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Cross-sectional area and echo intensity values of peripheral nerves: Ultrasonographic and cadaveric correlation

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Abstract

Introduction: Ultrasonography allows high-resolution visualisation of the peripheral nerves for quantitative and qualitative analyses. We report cross-sectional area values (quantitative measure) and echo intensity values (qualitative measure) for 46 peripheral nerve sites in upper and lower extremities in cadaveric specimens.

Objective: To determine cross-sectional area values and echo intensity values of peripheral nerves of upper and lower extremities at 46 nerve sites.

Methods: Nerve measurements were obtained using electronic callipers and ultrasonography for linear dimension and cross-sectional area measurements, respectively, in six cadaveric specimens for 46 peripheral nerve sites. Ultrasound images were further analysed to estimate echo intensity percentage values for 46 nerves.

Results: We present normal cross-sectional area values of various nerves of upper and lower extremities with their respective echo intensity values. Calculated cross-sectional area values from linear dimensions did not match the measured cross-sectional area values via trace method.

Conclusion: Cross-sectional area values (quantitative measure) and echo intensity values (qualitative measure) for 46 peripheral nerve sites in upper and lower extremities in cadaveric specimens are presented. The estimation of cross-sectional area via linear measurement is not a good approximation of the cross-sectional area (cross-sectional area measured by trace method on ultrasound image).

Keywords

Cadaveric, nerve cross-sectional area, echo intensity, ultrasonography, peripheral nerves

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Introduction

High-resolution ultrasonography is a safe, reliable, cost-effective and accurate tool that is increasingly used to screen, diagnose, monitor and facilitate treatment in peripheral nerve disorders. When used as an extension of clinical examination and as an adjunct to electrodiagnostic test, it provides structural perspective that may aid clinical decision-making. High-resolution ultrasonography allows detailed visualisation of nerve architecture, providing information concerning morphological alteration.[1] Changes in the size of the nerve as a consequence of a pathological process can be quantified by measuring cross-sectional area (CSA) which is the preferred measure that can quantify pathological changes in peripheral nerves.[2] In addition to CSA measurements, internal architecture can be studied and quantified by measuring echo intensity (EI) of nerves at various sites.[3]

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Table 1. Mean age and height of cadavers.

Variable	Mean	SD	Std. Err	95% confidence interval	
Age (years)	84.17	9.99	4.08	73.68	94.65
Height (inches)	68.25	5.21	2.13	62.78	73.72

SD: standard deviation.

EI is a measure of tissue composition or quality. EI is based on the concept that nerve tissue can be broadly divided into – (1) Fascicular tissue, mainly consisting of nerve tissue which appears hypoechoic on ultrasound (US) and (2) non-fascicular tissue consisting of connective tissue which appears hyperechoic on US. EI quantifies the mean pixel intensity in a defined region of interest and can provide important insight into changes in the internal architecture of the nerve as a result of pathological process.[4] Together, CSA and EI values can provide deeper insight into site-specific changes in nerves disorders. However, we need to first establish norms for CSA and EI for each nerve at various sites to understand the distribution of fascicular and non-fascicular (connective tissue) composition of the nerves.

CSA values reported in literature are mainly focused on common entrapment sites like carpal tunnel, cubital tunnel or tarsal tunnel. There is lack of data on CSA values for peripheral nerves except the commonly affected nerves in mononeuropathies. We aim to report the most comprehensive CSA, linear measurement and EI values for 46 nerve sites.

Figure 1. Nerve measurement in medial-lateral (ML) and anterior-posterior (AP) dimension using digital callipers.

Materials and methods

This study was approved by the Institutional Review Board (IRB) of Touro college #HSIRB 2112. We used six cadaver specimen, three male and three female for the measurement of linear dimensions (LDs), CSA and EI for 46 nerve sites. Table 1 shows mean age and height of cadavers.

Nerve and site selection was based on common compression sites, less common compression sites and optimal site for measurement of the nerves where compression sites are unknown.

LD measurement of peripheral nerves was measured using Neiko digital callipers (NEIKO 01407A Electronic Digital Calliper, China) with manufacture-reported accuracy of ±0.02 mm and repeatability measure of 0.01 mm. Each nerve was measured in medial-lateral (ML) and anterior-posterior (AP) dimension (Figure 1). When obtaining linear measurements with digital callipers, care was taken to measure the nerve without deforming it, applying enough pressure to keep the nerve between the calliper without altering its shape. Three measurements were obtained to calculate average linear measure in ML and AP dimension. Linear measurements were obtained by V.R.

Immediately following the manual linear measurements of the nerve using digital callipers, the nerve was imaged at the same site by another investigator (M.R.) using Konika Minolta HS1 (Sonimage HS1, Konica Minolta, Inc, Hino-shi, 191-8511 Japan) with linear probe of frequency range 4–18 Mhz. Parker laboratories Aquaflex Ultrasound Gel pad (Parker Laboratories Fairfield, NJ, USA) was placed above and below the nerve for optimal visualisation of the nerve in cadaver specimen (Figure 2) for CSA and EI measurements. For some nerve sites, gel pad was placed only on top of the nerve. Combination of gel and gel pad was used for optimal imaging keeping the same frequency (18 MHz) for all nerve imaging and same probe-to-nerve distance keeping nerve within 1.5 cm depth from the probe. Care was taken not to exert too much pressure to deform the nerve during probe placement. US images were obtained by MR for CSA and EI measurement. Both investigators worked in unison to first obtain

linear measurement and then US imaging at the same nerve site/region. Internal markers were used to ensure correct localisation of nerve and accuracy of CSA measurement using trace method.

US images were then processed to calculate EI at the same location where linear and CSA measurement were taken (Figures 3 and 4).

