Donor Activation Focused Rehabilitation Approach
Maximizing Outcomes After Nerve Transfers

Lorna Canavan Kahn, BSPT, CHT[a], Amy M. Moore, MD[b,*]

KEYWORDS

• Nerve transfer • Rehabilitation • Hand therapy • Physical therapy • Occupational therapy • DAFRA • Exercise

KEY POINTS

- Donor activation focused rehabilitation approach (DAFRA) is a rehabilitation model that recognizes the altered neural pathways created with nerve transfers and attempts to maximize functional outcomes by strengthening these pathways.
- There is no predetermined timeline for the progression of the rehabilitation program; the 3 phases of rehabilitation are adapted to the individual and their rate of motor recovery.
- Preservation of muscle length following a denervating injury is achieved with positioning and splinting to aid in counteracting the forces of antagonist muscles and gravity.

Video content accompanies this article at http://www.hand.theclinics.com

INTRODUCTION

Over the past 20 years, a paradigm shift toward the use of nerve transfers in peripheral nerve surgery has occurred. This shift has brought about a plethora of research and published articles focused on surgical innovation and outcomes; however, a concomitant interest in rehabilitation following nerve transfers is lacking. In a recent literature review involving 12 papers addressing nerve transfers for upper trunk plexopathies, rehabilitation models and outcomes following nerve transfers were compared.[1] Three groups were identified: papers in which no rehabilitation is mentioned, papers that refer to nonspecific or a generic physical therapy approach, and papers describing a donor activation focused rehabilitation approach (DAFRA). Beers and colleagues[1] found there was a significantly increased percentage of excellent outcomes in the DAFRA group following nerve transfers for elbow flexion.

DAFRA is a rehabilitation model that recognizes the altered neural pathways created by the nerve transfer and focuses on strengthening these pathways in an attempt to maximize functional outcomes. This approach emphasizes the importance of cortical plasticity, familiarity with the anatomic aspects of the surgery, and strong patient education regarding the altered control mechanism for movement. These components are vital to a successful motor re-education program. In this article, the factors influencing outcomes after nerve transfers are reviewed, including preoperative and postoperative interventions. Rehabilitation protocols for specific nerve transfers also are addressed. Although not

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[a] Milliken Hand Rehabilitation Center, The Rehabilitation Institute of St. Louis, 4921 Parkview Place, Suite 6F, St Louis, MO 63110, USA; [b] Division of Plastic and Reconstructive Surgery, Washington University School of Medicine, 660 South Euclid Avenue, CB 8238, St Louis, MO 63110, USA
* Corresponding author.
E-mail address: mooream@wustl.edu

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all-inclusive, the general principles presented can be applied to any nerve transfer performed.

FACTORS INFLUENCING RETURN OF FUNCTION AFTER NERVE TRANSFERS

Cortical Plasticity

It is widely accepted that adaptive changes occur at the sensory-motor cortex in response to motor learning.[2] Numerous investigators have demonstrated change or expansion in the sensorimotor cortex in response to training, and this has been seen with musicians, legally blind participants, and patients with limb amputations (and subsequent replants).[3–5] Anastakis and colleagues[6] suggest that the functional success of nerve transfers may require pre-existing interconnection on a cortical level between the donor and recipient muscles. From this, one may surmise that strengthening this pre-existing interconnectivity may improve functional outcomes.

The work of Nudo and colleagues[7] has demonstrated a clear relationship between cortical adaptation and acquisition of new skills. After-injury training, which involves developing new motor skills, has been shown to effectively correlate with neuroanatomic changes on a cortical level.[8] Based on their research using functional MRI with nerve transfers, Anastakis and colleagues[6] suggest several strategies to maximize functional outcomes. These strategies include the following:

1. Activate the nerve transfer with preoperative exercise instruction.
2. Educate the patient regarding the need for continued compliance with the home exercise program (HEP).
3. Activate the recipient muscle early using gravity-lessened planes.
4. Work with a hand therapist in the early stages of recovery, focusing on functional movements and repetition.
5. Plan for strengthening and endurance exercises for up to and possibly beyond 2 years following signs of reinnervation.

Exercise

In addition to cortical changes that occur following nerve transfer, the concepts that drive muscle recovery following peripheral nerve injury and repair must be kept in mind. Much of what is known regarding the effect of exercise on recovering peripheral nerve repair is from animal models. van Meeteren and colleagues[9] have shown that physical activity encourages functional motor and sensory recovery and increased motor nerve conduction velocity following sciatic nerve injury.[9] Udina and colleagues[10] demonstrated that maintaining activity in muscle with active or passive exercise may increase trophic factor release on regenerating motor neurons.

The level of intensity of exercise is also an important consideration when working with the peripheral nerve and brachial plexus–injured patient population. Although Sabatier and colleagues[11] demonstrated low-intensity training increased the length of regenerating axons after peripheral nerve repair, Herbison and colleagues[12] noted that intense training and exercise may have negative effects on axonal regeneration. As the recipient muscle gains strength following a nerve transfer, an effort should be made to limit the patient from overwhelming the muscle with high-intensity exercise and thereby potentially limiting his functional outcome.

Positioning

Following a denervating injury, muscle length may change because of the unopposed force of the antagonist muscle, improper positioning, or the weight of the limb due to gravity. Once the muscle begins to regain function following a nerve transfer, a muscle that is overly stretched or shortened may have difficulty generating force. The length-tension relationship has been clearly described by Gordon and colleagues[13] (**Fig. 1**). The ability of a muscle to generate tension is directly related to the overlap of the actin and myosin filaments. A muscle will contract with the largest amount of tension when it is close to its ideal length. Therefore, when shortened or stretched beyond this ideal length, the maximum active tension generated will decrease.

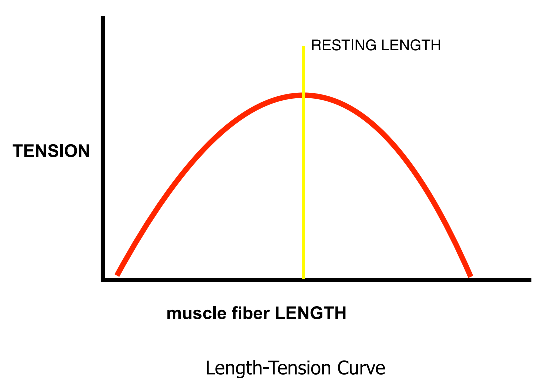

Fig. 1. The length tension curve. This curve illustrates the concept of muscle having an ideal length at which it can develop the greatest contraction force.[13] This concept applies to denervated muscle in which the length should be protected from the unopposed forces of antagonist muscles and gravity while awaiting reinnervation.

