Journal of Ultrasound (2019) 22:337–344
https://doi.org/10.1007/s40477-019-00370-9

ORIGINAL ARTICLE

Ulnar nerve instability in the cubital tunnel of asymptomatic volunteers

Stacey M. Cornelson[1] · Roberta Sclocco[1,2] · Norman W. Kettner[1]

Received: 24 January 2019 / Accepted: 25 February 2019 / Published online: 12 March 2019

Abstract

Purpose Ulnar nerve instability (UNI) in the cubital tunnel is defined as ulnar nerve subluxation or dislocation. It is a common disorder that may be noted in patients with neuropathy or in the asymptomatic. Our prospective, single-site study utilized high-resolution ultrasonography (US) to evaluate the ulnar nerve for cross-sectional area (CSA) and measures of shear-wave elastography (SWE). Mechanical algometry was obtained from the ulnar nerve in the cubital tunnel to assess pressure pain threshold (PPT).

Methods Forty-two asymptomatic subjects ($n = 84$ elbows) (25 males, 17 females) aged 22–40 were evaluated. Two chiropractic radiologists, both with 4 years of ultrasound experience performed the evaluation. Ulnar nerves in the cubital tunnel were sampled bilaterally in three different elbow positions utilizing US, SWE, and algometry. Descriptive statistics, two-way ANOVA, and rater reliability were utilized for data analysis with $p \leq 0.05$.

Results Fifty-six percent of our subjects demonstrated UNI. There was a significant increase in CSA in subjects with UNI (subluxation: 0.066 $mm^2 \pm 0.024$, $p = 0.027$; dislocation: 0.067 $mm^2 \pm 0.024$, $p = 0.003$) compared to controls (0.057 $mm^2 \pm 0.017$) in all three elbow positions. There were no significant group differences in SWE or algometry. Inter- and intra-observer agreements for CSA of the ulnar nerves within the cubital tunnel were assessed using intraclass correlation coefficient (ICC) and demonstrated moderate (ICC 0.54) and excellent (ICC 0.94) reliability.

Conclusions Most of the asymptomatic volunteers demonstrated UNI. There was a significant increase in CSA associated with UNI implicating it as a risk factor for ulnar neuropathy in the cubital tunnel. There were no significant changes in ulnar nerve SWE and PPT. Intra-rater agreement was excellent for the CSA assessment of the ulnar nerve in the cubital tunnel. High-resolution US could be utilized to assess UNI and monitor for progression to ulnar neuropathy.

Keywords Ulnar nerve instability · Ulnar nerve subluxation · Ulnar nerve dislocation · Ulnar neuropathy · Ultrasonography · Elastography

Introduction

The clinical significance related to stability of the ulnar nerve continues to be a source of controversy. Ulnar nerve instability (UNI) at the cubital tunnel has been reported in healthy individuals [1–3], and Zaltz et al. reported UNI in 17.7% of asymptomatic children [4]. However, UNI may predispose to cubital tunnel ulnar neuropathy [5–7]. The position of the elbow joint may be a relevant biomechanical variable in UNI [5]. Elbow flexion is associated with tightening of the retinaculum which decreases volume in the cubital tunnel resulting in increased pressure on the ulnar nerve which may alter intraneural blood flow triggering edema and enlargement [3]. Chronic nerve compression with intraneural edema results in inflammation, fibrosis, demyelination and eventual axonal loss [10]. In addition, during elbow flexion, an unstable ulnar nerve displaces medially, impacts and is transiently deformed by the humeral medial epicondyle [8]. Abnormal repetitive ulnar nerve dynamics associated with flexion may produce shear stress when the nerve impacts the edge of the humeral retroepicondylar groove [1, 9]. Nerve enlargement arising from repetitive mechanical

✉ Stacey M. Cornelson
staceycornelson@logan.edu

[1] Department of Radiology, Logan University, 1851 Schoettler Rd, Chesterfield, MO 63017, USA

[2] Department of Radiology, Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA

stressors results in increased cross-sectional area (CSA), a metric that defines peripheral neuropathy. However, even though CSA changes are reported on ultrasonography (US), altered morphology of the nerve may be accompanied by normal electrodiagnostic studies [6, 10, 11].

US is emerging as an important imaging resource for evaluation of the musculoskeletal and peripheral nervous systems [2, 12, 13]. US may detect ulnar neuropathy before other imaging modalities, such as MRI, in asymptomatic patients with UNI [11]. In healthy individuals, the ulnar nerve is located posterolateral to the medial epicondyle and resides within the cubital tunnel. The normal ulnar nerve located within the cubital tunnel is hypoechoic and unifascicular [12]. However, some nerves are hyperechoic or multifascicular. In addition, US has also been shown to reliably detect dynamic movement of the ulnar nerve and accurately evaluate peripheral nerve abnormalities [14, 15]. Rutter et al. found preoperative US agreed with the intraoperative findings of UNI in 88% of patients [16]. From a therapeutic standpoint, US is currently used as the standard for guidance in regional anesthesia procedures [17].

UNI has been defined as either subluxation or dislocation of the ulnar nerve from the cubital tunnel as described by Kawahara et al. [1]. Swelling with increased CSA, hypofascicularity [18], increased elastography-derived metrics [19], and nerve hyperemia [20] are the US findings of cubital ulnar nerve neuropathy [14]. US studies have defined upper limits of the ulnar nerve with CSA values of 0.075–0.09 cm^2 [12]. The presence of UNI increases the risk for ulnar neuropathy [5–7, 10, 21–23]. However, neuropathy of the ulnar nerve may occur in the stable or unstable (UNI) ulnar nerve, as underlying pathoetiologies differ [9, 22].

