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Case Report

Postoperative management and rehabilitation after the supercharged end-to-side anterior interosseous nerve to ulnar motor nerve transfer: A report of 3 cases

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ABSTRACT

Introduction: Compressive ulnar neuropathy at the elbow is the second most common compressive neuropathy. Nerve transfers are used for severe ulnar neuropathies as a means of facilitating recovery. Hand therapy and rehabilitation after nerve transfers have not been extensively explored.
Purpose of the Study: The aim of this repeated case study was to describe the responses, functional outcome, and neuromuscular health of three participants after the supercharged end-to-side (SETS) anterior interosseous nerve (AIN) to ulnar motor nerve transfer do describe the hand therapy and recovery of 3 cases reflecting different recovery potential mediators, trajectories, and outcomes.
Study Design: Repeated case study.
Methods: Three participants of similar age (76-80 years) that had severe ulnar neuropathy who underwent surgical treatment including a SETS AIN to ulnar motor nerve surgery were purposively selected from an ongoing clinical trial, based on their response to the surgical and the rehabilitation intervention (large, moderate, and small improvements). Clinical evaluations included measuring range of motion, strength testing, and clinical tests (ie, Egawa's sign) and, subjective assessment of rehabilitation adherence., Quick Disability of Arm, Shoulder and Hand and decomposition-based quantitative electromyography were performed at >23 months to evaluate patients.
Results: All the three participants completed the surgical and hand therapy interventions, demonstrating a variable course of recovery and functional outcomes. The Quick Disability of Arm, Shoulder and Hand scores (>23 months) for participants A, B, and C were 68, 30, and 18, respectively. The person with the least improvement had idiopathic Parkinson's disease, dyslipidemia, history of depression, and gout. Comparison across cases suggested that the comorbidities, longer time from neuropathy to the surgical intervention, and psychosocial barriers to exercise and rehabilitation adherence influenced the recovery process. The participants with the best outcomes demonstrated improvements in his lower motor neurons or motor unit counts (109 and 18 motor units in the abductor digiti minimi (ADM) and first dorsal interosseous, respectively) and motor unit stability (39.5% and 37.6% near-fiber jiggle in the ADM and first dorsal interosseous, respectively). The participant with moderate response to the interventions had a motor unit count of 93 for the ADM muscle. We were unable to determine motor unit counts and measurements from the participant with the poorest outcomes due to his physical limitations.

Conflicts of interest: None.

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Conclusions: SETS AIN to ulnar motor nerve followed by multimodal hand therapy provides measurable improvements in neurophysiology and function, although engagement in hand therapy and outcomes appear to be mediated by comorbid physical and psychosocial health.

Introduction

Aside from carpal tunnel syndrome, unlar nerve entrapment at the elbow (UNE) is the most prevalent compressive neuropathy.[1] Clinical presentation of ulnar neuropathy often includes clawing of the hand, significant intrinsic muscle weakness, and atrophy.[2] Sensory complaints from patients may include paresthesia and numbness, mostly in the ulnar digits along with medial elbow pain. Entrapment traction and increased pressure, with a decreased blood supply can lead to epineural ischemia.[3] Likewise, venous return may be affected which can lead to fibrosis and scar tissue formation with resulting intraneural edema. Initial management of mild ulnar neuropathies includes activity modification that avoids fixed elbow flexion postures and minimizing direct pressure over the epicondylar groove. The addition of night extension orthoses, neural mobilization, and hand therapy may help to maintain strength, range of motion (ROM), and prevent clawing.[4] Several surgical interventions may be performed to treat ulnar neuropathy at the elbow such as decompression,[5] ulnar nerve transposition,[6] nerve transfers,[7] or a combination of these techniques.[8] Overall, the prognosis and recovery from severe ulnar axonopathy are less than ideal in terms of motor functional outcomes.[9]

A new addition to the treatment options available is the technique of transferring the anterior interosseous nerve (AIN) as a donor nerve to the motor fascicle side of the ulnar nerve in the distal forearm to augment innervation closer to the target muscles. This surgical procedure is known as the supercharged end-to-side (SETS) nerve transfer technique.[10] Conceptually, the surgery utilizes the AIN to "supercharge" the motor fascicles of the ulnar nerve, allowing for reinnervation of the hand musculature.[11-13] Initial animal models have demonstrated increased nerve regeneration, muscle mass, and improved quality of nerve regeneration.[11,12] Past reports of the AIN to ulnar nerve SETS technique applied to human participants have demonstrated improved functional outcomes such as increased pinch and grip strength, and increased ability to abduct and adduct the affected hand intrinsic musculature.[8,10,11,13,14] Although standard clinical and qualitative nerve conduction studies and EMG procedures have been used to evaluate motor neuron and neuromuscular endplate properties, the use of quantitative EMG to examine neuromuscular changes after the SETS procedures have not been reported to date.

