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Hypothesis

Expansion of Intact Sensory-motor Territories in Proximal Neuraxial Lesions using Peripheral Nerve-muscle Weeding Interventions

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Abstract

Following complete peripheral nerve injury, collateral sprouting (CS) by adjacent nerves causes concentric shrinkage of the insensate area. Such take-over of insensate territory is unknown in proximal lesions such as stroke, spinal cord injury, and cauda equina syndrome, as peripheral nerves supplying insensate territories still maintain continuity from the cell body in the dorsal root ganglion (DRG) to the skin innervation territory. This preserved distal continuity opposes territory take-over by the expansion of adjacent sensate territories; sectioning peripheral nerves in insensate territories distal to DRGs disconnects nerve cell bodies from their skin territory, thus facilitating sensate territory expansion of adjacent nerves. Similar motor system applications in paralyzed territories include lower motor neurone lesioning and fasciectomies, facilitating motor territory expansion of adjacent nerves through CS. A search for evidence of previous conception of these hypotheses was conducted in the literature, using a combination of relevant terms from three categories (proximal neuraxial lesions, nerve-muscle interventions, collateral sprouting); however, this yielded no pertinent results, suggesting that these concepts are novel. Observations from the literature on peripheral nerve injury indicate a sound scientific basis for these hypotheses. Therefore, the suggested "weeding" interventions are likely to succeed in minimizing neurological deficits and improving patients' quality of life. Various interventions to expand sensory/motor territories are considered; these include nerve lesioning distal to DRGs and removing fascial barriers between innervated and paralyzed muscles. Experience from such interventions will help expand our understanding of the speed and extent of CS-mediated neurological recovery as well as brain's plastic abilities in reorienting after such procedures.

Introduction

Recovery patterns from neurological deficits follow different trajectories in central and peripheral lesions. Even in the scenario of peripheral nerve injuries (PNI), sensory and motor recovery patterns and extent differ. In complete PNI cases, shrinkage of the insensate area is observed despite absent motor recovery. This is due to the expansion of the preserved sensate territories of adjacent nerves through collateral sprouting (CS), which is a recognized modality of neurological recovery. Weddell *et al*.[1] attribute the first conception of CS to Schuh in 1911, while acknowledging Sherrington as having previously recognized "extensive overlap between cutaneous nerve fibers derived from successive nerve roots" in 1893. Many subsequent authors have studied and confirmed this phenomenon in various contexts, including Robinson,[2] Inbal *et al*.,[3] Diamond *et al*.,[4] Ibrahim *et al*.,[5] and Ducic *et al*.[6] as discussed subsequently.

This kind of peripheral nerve sensate territory expansion is not reported in central lesions like stroke and spinal cord injury (SCI), nor in preganglionic lesions such as complete cauda equina syndrome (CES) and pre-ganglionic brachial plexus injuries (pBPI). It appears that an alternative process is taking place in PNI cases, permitting the take-over of the insensate territory by adjacent nerves. Nerve conduction studies provide an important clue in this regard: normal peripheral sensory nerve conduction is observed in

Keywords: Nerve regeneration; Dorsal root ganglion; Stroke; Spinal cord injuries; Cauda equina syndrome; Neuronal plasticity.

Abbreviations: CES, cauda equina syndrome; CS, collateral sprouting; DRG, dorsal root ganglion; FSN, first-order sensory neurones; LMN, lower motor neurones; NLI, neurological level of injury; pBPI, pre-ganglionic brachial plexus injuries; PNI, peripheral nerve injuries; SCI, spinal cord injury; SEO, sensory end organs; UMN, upper motor neurone.

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all higher sensory lesions mentioned above, while sensory nerve conduction is absent in cases of complete PNI. This preservation of sensory nerve conduction in higher lesions is due to the cell bodies of first-order sensory neurones (FSN) in the dorsal root ganglion (DRG) remaining connected to sensory end organs (SEO) in the skin through peripheral nerves; hence, the FSN maintains its territory and opposes any attempts at territory take-over by adjacent nerves. In PNI, this peripheral continuity and control of the FSN are not maintained; thus, adjacent intact nerves with sensate territories can take over parts of this denervated territory, resulting in concentric shrinkage of the insensate area.

In their nerve section experiments on primates, Kirk *et al*.[7] demonstrated the expansion of intact nerve root dermatomes after neighboring roots are sectioned. This expansion was much larger with the post-ganglionic division of adjacent nerve roots; this suggests that nerve cell bodies of the FSN in DRGs of adjacent nerve roots played an important role in opposing any attempts of CS-mediated take-over of their sensory territories by the intact nerve. In a study on surgical flaps, Ibrahim *et al*.[5] reported collateral sprout growth and sensate area expansion across surgical scars into the denervated flap, underscoring the high CS potential of peripheral nerves. In their meta-analysis of 12 studies of sural nerve biopsy and harvest, Ducic *et al*.[6] reported that all these studies found some extent of improvement in sensory deficit, including substantial CS-mediated recovery in one of those, as cited later.