Elastography is an emerging technique that involves an US image-based quantification of tissue strain in response to an applied force [24]. There are several techniques in use. Shear-wave elastography (SWE) has emerged as a valuable technique for assessing peripheral neuropathy [25–27]. If the CSA is increased, the elastographic measurements typically increase as strain results from reduced fluid diffusion across the cell membrane [28]. Recent studies evaluating the median nerve in non-diabetic patients with carpal tunnel syndrome and the tibial nerve in diabetic patients without neuropathy have reported an increase in nerve stiffness with SWE [25, 26, 29]. Although SWE has been widely employed for the evaluation of tendons and muscles, it is likely that it will increasingly contribute to the diagnosis of peripheral neuropathy [19, 27, 30].

Detection of the pressure pain threshold (PPT) has proven reliable and valid in quantitatively assessing sensitization in muscle pain syndromes [31]. PPT occurs at the transition point when applied pressure is sensed as pain (pain threshold). Algometry devices identify the applied force which elicits the sensation of pain [32]. The use of algometry in assessing peripheral nerves is novel, and PPT evaluation of the ulnar nerve in UNI may prove valuable as it has not reported. Algometry in peripheral nerve assessment has been reported in controls and peripheral neuropathy [33, 34].

The aim of our study was to define and characterize the sonographic dynamics of UNI, ulnar nerve CSA, and SWE in asymptomatic volunteers. We hypothesized that UNI would be associated with increased CSA and SWE values. We also utilized algometry to evaluate the ulnar nerve in the cubital tunnel. We hypothesized that UNI would display lower PPT since recurrent subluxation and dislocation of the ulnar nerve have been correlated with friction neuralgia, a source of peripheral sensitization [35].

Methods

Participants

The Institution Review Board of the university approved this study. Participants were recruited internally through the university by class announcements. All participants provided a written informed consent. Criteria for inclusion were either gender, age 18-65, and provision of informed consent. Exclusion criteria included a history of shoulder, elbow, or wrist pain; peripheral neuropathy; systemic disease, such as diabetes mellitus or rheumatoid arthritis; and upper extremity fracture or surgery. Body mass index (BMI) was calculated for all participants. Additionally, demographic information regarding gender, height, weight, age, and handedness was recorded. Both elbows were examined in each participant.

Sonography

All US examinations were performed in the sonography suite of the radiology department. US examination of the ulnar nerve in the cubital tunnel was performed with participants in a supine position with the arm abducted (75°), elbow extended, and wrist supinated. The sonographic parameters of the ulnar nerve were measured with the elbow in three different positions: extension (as previously described), 45° flexion, and full flexion. The sonographic probe position was standardized for each exam with the footprint on an imaginary line between the medial epicondyle and the olecranon process. All images were acquired by a chiropractic radiologist with 4 years of experience in musculoskeletal ultrasound. A Logiq E9 (GE Healthcare, Wauwatosa, WI) ultrasound system operating at 15 MHz with high-frequency linear array transducer and coupling agent was employed.

Ulnar nerve CSA (cm^2) and SWE (kPa) were obtained within the cubital tunnel in all three elbow positions. The ulnar nerve was located in short axis within the cubital

tunnel. CSA of the ulnar nerve was then measured at its maximum diameter using the digital trace function tool. The region of interest (ROI) for elastography was set to the CSA of the ulnar nerve.

The normal position of the ulnar nerve is typically central within the cubital tunnel, with minimal nerve movement during elbow positional changes [36]. When the ulnar nerve was confined to the cubital tunnel, this finding was classified as a control. Instability of the ulnar nerve was classified into two types: subluxation (partial movement of the ulnar nerve to the 12 o'clock position on the medial epicondyle), or dislocation (movement of the ulnar nerve beyond the 12 o'clock position on the medial epicondyle) [1] (Fig. 1).

All US images were assessed for technical quality prior to analysis. Images were analyzed and stored in the Logic E9 hard drive.

Pressure pain threshold

Pressure pain threshold (PPT) was obtained utilizing an algometer. This measure was obtained bilaterally overlying the ulnar nerve in the cubital tunnel with all three positions of the elbow. The algometer measurements were expressed in pounds of pressure. The algometer, (Commander$_{TM}$ Algometer; JTECH Medical Industries, Midvale, UT) utilized a 1.0-cm circular probe with a rubber tip connected to the pressure transducer. Algometer pressure was gradually

