	0	1	1
51	1	1	0	0	1	1

AN dividing location	
Key	**Description**
0	**Division of the axillary nerve before the quadrangular space**
1	**Division of the axillary nerve within the quadrangular space**
2	**Division of the axillary nerve after the quadrangular space**

Appendix B.4: Observations (Axillary nerve in relation to the musculo-arterial triangle described by Bertelli *et al.*[4])

The raw data recorded of the axillary nerve found within the musculo-arterial triangle described by Bertelli *et al*.[4]

	AN in triangle	
Nr.	Left	Right
1	0	1
2	0	?
3	1	?
4	2	2
5	0	1
6	2	1
7	2	1
8	1	1
9	1	1
10	1	1
11	0	1
12	3	3
13	1	1
14	0	1
15	1	3
16	1	1
17	3	3
18	1	3
19	1	1
20	0	1
21	1	1
22	1	1
23	1	1
24	1	1
25	1	1
26	1	1

	AN in triangle	
Nr.	Left	Right
27	1	1
28	3	3
29	2	1
30	1	1
31	3	3
32	1	1
33	0	1
34	3	1
35	1	1
36	2	1
37	1	1
38	0	2
39	1	1
40	1	0
41	1	1
42	0	1
43	1	0
44	0	1
45	?	1
46	?	1
47	1	0
48	3	0
49	0	0
50	0	0
51	3	3

AN dividing location	
Key	**Description**
0	**The axillary nerve is not found within the musculo-arterial triangle**
1	**The axillary nerve is found within the msuculo-arterial triangle**
2	**Only a division of the axillary nerve is found within the musculo -arterial triangle**
3	**The musculo-arterial triangle was not formed properly due to variation**

Appendix B.5: Observations (Relations between the AN; RN, SA; PCHA)

The raw data of the observations made of the axillary nerves' origin in relation to the radial nerve, the axillary and radial nerves' course in relation to the subscapular artery and the relation of the axillary nerve to the posterior circumflex humeral artery.

	AN-RN		AN-SA		RN-SA		AN-PCHA	
Nr.	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
1	?	?	2	1	0	0	4	4
2	?	?	4	?	1	?	3	?
3	?	?	2	?	0	?	3	?
4	?	?	1	1	1	1	3	3
5	?	?	1	2	0	1	3	2
6	2	1	2	1	1	1	2	3
7	2	3	2	1	1	1	4	3
8	3	1	1	1	1	1	3	3
9	3	2	1	1	0	1	3	3
10	2	3	1	1	1	0	3	3
11	2	2	2	2	0	1	2	2
12	1	2	1	1	0	0	4	2
13	2	1	1	1	1	1	3	3
14	2	2	2	2	2	2	2	3
15	2	3	2	1	1	0	4	4
16	2	3	2	1	1	1	3	3
17	3	2	1	1	0	0	3	3
18	3	3	1	1	0	0	4	3
19	2	2	1	1	1	1	3	4
20	2	1	2	1	1	1	2	3
21	1	3	2	1	1	1	4	3
22	3	1	1	1	1	1	3	3
23	1	1	1	1	1	1	3	3
24	3	2	1	1	2	1	4	3
25	2	1	2	1	1	1	4	3
26	2	1	1	1	1	1	4	3
27	1	3	1	1	1	0	3	3
28	2	1	1	1	0	0	3	3
29	1	1	1	1	0	1	4	3
30	2	1	2	1	1	1	3	3
31	2	1	1	1	0	0	3	3
32	2	3	1	1	1	1	4	3
33	2	1	2	1	1	1	3	3
34	2	1	1	1	0	1	2	3
35	2	2	1	1	1	1	3	3
36	2	2	1	1	1	1	4	3
37	2	3	1	1	1	1	4	3
38	2	2	2	1	1	1	4	4
39	1	1	1	1	1	1	2	3
40	2	1	1	1	0	0	3	4
41	1	1	1	1	1	1	3	3
42	2	1	1	1	0	0	2	3
43	1	3	1	2	0	2	3	2
44	1	?	1	1	1	1	4	3
45	?	1	?	1	?	1	?	3
46	?	1	?	1	?	1	?	3
47	2	2	1	1	1	1	4	3
48	2	2	1	1	0	1	4	4
49	2	2	1	1	1	1	4	4
50	2	2	1	1	0	1	3	2
51	0	0	1	1	0	0	3	3

