SCIENTIFIC ARTICLE

Regional Ulnar Nerve Strain Following Decompression and Anterior Subcutaneous Transposition in Patients With Cubital Tunnel Syndrome

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Purpose Simple decompression and anterior subcutaneous transposition are effective surgical interventions for cubital tunnel syndrome and yield similarly favorable outcomes. However, a substantial proportion of patients demonstrate unsatisfactory outcomes for reasons that remain unclear. We compared effects of decompression and transposition on regional ulnar nerve strain to better understand the biomechanical impacts of each strategy.

Methods Patients diagnosed with cubital tunnel syndrome and scheduled for anterior subcutaneous transposition surgery were enrolled. Simple decompression, circumferential decompression, and anterior transposition of the ulnar nerve were performed during the course of the transposition procedure. Regional ulnar nerve strain around the elbow was measured for each surgical intervention based on 4 wrist and elbow joint configurations.

Results With elbow extension at 180°, both circumferential decompression and anterior transposition resulted in approximately 68% higher nerve strains than simple decompression. Conversely, with elbow flexion, simple decompression resulted in higher average strains than anterior transposition. Limited regional differences in strain were observed for any surgical intervention with elbow extension. However, with elbow flexion, strains were higher in distal and central regions compared with the proximal region within all surgical groups, and proximal region strain was higher after simple decompression compared with anterior transposition.

Conclusions As predicted by the altered anatomic course, anterior transposition results in lower ulnar nerve strains than simple decompression during elbow flexion and higher nerve strains during elbow extension. Irrespective of anatomic course, circumferential release of paraneurial tissues may also influence nerve strain. Nerve strain varies regionally and is influenced by surgery and joint configuration.

Clinical relevance Our data provide insight into how surgery resolves and redistributes traction on the ulnar nerve. These findings may help inform which surgical procedure to perform for a specific patient, guide rehabilitation protocols, and suggest regions of anatomic concern during index and revision surgery. *(J Hand Surg Am. 2016;41(10):e343−e350. Copyright © 2016 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Cubital tunnel syndrome, peripheral nerve, anterior transposition, decompression, biomechanics.

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Cubital tunnel syndrome (CubTS) is the most common ulnar nerve neuropathy and the second most common peripheral neuropathy of the upper extremity.[1] Although there is no consensus on its pathogenesis, leading theories hypothesize that anatomic constraints of the cubital tunnel and surrounding soft tissues elevate tension and/or compress the nerve, resulting in ischemia, fibrosis, and structural damage to nerve fibers.[2–4]

Accumulating evidence suggests that nerve traction has a central role in progression of the condition. Although not traditionally considered load-bearing tissues, peripheral nerves must accommodate tensile stresses during joint motion, and excessive tensile strain impairs nerve structure and function. Rat sciatic nerves undergoing prolonged strain of 15% exhibit irreversible loss of blood flow and electrical conduction, whereas strains of greater than 25% compromise neural structural integrity.[5–7] Human cadaveric studies have revealed that ulnar nerve strain varies regionally and, paradoxically, frequently exceeds injury thresholds determined in animals.[8–11] For example, ulnar nerves experience 30% strain at the elbow, and by suppressing nerve gliding, mechanical tethering of the ulnar nerve to the cubital tunnel retinaculum increases regional strain by almost 50%.[12]

Two surgical procedures commonly performed for CubTS refractory to nonsurgical management are simple decompression and anterior subcutaneous transposition. Consistent with a pathologic role for tensile strain in CubTS, the biomechanical rationale for both procedures is to restore nerve gliding as well as reduce compression and traction on the nerve. Simple decompression releases overlying anatomic constraints of the cubital tunnel and surrounding tissues, whereas transposition circumferentially releases anatomic constraints and alters the nerve's anatomic course.[13–15] Randomized clinical trials and meta-analyses comparing these 2 techniques have demonstrated net-positive results for both procedures with no significant differences in electrodiagnostic or clinical outcomes.[16–22] However, up to 30% of patients have only fair or poor outcomes for either procedure, and many patients experience recurrent symptoms.[16–23] It remains unclear why some patients' symptoms do not improve. In addition, it remains unclear whether there are subpopulations of patients who may benefit from one procedure more than another. In light of the biomechanical contributions to CubTS pathogenesis that have been hypothesized, a better understanding of differential effects of each surgical procedure on nerve strain may provide additional insight into mechanisms by which surgery restores function, as well as a possible basis for clinical failures.