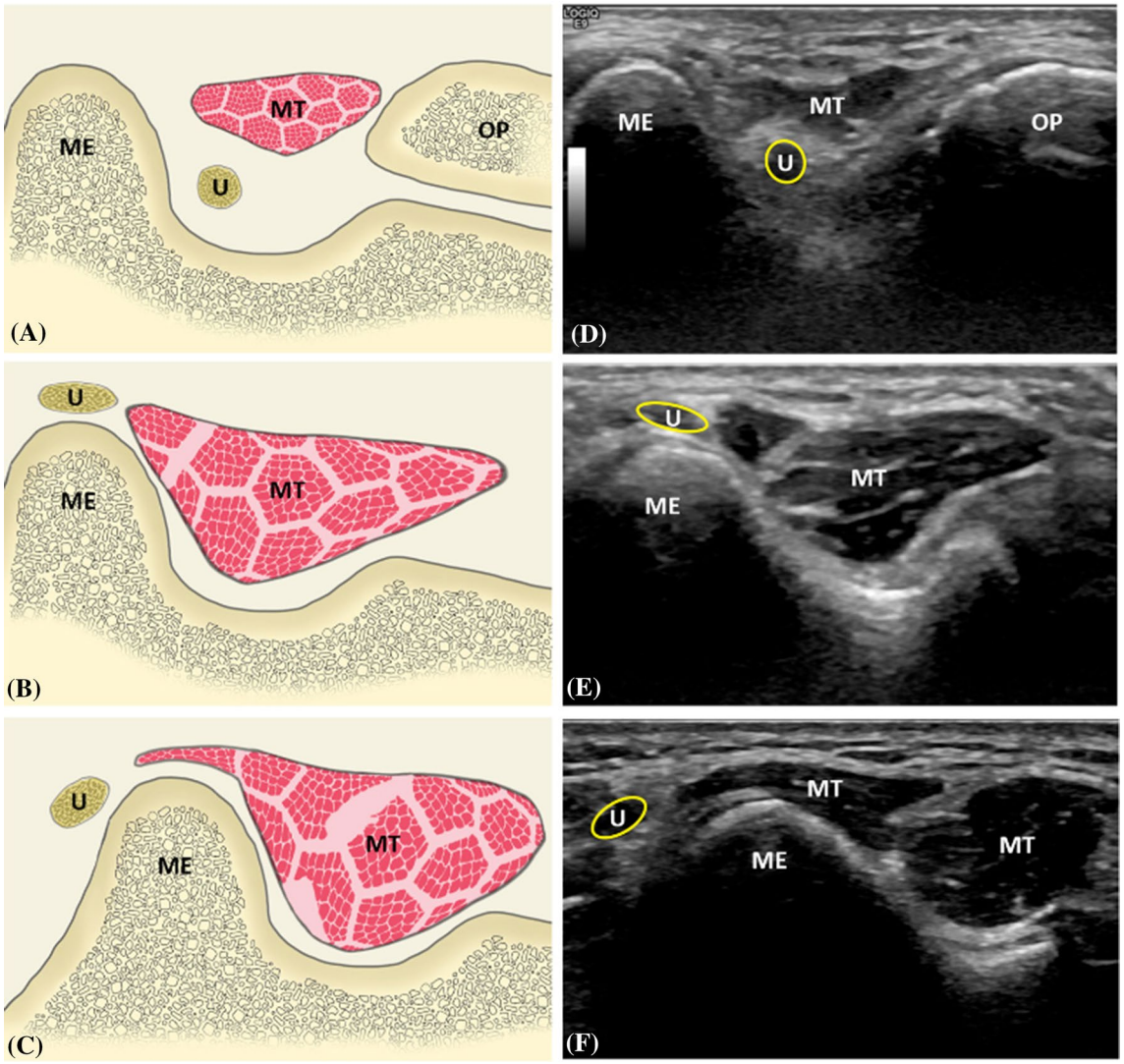

Fig. 1 UNI dynamics of the cubital tunnel. Diagram and correlative US images demonstrating the normal (**a**, **d**), subluxation (**b**, **e**), dislocation (**c**, **f**) of ulnar nerve (yellow oval) adapted from Kawahara et al. [1]. The top images (**a**, **d**) show the elbow in extension, while the subsequent images (**b**, **c**, **e**, **f**) are in full flexion. *ME* medial epicondyle, *MT* medial triceps muscle, *OP* olecranon process, *U* ulnar nerve. Created in Adobe Photoshop (color figure online)

increased over the cubital tunnel until the participant indicated pain (PPT) by verbal response. The algometer measurement was recorded in each of the three elbow positions. The readings were obtained with a 1-min rest period between each position. All PPT measurements were independently performed by a single examiner who was blinded to the sonographic metrics.

Statistical analysis

Descriptive statistics were presented as mean, standard deviation (SD), and ranges for continuous data or numbers (n) and percentages (%).

A two-way analysis of variance (ANOVA) was conducted in Matlab (The MathWorks, Natick, MA) to evaluate the influence of the three independent variables (arm position and condition) on each measurement (CSA, PPT, and SWE). Arm position included three levels (extension, 45° flexion, full flexion), and condition also consisted of three levels (control, subluxation, dislocation). Both main effects and interactions between factors were evaluated, and statistical significance was set at $p \leq 0.05$. Post hoc comparisons were performed to investigate the significant effects revealed by the ANOVA, and statistical significance was set at $p \leq 0.05$, Bonferroni-corrected for multiple comparisons.

Both intra- and inter-rater reliability of the ulnar nerve CSA within the cubital tunnel was performed using Cohen's Kappa and calculated in Bland–Altman plots [37]. Images of the ulnar nerve within the cubital tunnel were randomly selected for rater evaluation and performed independently. Ulnar nerve CSA measures for reliability were obtained in elbow extension. For intra-rater reliability, rater #1 re-measured 84 ulnar nerve CSAs 3 weeks after the original data collection. For the inter-rater reliability, a second rater randomly selected and analyzed 42 ulnar nerve CSAs 1 week later after rater #1.

Results

Forty-two subjects (25 males, 17 females) aged 22–40 years (mean age 26.7 years) were enrolled. The average BMI of our participants was 27.4 lbs/in^2 (range 18.6–40.2 lbs/in^2). Thirty-eight of the participants were right-hand dominant (90.5%). Each subject contributed two sets of measurements (right and left elbows) that were considered as independent data points, since the same subject could exhibit subluxation or dislocation unilaterally. The final dataset included $n = 84$ elbows in three different positions, for a total of 252 data points for each measurement (111 in the control group, 63 in the subluxation group, 78 in the dislocation group). The SWE measurements for one subject were excluded as an outlier.