After nerve transfer, it is important to educate the patient regarding positioning. The use of slings and/or splints to preserve ideal resting sarcomere length is important. Patients may presume that once their muscle shows early signs of recovery that they can then eliminate the support. In reality, keeping them in the shortened position in the sling (or other support) may help regain control and strength faster because of the preserved length of the involved muscles. In addition, the support will limit drag on the plexus, reduce arm pain, and decrease hand edema, which is often correlated to dependent positioning.

PREOPERATIVE THERAPY

In the ideal setting, a preoperative physical/occupational therapy evaluation is performed. The surgical plan is shared with the therapist to maximize this preoperative visit. Baseline measures of range of motion (ROM) and strength of potential muscle donors are obtained. This documentation will enable the therapist to accurately monitor postoperative functional recovery of both donor and recipient muscles as well as neighboring muscles (which may also benefit from increased use of the limb following nerve transfers). The patient is also taught exercises that activate the donor muscle(s) before surgery. Although it is not yet clear whether greater strength of the donor muscle has an effect on nerve transfer outcomes, the ability to activate the donor muscle is inherently important.

Furthermore, any issues of joint limitation, muscle length, and edema are addressed at this preoperative visit with patient education, positioning, splinting, and exercise. Early conservative management of edema may improve pain and comfort of the involved extremity. Elevation, maintenance of joint ROM, and compression garments are effective in pain and edema management.[14]

POSTOPERATIVE THERAPY

The DAFRA model encompasses 3 phases of rehabilitation: early, middle, and late. The timeline of phase entry is not predetermined. These phases should be adapted to the individual as they recover from each specific nerve transfer.

Early Phase

Patient education

Anatomy The importance of adequate patient education following nerve transfers cannot be overstated. The authors have witnessed patients who attended their first therapy visit 1 year after transfer with the assumption of surgical failure only to find that function existed once they were given adequate instruction in the new control mechanism for that movement. This finding underscores the importance of motor re-education and the possibilities of recovery if the patients learn how to activate their nerve transfer.

In order to adequately educate the patient, the operative report should be provided for the therapist—because often the preoperative plan and intraoperative procedures differ. If possible, include the therapist in the first patient postoperative visit as details of the case are discussed with the patient, allowing the physician-therapist-patient unit to be on the same page.

On the initial postoperative therapy visit, significant time should be spent instructing the patient about the involved anatomy of the nerve transfers and how the muscle innervation has been altered. The primary goal is for the patients to demonstrate a heightened understanding of their surgery by identifying the "donor" and "recipient" muscles. When describing the involved nerves and muscles, they are referred to as "donors" and "recipients." Labeling the nerve transfers by the muscle involved may improve patient understanding because these are more familiar words than the involved nerves. For example, in the case of the double fascicular transfer (DFT) for elbow flexion, there are 2 "donors": wrist flexors (ulnar fascicles) and finger flexors (median fascicles). A brief description of the involved muscles' function (ie, finger bending) is given to improve patient understanding. By the end of the first visit, the patient should be able to describe what donor muscle(s) must be fired in order to send a "message" to the recipient muscle.

When describing the altered neural pathway of a nerve transfer, the use of metaphors can be very helpful. The authors use a simple "lamp and electrical cord" metaphor to describe the basic relationship between the muscle and nerve. The patients begin to understand why their arm does not flex on command, that is, when the cord is cut or unplugged the lamp will not turn on. Furthermore, use of familiar language, such as "rewiring a lamp" or "diverting lanes of a highway on a detour," can aid in their understanding of the surgery and thereby improve their ability to actively participate in their recovery (Video 1).

Timeline for motor recovery One of the greatest challenges for a patient after undergoing nerve transfers is waiting for a functional outcome. Patients often get frustrated, depressed, and/or give up when no motor response is seen for months postoperatively. By adequately explaining expectations on a time line, the patient is more likely to be more compliant and dedicated to their HEP. Using a linear model of the manual muscle testing (MMT) scores, one can demonstrate 5/5 strength on an uninvolved limb and 0/5 with the involved muscle (Fig. 2). Using this model as a starting point, the first step in "success" is getting to a 1/5 because it means that nerve regeneration has reached the muscle and reinnervation has begun. This first step is an important milestone for patients who often dismiss a muscle twitch as unimportant.

The time frame to advance from 0/5 strength to 1/5 is described in relation to the distance from the nerve coaptation to the recipient muscle; this is a good segue to introduce the concept of axonal growth of "a millimeter a day," "an inch a month," and "a foot and a half a year." With information from the operative note and/or the surgeon, one can estimate when the first twitch or advancement to 1/5 on the timeline might happen. From there, it is helpful to describe the remaining MMT scores in relation to the expected movement and their corresponding time frame. Although often first broached by the surgeon, it important to set and/or reinforce realistic expectations.

Home exercise program Once the concept of donor and recipient muscles is understood, the specific home exercise instruction is initiated. The primary focus during the first phase of the postoperative period is to activate the donor muscles frequently in an effort to encourage neural activation and growth. Following a brief postoperative rest period of 10 to 14 days, the patient is instructed to contract the donor muscle. This contraction should be a simple movement that the patient can do easily without equipment, such as making a fist. They are advised to repeat the movement 10 to 20 times hourly. Passive ROM exercises for the involved joints should also be performed 2 to 3 times a day; this will not only limit joint contractures but also stimulate the motor cortex and regenerating neurons.[10]

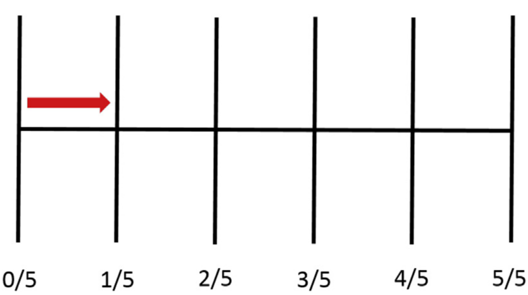

Fig. 2. The linear model of the MMT grading scale is a helpful visual aid when describing motor recovery in terms of the progression and time frame after nerve transfer. *Red arrow* depict direction of motion.

