Longitudinal Excursion and Strain in the Median Nerve during Novel Nerve Gliding Exercises for Carpal Tunnel Syndrome

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ABSTRACT: Nerve and tendon gliding exercises are advocated in the conservative and post-operative management of carpal tunnel syndrome (CTS). However, traditionally advocated exercises elongate the nerve bedding substantially, which may induce a potentially deleterious strain in the median nerve with the risk of symptom exacerbation in some patients and reduced benefits from nerve gliding. This study aimed to evaluate various nerve gliding exercises, including novel techniques that aim to slide the nerve through the carpal tunnel while minimizing strain ("sliding techniques"). With these sliding techniques, it is assumed that an increase in nerve strain due to nerve bed elongation at one joint (e.g., wrist extension) is simultaneously counterbalanced by a decrease in nerve bed length at an adjacent joint (e.g., elbow flexion). Excursion and strain in the median nerve at the wrist were measured with a digital calliper and miniature strain gauge in six human cadavers during six mobilization techniques. The sliding technique resulted in an excursion of 12.4 mm, which was 30% larger than any other technique ($p \leq 0.0002$). Strain also differed between techniques ($p \leq 0.00001$), with minimal peak values for the sliding technique. Nerve gliding associated with wrist movements can be considerably increased and nerve strain substantially reduced by simultaneously moving neighboring joints. These novel nerve sliding techniques are biologically plausible exercises for CTS that deserve further clinical evaluation. © 2006 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 24:1–9, 2006

Keywords: carpal tunnel syndrome; nonsurgical treatment; exercise; neurodynamic test; nerve biomechanics

INTRODUCTION

Carpal tunnel syndrome (CTS) is a clinical condition resulting from compression of the median nerve where it passes under the transverse carpal ligament at the wrist. With a prevalence of 3.8% in the general population,[1] it is the most common compressive neuropathy. Conservative management is the treatment of choice for patients with mild to moderate CTS.[2,3] Frequently advocated modalities include splinting, local corticosteroid injections, ultrasound, and oral medication (steroids and nonsteroidal anti-inflammatory drugs).[3−5] However, systematic reviews indicate that there is either limited evidence for the long term effects of these conservative treatment modalities[4,5] or

long term effects are considered to be poor.[3] If conservative treatment fails or the case is severe with signs of denervation in the thenar muscles, surgery is indicated. In the USA, 460,000 surgical interventions for CTS are performed annually with medical costs exceeding $2 billion dollars each year.[6] As it is not uncommon that CTS gradually worsens if left unchecked[7] and as complication rates following surgery are considerable,[8,9] it is vital to develop and evaluate effective conservative treatment approaches.

Recently, several narrative reviews have advocated nerve and tendon gliding exercises as a biologically plausible alternative for traditionally advocated treatment modalities in the conservative management of CTS.[2,7,10,11] Also in postoperative care, early mobilization and nerve and tendon gliding exercises have been recommended.[12−15] The beneficial effects of these exercises may include direct mobilization of the nerve, facilitation of venous return, edema dispersal, decrease of

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pressure inside the perineurium, and decrease of carpal tunnel pressure.[7,16–18] Specific to postoperative management, adhesion formation between the median nerve and flexor tendons may be prevented.[13,19]

The tendon gliding exercises were described by Wehbé and Hunter[20] and are identical to the exercises frequently prescribed in hand therapy to prevent adhesions and to promote tendon healing following tendon surgery (Fig. 1: 1–5). The median nerve gliding exercises that have been used in clinical trials for CTS[21,22] were proposed by Totten and Hunter[17] (Fig. 1A–F). This sequence of positions progressively elongates the median nerve bed (the tract formed by the structures that surround the nerve) in order to slide the median nerve through the carpal tunnel.