Mean and standard deviation values for the three measures (CSA, PPT, and SWE) across groups are reported in Table 1. The two-way ANOVA performed on CSA values revealed a significant main effect for the condition factor, yielding an F ratio of ($F(2, 243) = 6.53$, $p = 0.002$. Significance was not met for the main effect of position ($F(2, 243) = 0.59$, $p = 0.557$), or for factor interaction ($F(4, 243) = 0.05$, $p = 0.995$). Post hoc T tests showed that the control group had significantly smaller CSA values (0.057 ± 0.017 cm^2, mean ± SD) compared to subluxation (0.066 ± 0.024 cm^2, $p = 0.027$) and dislocation (0.067 ± 0.024 cm^2, $p = 0.003$) groups (Fig. 2). No significant main effects or interactions were found on either algometry or SWE measures. However, subjects with dislocation demonstrated an increased mean SWE measurement and decreased PPT. Inter- and intra-rater reliability was calculated using intraclass correlation coefficient (ICC). The inter- and intra-rater agreements were moderate (0.54) and excellent (0.94), respectively (Fig. 3).

Discussion

We hypothesized that UNI pathomechanics would increase the ulnar nerve CSA and SWE with a reduction of PPT. We observed significantly increased CSA measurements in the UNI group. There was no change in the PPT or SWE between the control and UNI groups. UNI was defined as either subluxation or dislocation of the ulnar nerve out of the cubital tunnel [1]. The pathomechanics of UNI are influenced by the elbow joint position. During elbow flexion, the unstable ulnar nerve can displace and undergo deformation by the medial epicondyle of the humerus [8]. As the elbow flexes, there is tightening of the retinaculum resulting in reduction of the cubital tunnel volume [22]. This elbow posture may prompt medial ulnar nerve movement with resulting dynamic compression [38]. The ulnar nerve normally undergoes some degree of movement within the tunnel during elbow flexion. A nerve without excursion from the cubital was identified as a control [1, 36, 38].

Flexion of the elbow commonly results in entry of the medial head of the triceps into the proximal aspect of the cubital tunnel [39]. The triceps tendon may contribute to ulnar movement and even instability in the snapping triceps

Table 1 CSA, PPT, and SWE values (mean ± SD) across groups (control, subluxation, dislocation)

	CSA (cm^2)	Algometry (lbs.)	Elastography (kPa)
Control	0.057 ± 0.017	12.163 ± 5.664	13.200 ± 11.262
Subluxation	0.066 ± 0.024*	12.187 ± 4.659	11.852 ± 12.785
Dislocation	0.067 ± 0.024*	11.736 ± 4.817	18.269 ± 23.821

*Significance $p \leq 0.05$

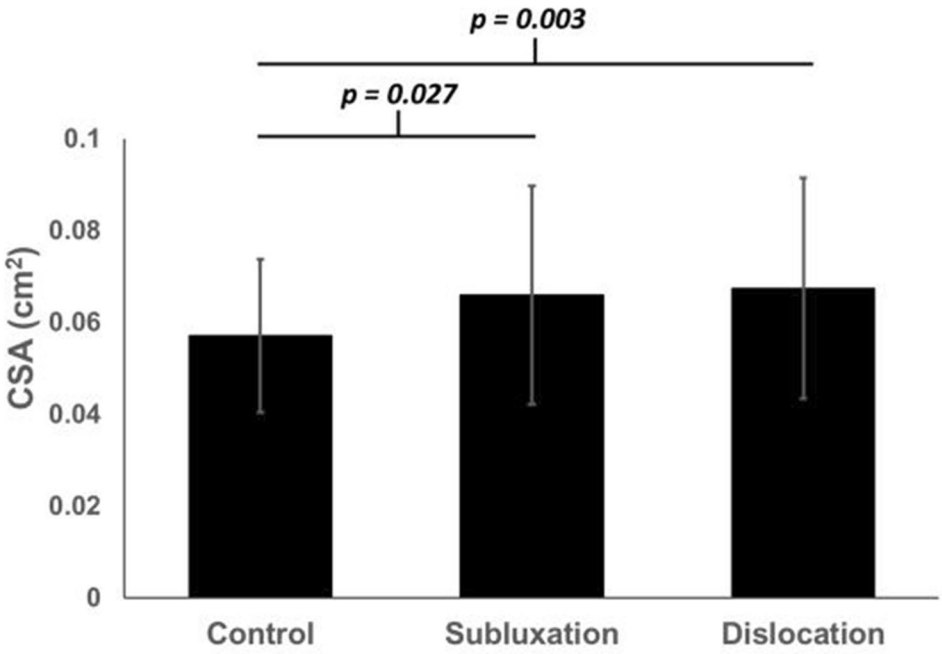

Fig. 2 Post hoc comparisons revealed that both subluxation and dislocation (UNI) groups had significantly higher values of CSA of the ulnar nerve compared to the control group. Error bars indicate standard deviation