Flood the donor High repetition with low resistance exercises for the donor muscles will limit fatigue while "flooding" the new neural pathway with "demand." This exercise is based on an extrapolation of the work of van Meeteren and colleagues,[9] who demonstrated that exercise training involving high repetition improves functional recovery and motor nerve conduction velocity after a peripheral nerve crush lesion in the rat. The concept of "more is more" is described to the patient at this time to encourage maximizing "messages sent" to the donor muscle. Follow-up visits will advance the HEP to exercises that combine resisted donor muscle contractions with passive or assisted recipient muscle contractions. Repetitive co-contractions also aid in strengthening the new altered motor pathway for the recipient muscle.

Once the patient demonstrates an understanding of the importance of donor activation and is accurate and compliant with their HEP, follow-up visits are scheduled monthly, often corresponding to the physician postoperative visits. Given the limitations set by insurance and the expected lengthy recovery time, it is best to use therapy visits judiciously. In the early phase of recovery, the HEP is important, but no progression is made until a response is noted in the recipient muscle.

Middle Phase

Monitoring for return of function

During monthly visits, MMT is performed on both the donor and the recipient muscles. The donor muscle strength is monitored and documented for (in most cases) return to normal strength. When the entire donor nerve is taken (vs only fascicles), obviously no return is expected in the donor muscle. To test for return of function in the recipient muscle, strong resistance is applied to the donor muscle while palpating the recipient muscle or tendon (Fig. 3). Depending on the muscle, it may be easier to palpate movement of the tendon than a muscle contraction in the early phase of recovery. Demonstrating and having the patient feel the contraction is a helpful, motivating tool; this is often the first time they "believe" that the nerve transfer is going to work.

Advancing the home exercise program

Once a twitch is perceived in the recipient muscle, the focus of the program advances to gravity lessened exercises. Active-assisted exercise is performed while simultaneously demanding a strong contraction of the donor. Every effort is made to

Fig. 3. To assess for recipient muscle return, strong resistance is applied to the donor muscle(s) while palpating the recipient muscle. Here the triceps is resisted while palpating the recipient deltoid muscle belly.

make the movement easier for the weak recipient muscle. To limit drag, one may use a slick surface or an arm skate (**Fig. 4**, Video 2). Positioning the limb in a gravity-assisted position may also help the patient demonstrate early control of the movement.

Continuation of donor activation exercises is also encouraged in effort to "flood" the recipient muscles for several months. Developing strength and muscle bulk in the recipient muscle is the goal. Separation of the 2 movements (donor contraction to restore recipient function) is generally easier and added to the HEP once there is significant strength in the recipient. The time period for this may be more than 12 months or when a 3+/5 or greater muscle grade is acquired. In some patients, donor activation persists indefinitely, but most patients are able to lessen the need to perform the combined motion with time.

When functional recovery moves beyond a twitch toward 2−/5 strength, the use of aquatic therapy can provide tremendous assistance and encouragement for the nerve transfer patient. By using the benefits of a buoyant environment, the patients experience some early active control in the formerly paralyzed muscle. Floatation devices such as a kick board, inflatable "water wings," and/or dumbbells may be used to aid in these exercises (**Fig. 5**).

Once the patient has progressed to 2+ to 3−/5 muscle strength (incomplete joint range of movement against gravity), instruction is given in "place-and-hold" exercises against gravity. To do this, the patient places the joint in an end range position with the uninvolved arm while strongly contracting the donor muscle. The support of the uninvolved hand is gradually lessened while they attempt to hold the position with the recipient muscle. Patients are encouraged to do this routinely throughout the day (**Fig. 6**).

Fig. 4. A sheet of nylon provides a decreased friction surface for the weak recipient muscle to successfully move the limb in the middle phase of motor reeducation. Following a triceps to axillary nerve transfer, this setup may be used to train the reinnervating deltoid. *Red arrow* depict direction of motion.

Fig. 5. When available, use of a pool for exercise will provide a buoyant environment in which the patient can successfully move the injured limb. In this example, elbow flexion is achieved under water by holding the dumbbells while activating the donor muscles.

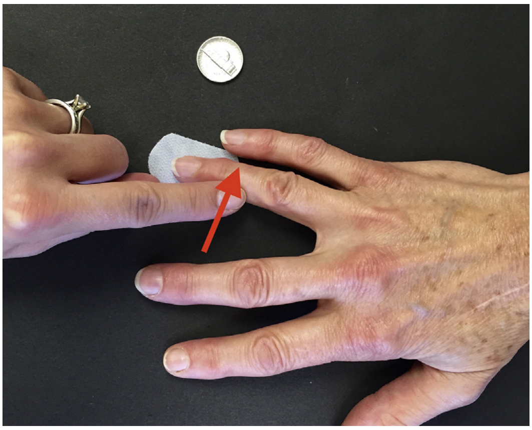

Fig. 6. The "place-and-hold" exercise applied to the ulnar intrinsic muscles following an AIN to deep ulnar nerve transfer. The finger is placed into end range abduction and the patient is asked to pronate the hand into the table while attempting to hold this position. *Red arrow* depict direction of motion.

Late Phase

Resisted exercise

Use of resistive equipment such as hand-held weights and elastic bands is initiated once a 3/5 muscle strength (full active elbow flexion against gravity) is achieved. Attempts before this may lead to early fatigue, pain, and frustration. Once again, reviewing the muscle strength progression timeline is helpful (see Fig. 2). With knowledge of the timeline, the patient may be more compliant and have a more realistic expectation for recovery.

If the recipient muscle recovers greater than 3/5 muscle strength, the HEP is progressed gradually. Keep in mind that due to the anatomic limitations of the nerve transfer (fewer motor nerve fibers than the original source), the end point of strength gains will vary and may take as much as 2 to 3 years. In addition, fatigue is a common complaint even once the strength has recovered to a functional level.

Neuromuscular electrical stimulation and biofeedback

Neuromuscular electrical stimulation (NMES) and biofeedback may be helpful in advancing muscle strength and assisting with activation of the recipient muscle in the nerve transfer patient. These tools are only useful once a significant contraction is observed in the recipient muscle. The authors emphasize that these therapies can augment the strength program but do not replace the existing HEP. Use of this modality may be especially helpful for patients with cognitive or emotional issues, such as those found with brain injuries, fear of pain, and limb dissociation. Increased muscle fatigue with NMES use is common. If used early in the recovery phase, keep in mind that it is best to avoid excessive fatigue in neurologically weak muscle. There is not a consensus for use of electrical stimulation following peripheral nerve injury. Some studies suggest it may impair functional recovery and accentuate skeletal muscle atrophy.[15]

When available, biofeedback can also be helpful as motor recovery becomes evident by aiding in activation of the recipient muscles. Once the muscle is innervated, the patient will often struggle to attain control of volitional contractions. Combining biofeedback with donor activation may enhance the patient's ability to improve the function of their recipient muscle.