Joint movements alter the length of the nerve bed and induce gliding of the nerve relative to its surrounding structures.[23–26] Movements that elongate the nerve may result in a substantial increase in nerve strain, which can be transmitted along a long section of a peripheral nerve.[23–26] For example, strain in the median nerve at the wrist increases significantly with elbow extension or shoulder abduction.[23,24,26] Nerve strain of 5–10% impairs intraneural blood flow,[27] axonal transport,[28] and nerve conduction,[29] and a minimal increase in nerve strain of 3% is sufficient to generate ectopic impulses when a nerve is inflamed, which may lead to pain or paraesthesia.[30] The concern that the above mentioned beneficial effects accredited to nerve gliding could be nullified by the poten-

tially deleterious effects of nerve strain led to the development of novel nerve gliding exercises.

With these novel exercises, joints are moved simultaneously in such a manner that a movement that lengthens the nerve bed and increases strain in the median nerve at the wrist (e.g., wrist extension) is simultaneously counterbalanced by a movement in an adjacent joint that reduces the length of the nerve bed and reduces median nerve strain at the wrist (e.g., elbow flexion). These techniques have been labeled "sliding techniques".[16,31] The clinical assumption is that this type of nerve gliding exercise results in a larger longitudinal excursion than techniques that simply elongate the nerve bed and that this larger excursion is associated with a minimal increase in tension.[16,31] A large excursion without a potentially deleterious increase in strain would imply that this type of exercise would be most appropriate in the conservative and postoperative management of CTS, especially when the tissue tolerance to mechanical loading is low. Although excursion of the tendons during the tendon gliding exercises has been documented in detail,[20] excursion and median nerve strain have never been investigated for nerve gliding exercises.

The aim of this study was to evaluate longitudinal excursion and strain in the median nerve at the wrist during a selection of single joint and combined movements of the wrist and elbow. In agreement with current clinical beliefs, we hypothesized that a sliding technique results in the largest longitudinal excursion of the median nerve
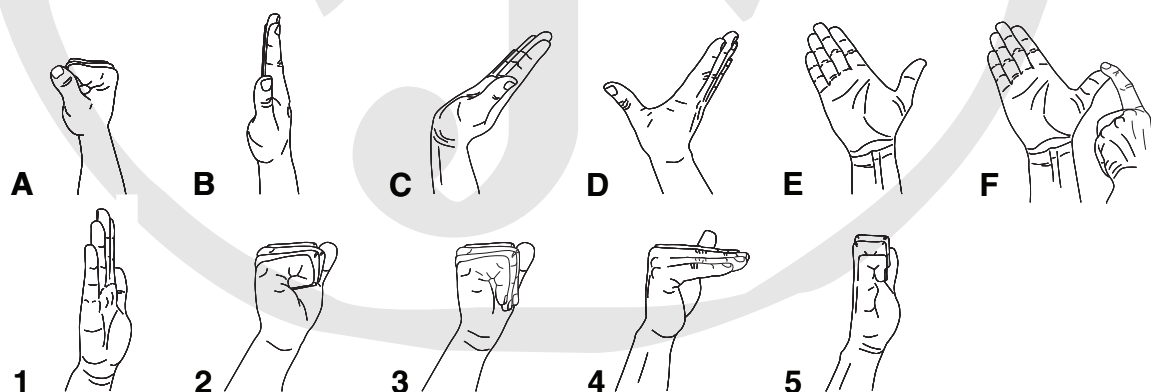

Figure 1. (A–F) Nerve gliding exercises as described by Totten and Hunter.[17] (A) Wrist in neutral, fingers and thumb in flexion; (B) wrist in neutral, fingers and thumb extended; (C) wrist and fingers extended, thumb in neutral; (D) wrist, fingers, and thumbs extended; (E) as in (D) with forearm in supination; (F) as in (E) with gentle stretch of thumb. (1–5) Tendon gliding exercises as described by Wehbé and Hunter.[20] (1) Straight; (2) hook; (3) fist; (4) table top; (5) straight fist.

at the wrist and that the excursion is associated with a minimal increase in nerve strain.

METHODS

Longitudinal excursion and strain in the median nerve were measured during various mobilization techniques in human cadavers. Ethical approval for the study was obtained from the Institutional Ethics Committee prior to commencement of the study. The cadavers were donated to the institution for purposes of teaching and research.