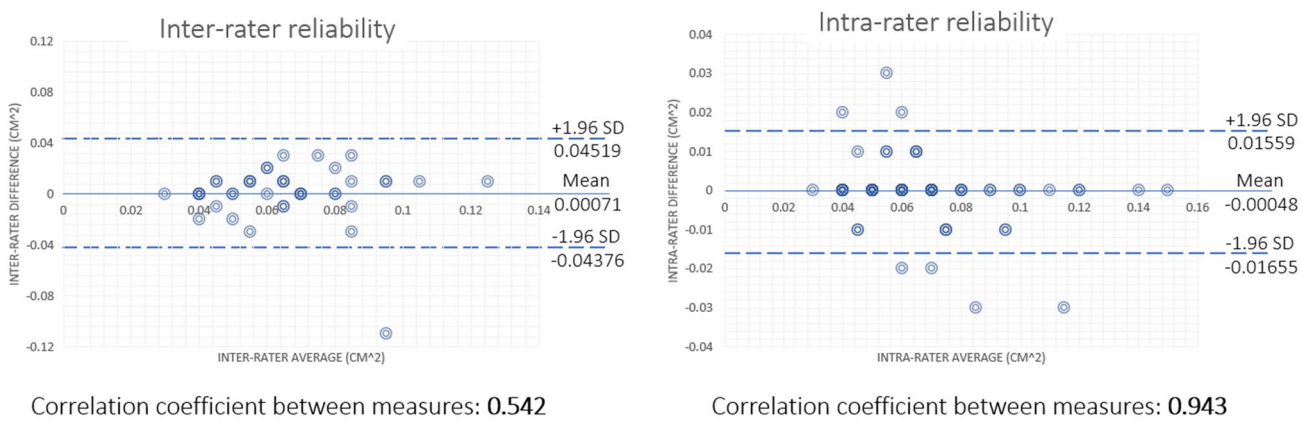

Fig. 3 Bland–Altman plots of the intraclass correlation coefficient for CSA of the ulnar nerve revealed moderate and excellent reliability for the inter- and intra-rater reliability, respectively

syndrome. Interestingly, on this question, Michael et al. found that participants with hypertrophic triceps muscles had an increased frequency of ulnar nerve subluxation or dislocation compared to controls [39]. There are several etiologic sources of UNI. They include absent retinaculum (Osborne ligament) [3, 21], anconeus epitrochlearis muscle [40], tight posterior medial collateral ligament bundle (pMCL) [22], increased cubital tunnel pressure [9, 41, 42], and congenital anomalies such as a shallow groove or dysplasia [1, 9, 12]. Hypertrophy and snapping of the medial head of the triceps brachii have also been associated with UNI [8, 12, 35, 39, 40]. We assessed ulnar nerve stability with high-resolution US and categorized the findings as control, subluxation, or dislocation. Fifty-six percent of the asymptomatic volunteers demonstrated UNI (25% subluxation and 31% dislocation). Multiple previous studies report differing percentages, from 15.4 to 30% for subluxation and 5.8 to 19% for dislocation of the ulnar nerve at the cubital tunnel [1, 2, 8, 12, 22]. Not all of these studies utilized US when assessing UNI. Kawahara et al. evaluated UNI with MRI [1]. In concordance with our study, Kang et al. [8] and Michelin et al. [22] evaluated similar elbow positions and age groups in their sample. However, in our study, a much higher percentage of participants demonstrated UNI. Our convenience sample included a number of athletes, which may have influenced our prevalence of UNI. In contrast to our study, Kang et al. [8] and Michelin et al. [22] did not assess CSA of the ulnar nerve. The operator dependence

of extremity nerve US may also underlie varying reports of reliability with the upper greater than the lower [43]. Michelin et al. reported difficulty in reliably differentiating subluxation and dislocation utilizing US [22], while Fink et al. demonstrated excellent reliability when sonographically assessing UNI [23].

Ulnar neuropathy at the cubital tunnel is the second most common entrapment neuropathy after median nerve in the carpal tunnel [41]. A few studies have demonstrated an increased risk of developing ulnar neuropathy with subluxation or dislocation of the ulnar nerve [5, 6]. Schertz et al. sonographically examined subjects with positive electrodiagnostic studies. Their study assessed the ulnar nerve for morphologic and dynamic differences between patients with and without neuropathy. They observed 49% of their subjects with ulnar neuropathy dislocated from the cubital tunnel compared to 23% of controls [5]. While we did not employ electrodiagnostic testing in our asymptomatic subjects, we found that our sample had significantly increased CSA of the ulnar nerve when associated with UNI. Omejec et al. found patients with ulnar nerve US morphologic abnormalities but normal electrodiagnostic studies. Those patients demonstrated dislocation more commonly when compared with controls [6].

Intriguingly, Leis et al. demonstrated that dislocation of the ulnar nerve seemed to have a protective effect when compared with subluxation. Ulnar nerve subluxation was shown to produce abnormal sonographic and electrodiagnostic findings compared to dislocation, suggesting subluxation may invoke greater risk for ulnar neuropathy [7]. Van den Berg et al. demonstrated that subluxation occurred more frequently, although not significantly, in patients with ulnar neuropathy compared to healthy controls. In contrast, he found no significant differences in electrodiagnostic or sonographic findings between the two groups [10]. However, Pelosi et al. demonstrated US had higher sensitivity than electrodiagnostic testing in detecting clinically mild ulnar neuropathy [44]. In our study, 56% of the asymptomatic subjects displayed UNI with abnormally increased CSA. The question of whether UNI predisposes to the development of ulnar neuropathy is debated. Our data derived by high-resolution US suggest UNI is associated with abnormally increased ulnar nerve CSA and may predispose to ulnar neuropathy.