Quantitative assessment of nerve EI using high-resolution nerve ultrasonography is a new area. We measured EI measure of various peripheral nerves of upper and lower extremity in cadaveric specimen using automatic thresholding techniques reported by Boom and Visser.[5] We used freely available programme, Image J software (National Institutes of Health, Bethesda, MD, USA) for processing and analysing pixel intensity for EI calculation. Black and white pixels correspond to values between 0 and 255 arbitrary units, respectively. The images were converted to 8 bit and then automatic thresholding method (MaxEntropy) was used to select the hypoechoic areas within the nerve to calculate hypoechoic fraction as described by Boom and Visser.[5]

Figure 2. Ultrasound imaging of the nerve using linear probe of frequency range 4–18 Mhz. Ultrasound gel pad was placed above and below the nerve for optimal visualisation of the nerve in cadaver specimen.

Statistical methods

Data were analysed using descriptive statistics in Stata version 14 (StataCorp LP, College Station, TX). Descriptive statistics were employed to characterise the linear measurement data, the CSA data, and the EI percentage data across the six cadavers, for each of the 46 nerves. Data were reported for groups, plus individually for males and females. Spearman's rank correlation coefficients were employed to describe the relationship between each cadaver's measured and calculated CSA, for each individual nerve. Then, to determine measurement reliability for each rater, we estimated intra-class correlations (ICCs) using a two-way random effects model (absolute agreement).

Results

Table 1 reports means and 95% confidence intervals (CIs) for cadaveric specimen. Table 2 reports description of location for each nerve site where measurements (LD, CSA and EI) were obtained. Tables 3–5 report means and 95% CIs

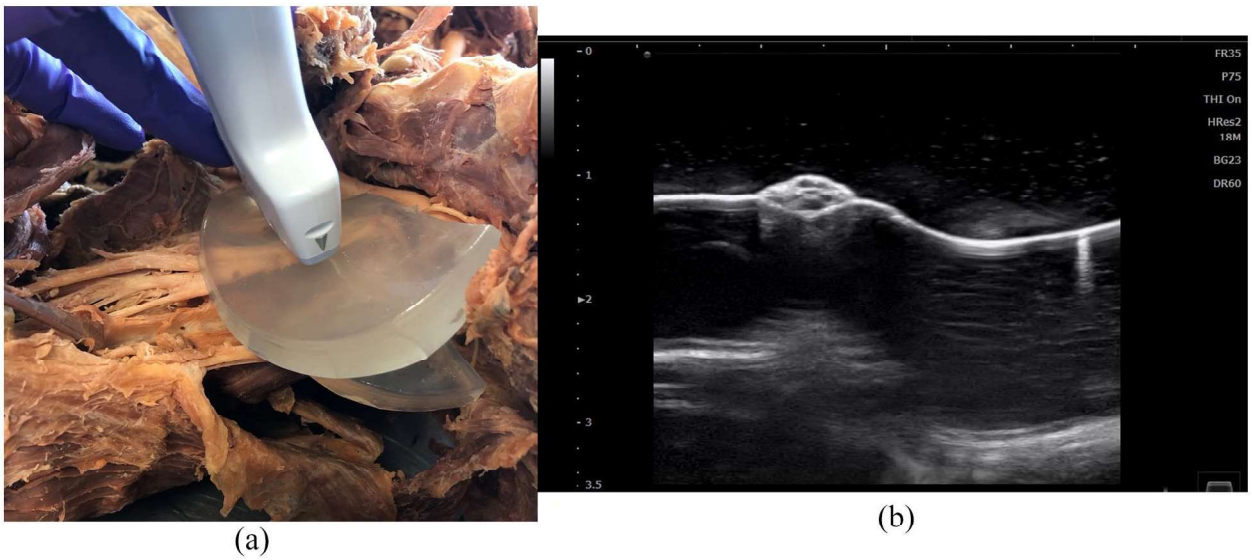

Figure 3. (a) Ultrasound image obtained at the same location where linear and cross-sectional area measurement were taken. (b) Corresponding ultrasound image which then processed to calculate echo intensity value.