Key	Description
0	Anterior
1	Posterior
2	Superior
3	Inferior
4	Medial
5	Lateral

Appendix C: Ethical approval documentation

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YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 22 May 2002 and Expires 03/20/2022.
- IRB 0000 2235 IORG0001762 Approved dd 22/04/2014 and Expires 03/14/2020.

13 November 2019

Approval Certificate
Annual Renewal

Ethics Reference No.: 428/2017
Title: Anatomical evaluation of the axillary approach to the axillary and radial nerves for nerve transfer or nerve grafting procedures

Dear Mr L Beytell

The **Annual Renewal** as supported by documents received between 2019-10-10 and 2019-11-06 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on its quorate meeting of 2019-11-06.

Please note the following about your ethics approval:

- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2020-11-13.
- Please remember to use your protocol number (428/2017) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

Dr R Sommers
MBChB MMed (Int) MPharmMed PhD
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

Research Ethics Committee
Room 4-60, Level 4, Tswelopele Building
University of Pretoria, Private Bag x323
Gezina 0031, South Africa
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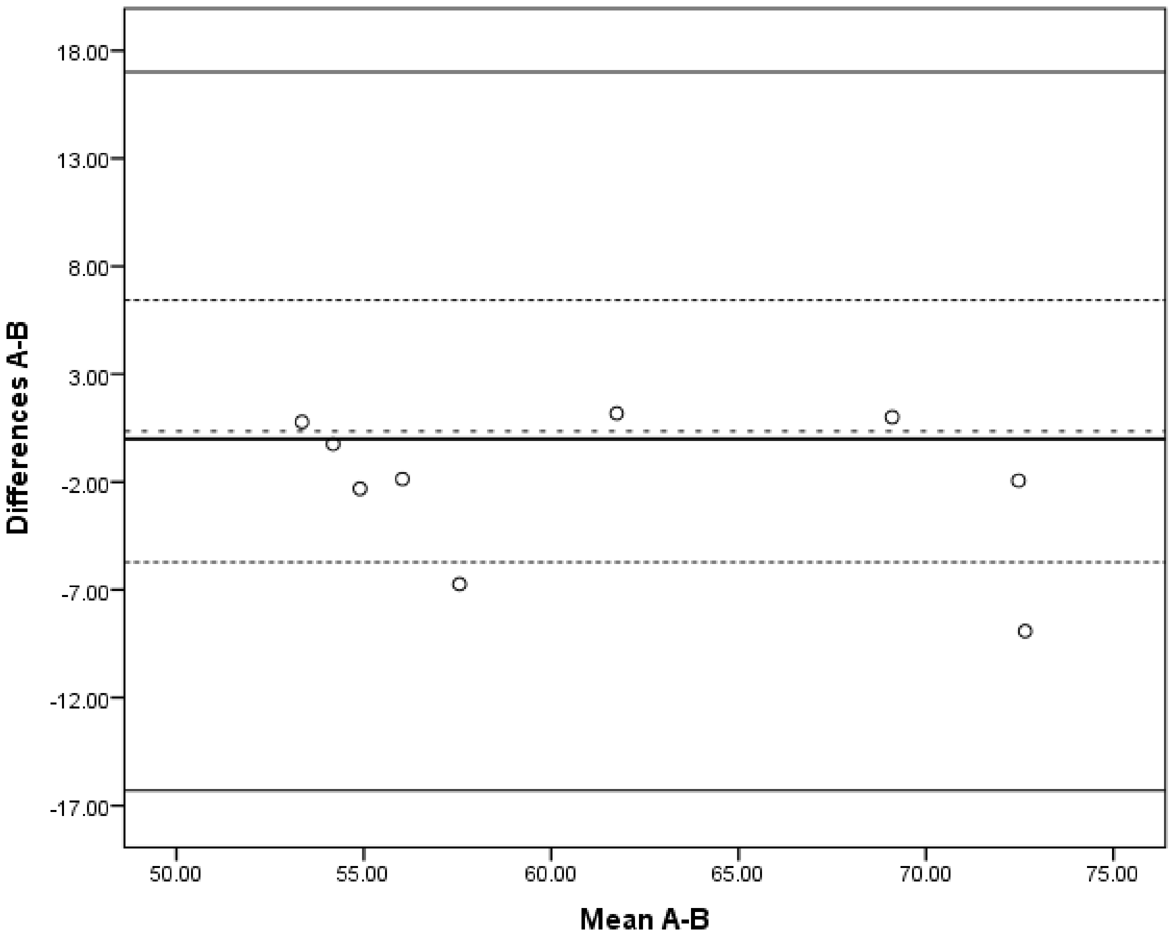
Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