Cadavers

Six intact embalmed cadavers that displayed no evidence of trauma or deformity to the spine or extremities were used for this study (five males, one female; age at time of death ranged between 65 and 92 years). In a comparison between embalmed and unembalmed cada-

vers, Kleinrensink et al.[32] concluded that it is justified to obtain data from embalmed cadavers to analyze the effect of limb movement on strain in peripheral nerve trunks, especially in comparative studies such as the present study. Measurements were performed on one side of the body (right arm: three; left arm: three).

Nerve Gliding Techniques

Six mobilization techniques were evaluated (Fig. 2). The first technique (Fig. 2A) was selected as a paradigm for sliding techniques[16,31] as it consisted of an alternation of combined movements of two joints in which one movement loads the peripheral nerve while the other movement simultaneously unloads the nerve. Elbow extension (loading) and wrist flexion (unloading) were alternated with elbow flexion (unloading) and wrist extension (loading). The second technique (Fig. 2B) was included as a paradigm for "tensioning techniques"[16,31] as the combined movements at the wrist and elbow resulted in a concurrent increase in length of the median
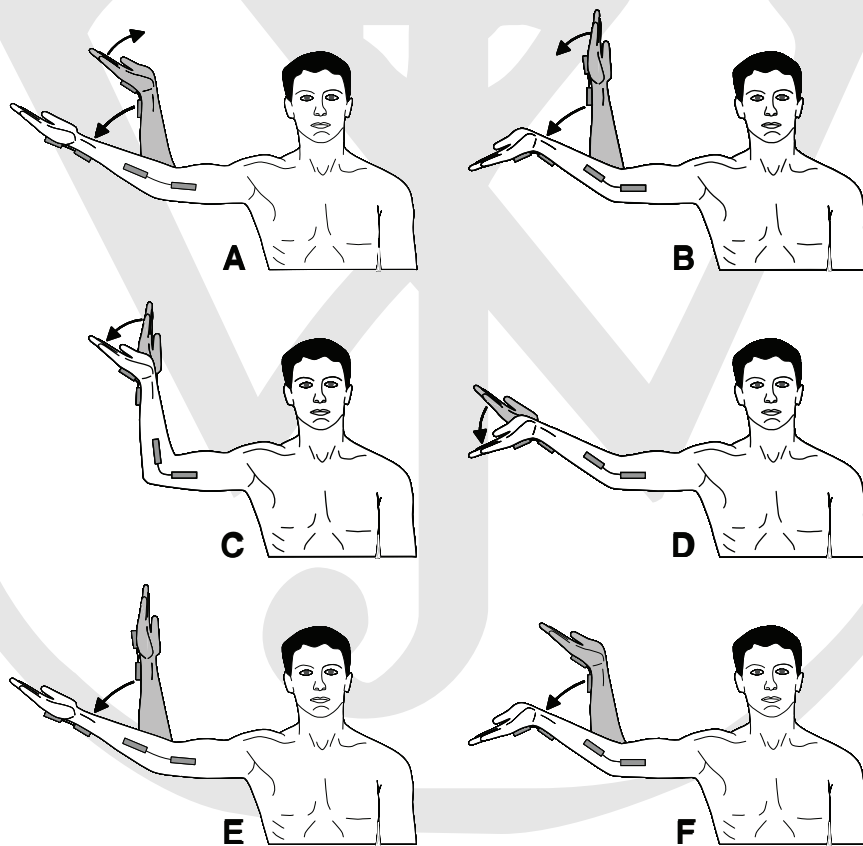

Figure 2. Illustration of the six different mobilization techniques evaluated in this study. (A) Sliding technique; (B) tensioning technique; (C) wrist motion with elbow in flexion; (D) wrist motion with elbow in extension; (E) elbow motion with wrist in neutral; (F) elbow motion with wrist in extension. The gray shaded hand and forearm illustrate the starting position. The arrows indicate the movements to reach the end position (unshaded body chart). The techniques consisted of repeated movements between the starting and end position. The electrogoniometers at the elbow and wrist are also shown.

nerve bed. Wrist extension (loading) and elbow extension (loading) were simultaneously performed, and alternated with wrist flexion (unloading) and elbow flexion (unloading). The effect of single joint movements was analyzed in four additional techniques (Fig. 2C–F). The wrist was mobilized while maintaining the elbow in flexion (Fig. 2C) and extension (Fig. 2D), and the elbow was moved with the wrist in neutral (Fig. 2E) and with the wrist in extension (Fig. 2F). The techniques were performed in random order.