THERAPY REGIMENS FOR SPECIFIC NERVE TRANSFERS

In the remaining discussion, the DAFRA therapy approach to common nerve transfers is described: shoulder, elbow, and hand. Nuances, considerations, tips, and tricks are presented for the specific therapy programs. The intervention is broken down by early, middle, and late phases of recovery.

Nerve Transfers to Regain Shoulder Function

The loss of shoulder function following peripheral nerve injury is life altering. Although the average healthy individual requires less than full active ROM to perform many common activities of daily living (ADL), adaptations for work and extracurricular activities may be needed for the patient with the paralyzed shoulder.[16] Nerve transfers to regain shoulder function have been successful.[17] However, it is important to keep in mind the variability in functional outcomes from isolated nerve injuries (axillary or suprascapular nerve) versus a complete or upper plexus injury. Furthermore, although it has been shown that increased reinnervation of the shoulder musculature improves abduction and external rotation,[18] it is important to recognize that the more "donors" that are used, the more "normal" strength structures are removed from the overall shoulder complex. For the therapist, it is important to recognize that the patients will present differently after nerve transfers to restore an isolated injury than one performed in a complete upper trunk injury.

Spinal accessory to suprascapular nerve transfer

Considerations Ideally, the lower branch of the spinal accessory nerve is donated to the suprascapular nerve, and branches and/or fascicles to the upper, middle, and lower trapezius are left to preserve function of the remaining muscle. In the past, the entire lower branch was harvested; however, the authors found the complete harvest left an unstable scapular base on which to build the newly transferred glenohumeral strength. In either situation, building strength in serratus anterior muscle (if available) is important to aid in stability and upward scapular rotation strength postoperatively.

Early phase Donor activation can be achieved early on with instruction in shoulder shrugs and backward shoulder rolls or "pulls," that is, squeezing the blades together. These exercises should be performed hourly with at least 10 repetitions. To pattern the newly combined motor functions, the patient uses the uninvolved hand to passively externally rotate the arm while performing active scapular retraction (Fig. 7). In addition, the patient is encouraged to position the arm in partial external rotation and abduction for parts of the day to maintain the ideal length of the supraspinatus/infraspinatus muscles.

Middle phase In the supine position, exercises that combine active-assisted shoulder abduction and external rotation with active scapular retractions are added to their routine once early motor return is noted. Motor return can also be achieved in sitting with a dowel or cane to assist external rotation/abduction with active scapular elevation and retractions (Fig. 8). When pool access is available, patients are encouraged to use the buoyancy of the water to advance early control of supraspinatus function with arm raises under water. Inflatable rings or flotation devices may aid this control. Donor activation continues to accompany all recipient muscle activation attempts. Prone and side-lying positioning are used for manually assisted middle and lower trapezius strengthening exercises as well as assisted external rotation and abduction exercises (Fig. 9).

Late phase Once supraspinatus/infraspinatus strength approaches 3/5 strength, wall slides are introduced. These exercises will aid in both trapezius and infraspinatus/supraspinatus strengthening. Patients with an isolated suprascapular nerve injury may advance more quickly to light resistive exercises. The dual function of the intact deltoid and teres minor muscles with the supraspinatus and infraspinatus may blur the accuracy of strength measures. Typically, the amount of resistance as measured by the single repetition maximum strength test (in the against gravity positions) will better capture the differences between involved and uninvolved sides. Those patients who demonstrate difficulty raising the arm over 90° may have incurred greater loss to their lower trapezius. Without this muscle action, it is very difficult to complete the scapulothoracic phase of shoulder abduction.

Fig. 7. Passive external rotation combined with active scapular retractions provides early patterning of the donor muscle (trapezius) and the recipient muscle (infraspinatus). *Red arrow* depict direction of motion.

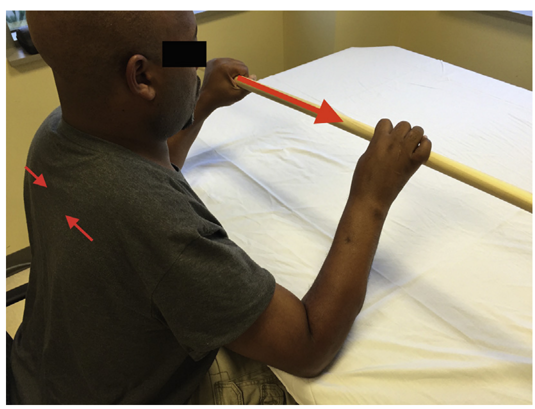

Fig. 8. Following a spinal accessory to suprascapular nerve transfer, combined active donor and passive or assisted recipient muscle exercise is achieved by squeezing the scapulae together while pushing the involved arm into external rotation with the uninvolved arm using a dowel. *Red arrow* depict direction of motion.

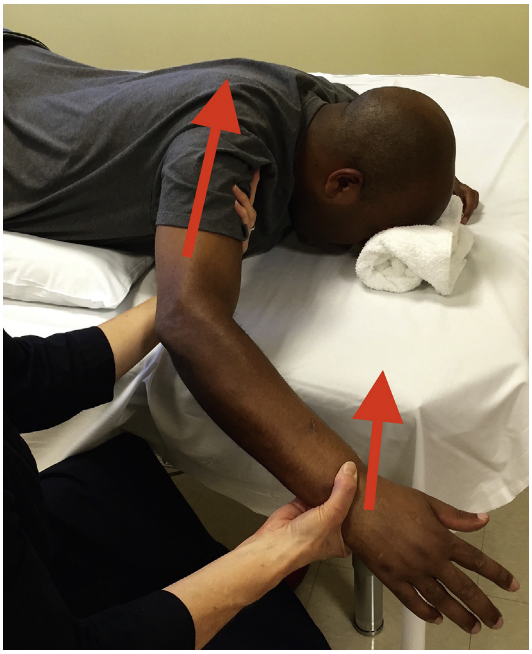

Fig. 9. Following the spinal accessory to suprascapular nerve transfer, the strength of the middle and lower trapezius muscles is often downgraded. Manual assistance is applied to the scapula for place-and-hold exercises to aid in strengthening and retraining. *Red arrow* depict direction of motion.