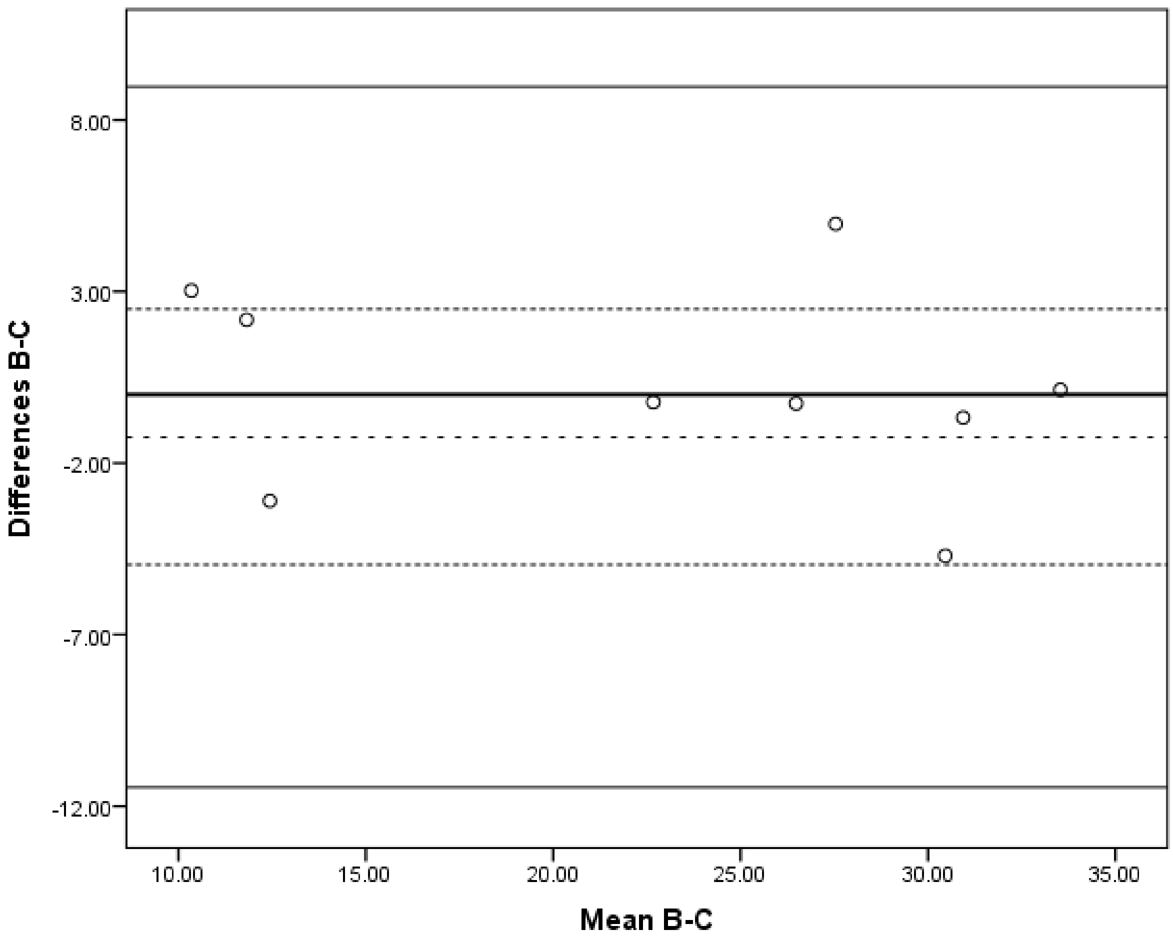
Appendix D: Inter- and intra-observer test graphs