Previous studies compared average strains in ulnar nerves of healthy cadavers subject to simple decompression and transposition.[14,24] The purpose of this study was to compare regional distributions of ulnar nerve strain in living patients with CubTS after simple decompression, circumferential decompression, and anterior subcutaneous transposition. We hypothesized that each surgical intervention would have a different effect on the location and magnitude of nerve strain, depending on elbow and wrist position.

MATERIALS AND METHODS

Our institutional review board approved this study. Nine patients consecutively diagnosed with CubTS were prospectively selected for inclusion into the study at a single center over 1 year. Patients were diagnosed with CubTS based on history, physical examination, and the results of electrodiagnostic tests. All patients failed nonsurgical management, including activity modification and/or nightly use of an orthosis. The same surgeon, who preferred to perform anterior transposition rather than simple decompression, operated on all of the patients. The first 2 enrolled patients were excluded from the final analysis owing to poor-quality intraoperative pictures, which left 7 patients in the final study sample. One patient had both ulnar nerves operated on at different times; both were included in the study. Hypermobility was not a criterion for inclusion. Exclusion criteria included prior elbow surgery or trauma of the affected extremity, and notable anatomic abnormalities about the elbow, as identified by medical history and physical examination. Patient characteristics are summarized in Table 1.

All surgeries were performed with patients supine and with monitored anesthesia care. A brachial tourniquet, inflated to 250 mm Hg, was used for all patients. A standard 12- to 14-cm skin incision was made overlying the ulnar nerve and centered at the medial epicondyle to expose the nerve. Simple decompression was performed by releasing the nerve proximally at the medial intermuscular septum and cubital tunnel retinaculum, and distally at the superficial and deep fascia overlying the 2 heads of the flexor carpi ulnaris and shared fascia of the flexor digitorum superficialis. Similar to established techniques,[6,12,25] 10 to 14 6-0 black nylon sutures were placed into the epineurium at 1-cm increments along the exposed nerve, centered at the medial epicondyle, providing minimally invasive markers to measure regional strain. The region between the central 5 sutures was designated as "central," and flanking regions were designated as

TABLE 1. Patient Characteristics

Patient	Age, y	Gender	Body Mass Index	Side Operated On	Dominant Extremity	Diabetes Status
1	49	M	39.0	Left	Left	Y
2	67	M	33.4	Left	Left	Y
3	62	M	33.7	Left	Right	Y
4	36	M	34.4	Right	Right	N
5	64	M	32.1	Right	Left	Y
6	49	F	21.5	Left	Right	N
7	64	M	29.5	Right	Right	N

proximal and distal. Arms were ranged through 4 different joint configurations (Fig. 1); the sequence of configurations was randomized for each case to negate effects of a specific sequence on nerve strain. Configuration 1 was defined as elbow flexion of 0° (180° extension) with the forearm/wrist neutral. Configuration 2 was defined as elbow flexion of 0°, wrist extension of 60°, and maximal forearm pronation. Configuration 3 was defined as elbow flexion of 90° with the forearm/wrist neutral. Configuration 4 was defined as elbow flexion of 90°, wrist extension of 60°, and maximal forearm pronation. Forearm pronation was combined with wrist extension based on combined use patterns in normal daily activities, and increased ulnar nerve strain at the elbow. Pictures were taken in each joint configuration with an 8-megapixel digital camera, with the nerve parallel to the image plane to prevent parallax. A surgical ruler was used to set scale. Joint angles were within ±5° from the targeted angle, based on analysis of digital images of the upper extremity by the lead author.

After simple decompression, the nerve was circumferentially decompressed; the nerve was fully released from all surrounding paraneurial (mesoneurial) tissues within the cubital tunnel and surrounding bed. It was thus freed of all soft tissue attachments along its exposed length, but not yet transposed to the anterior forearm. Pictures were again taken in each joint configuration. Circumferential decompression is not performed without transposition in clinical practice, owing to concerns of nerve instability in the absence of flap placement; in our hands, after circumferential decompression, the nerve subluxated out of the cubital tunnel with elbow flexion (3 of 8 patients in configuration 3 and 6 of 8 patients in configuration 4). However, we studied the impact of this intervention on nerve strain to (1) determine the role of the paraneurial attachments not removed during simple decompression, and (2) determine the relative contributions of removing paraneurial attachments and anatomic relocation of the nerve to the anterior forearm during the subsequent transposition.