Elastography has become a useful imaging technique for evaluating the mechanical property of tissue [45]. SWE is one of three types of elasticity imaging. SWE tracks propagation of sound waves through tissue estimating the tissue stiffness, and has been widely applied to the musculoskeletal system. SWE tracks healing progress, and predicts injury risk and/or prognosis of healing [24]. However, very few studies have been performed with SWE on peripheral nerves [25, 27, 29]. Paluch et al. demonstrated subjects with ulnar neuropathy had three times greater SWE values compared to controls [19]. We evaluated SWE of the ulnar nerve within the cubital tunnel to detect changes in tissue stiffness in different biomechanical positions [46]. Previous studies have reported that SWE can significantly improve the US evaluation of the median nerve within the carpal tunnel [29]. Our study demonstrated no elastographic changes of the ulnar nerve between the control and UNI groups in all three elbow positions. Although we observed increased CSA, the lack of accompanying elastographic changes is difficult to explain. One possibility is the asymptomatic group did not have sufficient levels of abnormal fluid diffusion to provoke abnormal mechanical strain detectable by SWE.

PPT is measured when a pressure stimulus transitions into a painful one [32]. Algometry provides a quantitative measure of the pain threshold [32]. Graven-Nielsen et al. revealed that cuff and manual pressure algometry are comparable in the assessment of PPT [47]. Our study employed manual pressure algometry over the cubital tunnel to measure PPT. Although between groups (controls versus UNI) PPT measurements were not significantly different, subjects with dislocation of the ulnar nerve had a decreased mean PPT compared to controls. The absence of peripheral sensitization was likely responsible for the negative group differences.

We are reporting the largest sample size of UNI investigated by US. The finding of increased CSA in UNI is novel. A few limitations have been identified that require discussion. First, this was a cross-sectional study of asymptomatic participants who were aged 22–40 years, limiting its generalizability. Second, our subjects were evaluated by self-report without a clinical evaluation. Third, our study did not include electrodiagnostic measurements as the participants were asymptomatic, which may have inadvertently included borderline, but asymptomatic ulnar neuropathy. Last, increased BMI has been shown to elevate the CSA of peripheral nerves, a potential confound for our CSA measures [48].

In conclusion, UNI is prevalent in asymptomatic elbows as measured by high-resolution US, and our study demonstrated a higher prevalence of UNI than previously reported. UNI has been implicated as a risk factor in ulnar neuropathy. In our study of asymptomatic volunteers, UNI was associated with an increased CSA. Although not significant, when compared to controls, subjects with dislocation demonstrated increased mean elastographic measurements and decreased values of PPT. A longitudinal study will inform the risk of progression from UNI to ulnar neuropathy. US is an available, noninvasive, and reliable means of assessing UNI.

Funding No funding was received.

Compliance of ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

Ethical approval This article does not contain any studies with animals performed by any of the authors.