Nerve transfer procedures provide promising results for improved patient recovery, but the rehabilitation approaches and protocols specific to these surgical procedures have not been explored extensively. Postoperative rehabilitation programs, usually performed by a hand therapist, were frequently reported as an integral part of the participants' care after the surgery. Aside from standard patient education and traditional hand therapy exercises, a focus on motor reeducation has also been incorporated.[8,10] The clinical observation that focuses on donor activation has been suggested to maximize functional outcomes of hand rehabilitation, after nerve transfer.[15]

The aim of this repeated comparative case study was to describe the responses of three participants to a specific hand therapy program aimed at improving function, after the AIN to ulnar nerve SETS surgery. By describing the outcome of multiple cases, we hope to provide potential explanations for the varied response of the participants. Furthermore, a patient-reported outcome measure (Quick Disability of Arm Shoulder and Hand [QuickDASH]) and the addition of neurophysiological measures using Decomposition-based Quantitative Electromyography (DQEMG) have been added to compare their postoperative recovery and neuromuscular health.

Case selection and description

Sampling

In a repeated comparative case study, specific patient cases are selected with intent. Patients in this study were recruited from an ongoing clinical trial which prospectively evaluates the SETS AIN to ulnar nerve technique for compressive UNE in comparison with a standard ulnar nerve transposition. Exclusion criteria for this study included patients with ulnar neuropathy at multiple anatomic locations along the course of the nerve. Three participants were purposively selected and represented three varying levels of improvement of small, moderate, and large to the surgical and therapeutic interventions as defined by their functional outcome >23 months after surgical intervention. Magnitude of improvement were selected based on their final outcomes from i) patient-reported outcome measure (QuickDASH) and ii) clinical assessment performed by the occupational therapist/hand therapist (J.L.S.). Using this approach provides a means of exploring the clinical decision-making and potential case factors that may have contributed to personalization of the rehabilitation and the outcomes achieved. Written informed consent was obtained from each participant (file number: 105546).

Patients

Overall, three retired older males (>60 years old) who underwent a SETS AIN to ulnar nerve procedure for severe ulnar neuropathy at the elbow were selected to participate in the present study. Table 1 presents the baseline characteristics and personal/environmental factors of each participant. Similarities between the three participants include their age, sex, occupation status (retired), and the surgical procedure that they received. Differences between the three participants include the mechanism of injury, time from neuropathy to surgery, comorbidities, and social history. Patient C had a unique mechanism of injury where he developed a compression neuropathy secondary to a humeral fracture. Furthermore, patient C had very few comorbidities (hypertension). By contrast, patient A was the only participant with a social history of living alone. Patient A also lived in a more remote and rural region, where access to therapy was more challenging. Furthermore, patient A also had idiopathic Parkinson's disease (PD). Patient B had a common comorbidity in UNE and was beginning to experience ulnar neuropathy in his contralateral upper extremity. Overall, this may have affected his upper extremity function, as it would decrease his ability to compensate with his contralateral limb.

Evaluative procedures

During the rehabilitation sessions, participants underwent a thorough history and physical examination with one occupational therapist/hand therapist, who is also a coauthor to this study (J.L.S.).

Table 1
Patient demographic information

Patient information	Patient A	Patient B	Patient C
Age (years old)	76	80	76
Sex	M	M	M
Handedness	*R*	*R*	*R*
Affected limb	L	*R*	*R*
Duration of symptoms (presurgical)	2-3 y before surgery	>3 y before surgery	~1 y before surgery
Mechanism of injury	Compressive neuropathy	Compressive neuropathy	Compressive neuropathy secondary to humeral fracture
Comorbidities	Parkinson's disease, atrial fibrillation, dyslipidemia, depression, gout	Dyslipidemia, hypertension, cerebrovascular accident (posterior cerebral artery), mild ulnar neuropathy (contralateral hand)	Hypertension
Personal barriers to recovery	Age, previous occupation (television technician), lives in more rural setting with less access to care	Age, previous occupation (electrician)	Age
Therapy attendance (sessions)	17	18	17
Therapy adherence	Low	Moderate	High
Social supports	None reported	Lives with spouse	Lives with spouse
Life roles	Father	Spouse, father	Spouse, father

Examination included screening for red flags, neurological assessment, strength testing (ie, MRC muscle scale, grip, pinch),[16] and ROM assessment. Several clinical motor tests were performed to evaluate the participants' hand function. To assess dysfunction of the interossei muscles, the crossed-finger test and Egawa's sign were performed.[17] Similarly, Froment's sign and Wartenberg's sign were documented to detect for adductor pollicis and hypothenar muscle dysfunction,[17] respectively. To evaluate overall finger and hand abduction, finger tracings of maximal hand abduction were performed.[10] Total abduction was measured using the distance from tip of the 1st digit to tip of the 5th digit with the hand flat and in the pronated position on a table (see Fig. 1). Hand therapy adherence was assessed by the hand therapist through therapy attendance, subjective evaluation by the therapist (J.L.S.), and self-reporting from the patient through simple and direct questions.[18]

A physical therapist not involved in the participants' care also evaluated study outcomes (author P.T.) A patient-reported outcome measure was obtained from all three participants as a long-term (>23 months) evaluation of their current upper extremity disability. Quantitative EMG was acquired from two of the participants to evaluate neuromuscular health.[19] Patient A did not participate in quantitative EMG testing because it was physically and logistically too demanding for him to attend.