Finally, anterior subcutaneous transposition was performed in the standard fashion by relocating the nerve outside the cubital tunnel and placing it onto the anterior forearm musculature, 1.5 cm from the epicondyle. With the nerve placed into its transposed position but before flap placement, the arm was again ranged through the joint configurations described previously and pictures were taken. In 6 of 16 instances in which the nerve would not stay in the position expected after flap placement, a Freer elevator was used to maintain nerve position. Epineurial sutures were then removed, the nerve was secured anteriorly by suture of the anterior adipocutaneous flap to the flexor pronator fascia, and the incision was closed. We did not analyze strain after flap placement because the flap obscured sutures.

Images were captured using a high-resolution digital camera and analyzed using ImageJ (National Institutes of Health, Bethesda, MD). Strain was calculated by measuring the difference in distance between 2 sutures in a given joint configuration after a specific surgical intervention, compared with the distance between the same 2 sutures in joint configuration 1 after simple decompression. Calculations were performed assuming 1-dimensional kinematics, along the longitudinal axis of the nerve. Strain (e) was calculated as:

$$e = (l_f - l_o)/l_o,$$

where l_o is the spacing between a pair of sutures at joint configuration 1 after simple decompression and l_f is the corresponding spacing at joint configuration 2, 3, or 4 for a given surgical intervention. Maximum strain and average strain along the entire length of the exposed nerve, as well as average regional strains at the central, proximal, and distal regions of the exposed nerve, were calculated for each joint configuration and surgical intervention.

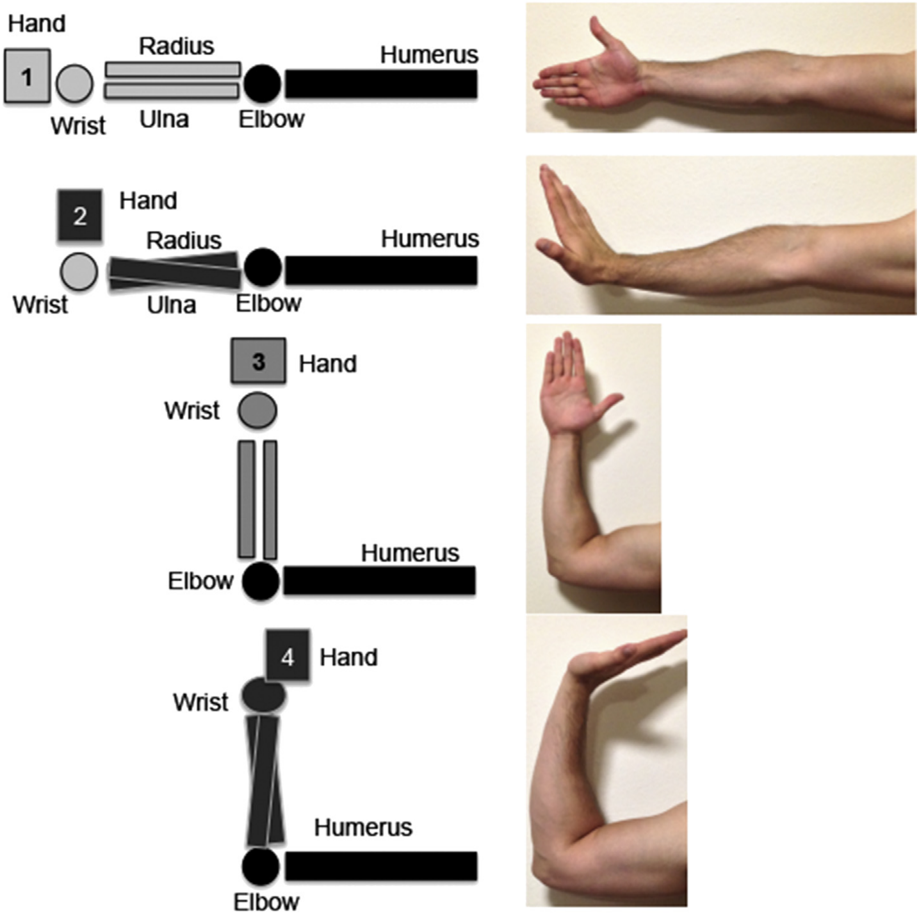

FIGURE 1: Joint configurations. Normal upper extremity demonstrating elbow and wrist joint configurations used during experiment, matched to intraoperative photos after simple decompression.