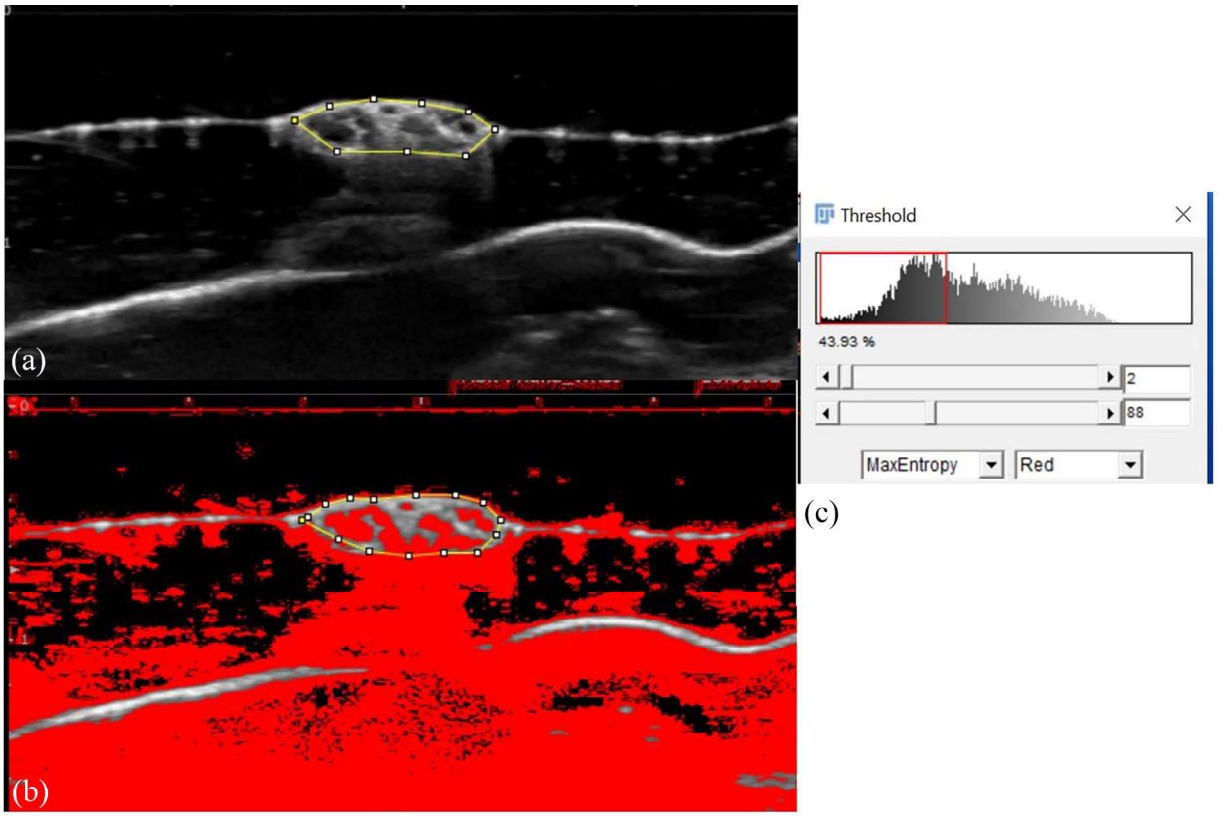

Figure 4. Quantitative assessment of nerve echo intensity: (a) cross-sectional ultrasound image of the nerve with region of interest manually selected and (b) Gaussian filter was used to enhance contrast between hypoechoic and hyperechoic areas within the nerve. Red area indicates area below threshold. (c) The threshold can be set manually by adjusting the sliding bar.

for each of the CSA, LD and percentage EI measures for each of the 46 nerves.

We tested the hypothesis that within each cadaver, the measured CSA would be significantly, positively related to the calculated CSA. Interestingly, less than one half of the nerves (20/46) exhibited a significant and strong positive relationship (see Table 6), suggesting that for the majority of nerves, the calculated CSA via linear measurement is not a good approximation of the measured CSA via trace method.

Finally, using a two-way random effects model, we found a strong correlation between raters over the 10 target nerves for both the linear (ICC = 0.978, 95% CI: 0.96–0.99, $p < 0.001$), and CSA measurements (ICC = 0.996, 95% CI: 987–0.999, $p < 0.001$; Figure 5). One investigator (V.R.) obtained linear measurements and another (M.R.) investigator obtained US imaging at the same site for CSA and EI measures. Both investigators have more than a decade of experience in respective skills.

Discussion

The purpose of this study was to report CSA values, EI values and LD values of peripheral nerves of upper and lower extremities at 46 nerve sites in cadavers. The use of CSA measurement is important role in the evaluation of peripheral nerve pathology and may be used as an adjunct to an electrodiagnostic evaluation. While CSA of various peripheral nerves have been reported in the literature, many studies report the measurement of the CSA at the most common site of entrapment (i.e. the median nerve at the wrist, ulnar nerve at the elbow, and fibular nerve at the knee). The CSA of the other nerve sites reported in this study may help inform clinicians evaluate peripheral nerve pathology that occur outside of the typical sites of focal entrapment.

In our study, we present the most comprehensive data on CSA and EI of 46 peripheral nerve sites in the upper and lower extremities. CSA for all upper and lower extremity nerves at all 46 nerve sites are reported in Table 3. The mean CSA reference values obtained in our cadaveric study appear to differ from previously reported values from Cartwright et al. and Kerasnoudis et al., and do fall within the reference ranges defined by Cartwright et al. as the mean ± 2 standard deviations.[2,6] A comparison of the results in our study compared to those obtained by previous authors is highlighted in Table 7. In our study, we examined six cadavers while other authors have examined CSA in healthy individuals. As highlighted by Kerasnoudis et al.,[2] several

Table 2. Description of the location for each nerve site where measurements were obtained.

Measured nerve	Description of location of measurement along the course
C5	Interscalene region
C6	Interscalene region
C7	Interscalene region
C8	Interscalene region
T1	Interscalene region
Lateral cord	Subpectoralis minor region
Medial cord	Subpectoralis minor region
Posterior cord	Subpectoralis minor region
Suprascap from upper trunk	Suprascapular nerve coming off of the upper trunk in supraclavicular region
Suprascap spino glenoid	Suprascapular nerve at the spino glenoid notch area
Axillary b/w subscap and CB	Axillary nerve between subscapularis and coracobrachialis (CB)
Axillary post. Br. quadr space	Axillary nerve posterior branch in quadrangular space
Musculocutaneous b/w SH & CB	Musculocutaneous nerve In the arm region between short head biceps (SH) brachii and coracobrachialis (CB)
LABC	Lateral antebrachial cutaneous (LABC) nerve in the anterior elbow region, lateral to distal biceps tendon
MABC	Medial antebrachial cutaneous (MABC) nerve at the medial mid-arm level
Radial spiral groove	Radial nerve at the spiral groove level
Ulnar ME	Ulnar nerve at the medial elbow next to the medial epicondyle (ME).
Radial motor elbow	Radial motor branch just proximal to arcade of frohse
Sup Br radial forearm	Superficial branch of radial nerve as it pierces the antebrachial fascia between ECRL and brachioradialis tendons, about 10 cm proximal from radial styloid process
Median elbow	Median nerve at the elbow joint level, medial to brachial artery
Median forearm	Median nerve at the mid-forearm level between flexor digitorum profundus and flexor digitorum superficialis muscles
Median wrist	Median nerve at the level of pisiform
Ulnar Guyon	Ulnar nerve in guyons canal
DUC 8 cm prox to ulna distal end	Dorsal ulnar cutaneous (DUC) nerve at 8 cm proximal from the distal ulnar head
LFCN	Lateral femoral cutaneous nerve (LFCN) at the level of ASIS (anterior superior iliac spine)
Ilioinguinal	Ilioinguinal nerve between internal and external oblique muscle, approximately 5 cm proximal to ASIS (anterior superior iliac spine)
Iliohypogastric	Iliohypogastric nerve between internal and external oblique muscle, approximately 5 cm proximal to ASIS (anterior superior iliac spine)