Appendix D.1: Inter-observer tests

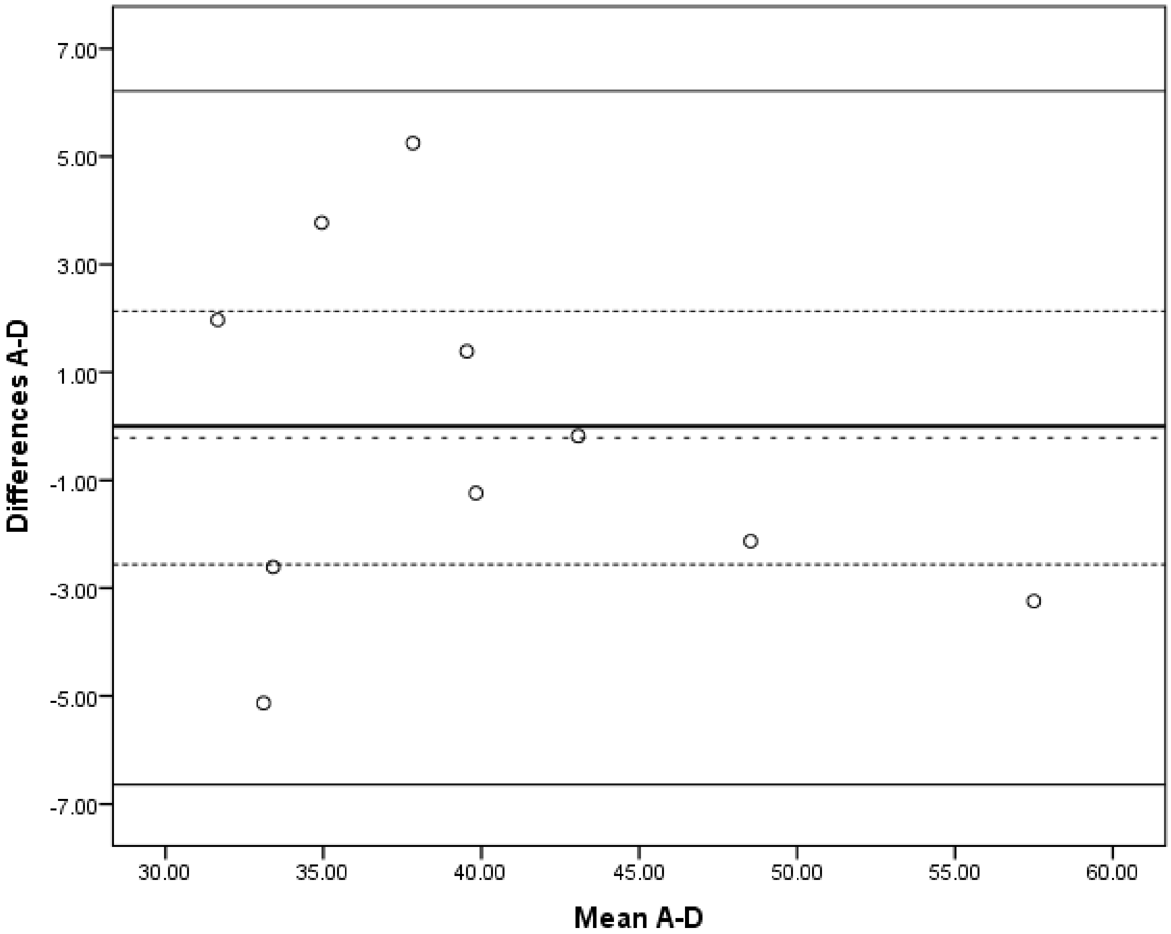
The Bland and Altman graphical method for the inter-observer test of the measurement A-B showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.