We used 2-way repeated-measures analysis of variance to analyze maximal or average nerve strains using factors of surgical intervention and joint configuration, and to analyze regional average nerve strains using factors of surgical intervention and regional distributions of nerve strain for each joint configuration. Post hoc comparisons of individual groups were made using Tukey's honestly significant difference.

Our sample size of $n = 8$ was based on power $(1 - \beta)$ of 0.8 and an effect size of 0.5, conservatively designated based on effect sizes calculated from mean and standard deviations of groups with significant regional differences in cadaveric ulnar nerve strain (Cohen's $d = 0.8 - 1.0$).[11,12] Post hoc sensitivity analysis yielded a statistical power of > 0.8 for all detected significant differences in means, further justifying sample size.

RESULTS

Maximal and average ulnar nerve strains at the elbow were measured for each surgical intervention and joint configuration (Figs. 2 and 3, respectively). After simple decompression, maximum strain was higher in joint configuration 4 (elbow flexed, wrist extended/pronated) compared with configuration 2 (elbow extended, wrist extended/pronated), with a significant mean strain difference of 12.3% ($P < .05$). Average strain was significantly reduced by 9.5% ($P < .05$) after transposition compared with simple decompression, with elbow flexion (joint configuration 3). Transposition significantly increased maximum strain by 10.8% ($P < .05$) when the elbow was extended (joint configuration 2). Maximum strain was similarly higher after circumferential decompression compared with simple decompression in joint configuration 2, with a significant mean strain increase of 10.9% ($P < .05$). Wrist/forearm configuration had no significant effect on maximum nerve strain after circumferential decompression or anterior transposition.

Average regional strains for different elbow and wrist configurations are shown in Figures 4 through 6. When the wrist was extended (joint configuration 2), strain was 12.3% higher in the proximal region than in the distal region after circumferential decompression

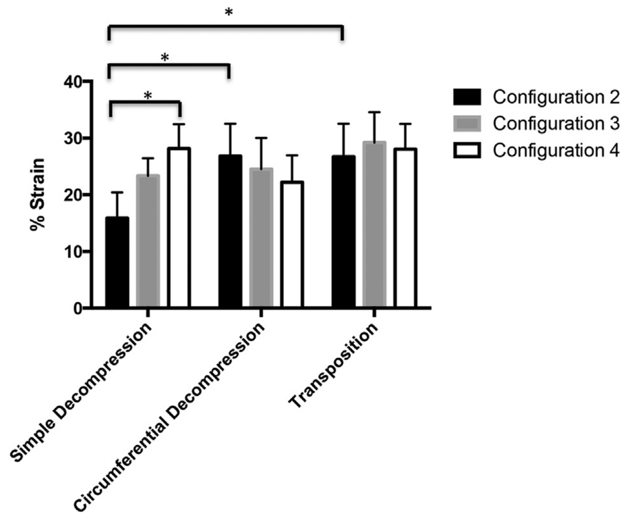

FIGURE 2: Maximum strain of entire length of exposed ulnar nerve with different surgical interventions (x axis) and joint configurations (different shaded bars). Strain values are calculated relative to suture spacing in simple decompression in configuration 1. Transposition results in reduced strain compared with simple decompression in joint configuration 3. *Indicates a statistically significant difference between groups ($P < .05$).

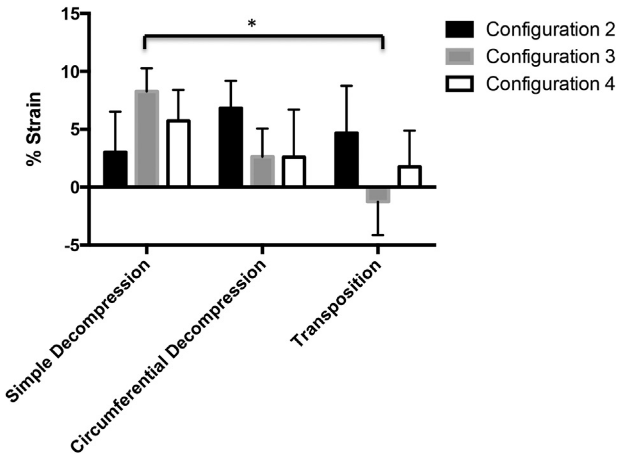

FIGURE 3: Average strain of entire length of exposed ulnar nerve with different surgical interventions (x axis) and joint configurations (different shaded bars). Strain values are calculated relative to suture spacing in simple decompression in configuration 1. Simple decompression results in reduced strain compared with circumferential decompression or transposition in joint configuration 2. *Indicates a statistically significant difference between groups ($P < .05$).