(Continued)

Table 2. (Continued)

Measured nerve	Description of location of measurement along the course
Femoral	Femoral nerve in the inguinal canal
Saphenous	Saphenous nerve in femoral triangle
Obturator	Obturator nerve as it exits the pelvis between pectineus and obturator externus before dividing into anterior and posterior divisions
Pudendal	Pudendal nerve overlying lesser sciatic notch
Sciatic piri	Sciatic nerve under the piriformis (piri) muscle
Sciatic post thigh	Sciatic nerve posteriorly at the mid-thigh level
Tibial pop	Tibial nerve at the proximal end of popliteal fossa (pop), as it branches off from main sciatic nerve
Common fib. pop	Common fibular nerve at the proximal end of popliteal fossa, as it branches off from main sciatic nerve
Common fib. fib head	Common fibular nerve at the level of fibular head
Deep fib. fib neck	Deep fibular nerve at the fibular neck level after branching off from common fibular nerve
Superficial fib. fib neck	Superficial fibular nerve at the fibular neck level after branching off from common fibular nerve
Sural	Sural nerve 14 cm proximal to lateral malleolus as it overlies proximal Achilles tendon
Saphenous N LL	Saphenous nerve in the lower leg (LL) at the medial aspect of tibia 14 cm proximal to medial malleolus
Superficial fib. sensory LL	Superficial fibular sensory at the lower leg (LL) 14 cm proximal to lateral malleolus
Deep fibular ankle	Deep fibular nerve at the level of anterior ankle
Tibial ankle	Tibial nerve in the tarsal tunnel level
Medial plantar	Medial plantar nerve as it branches off from tibial nerve
Lateral plantar	Lateral plantar nerve as it branches off from tibial nerve
Baxter	Baxter nerve or first branch of lateral plantar nerve as it branches off from main nerve at the medial ankle

studies only included unilateral measurements of the nerves which can impact the variance of the values reported. In addition, the CSA of certain nerves was larger than that expected in normal subjects for example ulnar nerve at the elbow. The average CSA of the ulnar nerve at the medial elbow in our study was 12 mm^2, while Kerasnoudis et al. reported an average CSA of 5.33 ± 1.4 mm^2 with a range of 2.53–8.13 mm^2. This increase in nerve CSA is likely due to pre-existing common focal neuropathy or non-clinical age-related focal changes in the size of the nerve at common site of entrapment.

EI is a measure of mean pixel intensity of a specific region of interest from US images. Changes in EI are believed to be caused by intraneural fibrous connective tissue which may be implicated in certain pathological processes. While the utility of EI is recent, previous literature has demonstrated good validity and reliability.[7]

EI measurement is a way of studying intraneural topography for which ultrasonography is appropriate examination tool. Kubiena et al.[8] reported good correlation of histologic findings with intraneural topography seen on US.

Table 3. Means and 95% confidence intervals for cross-sectional area (CSA) measures (cm^2) for each of the 46 nerves.

Nerve and site	Mean (cm^2)	SD	Std. Err.	95% confidence interval	
C5	0.06	0.04	0.02	0.02	0.11
C6	0.13	0.05	0.02	0.08	0.18
C7	0.16	0.04	0.01	0.12	0.19
C8	0.14	0.03	0.01	0.11	0.16
T1	0.07	0.02	0.01	0.05	0.09
Lateral cord	0.15	0.04	0.02	0.11	0.19
Medial cord	0.17	0.03	0.01	0.14	0.20
Posterior cord	0.23	0.04	0.02	0.19	0.27
Supra scap from upper trunk	0.03	0.01	0.00	0.02	0.05
Suprascap spino glenoid	0.03	0.01	0.00	0.02	0.04
Axillary b/w subscap and CB	0.06	0.02	0.01	0.04	0.07
Axillary post. Br. quadr space	0.10	0.07	0.03	0.03	0.17
Musculocutaneous b/w SH and CB	0.04	0.01	0.01	0.02	0.05
LABC	0.04	0.02	0.01	0.02	0.06
MABC	0.03	0.01	0.00	0.02	0.04
Radial spiral groove	0.10	0.03	0.01	0.06	0.13
Ulnar ME	0.12	0.04	0.02	0.08	0.16
Radial motor elbow	0.06	0.02	0.01	0.04	0.07
Sup Br radial forearm	0.04	0.01	0.01	0.02	0.05
Median elbow	0.12	0.02	0.01	0.10	0.14
Median forearm	0.06	0.01	0.01	0.05	0.08
Median wrist	0.12	0.02	0.01	0.10	0.14
Ulnar Guyon	0.07	0.01	0.01	0.06	0.09
DUC 8 cm prox to ulna distal end	0.03	0.03	0.01	−0.01	0.06
LFCN	0.02	0.01	0.01	0.01	0.04
Ilioinguinal	0.02	0.01	0.00	0.01	0.03
Iliohypogastric	0.03	0.01	0.00	0.01	0.04
Femoral	0.18	0.05	0.02	0.12	0.23
Saphenous	0.05	0.03	0.01	0.02	0.08
Obturator	0.06	0.01	0.01	0.04	0.07
Pudendal	0.02	0.02	0.01	0.00	0.04
Sciatic piri	0.63	0.27	0.11	0.34	0.91

(Continued)

Table 3. (Continued)