Within each cadaver, the range of motion through which the wrist and elbow were moved was identical for the various techniques. All techniques were repeated five times and the last three repetitions were used to calculate strain. If the target ranges were not accurately reached, up to two extra repetitions were performed. Excursion measurements were made during three additional repetitions.

Note that we use the term *nerve gliding exercises* to refer to a variety of different techniques, whereas the term *sliding techniques* is exclusively used to refer to the types of techniques that involve simultaneous movement of adjacent joints and which are thought to induce a large excursion with a minimal increase in strain.

Strain Measurements

Two linear displacement transducers (differential variable reluctance transducers; Microstrain, Burlington, VT) with a stroke length of 6 mm and a resolution of 1.5 μm were used to measure strain in the median nerve. The strain gauges were fixed by insertion of two barbed pins into the median nerve trunk just proximal to the wrist and at the level of the humerus, approximately 12 cm proximal to the medial epicondyle. To minimize disruption of surrounding soft tissues and local biomechanics, the strain gauges were inserted through small windows of approximately 7×4 cm into the skin and underlying subcutaneous tissues. Calibration equations provided by the manufacturer were used to convert the voltage output of the strain gauges into length measurements.

Strain in the median nerve in the anatomical position was used as an arbitrary reference to which changes in strain were expressed. In the anatomical position, the arm was positioned in $10°$ shoulder abduction, with the elbow in extension ($170°$), the forearm in supination and the wrist in a neutral position ($0°$ extension).

Excursion Measurements

A digital Vernier calliper was used to measure the longitudinal excursion of the median nerve in relation to a fixed marker that was screwed into the cortical bone of the distal end of the radius and the humerus. The marker consisted of a metal L-shaped pin that was placed perpendicularly over the nerve bed. The marker on the median nerve consisted of a suture that was placed around the nerve in the vicinity of the fixed marker.[23,25]

Goniometry

Twin axis electrogoniometers (Biometrics, Blackwood, Gwent, UK) were attached to the wrist (model SG65) and elbow (model SG110) to measure joint range of motion. To protect the devices from moisture, the electrogoniometers and cables were placed in plastic sleeves.

Data Collection and Analysis

The output from the displacement transducers and electrogoniometers was connected to a data acquisition system (Micro 1401; Cambridge Electronic Design, Cambridge, UK), which sampled at 50 Hz using Spike 2 software. An advantage of this set-up was that the investigator who performed the mobilization techniques received real time feed back of the position of the wrist and elbow via a computer screen, which also displayed the target angles. This method promoted accurate repositioning of joint angles during the six mobilization techniques. Throughout the experiment, the investigator was blinded from the output of the strain gauges.

From the continuous data sets, the strain in the median nerve in the starting and end position was determined for each repetition of the different mobilization techniques for each cadaver. A paired t-test was used to investigate whether the amount of excursion and changes in strain associated with each technique was significant (significantly different from zero). A one-way repeated-measures analysis of variance was used to determine the presence of statistical differences in excursion and strain between the six different techniques. Duncan's multiple comparison tests were used for posthoc comparison. The level of significance was set at $p < 0.05$.

RESULTS

Test Characteristics

The wrist was moved between (mean ± 1 SD) the neutral position [$0.2°$ (± 0.8) flexion] and $58.8°$ (± 14.9) extension. The elbow was moved between $89.9°$ (± 0.8) and $166.5°$ (± 3.4) extension. The range of motion through which the wrist and elbow were moved was not different for the different mobilization techniques (wrist: $p = 0.68$; elbow: $p = 0.21$).