Patient-reported outcome measure

One approach to capture disability as a result of upper extremity dysfunction is using a patient-reported outcome measure. The QuickDASH is an efficient outcome measure developed by Beaton et al as a short form to the Disability of Arm, Shoulder, and Hand (DASH).[20,21] The QuickDASH has been well validated in several clinical populations such as those with mixed upper extremity disorders,[22] patients with distal radius fractures[23] and patients undergoing rotator cuff surgery.[24]

Decomposition-based quantitative electromyography

DQEMG is an efficient approach to capturing several motor unit and neurophysiological variables regarding motor unit health and neuromuscular physiology.[19] DQEMG and the Sierra EMG system software (Sierra Inc) were used to collect the quantitative EMG data. The algorithms of DQEMG have been previously discussed.[19] Self-adhesive Silver Mactrode electrodes (GE Medical Systems, Milwaukee, WI) were used to detect surface signals with bandpass setting of 5 Hz to 5000 Hz. 25 mm × 30-gauge disposable concentric needle electrodes (TECA elite, CareFusion, Middleton, WI) were used to detect intramuscular needle EMG signals with bandpass settings of 10Hz to 10 KHz.

For EMG data collection, each participant's skin was cleansed with isopropyl alcohol before surface electrodes were placed. For the first dorsal interosseous (FDI) and abductor digiti minimi (ADM) muscles, the active electrode was positioned over the muscle belly, whereas the reference electrode was positioned over the 2nd and 5th metacarpal phalangeal joint line, respectively. The ipsilateral ulnar styloid process was used for the ground electrode

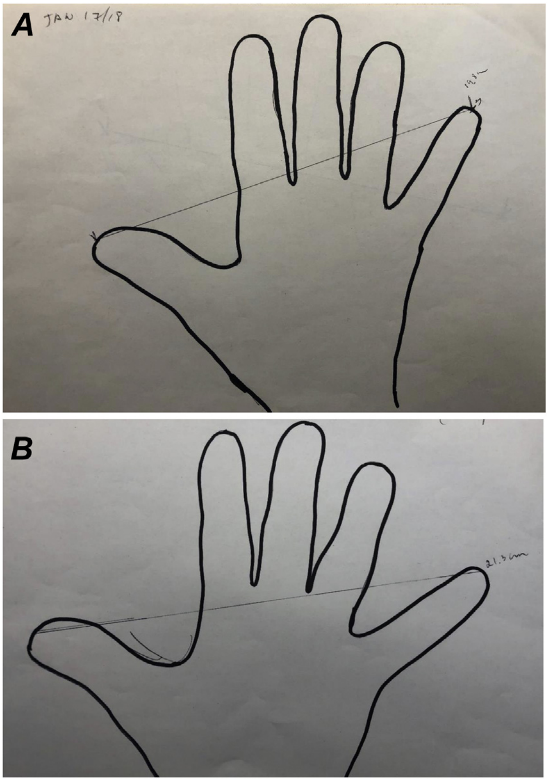

Fig. 1. Patient grip, key pinch, and tripod pinch strength over time after SETS AIN to ulnar nerve surgery. Patient C is represented by blue. Patient B is represented by red. Grip strength is shown with solid lines, dotted lines represent key pinch strength, and dashed lines represent tripod pinch strength. SETS AIN = supercharged end-to-side anterior interosseous nerve.

placement. A bipolar stimulator was used to elicit a maximum compound muscle action potential (CMAP) by stimulating the ulnar nerve at the wrist. The stimulus intensity was gradually increased until the CMAP negative peak amplitude no longer increased and was determined to be supramaximal.[25]

A concentric needle was inserted into the muscle belly of the FDI and ADM. For the FDI and ADM, the needle electrode was always positioned a minimum of 2 mm away from the active surface electrode. Participants were asked to perform mild isometric finger abduction contractions, while an optimal needle position was determined using the minimal rise times of the motor unit potentials (MUPs) generated. Once an optimal position was obtained, participants were asked to maintain a mild contraction (approximately 15% MVC). Each contraction was held for ~30 s. During each contraction, participants received verbal feedback from the investigator to maintain the desired contraction intensity. Subsequent contractions were performed until a minimum of 20 suitable MUP trains were collected. Contractions were separated by ~30 s breaks or longer if needed by the participant. To capture motor units from various parts of the muscle, the needle was repositioned between contractions.

EMG signals were reviewed offline to screen for the acceptability of MUP trains. Criteria for accepting MUP trains included a minimum of 51 MUPs with consistent and physiological MU firing rate, an interdischarge interval histogram with a Gaussian-shaped main peak, and a coefficient of variation of the interdischarge interval of less than 0.3.[26] Raster plots were examined visually to determine whether the MUPS were all originating from the same motor unit. Motor unit number estimation (MUNE) for the FDI and ADM were calculated by dividing the CMAP negative peak amplitude by the surface motor unit potential (SMUP) negative peak amplitude mean.[19]

Interventions

All three patients received the same surgical treatment and the SETS AIN to ulnar nerve surgery. The surgical process involved an internal neurolysis to identify the ulnar motor fascicles of the ulnar nerve and confirmed with intraoperative electrical stimulation. The AIN was then harvested and coapted to the motor fascicles of the ulnar nerve through a neurorrhaphy and end-to-side procedure in the standard fashion. Further details of the SETS AIN to ulnar nerve procedure have been previously reported.[10,11] Subsequent surgical care was required for patient B as he had issues with hand and finger dystonia and finger deformities due to his underlying neurological condition (ie, PD). Therefore, botulinum toxin injections were applied at approximately 9 months after ulnar nerve surgery.