Triceps branch to axillary nerve transfer

Early phase A simple way to achieve donor activation of the triceps branch is to instruct the patient to slide his hand on the thigh toward the knee. Isometric triceps activation is another option and can easily be performed sitting or standing. Combined active donor and passive recipient action is achieved with seated table slides (Fig. 10).

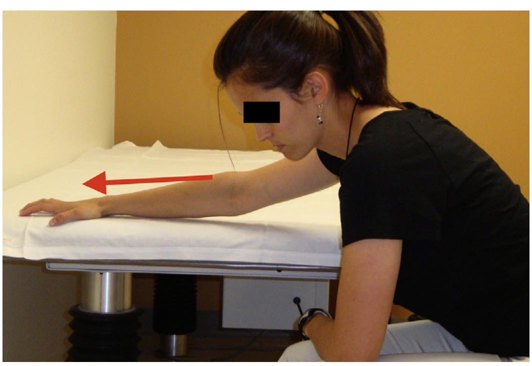

Fig. 10. In the early phase following a triceps to axillary nerve transfer, combined donor and recipient patterning is achieved with seated shoulder flexion slides. This patient actively extends her elbow while passive shoulder flexion and abduction are achieved with trunk flexion. *Red arrow* depict direction of motion.

Middle phase Because of the anatomic course of the axillary nerve running from posterior to anterior, re-innervation of the posterior head of the deltoid muscle typically occurs first. To test for this, the patient will contract the triceps muscles while attempting shoulder extension and abduction. One can palpate the deltoid along the posterior aspect of the acromion. Having the patient perform exercises in the prone position will encourage co-contraction with triceps and limit pectoralis major substitution. Shoulder extension exercises will primarily work triceps at first (as this also crosses the shoulder joint and aids in extension), but as more power returns to the deltoid, it will contribute to this motion. In the prone position, the patient is also instructed in shoulder abduction exercises (Fig. 11).

With the understanding that increased recipient output is correlated with increased effort of the donor muscle contraction, the therapist is challenged to position the patient in the appropriate way to achieve this. For example, in supine triceps, effort increases by extending the straight arm into the bed/floor while abducting the shoulder. In addition, performing the movement bilaterally with resistance to uninvolved deltoid can aid in training and increase muscle activation on the affected side.[19] The patient lies supine close to a wall on the uninvolved side and presses against it during bilateral abduction.

In the side-lying position, the weak deltoid can be exercised with the shoulder in 90° of abduction

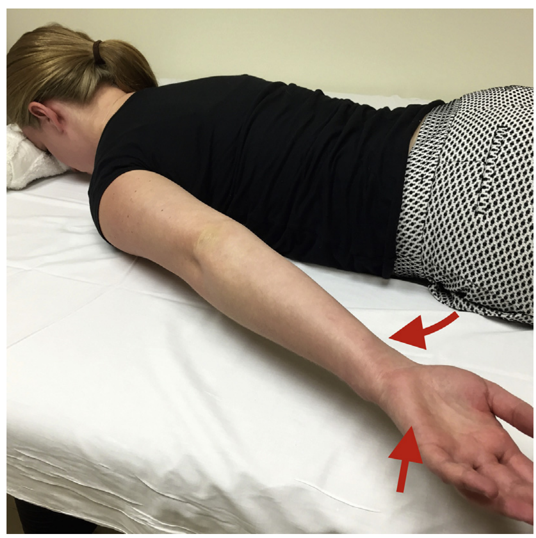

Fig. 11. A patient with a triceps to axillary nerve transfer is instructed to extend the elbow, activating the triceps, while attempting to abduct the shoulder. With the patient positioned in the prone position, there is greater demand on the triceps (donor), and the pectoralis muscle is at a disadvantage for substitution. *Red arrow* depict direction of motion.

with the elbow straight. Therapist support is given to the proximal arm as an attempt is made to move it in a circular motion ("arm circles"). This position puts reasonable demand on the triceps while gaining some assisted control of the deltoid.

Task-oriented activities are helpful in patterning this new combined shoulder movement. For example, slide the arm up an inclined surface on a slick cloth or use the crank or ladder tool on the BTE rehabilitation tool (Corporate Headquarters & Rehabilitation Equipment, Hanover, MD, USA) (**Fig. 12**). These activities can be set to provide greater demand on the donor (triceps) while achieving shoulder elevation. The functional orientation and repetitive nature of BTE activities follow the tenets of cortical plasticity to aid in motor re-education. Patients also tend to be motivated by the visual computer feedback given by the BTE.

Late phase Once the patient demonstrates increased deltoid strength with gains in arm elevation against gravity, the exercises are gradually advanced to light strengthening. Often patients with an isolated axillary nerve injury can raise the arm to some degree against gravity before their nerve transfer; this typically occurs in young men who have a well-developed supraspinatus muscle. The challenge for this group of patients is to carefully tease out actual deltoid recovery and to adjust exercise advancement accordingly. Use of the single repetition maximum test is one way to measure progress beyond the 3/5 strength.[20]

Nerve Transfers to Restore Elbow Flexion

Elbow flexion is vitally important to all aspects of ADLs. Performing basic functional tasks, including opening a door, eating, and using a telephone, requires anywhere from 30° to 130° of elbow flexion and approximately 50° of supination.[21] Without elbow flexion, a functional hand is made useless.

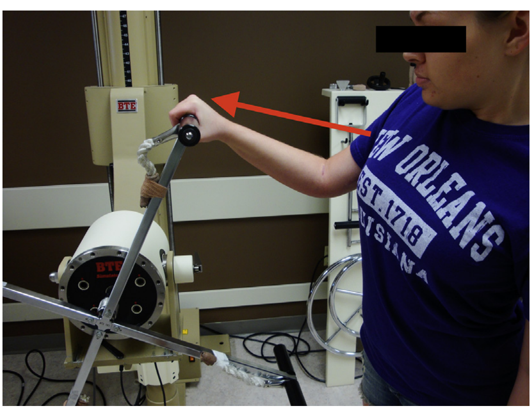

Fig. 12. The ladder tool on the BTE (tool simulator) provides graded resistance to the donor triceps (elbow extension) while assisting recipient deltoid in arm elevation. *Red arrow* depict direction of motion. (*Courtesy of* BTE, Hanover, MD.)