Median Nerve at the Wrist

Figure 3 demonstrates the longitudinal excursion (top panel) and change in strain (lower panel) in the median nerve at the wrist during the six mobilization techniques.

Although all techniques resulted in a significant amount of median nerve gliding at the wrist ($p \leq 0.006$), there were significant differences in the amount of nerve gliding between the different
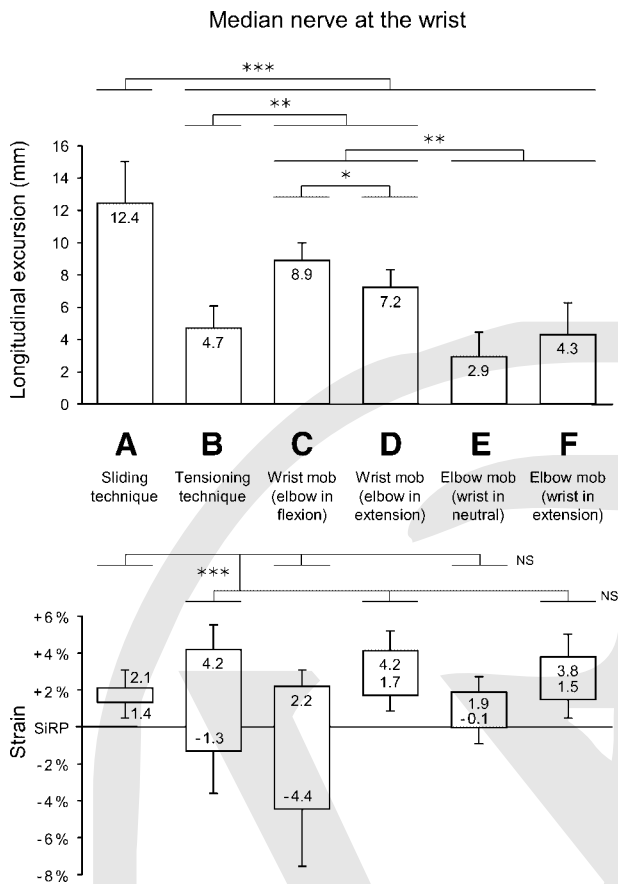
Figure 3. Longitudinal excursion (mean ± 1 SD) of the median nerve at the wrist (top panel) and changes in nerve strain relative to strain in the reference position during six mobilization techniques (lower panel). The top border of the boxes in the lower panel corresponds with the mean maximum strain value (±1 SD) measured during the respective technique; the bottom edge corresponds with the mean minimum value (±1 SD). Due to concurrent movements at the wrist and elbow, which simultaneously load and unload the median nerve, the smallest variation in strain was observed during the sliding technique. The sliding technique was also one of the techniques that was associated with the lowest peak strain. In addition to low strain values, the sliding technique generated the largest gliding of the median nerve at the wrist. SiRP, strain in reference position; mob, mobilization; *$p < 0.05$; **$p < 0.005$; ***$p < 0.0005$; NS, not significant.

techniques ($p < 0.00001$). The excursion associated with the sliding technique (A) was significantly larger than the nerve movement in any of the other techniques (B–F) ($p \leq 0.0002$). For single joint movements, the two techniques that involved wrist movements (C and D) resulted in a significantly larger excursion of the median nerve at the wrist than the two techniques that evaluated the effect of

elbow movements (E and F) ($p \leq 0.0009$). With the median nerve unloaded at the elbow by elbow flexion, wrist extension (C) resulted in a significantly larger nerve excursion than when the nerve was already pretensioned by elbow extension (D) ($p = 0.03$). Wrist movements with the elbow in either flexion (C) or extension (D) resulted in a larger nerve excursion at the wrist than the tensioning technique (B) ($p \leq 0.0027$).

The techniques that involved maximum nerve bed elongation, that is, simultaneous extension of the wrist and elbow (B, D, F), were associated with a significantly larger maximum increase in strain ($\approx +4\%$) than the techniques in which wrist extension and elbow extension never occurred concurrently (A, C, E; $\approx +2\%$) ($p \leq 0.0005$). There was no difference in maximal strain across techniques with maximum nerve bed elongation (B, D, F; $p \geq 0.33$) or across techniques where the nerve bed was elongated at only one joint (A, C, E; $p \geq 0.44$).