References

1. Kawahara Y, Yamaguchi T, Honda Y, Tomita Y, Uetani M (2016) The ulnar nerve at elbow extension and flexion: assessment of position and signal intensity on MR images. Radiology 280(2):483–492. https://doi.org/10.1148/radiol.2016150173
2. Erez O, Khalil JG, Legakis JE, Tweedie J, Kaminski E, Reynolds RA (2012) Ultrasound evaluation of ulnar nerve anatomy in the pediatric population. J Pediatr Orthop 32(6):641–646. https://doi.org/10.1097/BPO.0b013e318263a3c0
3. O'Driscoll SW, Horii E, Carmichael SW, Morrey BF (1991) The cubital tunnel and ulnar neuropathy. J Bone Jt Surg Br 73(4):613–617
4. Zaltz I, Waters PM, Kasser JR (1996) Ulnar nerve instability in children. J Pediatr Orthop 16(5):567–569
5. Schertz M, Mutschler C, Masmejean E, Silvera J (2017) High-resolution ultrasound in etiological evaluation of ulnar neuropathy at the elbow. Eur J Radiol 95:111–117. https://doi.org/10.1016/j.ejrad.2017.08.003
6. Omejec G, Podnar S (2016) Does ulnar nerve dislocation at the elbow cause neuropathy? Muscle Nerve 53(2):255–259. https://doi.org/10.1002/mus.24786
7. Leis AA, Smith BE, Kosiorek HE, Omejec G, Podnar S (2017) Complete dislocation of the ulnar nerve at the elbow: a protective effect against neuropathy? Muscle Nerve 56(2):242–246. https://doi.org/10.1002/mus.25483
8. Kang JH, Joo BE, Kim KH, Park BK, Cha J, Kim DH (2017) Ultrasonographic and electrophysiological evaluation of ulnar nerve instability and snapping of the triceps medial head in healthy subjects. Am J Phys Med Rehabil 96(8):e141–e146. https://doi.org/10.1097/PHM.0000000000000706
9. Carter GT, Weiss MD, Friedman AS, Allan CH, Robinson L (2015) Diagnosis and treatment of work-related ulnar neuropathy at the elbow. Phys Med Rehabil Clin N Am 26(3):513–522. https://doi.org/10.1016/j.pmr.2015.04.002
10. Van Den Berg PJ, Pompe SM, Beekman R, Visser LH (2013) Sonographic incidence of ulnar nerve (sub)luxation and its associated clinical and electrodiagnostic characteristics. Muscle Nerve 47(6):849–855. https://doi.org/10.1002/mus.23715
11. Pisapia JM, Ali ZS, Hudgins ED, Khoury V, Heuer GG, Zager EL (2017) Ultrasonography detects ulnar nerve dislocation despite normal electrophysiology and magnetic resonance imaging. World Neurosurg 99:809 e801–809 e805. https://doi.org/10.1016/j.wneu.2017.01.007
12. Jacobson JA, Fessell DP, Lobo Lda G, Yang LJ (2010) Entrapment neuropathies I: upper limb (carpal tunnel excluded). Semin Musculoskelet Radiol 14(5):473–486. https://doi.org/10.1055/s-0030-1268068
13. Haun DW, Cho JC, Kettner NW (2010) Normative cross-sectional area of the C5-C8 nerve roots using ultrasonography. Ultrasound Med Biol 36(9):1422–1430. https://doi.org/10.1016/j.ultrasmedbio.2010.05.012
14. Fink A, Teggeler M, Schmitz M, Janssen J, Pisters M (2017) Reproducibility of ultrasonographic measurements of the ulnar nerve at the cubital tunnel. Ultrasound Med Biol 43(2):439–444. https://doi.org/10.1016/j.ultrasmedbio.2016.09.022
15. Battaglia PJ, Carbone-Hobbs V, Guebert GM, Mackinnon SE, Kettner NW (2017) High-resolution ultrasonography and shear-wave sonoelastography of a cystic radial nerve Schwannoma. J Ultrasound 20(3):261–266. https://doi.org/10.1007/s40477-017-0254-5
16. Rutter M, Grandizio LC, Malone WJ, Klena JC (2019) The use of preoperative dynamic ultrasound to predict ulnar nerve stability following in situ decompression for cubital tunnel syndrome. J Hand Surg Am 44(1):35–38. https://doi.org/10.1016/j.jhsa.2018.10.013
17. Palmeri ML, Dahl JJ, MacLeod DB, Grant SA, Nightingale KR (2009) On the feasibility of imaging peripheral nerves using acoustic radiation force impulse imaging. Ultrason Imaging 31(3):172–182. https://doi.org/10.1177/016173460903100303
18. Tang DT, Barbour JR, Davidge KM, Yee A, Mackinnon SE (2015) Nerve entrapment: update. Plast Reconstr Surg 135(1):199e–215e. https://doi.org/10.1097/PRS.0000000000000828
19. Paluch L, Noszczyk B, Nitek Z, Walecki J, Osiak K, Pietruski P (2018) Shear-wave elastography: a new potential method to diagnose ulnar neuropathy at the elbow. Eur Radiol 28(12):4932–4939. https://doi.org/10.1007/s00330-018-5517-9
20. Kowalska B (2015) Assessment of the utility of ultrasonography with high-frequency transducers in the diagnosis of posttraumatic neuropathies. J Ultrason 15(60):15–28. https://doi.org/10.15557/JoU.2015.0002
21. Granger A, Sardi JP, Iwanaga J, Wilson TJ, Yang L, Loukas M, Oskouian RJ, Tubbs RS (2017) Osborne's ligament: a review of its history, anatomy, and surgical importance. Cureus 9(3):e1080. https://doi.org/10.7759/cureus.1080
22. Michelin P, Leleup G, Ould-Slimane M, Merlet MC, Dubourg B, Duparc F (2017) Ultrasound biomechanical anatomy of the soft structures in relation to the ulnar nerve in the cubital tunnel of the elbow. Surg Radiol Anat 39(11):1215–1221. https://doi.org/10.1007/s00276-017-1879-y
23. Pais RFD, Fisher T (2009) Bilateral cubital tunnel syndrome: case report with review of the literature. Med Ultrasonogr 11(2):31–36
24. Li Y, Snedeker JG (2011) Elastography: modality-specific approaches, clinical applications, and research horizons. Skelet Radiol 40(4):389–397. https://doi.org/10.1007/s00256-010-0918-0
25. Ishibashi F, Taniguchi M, Kojima R, Kawasaki A, Kosaka A, Uetake H (2016) Elasticity of the tibial nerve assessed by sonoelastography was reduced before the development of neuropathy and further deterioration associated with the severity of neuropathy in patients with type 2 diabetes. J Diabetes Investig 7(3):404–412. https://doi.org/10.1111/jdi.12408
26. Dikici AS, Ustabasioglu FE, Delil S, Nalbantoglu M, Korkmaz B, Bakan S, Kula O, Uzun N, Mihmanli I, Kantarci F (2017) Evaluation of the tibial nerve with shear-wave elastography: a potential sonographic method for the diagnosis of diabetic peripheral neuropathy. Radiology 282(2):494–501. https://doi.org/10.1148/radiol.2016160135
27. Paluch L, Noszczyk BH, Walecki J, Osiak K, Kicinski M, Pietruski P (2018) Shear-wave elastography in the diagnosis of ulnar tunnel syndrome. J Plast Reconstr Aesthet Surg 71(11):1593–1599. https://doi.org/10.1016/j.bjps.2018.08.018