The formal neuromuscular rehabilitation sessions for all three cases were initiated at approximately 6 to 8 months after surgery, when reinnervation is first noticed either clinically (MRC 1) and/or through the presence or new MUPs on clinical follow-up EMG studies assessing the FDI, ADM, and fourth dorsal interosseous muscles. All patients were instructed in active and passive ROM exercises to ensure that mobility of the digits would not be compromised. Hand orthoses were fitted and prescribed to address patient issues with hand contractures.[27] Education and treatments regarding edema and scar management were provided in the early months and visualization exercises were begun immediately including activation of the donor nerve. Examples of scar management strategies included the use of silicone gel sheets and desensitization techniques.[28] An example of a visualization exercise may encourage patients to mentally practice spreading out their fingers on the affected side as wide as possible and then closing them (finger abduction and adduction).[29]

Formal rehabilitation comprised of exercises to encourage the activation of the donor nerve. Patients were provided with an exercise program that involved the coactivation of donor and recipient muscles (ie, pronation combined with finger abduction, adduction, and intrinsic plus flexion). EMG biofeedback (NeuroTrac Myoplus 2 Pro) was utilized when reinnervation was found on EMG studies and first noticed (MRC 1-2) Figure 2. The rationale of early biofeedback was to facilitate motor relearning and cortical plasticity. Surface, self-adhesive electrodes were placed over recipient muscles while patients performed donor activation exercises. During this phase, the goal of the EMG biofeedback was to reach a threshold, determined as a percentage of the maximum voluntary contraction (MVC) (ie, approximately 50% MVC). The goal of using an approximate threshold of ~50% MVC with a sustained isotonic contraction of ~5 s was to implement therapeutic exercises that would facilitate optimal challenge and learning.[30] The threshold was gradually increased with the progression of the patients' performance.

Once there were signs of increased innervation both clinically (MRC 3) and through EMG studies (increased number of maturing motor units), EMG-triggered muscle stimulation (ETS) was introduced Figure 3. The goal of ETS utilization at later stages was to improve strength and endurance, while still encouraging the facilitation of cortical plasticity and learning. Using ETS is beneficial due to a specific feature. The neuromuscular stimulation of the ETS was only triggered by volitional muscle activation up to a threshold. It should also be noted that the biofeedback and ETS device had algorithms that adjusted the muscle activation threshold based on the participants' performance. When participants reached an activation threshold with ease, the algorithm would adjust the threshold to a new EMG activation level. Neuromuscular electrical stimulation (NMES) was only used in the latter part of the rehabilitation process with the goal of facilitating muscular endurance and capacity. NMES in peripheral nerve rehabilitation is becoming increasingly popular and protocols have even been developed to guide treatments.[31]

Outcomes

Patient A, B, and C's demographic information can be found in Table 1. All three patients demonstrated a similar adherence to attending their hand therapy sessions. Progress of clinical performance measurements such as grip strength and pinch strength can be observed in Figure 4. Due to patient A's complications during the

Fig. 2. Patient QuickDASH scores at long-term evaluation (>23 months after SETS AIN to ulnar nerve surgery). Higher scores indicate greater upper extremity disability with a maximum score of 100 and a minimum score of 0. QuickDASH = Quick Disability of Arm, Shoulder and Hand; SETS AIN = supercharged end-to-side anterior interosseous nerve.

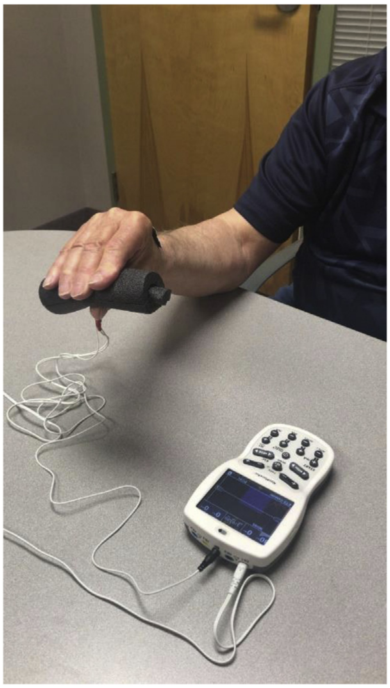

Fig. 3. An example of a hand therapy session using EMG biofeedback. The electrodes were placed on the intrinsic hand muscles on the dorsal and volar side, excluding the hypothenar eminence. Participant was instructed to practice gravity eliminated donor activation with intrinsic plus flexion.

rehabilitation and recovery period, several clinical measures such as grip strength and pinch strength were not obtained. QuickDASH measures were obtained from all three patients as a long-term evaluation (>23 months) of their function (Figure 5). A higher score represents a greater degree of upper extremity disability experienced by the patient. Normative score for the DASH (full version) in the general population has been reported to be 10.1 with a standard deviation of 14.7.[32] Patient C is less than one standard deviation away from the population norm and patient B within 2 standard deviations. However, patient A is approximately 4 standard deviations away from the population norm.