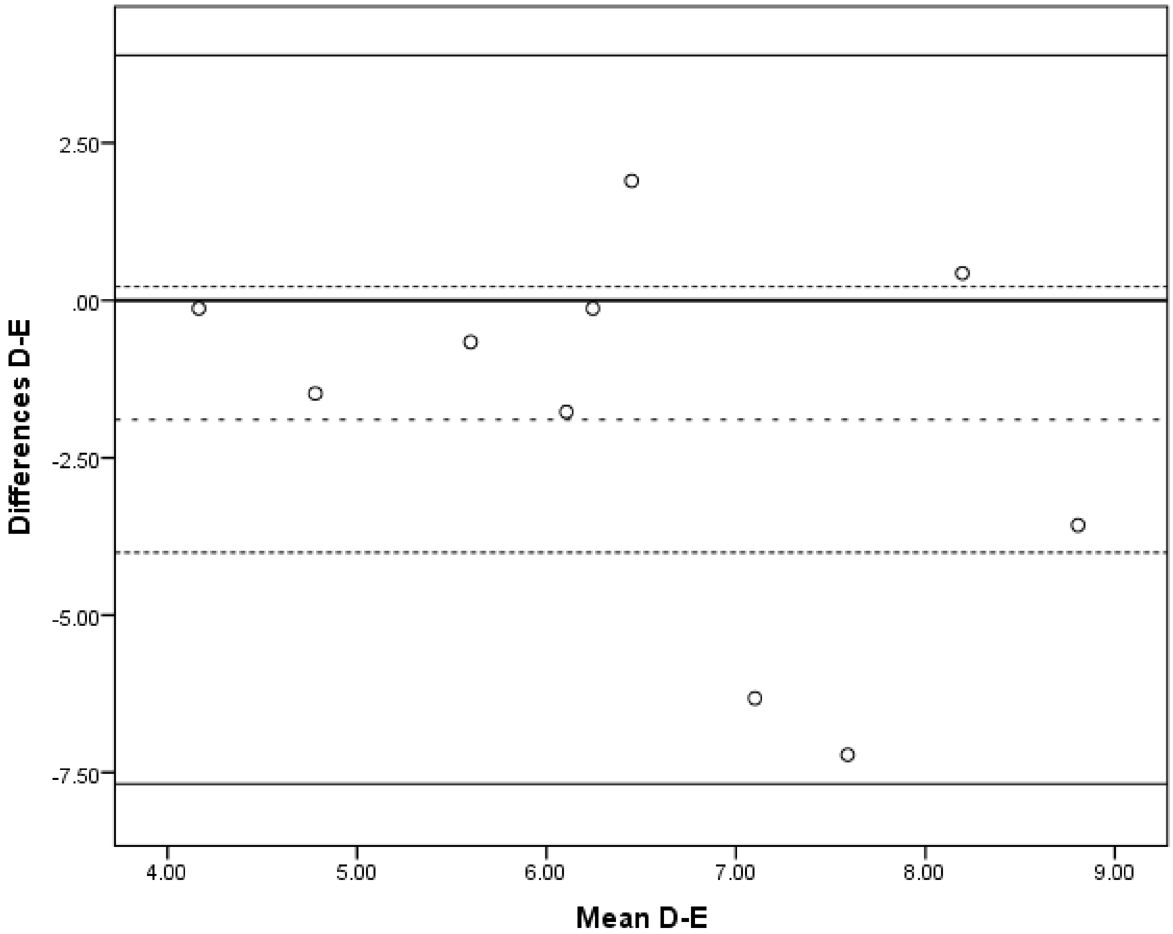
The Bland and Altman graphical method for the inter-observer test of the measurement B-C showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.