Double fascicular nerve transfer

Considerations The DFT refers to transferring fascicles of the flexor digitorum superficialis (FDS) to the brachialis branch and the flexor carpi ulnaris (FCU) fascicles to the biceps branch of the musculocutaneous nerve (MC). Working with patients following a DFT for elbow flexion restoration is a rewarding experience for a therapist. DFT is one of the most successful nerve transfers, with papers citing outcomes with an average of 4/5 elbow flexion strength.[22] Given the fact that most humans have been fisting and bringing their hands to their mouths since the womb, one would infer that there is a clear cortical interconnectedness, as Malessy and colleagues[2] described, between these functions. Thus, motor re-education is relatively easy and successful after this transfer. Recovery of muscle twitch has been seen as early as 2.5 months postoperatively given the short distance from the donor to the recipient nerve.

Furthermore, although the transfer has been successfully performed with the FCU fascicle to brachialis branch and FDS fascicle to biceps branch, the authors recommend the originally described orientation of the transfer (ulnar to biceps and median to brachialis). The median nerve controls pronation (pronator teres [PT] and pronator quadratus), and thus, using the median nerve to also control supination with biceps function is theoretically antagonistic and could lead to increased difficulty with motor re-education and potentially decreased efficacy of the transfer.

Early phase Considering that the nerve transfer is performed in the proximal arm and without tension on the repair, activation of the distal donor muscles can start as early as day 1 or 2 postoperatively without compromising the repair. Active fisting and wrist ROM within the postoperative sling will discourage postoperative hand edema while creating early demand on the donor motor efferents. At the 2 to 4 week postoperative initial visit, a hand gripper or Theraputty may be issued to increase this demand and start to restrengthen the potentially weak FDS muscle. Instruction in wrist flexion curls with a 1-pound weight may also be initiated. The concept of high-frequency exercise with low resistance is encouraged.

At 3 to 4 weeks postoperative, exercises that combine active donor contraction with passive recipient motion are introduced. Specifically, this includes the following 2 options:

a. Supine bilateral elbow flexion with forearms supinated using a dowel; a foam buildup may be added to the involved side of the dowel to encourage simultaneous active donor fisting.
b. Active fist and wrist flexion while passively flexing the elbow with the uninvolved arm.

Middle phase Once a muscle twitch is present, gravity-lessened exercises are added to the exercise program. With the arm on a surface at shoulder height, active-assisted elbow flexion is performed while gripping and flexing the wrist simultaneously. A slick cloth or skate to lessen the frictional force of the surface and assist the weak elbow flexors is also encouraged (see **Fig. 4**, Video 2). Donor activation and motor patterning exercises, as with the dowel, are continued as well (Video 3).

When elbow flexion strength approaches a 2+/5, advancement to place-and-hold exercises against gravity is initiated with the uninvolved arm flexing the involved arm to 90+ degrees. Strong donor muscle contractions are made as they attempt to keep the arm flexed while support is gradually removed. This exercise can be performed anywhere, and patients are encouraged to do this frequently throughout the day.

Use of elbow flexion support (such as a sling) and activation of the donor muscles with the elbow flexed continue to be important and emphasized in this phase of therapy. Although the patient may be able to fully flex against gravity without simultaneous gripping, elbow flexion force will continue to increase when there is co-contraction of the donor muscles.

Late phase Use of resistive equipment such as hand-held weights and elastic bands is initiated once 3/5 strength is achieved. Attempts before this may lead to early fatigue, pain, and frustration. As elbow flexion strength increases, dependency on donor muscle contraction will lessen. Patients generally see a separation of function by 1 year as their functional use of the arm improves.

Intercostal nerves to musculocutaneous nerve

Early phase There are 3 functions to consider with the intercostal (IC) muscle donor: inhalation, exhalation, and trunk flexion. Chalidapong and colleagues[23] looked at these 3 functions in patients with IC to MC nerve transfers and found that trunk flexion correlated with the highest response in the recipient muscle electromyography. By the end of the first month, patients are instructed to activate the donor by performing trunk curls in supine and sitting with forced exhalation. Combined donor-recipient exercises are performed with the patient in the seated position with the forearm on a table next to them. In this position, active trunk flexion will passively flex the elbow.

The regenerative distance from the nerve coaptation to muscle motor endplates is longer in this transfer than the DFT. Often the surgeon is able to perform the transfer proximal to the MC branch to the coracobrachialis muscle. Therefore, when testing for a muscle twitch, one should palpate the proximal medial humerus for this muscle as the patient flexes the trunk with exhalation. Typically, the coracobrachialis muscle is not considered important to shoulder function; however, when no other shoulder muscles are intact, it can provide limited shoulder flexion. Active assistance to this muscle is provided when the patient performs shoulder flexion slides with the arm on a table as he trunk flexes/exhales.

Middle phase Once a twitch is noted in the elbow flexors, the program should be expanded to include supine or sitting trunk curls with dowel-assisted bilateral elbow flexion. This exercise is performed in a supine or sitting position. Alternatively, in the side-lying position, elbow and shoulder flexion is enhanced when practiced on a downward sloped bolster (gravity assisted) with simultaneous trunk flexion (**Fig. 13**). During the middle phase of recovery, use of a pool can be helpful and motivating by allowing independent arm movement in this buoyant environment.

Late phase This phase is identical to the DFT late phase. Once adequate elbow flexion strength against gravity is achieved, separation of recipient muscle action from donor co-contraction occurs with minimal effort.

Fig. 13. Intercostal to MC transfer: the patient is positioned in side lying position with the arm supported on a slick bolster. Combined trunk flexion with forced exhalation is performed with active shoulder and elbow flexion. *Red arrow* depict direction of motion.

Nerve Transfers to Restore Hand Function

Median nerve

A proximal median nerve injury limits pronation, which in the modern digital world compromises the ability to communicate via keyboard and computers. When the biceps and supinator are left unchecked, strong supination can become dominant, thereby limiting hand and wrist function. Loss of finger and wrist flexion as well as thumb opposition will further compromise the function of the hand as it demonstrates dominant intrinsic positive posturing.