Nerve and site	Mean (cm^2)	SD	Std. Err.	95% confidence interval	
Sciatic post thigh	0.44	0.15	0.06	0.28	0.60
Tibial pop	0.26	0.12	0.05	0.14	0.38
Common fib. pop	0.15	0.08	0.03	0.06	0.24
Common fib. fib head	0.15	0.05	0.02	0.10	0.20
Deep fib. fib neck	0.06	0.03	0.01	0.02	0.09
Superficial fib. fib neck	0.12	0.06	0.02	0.06	0.18
Sural	0.03	0.02	0.01	0.01	0.05
Saphenous N LL	0.02	0.01	0.01	0.00	0.03
Superficial fib. sensory LL	0.02	0.01	0.00	0.01	0.04
Deep fib. ankle	0.03	0.02	0.01	0.01	0.05
Tibial ankle	0.16	0.06	0.02	0.10	0.22
Medial plantar	0.08	0.03	0.01	0.05	0.11
Lateral plantar	0.07	0.02	0.01	0.05	0.10
Baxter	0.02	0.01	0.01	0.01	0.04

SD: standard deviation; CB: coracobrachialis; SH: short head; LABC: lateral antebrachial cutaneous; MABC: medial antebrachial cutaneous; ME: medial epicondyle; DUC: dorsal ulnar cutaneous; LFCN: lateral femoral cutaneous nerve; N: nerve; LL: lower leg.

This is the first study to report reference values of quantitative EI of multiple sites of peripheral nerves in the upper and lower extremities. EI of the recorded nerve sites are reported in Table 5. There were no significant differences between EI between male and female cadavers. It should be noted that measurements were only recorded in six cadavers. This suggests there may not have been sufficient subjects to detect differences that may exist resulting in type II error. We noted EI measures of lower extremity nerves were lower than upper extremity nerves which correlate well with higher non-fascicular component in lower-extremity nerves compared to upper extremity nerves. Similar trend was noted in proximal versus distal sites where lower EI values were observed distally which correlates well with the nerve architecture quantification studies by Moayeri and Groen[9] and Moayeri et al.[10] EI measures along with CSA measurements provide complete picture of nerve structure which differs in upper and lower extremity nerves and at various sites of the same nerve as it courses from proximal to distal in the limb.

Previously, several studies have examined EI of peripheral nerves in healthy subjects and subjects with neuropathy, but these are often recorded in frequent entrapment sites of focal neuropathy and often ignore other sites of nerves that could be subject to trauma or pathologic changes. The clinical application of this technique should be subject to future studies examining EI across these sites in healthy human subjects before normative values for each nerve can be determined.

The last aim of our study was to compare calculated CSA values from LDs to measured CSA values obtained by ultrasonography. LDs of peripheral nerve sites are reported in Table 4. The calculated CSA of various measurement sites using linear measurements was only significantly correlated to measured CSA in approximately 43% of nerve sites (Table 6).

A possible explanation for the difference noted in our reporting of measured CSA and calculated CSA using linear measurements via callipers is that the calculated CSA from linear measurement assume long and short axis for area calculation which may not be the accurate representation of the area as nerve is rarely a perfect circle or oval in short-axis view of US image. This may lead to a CSA measurement that is an underestimation or overestimation of the CSA via linear measurement. On the contrary, trace measure of CSA (measured CSA) considers the actual shape of the nerve which may accurately depict the complete nerve anatomy. It is important to establish the correct method of CSA measurements before we establish the CSA norms for various nerves.

Table 4. Means and 95% confidence intervals for linear dimension (LD) measures (mm) for each of the 46 nerves.

Nerve and site	Mean (mm)	SD	Std. Err.	95% confidence interval	
C5 M/L	3.40	1.61	0.66	1.71	5.09
C5 A/P	1.75	0.54	0.22	1.18	2.32
C6 M/L	5.37	1.78	0.73	3.50	7.24
C6 A/P	2.68	0.50	0.20	2.16	3.21
C7 ML	4.89	1.84	0.75	2.96	6.83
C7 AP	2.91	0.75	0.31	2.11	3.70
C8 ML	4.78	1.44	0.59	3.26	6.29
C8 AP	2.53	0.42	0.17	2.08	2.97
T1 ML	4.53	1.97	0.80	2.46	6.60
T1 AP	2.24	0.72	0.29	1.49	3.00
Lateral cord ML	4.82	1.17	0.48	3.59	6.05
Lateral cord AP	2.59	0.42	0.17	2.15	3.04
Medial cord ML	4.73	0.37	0.15	4.35	5.12
Medial cord AP	3.04	0.43	0.18	2.58	3.49
Posterior cord ML	6.73	1.26	0.51	5.41	8.05
Posterior cord AP	3.94	0.52	0.21	3.39	4.48
Supra scap from upper trunk ML	2.08	0.49	0.20	1.56	2.59
Supra scap from upper trunk AP	1.31	0.30	0.12	0.99	1.63
Suprascap spino glenoid ML	2.63	0.72	0.29	1.87	3.39
Suprascap spino glenoid AP	0.59	0.16	0.07	0.42	0.76
Axillary b/w subscap and CB ML	3.99	0.83	0.34	3.12	4.86
Axillary b/w subscap and CB AP	1.36	0.35	0.14	1.00	1.72
Axillary post. Br. quadr space ML	3.04	1.75	0.71	1.20	4.87
Axillary post. Br. quadr space AP	1.76	1.48	0.60	0.20	3.31
Musculocutaneous b/w SH & CB ML	2.92	0.65	0.27	2.23	3.60
Musculocutaneous b/w SH & CB AP	1.27	0.34	0.14	0.90	1.63
LABC ML	2.52	0.62	0.25	1.87	3.17
LABC AP	0.63	0.29	0.12	0.33	0.94
MABC ML	2.46	0.62	0.25	1.81	3.11
MABC AP	0.70	0.15	0.06	0.55	0.86
Radial spiral groove ML	4.16	1.29	0.53	2.80	5.51