The Bland and Altman graphical method for the inter-observer test of the measurement A-D showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.

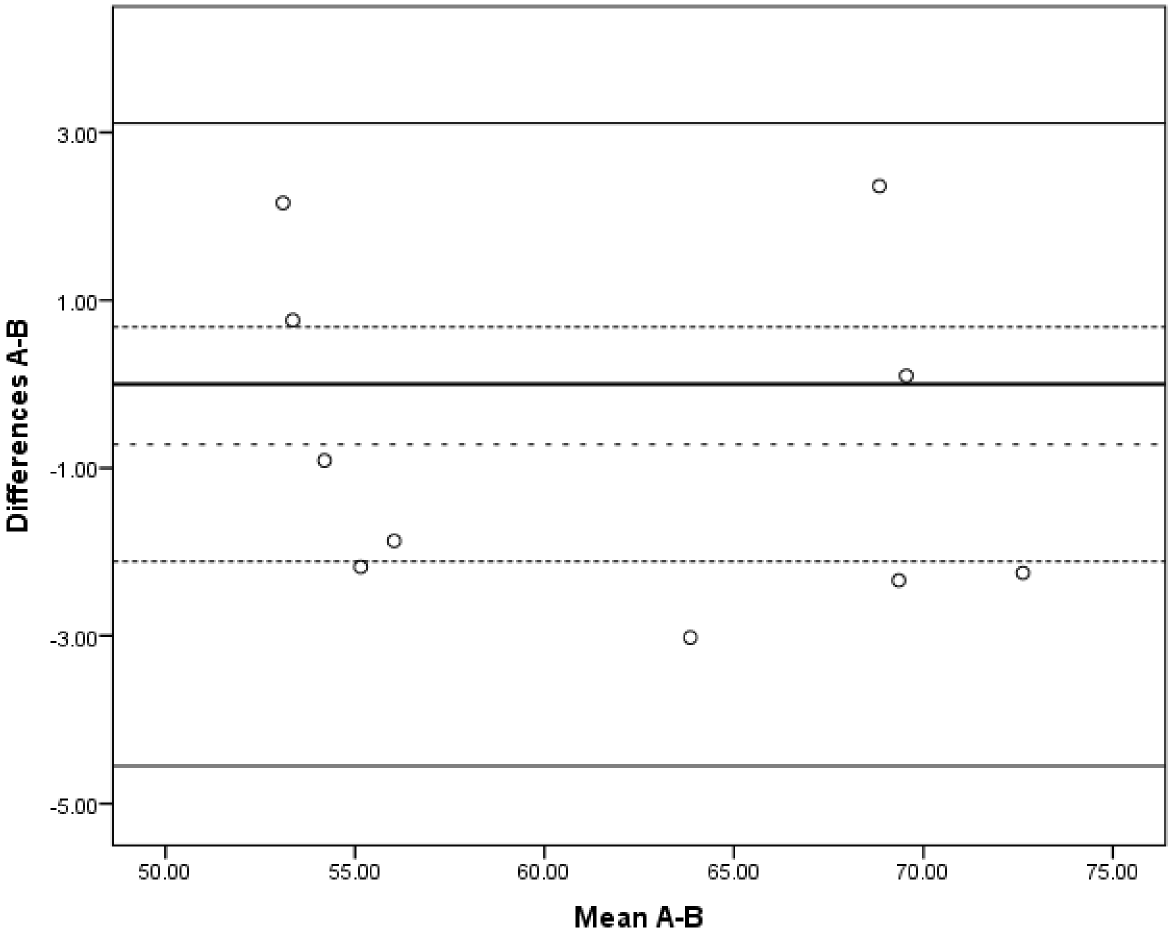


The Bland and Altman graphical method for the inter-observer test of the measurement D-E showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.