With this understanding, the research hypothesis about potential interventions to facilitate such sensate territory expansion in the case of proximal sensory lesions can now be formulated (as stated in the next section).

Similar territory take-over of paralyzed muscles by intact adjacent nerves is not commonly evident in PNI cases, due to muscles being separated from each other by fascial and aponeurotic barriers that nerves cannot readily cross (In contrast to skin, mucosae, and parietal peritoneum which are laid out as continuous sheets, stretching across multiple nerve territories). Additionally, regular contraction and movement of muscles against each other generate significant shear forces, disrupting motor nerve collateral sprouts attempting to grow across neighboring muscles.

However, if no such barriers exist, as in the case of a single muscle supplied by two nerves, with one of those lesioned, CS-mediated motor territory expansion of the other nerve takes place, as shown by Lamaitre & Court in their animal experiments.[8] Targeted muscle reinnervation studies by Kuiken TA *et al*.[9] showed that motor nerves can take over and innervate new muscles when surgically facilitated. There is evidence from other animal and human studies supporting the role of CS-led motor unit expansion and improved muscle power after PNI and other lower motor neurones (LMN) lesions with partial paralysis of muscles.[10–12] Therefore, interventions such as fasciectomies and juxtaposition of paralyzed and unaffected muscles together can facilitate CS-mediated territory expansion of intact motor nerves.

Motor territory expansion can occur without fasciectomy-like interventions in complete SCI with a neurological level of injury (NLI) at the lower thoracic level (7th–11th thoracic segments), as many abdominal and posterior spinal muscles are continuous sheets or straps spanning multiple myotomes, with no fascial barriers in between. Therefore, an environment conducive to the downward expansion of the motor territory of the last spinal nerve (at the NLI) can be facilitated by lesioning LMN for a few levels, commencing immediately below the NLI. Such recovery of lower spinal muscles is likely to provide improved trunk control during sitting and transfers; recovery of lower abdominal muscles is likely to result in greater expiratory ability and stronger cough.

Hypotheses

Two hypotheses regarding sensory and motor territory expansion can be postulated as follows:

The sensory system hypothesis

In cases of proximal sensory discontinuity (stroke, SCI, CES & pBPI), the expansion of adjacent sensate territory can be facilitated by creating a new PNI distal to the central lesion. This results in an environment conducive to CS-mediated territory expansion of adjacent nerves with intact connections to the brain.

The motor equivalent of this hypothesis

In cases of proximal motor discontinuity (upper motor neurone lesion – stroke & SCI), the expansion of motor territory can be facilitated by creating a new LMN lesion distal to the central lesion. In cases of distal motor discontinuity (LMN lesion – cauda equina syndrome), the expansion of motor territory can be facilitated by excising fascial barriers between donor and recipient muscles and/or juxtaposing an innervated muscle against paralyzed ones. These interventions result in an environment conducive to CS-mediated territory expansion of adjacent nerves with intact connections to the brain, resulting in the enlargement of motor units.

These hypotheses are now considered further, with examples and illustrations.

In higher sensory lesions (stroke, SCI, CES & pBPI), the cell bodies of the FSN retain their connection to SEOs in the skin and mucosae through peripheral nerves. Therefore, the FSN maintains its territory and opposes any attempt at take-over by adjacent nerves. In PNI, this peripheral continuity and control of the FSN are not maintained; thus, adjacent nerves with intact sensate territories can readily grow into outer parts of these territories, resulting in concentric shrinkage of the insensate area.

Therefore, in a case of proximal sensory discontinuity (stroke, SCI, CES & pBPI), distal peripheral nerve transection is expected to facilitate the shrinkage of the insensate skin area by creating an environment conducive to CS-mediated territory expansion by adjacent nerves with preserved sensate territories, resulting in the take-over of the insensate territory (as illustrated in Fig. 1 below for a complete CES case).

In stroke cases, however, suggested interventions aimed at achieving the growth of sensory nerve collaterals across the midline. Thus, the impulse from the newly sensate territory reaches the other (ipsilateral) hemisphere of the brain (Fig. 2). Therefore, it can be more challenging for the brain to reallocate this sensation to the correct part of the body. This is similar to expanding the intact visual field using prism lenses in hemianopia cases to restore vision across the midline to some extent. After such FSN interventions brain retraining using techniques such as mirror therapy, biofeedback, and visual-tactile corroboration might help in learning to reallocate sensations to correct parts of the body.