28. Cingoz M, Kandemirli SG, Alis DC, Samanci C, Kandemirli GC, Adatepe NU (2018) Evaluation of median nerve by shear wave elastography and diffusion tensor imaging in carpal tunnel syndrome. Eur J Radiol 101:59–64. https://doi.org/10.1016/j.ejrad.2018.02.005
29. Miyamoto H, Halpern EJ, Kastlunger M, Gabl M, Arora R, Bellmann-Weiler R, Feuchtner GM, Jaschke WR, Klauser AS (2014) Carpal tunnel syndrome: diagnosis by means of median nerve elasticity—improved diagnostic accuracy of US with sonoelastography. Radiology 270(2):481–486. https://doi.org/10.1148/radiol.13122901
30. Creze M, Nordez A, Soubeyrand M, Rocher L, Maitre X, Bellin MF (2018) Shear wave sonoelastography of skeletal muscle: basic principles, biomechanical concepts, clinical applications, and future perspectives. Skelet Radiol 47(4):457–471. https://doi.org/10.1007/s00256-017-2843-y
31. Özdolap S, Sarikaya S, Köktürk F (2014) Evaluation of pain pressure threshold and widespread pain in chronic low back pain. Turk J Phys Med Rehabil 60:32–36
32. Parhizgar SEH (2010) A review on experimental assessments of pain threshold in healthy human subjects. BCN 1(4):62–67
33. Sterling M, Treleaven J, Edwards S, Jull G (2000) Pressure pain thresholds of upper limb peripheral nerve trunks in asymptomatic subjects. Physiother Res Int 5(4):220–229
34. Fernandez-de-Las-Penas C, Cleland J, Palacios-Cena M, Fuensalida-Novo S, Alonso-Blanco C, Pareja JA, Alburquerque-Sendin F (2017) Effectiveness of manual therapy versus surgery in pain processing due to carpal tunnel syndrome: a randomized clinical trial. Eur J Pain 21(7):1266–1276. https://doi.org/10.1002/ejp.1026
35. Lasecki M, Olchowy C, Pawlus A, Zaleska-Dorobisz U (2014) The snapping elbow syndrome as a reason for chronic elbow neuralgia in a tennis player—MR, US and sonoelastography evaluation. Pol J Radiol 79:467–471. https://doi.org/10.12659/PJR.891393
36. Yang SN, Yoon JS, Kim SJ, Kang HJ, Kim SH (2013) Movement of the ulnar nerve at the elbow: a sonographic study. J Ultrasound Med 32(10):1747–1752. https://doi.org/10.7863/ultra.32.10.1747
37. Euser AM, Dekker FW, le Cessie S (2008) A practical approach to Bland–Altman plots and variation coefficients for log transformed variables. J Clin Epidemiol 61(10):978–982. https://doi.org/10.1016/j.jclinepi.2007.11.003
38. Nakano K, Murata K, Omokawa S, Nakanishi Y, Shimizu T, Kira T, Onishi T, Tanaka Y (2014) Dynamic analysis of the ulnar nerve in the cubital tunnel using ultrasonography. J Shoulder Elbow Surg 23(7):933–937. https://doi.org/10.1016/j.jse.2014.01.039
39. Michael AE, Young P (2018) Is triceps hypertrophy associated with ulnar nerve luxation? Muscle Nerve 58(4):523–527. https://doi.org/10.1002/mus.26183
40. Assmus H, Antoniadis G, Bischoff C, Hoffmann R, Martini AK, Preissler P, Scheglmann K, Schwerdtfeger K, Wessels KD, Wustner-Hofmann M (2011) Cubital tunnel syndrome—a review and management guidelines. Cent Eur Neurosurg 72(2):90–98. https://doi.org/10.1055/s-0031-1271800
41. Dong Q, Jacobson JA, Jamadar DA, Gandikota G, Brandon C, Morag Y, Fessell DP, Kim SM (2012) Entrapment neuropathies in the upper and lower limbs: anatomy and MRI features. Radiol Res Pract 2012:230679. https://doi.org/10.1155/2012/230679
42. Ochi K, Horiuchi Y, Morisue H, Harato K, Tanikawa H, Okubo M (2013) Association between the disease severity and extraneural pressure induced by maximum elbow flexion in patients with cubital tunnel syndrome. J Plast Surg Hand Surg 47(3):219–223. https://doi.org/10.3109/2000656X.2012.747962
43. Telleman JA, Herraets IJT, Goedee HS, Verhamme C, Nikolakopoulos S, van Asseldonk JH, van der Pol WL, van den Berg LH, Visser LH (2018) Nerve ultrasound: a reproducible diagnostic tool in peripheral neuropathy. Neurology. https://doi.org/10.1212/wnl.0000000000006856
44. Pelosi L, Mulroy E (2018) Diagnostic sensitivity of electrophysiology and ultrasonography in ulnar neuropathies of different severity. Clin Neurophysiol. https://doi.org/10.1016/j.clinph.2018.11.018
45. Orman G, Ozben S, Huseyinoglu N, Duymus M, Orman KG (2013) Ultrasound elastographic evaluation in the diagnosis of carpal tunnel syndrome: initial findings. Ultrasound Med Biol 39(7):1184–1189. https://doi.org/10.1016/j.ultrasmedbio.2013.02.016
46. Greening J, Dilley A (2017) Posture-induced changes in peripheral nerve stiffness measured by ultrasound shear-wave elastography. Muscle Nerve 55(2):213–222. https://doi.org/10.1002/mus.25245
47. Graven-Nielsen T, Vaegter HB, Finocchietti S, Handberg G, Arendt-Nielsen L (2015) Assessment of musculoskeletal pain sensitivity and temporal summation by cuff pressure algometry: a reliability study. Pain 156(11):2193–2202. https://doi.org/10.1097/j.pain.0000000000000294
48. Lothet EH, Bishop TJ, Walker FO, Cartwright MS (2018) Ultrasound-derived nerve cross-sectional area in extremes of height and weight. J Neuroimaging. https://doi.org/10.1111/jon.12590