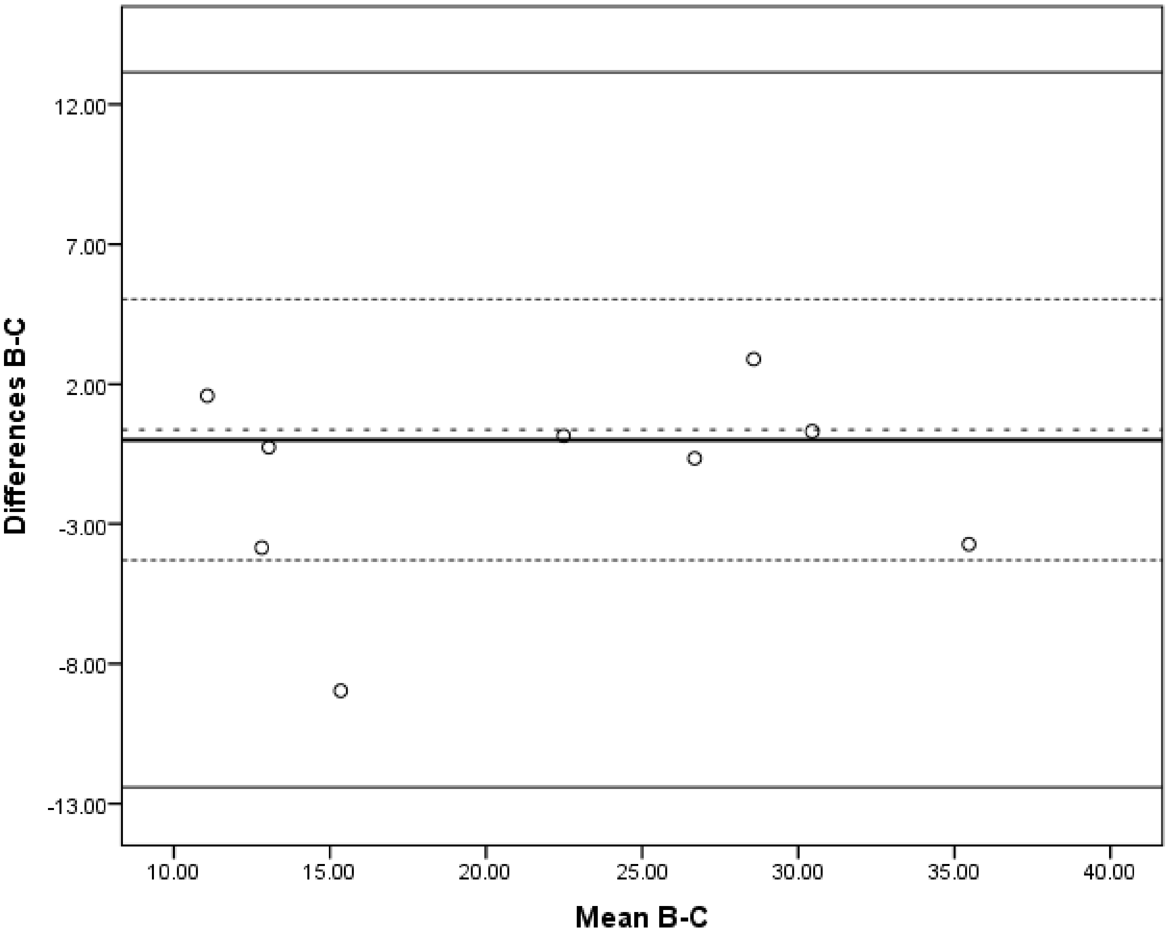


Appendix D.2: Intra-observer tests

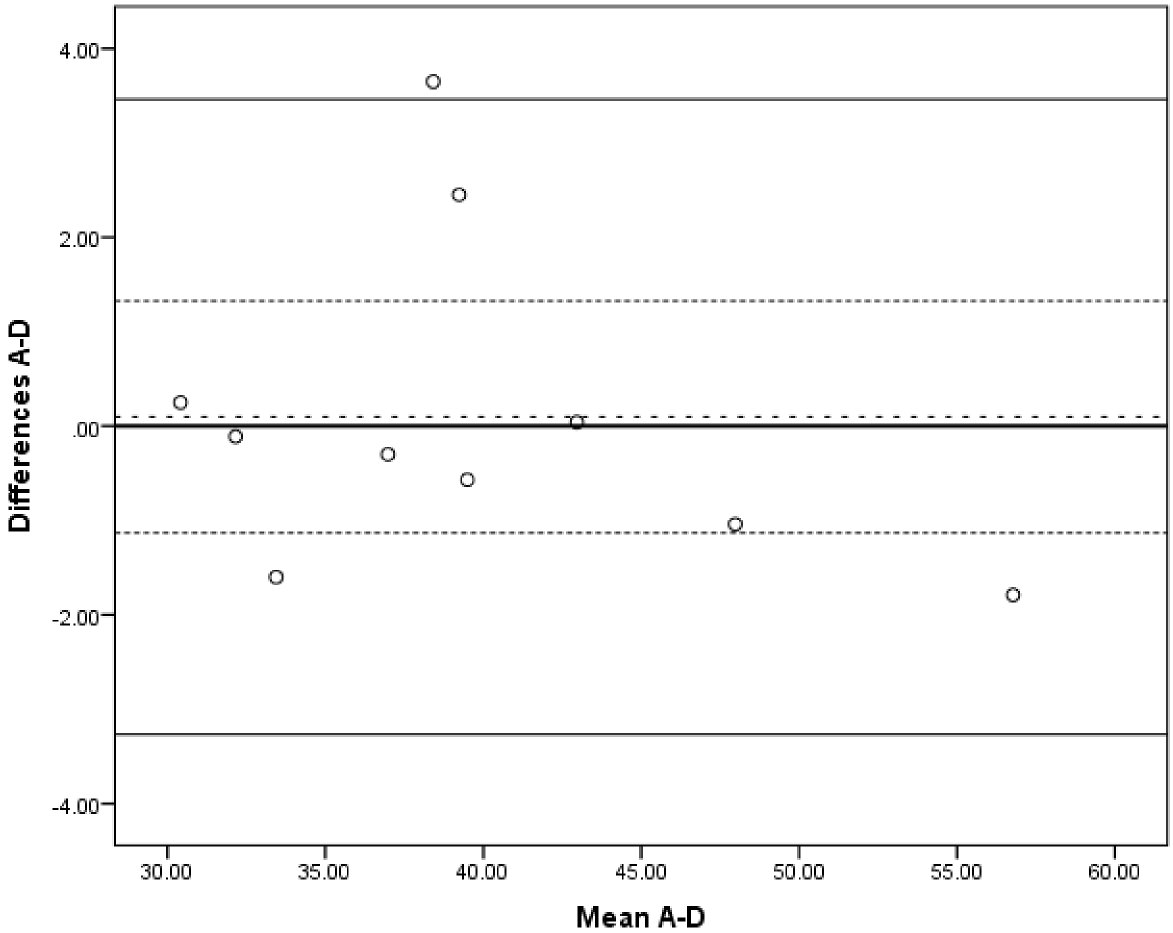
The Bland and Altman graphical method for the intra-observer test of the measurement A-B showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.



The Bland and Altman graphical method for the intra-observer test of the measurement B-C showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.



The Bland and Altman graphical method for the intra-observer test of the measurement A-D showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.



The Bland and Altman graphical method for the intra-observer test of the measurement D-E showing the upper and lower agreements as normal lines, 95% confidence interval as dashed lines, the mean as a dashed line with larger gaps and zero as a solid thick line.