Extensor carpi radialis brevis to pronator teres nerve transfer

Early phase Active wrist ROM should be started after a 2-week resting period. In this transfer, the nerve coaptation is performed in close proximity to the muscles involved. Care should be taken to avoid complications such as a seroma or hematoma during the early postoperative phase by limiting hand and wrist activity. The patient is instructed to rest the arm, elevated on a pillow or in a sling, with the forearm pronated to maintain muscle length. Following the rest period, patients may begin active wrist extension exercises hourly. For donor and recipient patterning, light resisted wrist extension with passive forearm pronation exercises are performed daily.

Middle phase As active pronation returns, functional exercises such as the BTE steering wheel tool are helpful in simulating a task that involves both donor and recipient muscle action. A lightweight bat or dowel may be used to combine wrist extension and pronation with minimal resistance for the donor and gravity assistance for the recipient pronator. Cues are given for strong donor contraction throughout the pronation portion to provide increased response in the recipient muscle.

Late phase Testing pronation strength with the elbow flexed (isolating PT) versus extended (isolating pronator quadratus) may clarify the amount of force contribution provided by each pronator muscle. Resistance to the functional exercises should be added gradually, making sure the elbow is kept in 90° of flexion to limit substitution and ensure PT contribution.

Flexor digitorum superficialis branch to anterior interosseous nerve

Considerations There are consistent strategies to deal with the unopposed finger and thumb extension in anterior interosseous nerve (AIN) palsy. Regardless of the donor used, the patient will benefit from finger-based splints to block hyperextension of the distal interphalangeal (IP) joints of the index and thumb. This splint not only preserves muscle length, but also can improve fine motor opposition by limiting fingertip collapse during pinch activities (Fig. 14).

Early phase The beauty of this transfer is that there is a clear synergistic relationship between the flexor digitorum profundus, flexor pollicus longus (FPL), and the FDS muscles. Donor activation is initiated at 2 to 4 weeks postoperatively and achieved with simple gripping exercises. Light resisted donor exercises may begin once all postoperative edema is resolved. Patients are encouraged to wear finger splints blocking the distal joints as able during the day and to perform passive flexion exercises to the fingers and thumb. Thumb IP joint and index finger distal interphalangeal (DIP) joint restriction are common with AIN palsy. Exercises should encompass both composite flexion as well as blocked DIP flexion to ensure stretch to the oblique retinacular ligament.

Middle phase A twitch may be noted in the recipient muscle as early as 3 months postoperatively. Training advances to include place-and-hold exercises to the thumb and index tips while fisting tightly (Video 4). Resistive donor exercises with a gripper or putty are also strongly encouraged.

Late phase Although signs of reinnervation, that is, a twitch, develop early, recovery of greater than 3/5 strength or resistance through the thumb and index tip may take another 12 to 15 months. Persistence with gripping exercises and protection

Fig. 14. Finger-based splints are used to limit IP joint hyperextension in patients with AIN palsy. The splints improve function by limiting IP collapse with pinch activities and preserve joint and muscle length.

of FPL length may enhance this time line. Functional activities that demand IP joint flexion, such as spherical grasp, peg boards, and wide-handled gripping (dowel pulls through putty), should be included in the HEP. Success is seen when patients report ability to once again unbutton a shirt or pull up a zipper (Video 5).

Brachialis branch of the musculocutaneous to anterior interosseous nerve

Considerations In this transfer, the nerve coaptations are in the upper arm. The distance from coaptation to the recipient muscle is long. Patient education regarding this timeline is useful to maintain compliance of the HEP.

Early phase Elbow movement is restricted in the first 2 weeks to protect the nerve repair and limit edema. Active elbow flexion with the forearm in pronation will promote donor activation and can be advanced to resisted elbow curls by the end of the first month. When hand function is absent, a splint may be fabricated to support the wrist and position the thumb and index finger in distal joint flexion. Resistance tubing is used for these exercises.

Middle phase Splinting is encouraged to position the hand in pinch for support in order to initiate function with active elbow flexion. Advanced patterning with donor and recipient muscle action can be achieved with the BTE lever tool; this may require a mitt or taping to support the hand placement for resisted elbow flexion. To simulate this at home, a resistance band with a foam tube handle can be used.

Late phase Once the patient has gained isolated movement, putty exercises may be added for resisted pinch and finger flexion exercises. In addition, by grasping a short dowel to pull through the resistance putty, functional demand is placed on the AIN muscles and elbow flexors simultaneously. Buttoning and pulling zippers should be achievable at this point.

Radial nerve

Median to radial nerve transfers

Considerations Median to radial nerve transfers are described as the transfer of the flexor carpi radialis branch to restore finger and thumb extension (posterior interosseous nerve, PIN) and transfer of the FDS branch to restore wrist extension (ECRB). Nerve transfer patients have the potential to regain full independent finger extension and reasonably strong wrist extension.[24] The time line is typically 4 to 5 months to achieve muscle twitch and 10 to 12 months to regain functional movement.

Early phase Postoperative dressings are replaced with a forearm-based "P1 block" splint with thumb extension to support the wrist, thumb, and the proximal fingers in extension. This splint is worn for 2 weeks for tissue rest (**Fig. 15**). Following this period, intermittent use of static or dynamic extension splinting is strongly encouraged until active control of the reinnervating muscles is achieved. The splints maintain recipient muscle length and improve hand function during this time.

Donor activation exercises begin after the first 2 weeks. The exercises include finger IP flexion and isometric wrist flexion. Resisted finger flexion exercises are added when postoperative edema is resolved. Although the authors encourage splint use, the exercises may be performed in or out of the splint. Active use of the hand is encouraged.

It should be noted that some surgeons may opt to perform a PT to ECRB tendon transfer at the same time as this nerve transfer. In these cases, the protocol is deferred to the tendon transfer guidelines in order to protect the tendon repairs.

Middle phase Exercises are advanced once the presence of muscle activation is noted. Patients may begin resisted donor exercises with putty. The following exercises will provide resistance to the donor muscles while passively assisting the recipient muscles. These exercises include (Videos 6 and 7) the following:

1. Log rolls are performed on the table and then turned sideways into a vertical cylinder. Place the palm on top of putty and flex the wrist to flatten putty allowing the putty to passively extend the thumb and fingers.
2. Finger digs are performed with the forearm on a table creating assistance to wrist extension with resisted finger flexion.

Fig. 15. A forearm-based "P1 block" splint is used to maintain wrist and finger extension muscle length in patients with radial nerve palsy.