($P < .05$). However, this difference was eliminated after transposition. There was decreased strain in the proximal region after transposition compared with circumferential decompression (mean difference of 10.2%; $P = .07$).

In elbow flexion (joint configuration 3), strain was higher centrally than proximally after both simple decompression and circumferential decompression, with mean differences of 10.9% and 10.4%, respectively ($P < .05$). After transposition, strain was higher distally compared with the proximal region, with a mean strain difference of 15.2% ($P < .05$). Strain was lower in both the proximal and central regions after transposition compared with simple decompression, with mean differences of 12.9% ($P < .05$) and 17.8% ($P < .05$), respectively. There was lower proximal strain after circumferential decompression compared with simple decompression (mean difference of 8.6%; $P = .10$).

Regional nerve strain distributions with combined elbow flexion and wrist extension/pronation (joint configuration 4) were similar to those observed with elbow flexion alone. Transposition resulted in lower strains in the proximal region compared with simple decompression (mean difference of 8.3%; $P < .05$). Regional strain differences were most pronounced in the transposition group, where strain was significantly higher in both the central and distal regions compared with the proximal region within all surgery groups (Fig. 5) ($P < .05$ for all comparisons). Cumulatively, with elbow flexion irrespective of wrist extension-pronation, circumferential decompression created strain distributions more like those observed after transposition than simple decompression.

DISCUSSION

Cubital tunnel syndrome is the second most common peripheral neuropathy of the upper extremity. Although treatment of CubTS with simple decompression and anterior transposition is comparable and generally efficacious, many patients do not improve after surgery or require revision surgery.[16,17,20,23] The reason for these clinical failures is not always clear, in part because we do not fully understand the mechanisms by which surgery alleviates symptoms or alters disease pathogenesis.[1,3,4] It is also not known whether there are subpopulations of patients who would benefit from one procedure over another. Increased nerve traction resulting from anatomic constraints at either the cubital tunnel or surrounding muscle fasciae have been proposed as potential causes of the disease[1,3,4] because elevated or prolonged strains in animal models lead to neurovascular deficits.[2,5,7,12,26,27]

Whereas surgical techniques address the perceived anatomic constraints of the nerve, they likely also alter nerve strain distributions. Thus, a comprehensive understanding of ulnar nerve biomechanics in CubTS is essential. However, only one study has

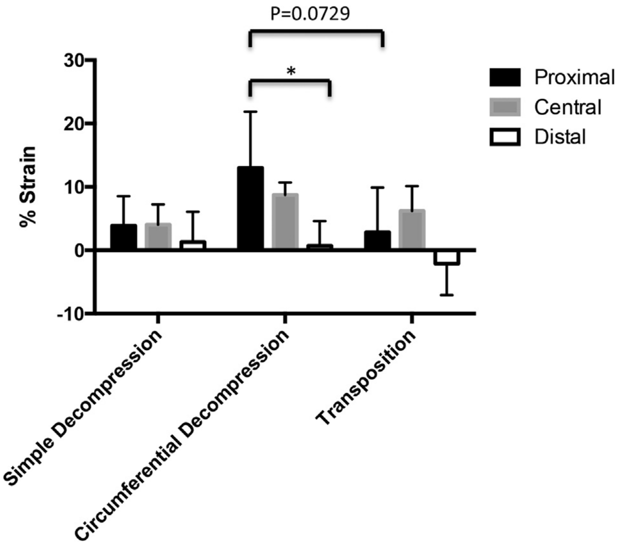

FIGURE 4: Regional ulnar nerve strain in joint configuration 2. Average ulnar nerve strain in different regions (different shaded bars) after different surgical interventions (x axis). After circumferential decompression, proximal strain is higher than distal strain. *Indicates a statistically significant difference between groups (*P* < .05).