DQEMG was obtained from patient B and C to examine their neurophysiological and neuromuscular health. Due to patient B's atrophy of the FDI muscle, DQEMG was only obtained from his ADM (hypothenar) muscle. DQEMG was obtained from both the FDI and ADM for patient C (Table 2). Due to patient A's health complications and lack of transportation, we were unable to obtain DQEMG measurements from him. In contrast to patient B, patient C's ADM muscle demonstrated greater motor unit counts. Patient C's intramuscular EMG variables such as shorter MUP duration and smaller MUP area suggest that overall his motor units may be smaller. We propose that this may be possibly due to greater recovery of new or immature motor unit numbers. Patient C's ADM muscle demonstrated higher near-fiber jiggle in comparison with patient B's, suggesting decreased motor unit stability. This may be due to an increase in the number of new or nascent motor units, which in theory will provide long-term benefits as they grow and mature.

Patient A was a gentleman who had a mild response to the surgical and rehabilitation intervention implemented. Patient A's demographic and presurgical history can be found in Table 1. In addition to ulnar neuropathy, his health history indicated issues with gout, depression, and idiopathic PD. Patient A attended his scheduled rehabilitation sessions but admitted to a low adherence to his rehabilitation exercises, as he only performed them once per week with another therapist. Patient A also had issues with hand tone-related rigidity and contractures due to Parkinsonism. Several hand orthoses were applied in attempt to mitigate hand stiffening. The improvement of his fingers' ROM was minimal as observed in Table 3. Even during late stages of rehabilitation, patient A showed diminishing signs of intrinsic hand function, such as increased ulnar clawing. Throughout patient A's rehabilitation process, it was challenging to complete the progressions necessary to increase his hand function.

Patient B had a moderate response to the surgical and hand therapy interventions. He demonstrated a modest adherence to his home program. One barrier and challenge that was identified by his therapist was his limited ability to understand instructions for his home exercise program. Clinical special tests revealed that patient B still experienced dysfunction with his adductor pollicis and

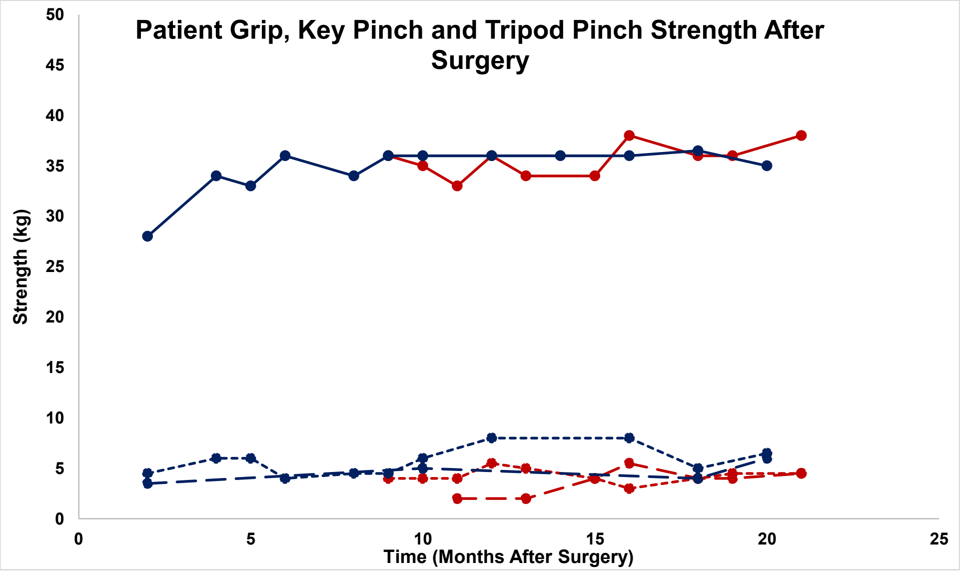

Fig. 4. An example of EMG-triggered stimulation (ETS). The electrodes were placed on the intrinsic hand muscles on the dorsal and volar side, excluding the hypothenar eminence. Participant was encouraged to activate the donor nerve while performing resistance against a roll.