When treating an isolated PIN palsy (intact wrist extension), a hand-based P1 block splint may be useful with training extensor digitorum communis to pull into end range metacarpal phalangeal joint (MP) extension with active wrist flexion. Patients may provide resistance to the wrist flexors with their uninvolved hand for this. These patients are followed monthly for monitoring return of function and advancing HEP.

Late phase When control of the extension function is attained, strengthening may be advanced with light resistance. One-pound eccentric wrist extension with full assist during the concentric phase is an example that stresses the donor finger flexors while working to achieve end range wrist extension. Theraputty or resistance bands are used to provide resistance for thumb and finger extension.

Ulnar nerve

Anterior interosseous nerve to pronator quadratus transfer to ulnar motor nerve

Considerations Ulnar nerve palsies result in claw deformity. It is important to address (and prevent) the proximal interphalangeal joints (PIP) contractures perioperatively with splinting and exercise.

Early phase A neutral wrist splint is used for the first 2 weeks postoperatively to limit edema and overuse.

Patients are generally instructed to limit hand use during the first month to light activity. Active forearm pronation exercises are initiated, and baseline measures are taken to monitor changes in motor control, hand girth, and claw deformity. Use of an anti-claw splint is advised to help maintain length of the intrinsic muscles and limit PIP contractures (Fig. 16).

Fig. 16. The anti-claw splint limits hyperextension of the MP joints of the ring and small fingers while encouraging active IP extension.

Middle phase Because of the distance from coaptation in the distal forearm to the intrinsic muscles, expectation for a twitch is often 6 months. The patient is asked to spread the fingers while resisting forearm pronation. One may see a small twitch of tendon bulge at the radial and ulnar aspects of the proximal fingers. The authors follow responses along the path of ulnar nerve, that is, intrinsics to the small finger recover before the ring finger, and so forth.

Patients are instructed in individual interossei exercises for both passive and active assisted finger abduction/adduction. Place and hold exercises in the intrinsic plus position are used to aid in regaining lumbrical muscle function. In order to increase recipient muscle effort, the patient is instructed to press the radial aspect of the hand into a wad of putty for resisted pronation (Fig. 17). Furthermore, finger extension splints are helpful in isolating intrinsic function and aid in correcting substitution patterns. An IP flexion block splint for the thumb will allow isolated pinch strengthening while limiting contribution of the FPL (Fig. 18).

Late phase As strength improves and control of the intrinsic muscles improves, resistance exercises are introduced. Resistance putty is used for a series of exercises, which include the following:

1. Log roll with fingers adducted
2. Abduct/adduct: place the "log" between the fingers and gently abduct/adduct and pull with 2 fingers at a time

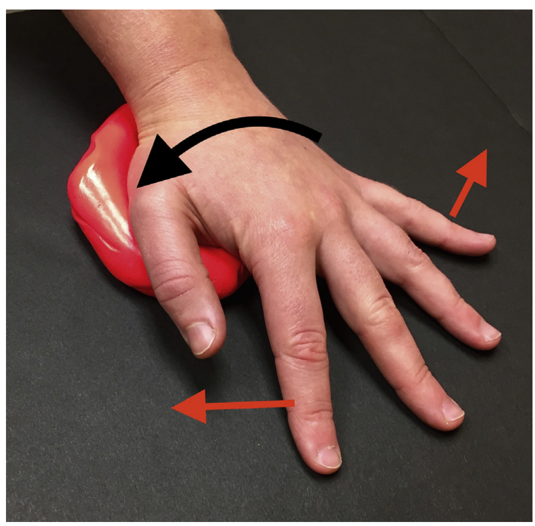

Fig. 17. Following an AIN (pronator quadratus branch) to ulnar motor nerve transfer, intrinsic muscle exercises are enhanced by resisted donor activation with pronation into putty. *Black arrow* depicts forearm pronation and red arrows depict finger finger abduction. *Red arrows* depict direction of motion.

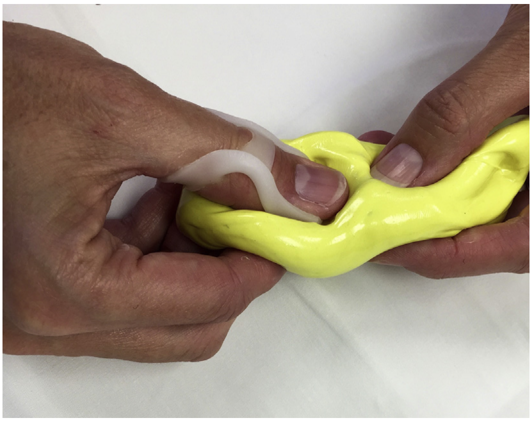

Fig. 18. A thumb-based IP joint extension splint blocks the contribution of the FPL during pinch activity. With the substitution pattern removed, there is greater isolation of the adductor pollicus muscle during pinch strengthening exercises.

3. Intrinsic plus "card draw": place fingers on the putty and pull hand up into MP flexion with IP extension (Fig. 19)
4. Various diameter dowels gripped and pulled through putty

SUMMARY

As nerve transfers become the mainstay in treatment of brachial plexus and isolated nerve injuries, the preoperative and postoperative therapy performed to restore motor function requires continued dedication and appreciation. Through the understanding of the general principles of muscle activation and patient education, the therapist has a unique impact on the return of function in patients with nerve injuries. As surgeons continue to develop novel nerve transfers, the perioperative training, education, and implementation of the DAFRA model are critical to ensure successful outcomes.

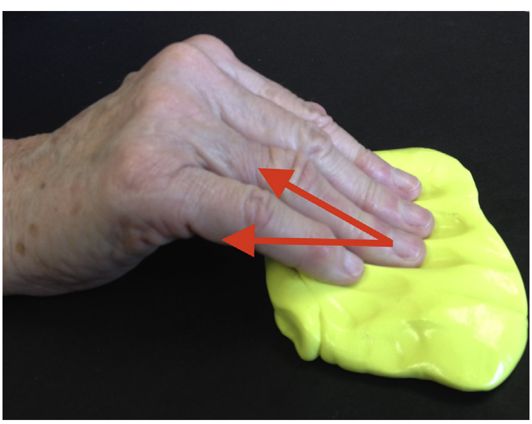

Fig. 19. Resistance putty is used to resist intrinsic plus positioning during lumbrical strengthening exercises. *Red arrows* depict direction of motion.

SUPPLEMENTARY DATA

Videos related to this article can be found at http://dx.doi.org/10.1016/j.hcl.2015.12.014.

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