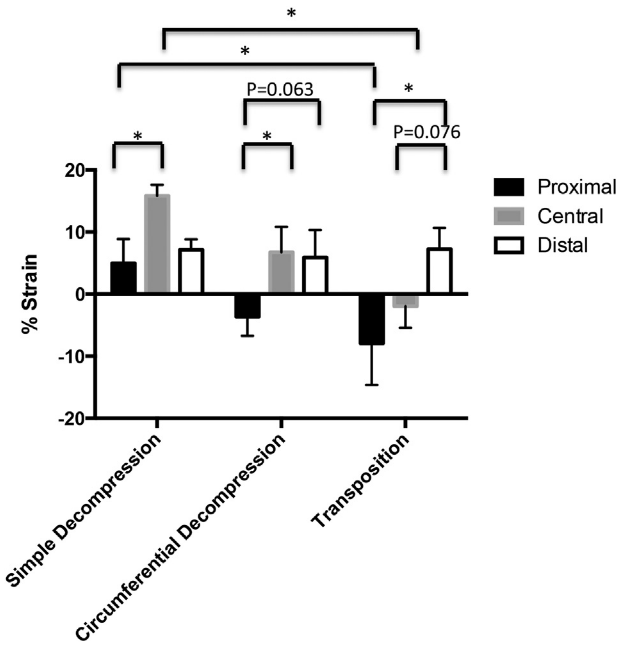

FIGURE 5: Regional ulnar nerve strain in joint configuration 3. Average ulnar nerve strain in different regions (different shaded bars) after different surgical interventions (x axis). Transposition results in reduced strain compared with simple decompression in both the proximal and central regions. Distal and central strains are higher than proximal strain after circumferential decompression or transposition. *Indicates a statistically significant difference between groups (*P* < .05).

studied the effect of surgical intervention (simple decompression) on ulnar nerve kinematics in patients,[25] and that study only calculated strain in a single region (proximal to the medial epicondyle) in a single joint configuration. Our findings indicate that in patients with CubTS, ulnar nerve strain at the elbow depends on the surgical intervention and wrist and elbow configuration, and displays substantial regional variation.

Absolute values of ulnar nerve strains obtained after simple decompression in this study were similar to those from both cadaveric studies[6,11,12,14,24] and clinical studies,[25] which ranged from 13% to 29% in articular regions and up to 20% in proximal regions. This consistency validates our measurements and suggests that simple decompression recreates native ulnar nerve strains measured in cadavers.[6,11,12,14,24] Based on previous data,[14,24] we hypothesized that transposition would decrease ulnar nerve strain with elbow flexion relative to simple decompression. Our data support this hypothesis, demonstrating decreased strain with transposition compared with simple decompression. This phenomenon may be explained by gross observation of ulnar nerve strain; the medial epicondyle acts as a bending fulcrum for the nerve, and this fulcrum is neutralized when the ulnar nerve is transposed anteriorly.[9] Our observation of increased ulnar nerve strain with elbow extension after anterior transposition was also predicted by prior cadaveric findings; radiographic measurement of ulnar nerve strain demonstrated that after transposition, strain with the elbow extended was similar to strain with the elbow in flexion before transposition.[14] It is possible that transposition places the nerve farther anterior to the elbow axis of rotation, thereby stretching it over the anterior musculature during elbow extension.

Despite these consistencies with prior findings, we encountered 2 unexpected results that warrant reexamination of the underlying therapeutic mechanism for anterior transposition. First, circumferential decompression without transposition also resulted in a significant increase in strain with elbow extension that was similar to that observed with transposition. This finding suggests that paraneurial attachments released before transposition, in addition to the anatomic change itself, may have a role in distributing nerve strain after transposition. The differential effects of joint configuration on strain after each surgical intervention also suggest a possible role for the paraneurial attachments. The position of lowest strain after simple decompression was with the elbow extended and the wrist neutral. In contrast, joint configuration had no effect on maximum or average