The variation in strain (difference between maximal and minimal increase in strain throughout the technique) was also significantly different for the different techniques ($p = 0.00001$). The sliding technique (A) was associated with a significantly smaller variation in strain than the tensioning technique (B) and than mobilization of the wrist with the elbow in flexion (C) ($p \leq 0.0002$). The differences between the sliding technique (A) and the other techniques (D, E, F) did not reach the level of significance ($p \geq 0.22$).

Median Nerve Proximal to the Elbow

Although the primary focus of this study was the measurement of excursion and strain of the median nerve at the wrist, recordings were also made at the level of the humerus. The longitudinal excursion and strain associated with the six mobilization techniques are presented in Figure 4.

Similar to the median nerve at the wrist, all techniques resulted in a longitudinal excursion of the median nerve in relation to the humerus ($p \leq 0.029$), with differences in the amount of gliding between different techniques ($p < 0.00001$). The substantial excursion (≥ 10 mm) associated with the techniques that involved elbow movements (A, B, E, F) was significantly larger than the relatively small excursion (≤ 2.5 mm) associated with movements of the wrist alone (C, D) ($p \leq 0.0005$). The tensioning technique (B) was associated with the largest excursion ($p \leq 0.039$), larger than the sliding technique. This seemingly contradictory finding can be explained by the fact that a nerve slides toward the joint where the nerve
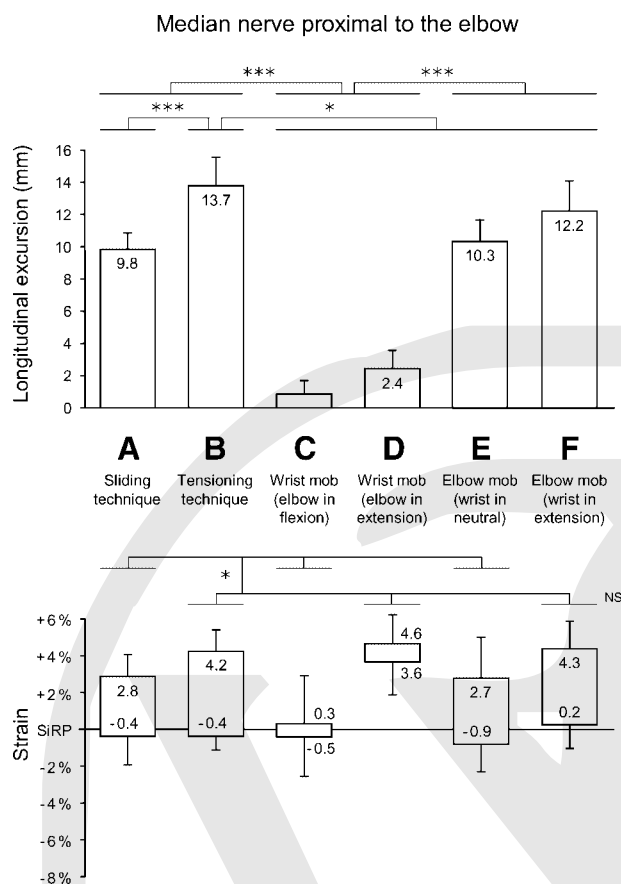
Median nerve proximal to the elbow

Figure 4. Longitudinal excursion (top panel) and changes in strain (lower panel) of the median nerve at the humerus during six mobilization techniques (mean ± 1 SD). All techniques resulted in a longitudinal excursion of the median nerve in relation to the humerus and apart from mobilization of the wrist with the elbow in flexion, and all techniques resulted in a significant change in strain. SiRP, strain in the reference position; mob, mobilization; $*p < 0.05$; $**^{AQ1}p < 0.005$; NS, not significant.

bed is elongated,[24,33,34] and, in the case of the tensioning technique, both elongating maneuvers were located distally from the excursion measurement at the level of the humerus, resulting in a cumulative effect.