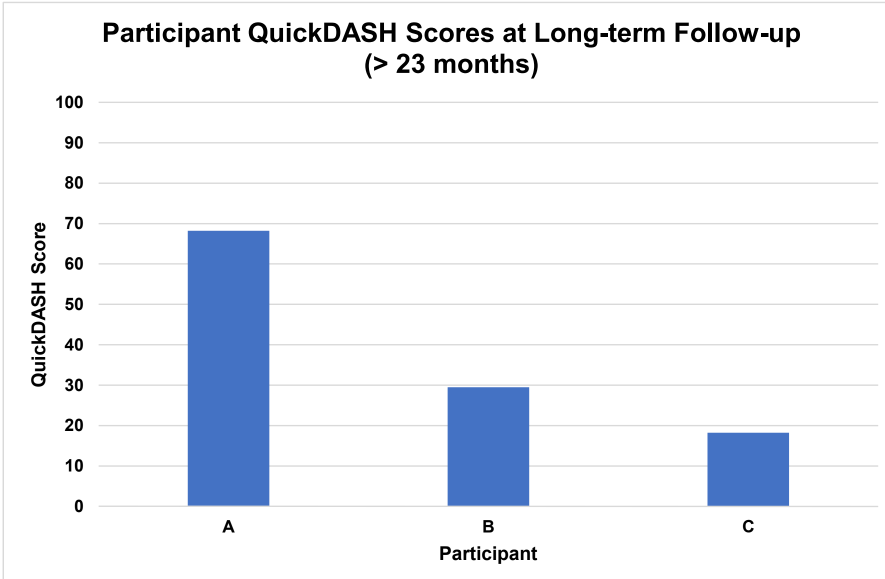

Fig. 5. An example of hand-tracing to measure the participant's total finger abduction (patient C). Total abduction was measured using the total distance from tip of the 1st digit to tip of the 5th digit. **(A)** ~9 wk postoperative. Initial hand therapy assessment. Total finger abduction was ~19 cm with very little muscle bulk observed at the hypothenar eminence. **(B)** ~43 wk postoperative. Total finger abduction was ~21.5 cm with substantial increase in muscle bulk at the hypothenar eminence.

hypothenar muscles (ie, positive Froment's and Wartenburg's sign) at 19 months follow-up. Collectively, these deficits made it moderately challenging for patient B to perform activities of daily living such as opening a tight jar and washing his back.

Finally, patient C had a strong response and functional improvements from the surgical and hand therapy interventions. Patient C demonstrated excellent adherence to his home program and even took the initiative to purchase an NMES device for home use (Allevia 2-in-1 TENS and EMS unit by ProActive). At his 18 months follow-up, patient C demonstrated no dysfunctions with his hypothenar muscles or hand intrinsic interossei muscle (ie, negative Wartenburg's, crossed-finger test, Egawa's sign). However, he still demonstrated a positive Froment's sign, which he functionally compensated by using his flexor pollicus longus.

Discussion

Severe ulnar neuropathies frequently do not have optimal long-term functional outcomes. However, innovative surgical and rehabilitation interventions have been developed to improve patient outcomes. The current investigation explored three different patients' response to the SETS AIN to ulnar motor nerve surgery and the subsequent rehabilitation. Three participants were chosen to explore the clinical decision-making and potential mediators that might affect different responses to surgery and rehabilitation. This is important because we know even within clinical trials, when outcomes are improved, that the responses to treatments are variable between patients. For clinicians, it is important to understand the general approach to postoperative management, and the factors that limit or might be leveraged to optimize rehabilitation programs, given that patients can be highly variable. Because our purpose was to explore variations in outcomes, we purposely selected patients that demonstrated large, moderate, or small improvements after surgery and rehabilitation. The patient outcomes were demonstrated by their respective QuickDASH scores at a long-term follow-up (>23 months) and from the patients' clinical performance assessed by the hand therapist.

Presurgical factors such as comorbidities may have contributed to the patient's response to the interventions. Our investigation uniquely highlights the differences in metabolic and neurological comorbidities observed in the three participants and the potential influence that these comorbidities had on their improvements. Similarly, facilitators and barriers within the rehabilitation process, such as adherence to the proposed rehabilitation program, may have also influenced the patients' observable outcomes. The three participants within this study uniquely allow for us to describe and explore how social and mental health history may influence

Table 2
DQEMG outcomes from patient B's abductor digiti minimi (ADM) muscle and patient C's ADM and first dorsal interosseous (FDI) muscles at long-term evaluation (>2 y after SETS AIN to ulnar nerve surgery)

	Patient B–ADM	Patient C–ADM	Patient C–FDI
SMUP (μV)	42.9	50.4	165.9
CMAP amplitude (mV)	4	5.5	3
MUNE	93	109	18
MUP duration (ms)	10.6	7.9	10.7
MUP area (μVms)	4843.1	2660.3	3695.3
NF count	2.8	2.8	3.8
NF jiggle (%)	33.6%	39.5	37.6
NF jitter (μs)	51.3	45.8	78.5

CMAP = compound muscle action potential; MUNE = motor unit number estimation; QuickDASH = Quick Disability of Arm, Shoulder and Hand; SETS AIN = supercharged end-to-side anterior interosseous nerve; NF = near-fiber.

Table 3
Patient A: Range of motion progress at D4 and D5 of the affected hand

	Joint	12 mo		16 mo	
		Flexion active ROM (°)	Extension active ROM (°)	Flexion active ROM (°)	Extension active ROM (°)
D4	MCP	0	−80	0	−85
	PIP	−45	−85	−50	−95
	DIP	−10	−55	−15	−55
D5	MCP	0	−85	+10	−85
	PIP	−50	−80	−55	−95
	DIP	−10	−45	0	−65