(Continued)

Table 4. (Continued)

Nerve and site	Mean (mm)	SD	Std. Err.	95% confidence interval	
Radial spiral groove AP	1.59	0.19	0.08	1.39	1.78
Ulnar ME ML	3.72	0.50	0.20	3.20	4.25
Ulnar ME AP	2.43	0.38	0.15	2.04	2.83
Radial motor elbow ML	4.18	1.34	0.55	2.77	5.58
Radial motor elbow AP	1.18	0.34	0.14	0.82	1.53
Sup Br radial forearm ML	2.70	0.82	0.34	1.83	3.56
Sup Br radial forearm AP	0.93	0.25	0.10	0.67	1.19
Median elbow ML	4.78	0.92	0.38	3.81	5.74
Median elbow AP	2.57	0.71	0.29	1.82	3.31
Median forearm ML	3.00	0.54	0.22	2.43	3.57
Medial forearm AP	1.55	0.26	0.11	1.27	1.83
Median wrist ML	5.33	1.41	0.57	3.86	6.80
Median wrist AP	2.02	0.44	0.18	1.55	2.48
Ulnar Guyon ML	2.88	0.79	0.32	2.04	3.71
Ulnar Guyon AP	1.80	0.24	0.10	1.55	2.05
DUC 8 cm prox to ulna distal end ML	1.93	1.18	0.48	0.69	3.16
DUC 8 cm prox to ulna distal end AP	0.73	0.32	0.13	0.39	1.07
LFCN ML	1.85	0.99	0.41	0.81	2.90
LFCN AP	0.71	0.41	0.17	0.27	1.14
Ilioinguinal ML	1.40	0.96	0.43	0.21	2.59
Ilioinguinal AP	0.60	0.32	0.14	0.21	1.00
Iliohypogastric ML	2.27	0.79	0.35	1.29	3.25
Iliohypogastric AP	0.97	0.40	0.18	0.48	1.47
Femoral ML	7.38	1.95	0.79	5.34	9.42
Femoral AP	2.24	0.64	0.26	1.57	2.91
Saphenous ML	2.58	1.11	0.45	1.42	3.74
Saphenous AP	0.90	0.42	0.17	0.45	1.34
Obturator ML	2.55	1.01	0.41	1.48	3.61
Obturator AP	1.35	0.28	0.11	1.06	1.64
Pudendal ML	2.12	0.63	0.26	1.45	2.78
Pudendal AP	0.67	0.19	0.08	0.47	0.87

(Continued)

Table 4. (Continued)

Nerve and site	Mean (mm)	SD	Std. Err.	95% confidence interval	
Sciatic piri ML	13.76	2.60	1.06	11.03	16.49
Sciatic piri AP	5.86	1.25	0.51	4.55	7.17
Sciatic post thigh ML	8.44	1.81	0.74	6.54	10.33
Sciatic post thigh AP	4.93	1.65	0.68	3.19	6.67
Tibial pop ML	5.63	1.78	0.73	3.76	7.51
Tibial pop AP	3.79	1.01	0.41	2.73	4.85
Common fib. pop ML	4.45	1.94	0.79	2.41	6.49
Common fib. pop AP	2.43	0.72	0.29	1.67	3.18
Common fib. fib head ML	6.10	1.42	0.58	4.61	7.59
Common fib. fib head AP	2.02	0.45	0.18	1.54	2.49
Deep fib. fib neck ML	2.85	1.21	0.50	1.57	4.12
Deep fib. fib neck AP	0.77	0.18	0.07	0.58	0.95
Superficial fib. fib neck ML	4.75	1.36	0.56	3.32	6.18
Superficial fib. fib neck AP	1.64	0.48	0.20	1.13	2.15
Sural ML	2.22	0.83	0.34	1.35	3.09
Sural AP	0.64	0.16	0.06	0.47	0.80
Saphenous N LL ML	1.27	0.52	0.21	0.72	1.81
Saphenpous LL AP	0.44	0.14	0.06	0.29	0.58
Superficial fib. sensory LL ML	1.65	0.65	0.27	0.97	2.33
Superficial fib. sensory LL AP	0.76	0.18	0.07	0.57	0.95
Deep fib ankle ML	2.30	0.70	0.29	1.57	3.04
Deep fib ankle AP	0.71	0.13	0.05	0.57	0.85
Tibial ankle ML	5.46	1.36	0.55	4.03	6.89
Tibial ankle AP	2.10	0.52	0.21	1.55	2.64
Medial plantar ML	3.27	0.75	0.31	2.49	4.06
Medial plantar AP	1.55	0.28	0.11	1.26	1.84
Lateral plantar ML	3.24	0.41	0.17	2.81	3.68
Lateral plantar AP	1.53	0.41	0.17	1.11	1.96
Baxter ML	1.49	0.57	0.23	0.89	2.08
Baxter AP	0.57	0.17	0.07	0.39	0.76

SD: standard deviation; ML: medial-lateral; AP: anterior-posterior; CB: coracobrachialis; SH: short head; LABC: lateral antebrachial cutaneous; MABC: medial antebrachial cutaneous; ME: medial epicondyle; DUC: dorsal ulnar cutaneous; LFCN: lateral femoral cutaneous nerve; N: nerve; LL: lower leg.

Table 5. Means and 95% confidence intervals for Echo Intensity (EI) measures for each of the 46 nerves.