Apart from mobilization of the wrist with the elbow in flexion (C) ($p = 0.10$), all techniques resulted in a significant change in strain ($p \leq 0.0005$). Similar to the strain at the wrist, the maximum increase in strain at the level of the humerus was not identical across techniques ($p < 0.00001$). The techniques that maximally elongated the nerve bed by simultaneous extension of the wrist and elbow (B, D, F) resulted in larger maximum strain recordings than the techniques in

which the nerve bed was only elongated at one joint (A, C, E) ($p \leq 0.014$). There was no significant differences in maximum strain values between techniques that maximally elongated the nerve bed (B, D, F) ($p \geq 0.49$).

DISCUSSION

The primary aim of this study was to evaluate longitudinal excursion and strain in the median nerve at the wrist during a variety of nerve gliding exercises. The results clearly demonstrate that different techniques result in different amplitudes of nerve gliding and differences in nerve strain. The position or simultaneous movement at the elbow has a strong effect on the amount of excursion and strain in the median nerve at the wrist. Given the continuity of the median nerve and the findings of this study, it is evident that the position and movement of neighboring joints need to be considered to optimize the nerve gliding exercises currently used in the conservative and postoperative management of CTS, such as the exercises described by Totten and Hunter.[17]

Optimal nerve gliding through the carpal tunnel is obtained when movements of the wrist are accompanied by movements in adjacent joints in such a manner that elongation of the nerve bed caused by motion at one joint is counterbalanced by a simultaneous decrease in the length of the nerve bed at the other joint (sliding technique). A decrease in strain in the median nerve in the forearm as a result of elbow flexion enables a maximal distal glide of the median nerve through the carpal tunnel during wrist extension. Similarly, the increase in tension in the median nerve in the forearm induced by elbow extension increases the proximal excursion of the median nerve through the carpal tunnel during wrist flexion. In contrast, the increase in tension in the median nerve in the forearm with elbow extension restricts the distal excursion of the median nerve through the canal during wrist extension (tensioning technique).

For an identical range of motion at the wrist, integration of elbow movements in such a manner that total nerve bed elongation was limited (sliding technique) resulted in a ≈30% larger excursion of the median nerve [12.4 (±2.6) mm vs. 8.9 (±1.0) and 7.2 (±1.1) mm]. In addition, strain throughout the sliding technique was low. In contrast, when the wrist and elbow were moved through a similar range of motion but in such a way that the nerve bed was simultaneously lengthened at the wrist and elbow (tensioning technique), excursion of the

median nerve at the wrist was reduced to less than half of the excursion associated with the sliding technique [4.7 ($\pm$1.4) mm vs. 12.4 ($\pm$2.6) mm] and peak strain in the median nerve at the wrist was high.

The majority of the nerve gliding exercises suggested by Totten and Hunter[17] involve extension of the wrist and fingers. Wright et al.[24] reported that the increase in strain associated with these movements approaches the level that affects vital nerve processes, such as axonal transport,[28] intraneural microcirculation,[27] and nerve conduction.[29] Although Wright et al.[24] reported higher strain values than Byl et al.,[23] a minimal increase in nerve strain of 3% is sufficient to generate ectopic impulses when a nerve is inflamed,[30] which may exacerbate symptoms such as pain and paraesthesia. Given the positive effects that have been attributed to nerve gliding,[7,16–18] and the potentially deleterious effects of nerve strain,[27–30] we suggest that nerve sliding techniques that result in a larger longitudinal excursion and a minimal increase in strain are types of exercises that are biologically more plausible than mobilization techniques that aim to facilitate nerve gliding by elongation of the nerve bedding. Sliding techniques may be especially useful in the stages of the rehabilitation program when the tolerance to mechanical loading of the tissues in the carpal tunnel is relatively low.