program adherence. Another unique aspect of this repeated case study was that we were able to perform DQEMG for two of the cases. This provided unique data about the changes that occurred at the level of the motor unit physiology. The participant that demonstrated the most improvements also showed the most substantial increases in MUNE, possibly suggesting a relationship between motor unit reinnervation and functional outcomes. To assist in patient prognosis, clinicians should consider patients' pre-existing comorbidities. Cardiovascular and metabolic factors such as hyperlipidemia, obesity, and diabetes should be examined. Patients A and B both had pre-existing dyslipidemia before surgery. Although not commonly associated with neuropathies, dyslipidemia or hyperlipidemia may have factored to their responses to the interventions. Some experimental studies have shown that hyperlipidemia may have direct neurotoxic effects on peripheral nerves and increased progression of peripheral neuropathy with elevated triglycerides.[33] Similar risk factors such as hypertension should also be considered. Within our cohort, patients B and C both had hypertension. Although the mechanism of hypertension on peripheral neuropathies is not as well defined, hypertension has been previously identified as a contributor to specific neuropathies.[34,35] Possible mechanisms may include hypertension leading to changes in epineurial arteriolar function and endoneurial perfusion.[36] Targeting metabolic factors such as hyperlipidemia and hypertension in neuropathic populations have been recommended previously as a direct form of therapeutic intervention.[33] Proposed interventions are typically pharmaceutical in nature. However, adjunct interventions such as aerobic exercise may have potent mediating effects that may augment metabolic factors such as hypertension[37] and hyperlipidemia.[38] In ulnar neuropathy, factors such as the onset of symptoms and the timing of surgical interventions may influence patient clinical outcomes. Patient C received his surgical intervention at a relatively earlier time. By contrast, the other participants had a longer wait time before their surgical intervention. There are several factors that may influence the timing of surgical interventions including diagnostic and clinical indications for surgery. Typically, early surgical intervention for indicated patients provides the recipient muscles with more receptive and functioning motor endplates for reinnervation.[39] Increased reinnervation of the recipient muscles allows for improved functional outcomes. One recent report has provided specific indications for SETS surgical intervention after the onset and diagnosis of cubital tunnel syndrome. These protocols may provide the opportunity for increases in surgical success and improved functional outcomes.[39]

Neurological conditions that impact the central nervous system (CNS) are critical to evaluate in patients recovering from peripheral neuropathies. Patient B had a previous cerebrovascular accident (CVA) of his posterior cerebral artery approximately 13 years before the onset of his ulnar neuropathy. After CVAs (greater than 6 months), approximately 60 to 70% of patients experience impaired hand functions.[40] We believe that patient B's CVA might have left residual cortical sensorimotor dysfunctions leading to his decreased ability to activate and utilize the recipient muscles after surgery (ie, minimal recovery of FDI). Similarly, patient A had idiopathic PD, a neurogenerative movement disorder known to impair central sensorimotor hand circuitry and hand control.[41,42] Patients with PD may present with decreased hand function,[43] increased hand rigidity,[44] and hand contractures[45] due to motor impairment. One major barrier to patient A's recovery was hand contractures that developed after the surgery. In the presence of limited hand mobility, patient A's functional recovery was diminished and likely contributed to his poor outcomes. Understanding the CNS's mechanisms and influence on peripheral neuropathies will hopefully allow for future interventions that concurrently influence the peripheral and CNS (ie, Hebbian plasticity).[46]

Psychosocial factors and adherence to the rehabilitation regime should be considered after surgical interventions. Adherence to exercise programs is a critical factor to successful recovery in rehabilitation.[47] Patients with better adherence often achieve better outcomes.[48] Conversely, patients with better physical recovery may be more capable of performing some components of their rehabilitation program. The World Health Organization has provided a framework for understanding adherence that includes considering health care systems, therapy (ie, exercise), condition, patient, and socioeconomic-related barriers.[48] All the three patients demonstrated similar adherence to attending in-clinic hand therapy sessions but had varying levels of adherence to home programs or abilities to progress their therapy program. Our cases illustrate that several patient factors can influence an individual's ability to accurately (fidelity) and consistently adhere to home exercise programs. Specifically, in our cases, patient factors may include mental health status and social connectivity. For example, patient A demonstrated low home exercise adherence throughout his hand therapy. Although he attended weekly sessions with a different local therapist, he admitted to being inconsistent with his home exercises. One contributing factor to his low adherence to exercise may be due to his previous history of depression. Depression reportedly affects exercise adherence.[49,50] In addition, patient A lived by himself, possibly leading to decreased social connectivity which is also known to negatively impact exercise adherence.[49,51] By contrast, patient B and C's adherence to hand therapy may have been enhanced due to residing with their spouse and having increased social and familial support.[49,52] Patient C had a high commitment to his rehab adhering to his traditional hand therapy exercises, and he purchased an NMES device for home use which may have had an additional therapeutic benefit. This was associated with the best the best improvements in grip strength across time across the cases.