Nerve and site	Mean	SD	Std. Err.	95% confidence interval	
C5	59.91	5.10	2.08	54.56	65.26
C6	63.35	9.39	3.83	53.50	73.20
C7	56.44	6.19	2.53	49.94	62.93
C8	54.00	3.88	1.58	49.93	58.08
T1	60.49	5.94	2.42	54.26	66.72
Lateral cord	54.52	8.55	3.49	45.54	63.49
Medial cord	62.10	7.78	3.17	53.94	70.26
Posterior cord	50.65	4.70	1.92	45.72	55.59
Supra scap from upper trunk	44.34	13.41	5.47	30.27	58.41
Suprascap spino glenoid	13.99	4.96	2.03	8.78	19.19
Axillary b/w subscap and CB	48.87	7.73	3.16	40.76	56.98
Axillary post. Br. quadr space	33.22	5.71	2.33	27.23	39.21
Musculocutaneous b/w SH & CB	45.18	13.55	5.53	30.96	59.40
LABC	28.30	8.24	3.37	19.65	36.95
MABC	35.43	10.89	4.44	24.01	46.86
Radial spiral groove	39.86	9.74	3.98	29.64	50.09
Ulnar ME	62.43	4.61	1.88	57.59	67.28
Radial motor elbow	36.43	8.07	3.29	27.96	44.89
Sup Br radial forearm	35.77	13.24	5.41	21.87	49.67
Median elbow	53.72	7.15	2.92	46.22	61.22
Median forearm	53.56	9.33	3.81	43.77	63.36
Median wrist	60.65	6.18	2.52	54.17	67.13
Ulnar Guyon	48.13	6.51	2.66	41.30	54.97
DUC 8 cm prox to ulna distal end	30.86	9.04	3.69	21.37	40.35
LFCN	27.69	11.54	4.71	15.58	39.80
Ilioinguinal	24.59	10.12	4.53	12.02	37.16
Iliohypogastric	28.43	8.76	3.92	17.56	39.31
Femoral	42.12	3.72	1.52	38.22	46.02
Saphenous	30.91	9.80	4.00	20.62	41.19
Obturator	46.53	4.93	2.01	41.35	51.70

(Continued)

Table 5. (Continued)

Nerve and site	Mean	SD	Std. Err.	95% confidence interval	
Pudendal	25.15	6.72	2.74	18.10	32.20
Sciatic piri	48.30	3.67	1.50	44.45	52.15
Sciatic post thigh	46.67	5.80	2.37	40.58	52.76
Tibial pop	49.03	7.61	3.11	41.04	57.01
Common fib. pop	41.49	4.06	1.66	37.23	45.76
Common fib. fib head	36.09	3.82	1.56	32.08	40.10
Deep fib. fib neck	24.44	6.66	2.72	17.44	31.43
Superficial fib. fib neck	28.43	5.61	2.29	22.54	34.31
Sural	27.60	5.54	2.26	21.78	33.42
Saphenous N LL	20.66	8.59	3.51	11.64	29.67
Superficial fib. sensory LL	26.51	7.96	3.25	18.16	34.87
Deep fib. ankle	30.39	5.88	2.40	24.22	36.56
Tibial ankle	39.70	6.94	2.83	32.42	46.98
Medial plantar	46.48	5.15	2.10	41.08	51.89
Lateral plantar	38.63	11.56	4.72	26.49	50.76
Baxter	22.18	8.86	3.62	12.88	31.48

SD: standard deviation; CB: coracobrachialis; SH: short head; LABC: lateral antebrachial cutaneous; MABC: medial antebrachial cutaneous; ME: medial epicondyle; DUC: dorsal ulnar cutaneous; LFCN: lateral femoral cutaneous nerve; N: nerve; LL: lower leg.

In addition, the use of linear measurements to calculate approximate CSA via US calculation methods, that is, ellipse tool may not accurately represent the peripheral nerve CSA due to the nature of peripheral nerve structure. Traditional CSA measurements operate under the assumption that peripheral nerves are elliptical in shape and use M-L and A-P measurements across the two elliptical axes to calculate CSA. Similar calculations are used when ellipse tool is used instead of trace method for CSA measurement. Peripheral nerves are subject to a number of external forces as they pass through a variety of anatomic structures to reach their end organ. This normal anatomic course, in the presence or absence of pathology, may distort the nerve away from an elliptical shape, thus changing the CSA.

Limitations

Limitations of this study include the small sample size and the use of cadavers. Although similar values were reported from previous studies, the external generalisability of our results is unknown. Future research should seek to determine baseline data of CSA and EI in healthy humans.

Conclusion

In conclusion, this is the first study to record CSA and EI as quantitative and qualitative measures of multiple nerve sites in the lower and upper extremities. We report a discrepancy of measured CSA compared to calculated CSA from linear measurements which may lead to an overestimation or underestimation of the CSA. We suggest the use of trace method for CSA measurement rather than the ellipse tool as peripheral nerves are subject to a number of external forces that may distort the nerve away from an elliptical shape, thus changing the CSA.

Table 6. Measured versus calculated CSA correlations.

Nerve and site	Correlation coefficient (rho)	*p* value
C5	**0.986**	$p < 0.001$
C6	0.377	$p = 0.462$
C7	0.493	$p = 0.321$
C8	0.377	$p = 0.462$
T1	**0.841**	$p = 0.036$
Lateral cord	**0.841**	$p = 0.036$
Medial cord	–0.058	$p = 0.913$
Posterior cord	0.116	$p = 0.827$
Supra scap from upper trunk	0.000	$p = 1.00$
Suprascap spino glenoid	0.617	$p = 0.192$
Axillary b/w subscap and CB	0.516	$p = 0.295$
Axillary post. Br. quadr space	**0.899**	$p = 0.0149$
Musculocutaneous b/w SH & CB	**0.883**	$p = 0.020$
LABC	**0.837**	$p = 0.0378$
MABC	0.34	$p = 0.5104$
Radial spiral groove	0.638	$p = 0.1731$
Ulnar ME	**0.899**	$p = 0.0149$
Radial motor elbow	0.486	$p = 0.329$
Sup Br radial forearm	0.5	$p = 0.312$
Median elbow	0.53	$p = 0.280$
Median forearm	**0.941**	$p = 0.005$
Median wrist	**0.812**	$p = 0.0499$
Ulnar Guyon	**0.841**	$p = 0.036$
DUC 8 cm prox to ulna distal end	**0.939**	$p = 0.0054$
LFCN	**0.926**	$p = 0.008$
Ilioinguinal	0.527	$p = 0.362$
Iliohypogastric	0.707	$p = 0.182$
Femoral	0.754	$p = 0.084$
Saphenous	**0.971**	$p = 0.0012$
Obturator	0.741	$p = 0.092$
Pudendal	0.463	$p = 0.355$