It is important to emphasize that the chosen techniques should only be regarded as examples of different types of mobilization techniques and that variations on the techniques should be considered when designing a conservative or postoperative rehabilitation program. The only reason why wrist flexion beyond the neutral position was not incorporated was because of nerve buckling, which has been reported previously with wrist flexion in fresh cadavers.[24] Due to a limited range of motion in the metacarpophalangeal and interphalangeal joints, it was not possible to investigate nerve gliding exercises that involved the fingers. In fresh cadavers, Wright et al.[24] demonstrated a 6.3 mm distal excursion of the median nerve at the wrist with hyperextension of the fingers and a proximal excursion of 3.4 mm with the fingers fully flexed. A sliding technique that consists of wrist extension (loading) and finger flexion (unloading), in alternation with wrist flexion (unloading) and finger extension (loading) is likely to be a valuable mobilization technique in the rehabilitation program of patients with CTS. An additional advantage of this technique in the postoperative management of CTS is that simultaneous flexion of the wrist and fingers, which is the position that has been reported to be most prone to bowstringing of the flexor tendons,[12] is avoided.

The concern that division of the transverse carpal ligament may permit bowstringing of the tendons, entrapment of the median nerve in scar tissue, or wound dehiscence has been the principal motivation for splinting the wrist after carpal tunnel surgery.[35] Although the transverse carpal ligament serves as a pulley restraining the digital flexor tendons when the wrist is flexed, studies that investigated early mobilization did not observe or report bowstringing or wound problems.[12,13] Because immobilization following carpal tunnel surgery has been associated with pain, stiffness, and delay in recovery, Cook et al.[12] concluded that splinting the wrist for 2 weeks following carpal tunnel surgery is largely detrimental. Active range of motion exercises for the hand and wrist, and exercises to promote longitudinal nerve gliding are recommended to commence on the first postoperative day.[13]

Nerve and tendon gliding exercises may also be of benefit to patients considered for surgery. In a retrospective study, Rozmaryn et al.[21] reviewed the treatment of 197 patients under consideration for carpal tunnel decompression and showed that 71% (74/104) of patients who were not offered nerve and tendon gliding exercises received surgery, whereas only 43% (40/93) of the patients who performed the exercises required surgery. All patients received traditional conservative treatment modalities, such as splinting, nonsteroidal anti-inflammatory medication, and/or steroid injections, with 104 patients also performing nerve and tendon gliding exercises. Unfortunately, high level evidence from high quality randomized clinical trials is not yet available.

Excursion and strain in the median nerve have been studied in fresh,[23,36] fresh frozen,[24,37] and embalmed[38,39] cadavers. Little is known about the effects of freezing and thawing or the impact of embalmment on mechanical properties of nerves, such as elasticity and maximal tensile strength. Based on a comparison between embalmed and fresh cadavers, Kleinrensink et al.[32] concluded that it is justified to use embalmed cadavers to analyze changes in strain in peripheral nerves during limb movements, especially in comparative studies such as the present study. Although an exact comparison of the magnitude of the increase in strain between studies is impossible due to differences in starting positions and range of motion, some of the movements we analyzed in this study were also performed in a previous study using fresh

cadavers.[23] Byl et al.[23] reported a 5.5% increase in strain with elbow, wrist, and finger extension, while we recorded a relatively similar 4.2% increase with elbow and wrist extension (we did not include finger extension), suggesting that embalment may not dramatically alter the mechanical properties of nerves. Even if embalment has some effect on the absolute values for excursion and strain, we believe that by using a repeated measures design, the main finding of this study, that is, that sliding techniques result in the largest excursion with a minimal increase in strain, is justified.

In conclusion, sliding techniques induce the largest longitudinal excursion of the median nerve relative to its surrounding structures without being associated with a potentially detrimental increase in nerve strain. Because exercises should be performed without exacerbation of CTS symptoms,[7] and because it is more biologically plausible to slide the median nerve through the carpal tunnel without a substantial increase in strain, the results of this study support the introduction of these novel nerve gliding techniques aimed at optimizing the rehabilitation of patients with CTS. High quality randomized clinical trials to investigate the clinical efficacy of these novel nerve gliding exercises in patients with CTS are required.

ACKNOWLEDGMENTS

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