A variety of factors related to therapist or the health system can also influence adherence. There has been a proposed strategy, specifically targeted toward physiotherapists and occupational therapists to increase patient adherence in musculoskeletal rehabilitation.[18] Although not all components of the strategy were implemented in our study, such as using an objective measurement of adherence, many of these strategies were implemented in the three participants' rehabilitation program. In this comparative case study, we reduced some variation by having similar aged men as patients and the same therapist provide treatment for all three cases. However therapeutic alliance between a therapist and different patients can vary and still be a modifier of adherence. Components of increasing therapeutic alliance may involve patient-therapist interactions that encouraged the formation of individualized treatment plans. These treatment plans involve setting short-term and long-term goals that were agreed on by the participants and the therapist. For example, patient C had a specific goal to control his 5th digit's finger adduction (ie, no more positive Wartenberg's sign). The hand therapist developed a home exercise program and smaller goals to scaffold toward Patient C's goal. Mutual contribution in creating goals and treatment plans can increase the patients' sense of connectedness, autonomy, and competence, which are key components of therapeutic alliance and self-determination theory.[53,54] Furthermore, during their hand therapy sessions, educational and behavioral strategies such as providing feedback or providing supervised exercises may have enhanced participant adherence. The hand therapist overseeing their rehabilitation (J.L.S.) used a similar individualized approach for all three participants' treatment plans. It is important to increase clinician's understanding of all the factors that influence adherence via knowledge translation. Knowledge translation interventions have been shown to affect how therapists plan to assess, facilitate, and monitor adherence.[18] Collectively, optimizing barriers and facilitators to their rehabilitation adherence may impact the participants' outcomes and response to surgery and hand therapy.

A novel aspect of our study is the use of DQEMG to obtain MUNE from two of the intrinsic hand muscles (FDI and ADM) in two cases. In comparison with patient C, patient B demonstrated lower MUNE, decreased SMUP amplitudes, and decreased CMAP amplitudes in the ADM muscle. Lower estimations of motor units (lower MUNE) in the ADM muscle may indicate less reinnervation and recovery of patient B's hypothenar muscles in comparison with patient C. With nerve transfers, one of the goals is to improve the number of axon to endplate connections which is known to maximize functional outcomes.[11] Likewise, muscles with a greater number of motor units may allow for more fine motor control.[55] Decreases in motor unit counts have also been associated with decreases in muscle performance such as lower power, torque, and MVC.[56–58] The smaller SMUP amplitudes observed at patient B's ADM in comparison with patient C's may also indicate that patient B had less collateral reinnervation across muscle fibers. Collateral reinnervation is typically a protective mechanism to continually maintain muscle function and strength.[59] Collateral sprouting of new nerves and muscle fiber atrophy may lead to decreased conduction velocity and result in greater SMUP amplitudes.[60] It is interesting to note that patient C demonstrated greater near-fiber jiggle, a measure of motor unit instability. Patient C's increased motor unit instability may be indicative of an increased number of nascent motor units which typically demonstrate less stable motor unit potentials.[60,61] Collectively, observing these differences in neuromuscular health between patient C and patient B's ADM may elucidate some possible mechanisms that contributed to the differences in hypothenar function after surgery and rehabilitation. Furthermore, in comparison with a healthy aging population,[62] patient C's FDI showed decreases in MUNE, increased SMUP amplitude, and increased MUP area. Increased SMUP amplitude and MUP area are inversely related to lower motor unit counts due to collateral reinnervation. However, although motor unit counts were substantially lower in patient C compared with normative older adults, patient C did not demonstrate functional deficits with his interossei muscle or any significant decreases in motor unit stability.

Although these cases highlight clinical decision-making issues in a novel surgical approach to treating sever ulnar neuropathy, we acknowledge the study's limitations. Our current cases do not represent all recovery trajectories or all their possible mediators. Furthermore, although comparative case studies provide a platform for discussing clinical reasoning around differences in outcomes, the associations we observed can only be hypothesized because causation cannot be inferred from the study design. We believe that it would be beneficial for future investigations with larger sample sizes to explore the effectiveness of structured rehabilitation regimes after nerve transfers.

Emerging evidence suggests that SETS AIN to ulnar nerve is a useful surgical solution for a difficult clinical problem. Given the severity of the pathology in patients who are candidates for this procedure, we expect that normal nerve function and restoration of all physical capacity is not a realistic expectation. This study highlights that presurgical neurological and metabolic comorbidities, and the timing of surgical intervention may impact recovery. It also illustrates that adherence barriers and facilitators (ie, social connectivity) are critical issues that should be considered in customizing hand therapy as they may ultimately influence patient outcomes. Our study has also provided an opportunity to observe the associations with hand functional outcomes with neurophysiological measures and neuromuscular health (DQEMG). It is important for future quantitative studies to explore surgical outcomes, predictors, and their relationship to nerve functioning. Qualitative studies may inform our understanding of how to best optimize adherence and rehabilitation in this new surgical procedure.

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1. The study design was
 a. RCTs
 b. repeated case study
 c. qualitative
 d. retrospective cohort

2. The AIN is a pure motor branch of the median nerve and innervates the
 a. FDS to the index and long fingers
 b. FPL
 c. pronator quadratus
 d. all of the above

3. Initial evaluation included
 a. Meal's interosseous test
 b. Moberg pick up test
 c. Egawa's sign
 d. Phaelen's sign

4. Delaying surgery
 a. had no bearing on outcomes
 b. adversely affected outcomes
 c. was not noted in this report
 d. improved outcomes

5. Critical outcomes were determined by assessing motor units of the ADM and 1st dorsal interosseous muscles
 a. true
 b. false

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