(Continued)

Table 6. (Continued)

Nerve and site	Correlation coefficient (rho)	*p* value
Sciatic piri	**0.943**	$p = 0.005$
Sciatic post thigh	**1.000**	$p < 0.001$
Tibial pop	0.6	$p = 0.208$
Common fib. pop	**1.000**	$p < 0.001$
Common fib. fib head	**0.928**	$p = 0.0077$
Deep fib. fib neck	**0.812**	$p = 0.0499$
Superficial fib. fib neck	−0.029	$p = 0.9572$
Sural	**0.883**	$p = 0.0198$
Saphenous N LL	0.655	$p = 0.158$
Superficial fib. sensory LL	0.618	$p = 0.191$
Deep fib. ankle	0.463	$p = 0.355$
Tibial ankle	0.559	$p = 0.249$
Medial plantar	0.577	$p = 0.231$
Lateral plantar	0.754	$p = 0.084$
Baxter	**0.926**	$p = 0.008$

Bold text represents statistically significant.
CSA: cross-sectional area; CB: coracobrachialis; SH: short head; LABC: lateral antebrachial cutaneous; MABC: medial antebrachial cutaneous; ME: medial epicondyle; DUC: dorsal ulnar cutaneous; LFCN: lateral femoral cutaneous nerve; N: nerve; LL: lower leg.

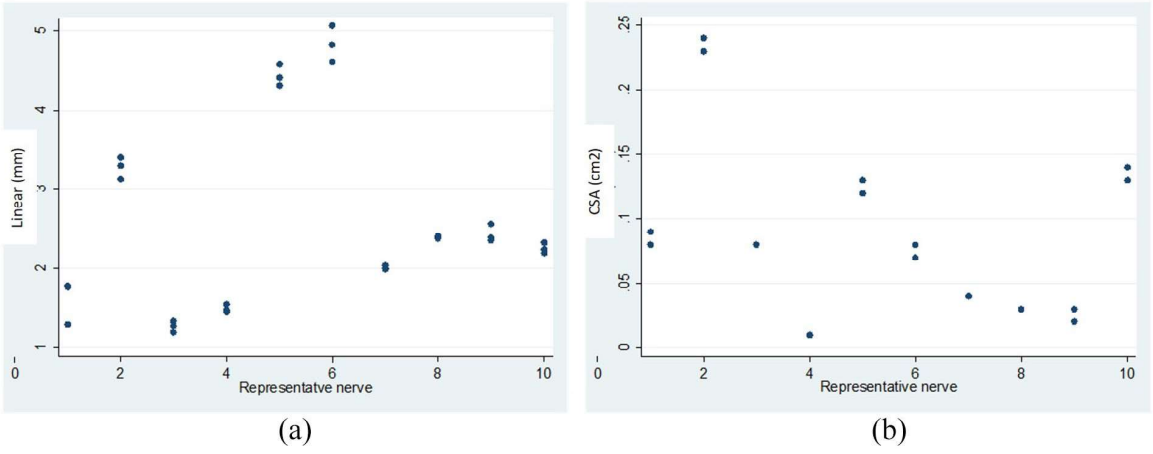

Figure 5. Intra-class correlation for (a) linear measurement and (b) CSA measurements measurement.

Table 7. Nerve cross-sectional area (mm^2) with comparison to previous established normative values.

Nerve	Site	Rawat et al.	Cartwright et al.	Kerasnoudis et al.
Radial	Spiral groove	9.6 ± 3.1	7.9 ± 2.7 [4.5–14.3]	3.26 ± 1.52 [0.22–6.3]
Median	Wrist	11.8 ± 2.0	Not reported	8.43 ± 2.07 [4.29–12.57]
Ulnar	Guyons canal	7.1 ± 1.5	Not reported	5.16 ± 1.03 [3.1–7.22]
Fibular	Popliteal fossa	14.8 ± 8.4	11.7 ± 4.6 [2.5–20.9]	8.6 ± 1.77 [4–13.2]
Fibular	Fibular head	15.0 ± 4.6	11.2 ± 3.3 [4.6–17.8]	7.1 ± 2.3 [2.5–11.7]
Sural	Calf	3.0 ± 1.5	5.3 ± 1.8 [1.7–8.9]	1.82 ± 0.64 [0.54–3.01]
Tibial	Ankle	16.2 ± 5.9	13.7 ± 4.3 [5.1–22.3]	6.36 ± 1.45 [3.46–9.26]

All values are presented in mm2 for direct comparison to Cartwright et al. and Kerasnoudis et al.

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Ethics approval

The Touro College Human Subject Institutional Review Board approved the study (#HSIRB_2112). This cadaver research study was granted IRB exempt status by the Touro Institutional Review Board.

(Include full name and address of committee or organisation approving the research and if available mention reference number and date of that approval).

If ethics approval is not submitted or was not required then a statement of waiver by a named authorised body or organisation must be submitted along with date of waiver, the full name and address of the relevant institution who/which waived ethics approval.

Permission from patient(s) or subject(s) obtained in writing for publishing their case report

Not applicable

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