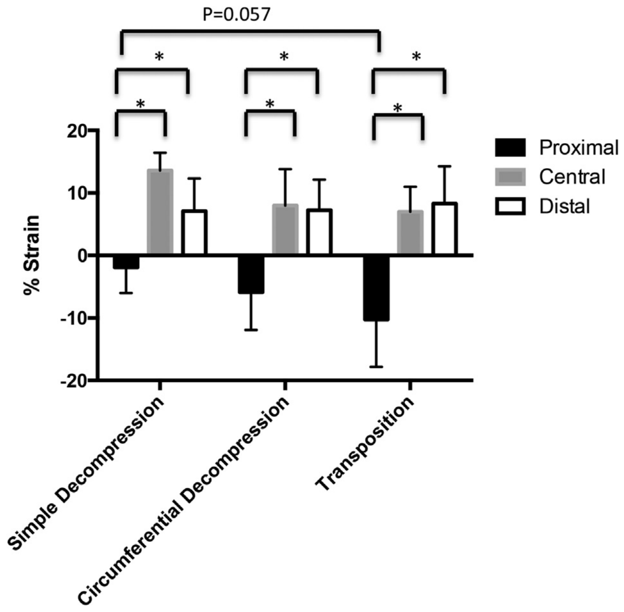

FIGURE 6: Regional ulnar nerve strain in joint configuration 4. Average ulnar nerve strain in different regions (different shaded bars) after different surgical interventions (x axis). There is a possible trend toward transposition resulting in reduced strain compared with simple decompression in the central region. Distal and central strains are higher than proximal strain after any intervention. *Indicates a statistically significant difference between groups ($P < .05$).

strain after either circumferential decompression or transposition, which again suggests an influence of paraneurial tissue lysis. A confounding limitation to the latter findings is that the nerve frequently subluxated from the cubital tunnel after circumferential decompression during elbow flexion (configurations 3 and 4), reducing the reliability of these results. Such subluxation changed the anatomic course intermediately between that of the nerve in its original bed and after anterior transposition.

Second, our findings contrasted with prior cadaveric work suggesting that the region of highest strain was at the level of, or just proximal to, the medial epicondyle regardless of surgical intervention or joint position.[9,14,15] When the elbow was flexed (configurations 3 and 4), all surgical groups demonstrated higher strain in the distal and central regions compared with the proximal region. In addition, in these configurations transposition substantially decreased proximal strain compared with simple decompression. In joint configuration 2, there was no difference between proximal, central, or distal strain after simple decompression or transposition. This phenomenon could be explained by the fact that the deforming force (the wrist) was distant from the measured region, and in the absence of an intervening fulcrum at the elbow, strain was distributed more evenly in the measured region.

These findings have several clinical implications. First, they highlight regions of continuing anatomic concern after surgery, most notably the central and distal regions. A recent cadaveric study echoes this concern, citing the intermuscular aponeurosis between the flexor carpi ulnaris and flexor digitorum superficialis muscles as a potential region of postsurgical entrapment.[15] These regions may need greater attention during initial decompression, and especially during revision surgery, to ensure adequate neural release. Our data may also guide patient selection and postoperative rehabilitation protocols. For example, patients whose elbows hyperextend or who frequently extend their elbows (eg, gymnasts or individuals whose employment requires overhead reaching tasks) may benefit more from simple decompression than anterior transposition, because transposition increases strain during elbow extension. Similarly, patients who by activity frequently flex their elbows (eg, a truck driver or computer programmer) or whose symptoms are exacerbated by flexion may benefit more from transposition, because this lowers strain more than simple decompression in that position. In light of observed changes in regional strain after circumferential decompression, our findings may also drive future investigation into a role for paraneurial soft tissues in defining local strains, especially in the context of their surgical release; these tissues may have a more important role than previously realized.

Our study has several limitations. Because of ethical concerns, we did not study patients without CubTS as a control group. In addition, we could not measure nerve strain before simple decompression, because epineurial suture placement necessitated simple decompression. Therefore, all strain data are referenced to simple decompression in joint configuration 1, rather than to the native uncompressed state of the nerve. Thus, although strains measured in this study are similar to those in studies on non-entrapped nerves,[6,11,12,14,24,25] this study should be viewed as a comparison of different surgical techniques rather than with the native state of the ulnar nerve. Also, we imposed a maximum elbow flexion of 90°, a configuration that was readily reproducible intraoperatively. Cadaveric studies suggest that strain and pressure at the cubital tunnel are elevated at this angle, although further increases in strain occur with elbow flexion beyond 90°.[9,28] Furthermore, strain was measured only on the medial (exposed) portion of the nerve, where sutures were placed; however, nerve fascicles on the lateral aspect of the nerve could experience different strains. Finally, we analyzed nerve strain by measuring displacement of epineurial sutures rather than with a microstrain gauge, which could damage neural elements.

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