These novel denervation procedures (disconnecting the DRG from SEO) may be likened to weeding in gardening. Though disconnected from the brain, the FSN is still connected to the SEO in the skin and mucosae, preventing any collateral sprouts from growing into its territory. Thus, it behaves like weeds in the garden, preventing the growth of desired plants (CS from adjacent sensate nerve territories, in this instance). “Weeding” by interventions at

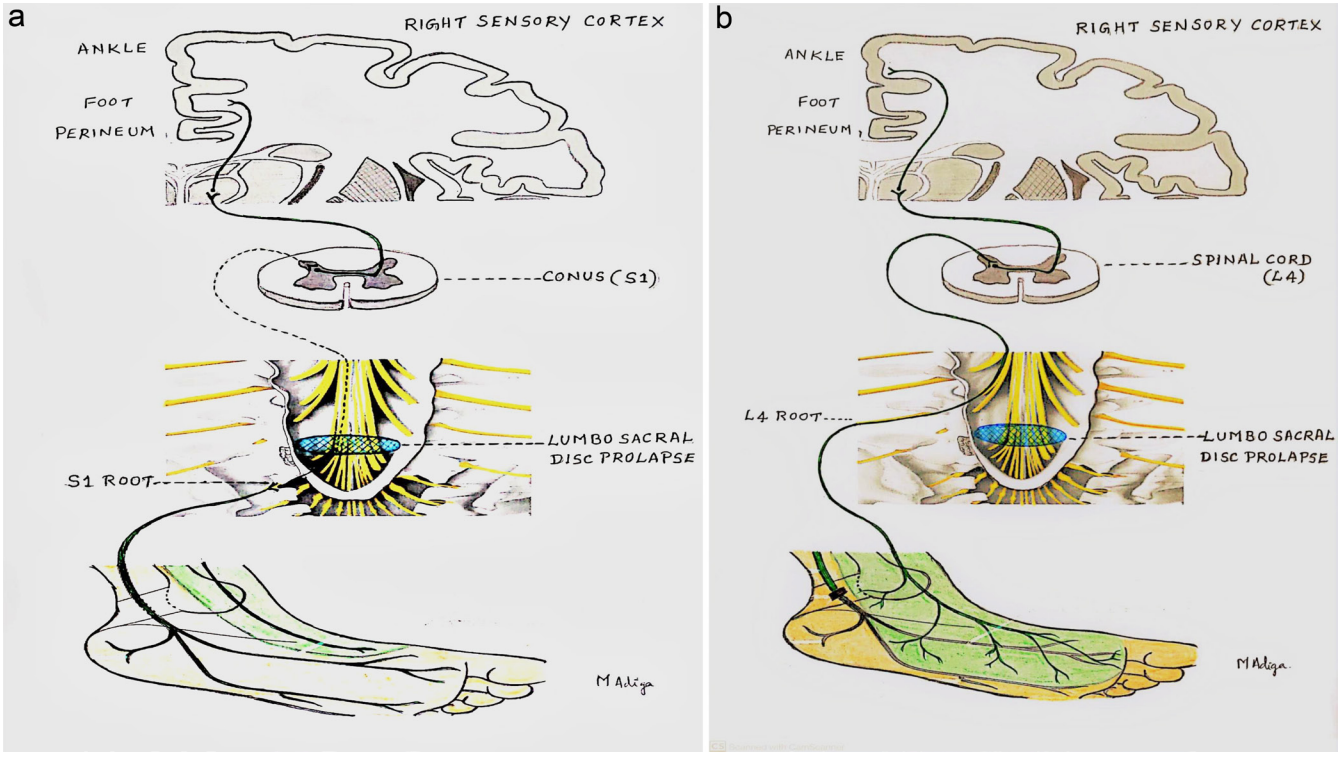

Fig. 1. Depiction of rerouting of sensory conduction to the brain in a complete cauda equina syndrome (L5-S1 level central disc prolapse) case. (a) Tibial nerve (territory shown in beige color) is continuous peripherally from the dorsal root ganglion at the first sacral foramen to the skin at the sole of the foot. Therefore, though it is disconnected from the spinal cord by the disc herniation, it opposes any attempts of territory take-over through collateral sprouting by the adjacent intact saphenous nerve (green-shaded territory). While the second- and third-order sensory neurones are still intact, reaching the foot area of sensory homunculus, the sensation does not reach the brain due to the degeneration of the proximal process of the first-order neurone from the level of disc prolapse up to conus medullaris. (b) The same case after the neurectomy (shown as a black solid rectangle over the tarsal tunnel area) of cutaneous branches of the tibial nerve in the tarsal tunnel. Now, the sensate saphenous nerve (connecting to the central nervous system at L4, above the disc prolapse) extends collateral sprouts into this newly denervated territory on the sole of the foot, thus expanding its sensate territory. The newly acquired sensory territory on the sole of the left foot is now connected to the right sensory cortex through the L4 sensory root. As the rediscovered sensation from the sole of the foot now reaches the ankle area on the same sensory homunculus, very close to the original foot area, re-orientation through cortical plasticity may be easier (compared to the stroke scenario discussed later).

the DRG or the peripheral nerves' level facilitates the growth of the "good crops" of collateral sprouts from adjacent sensate nerve territories, as noted above.

Motor nerves can also take over adjacent territories if no fascial barriers exist, and an adjacent field of LMN-paralyzed recipient muscles is available. Therefore, by creating additional LMN lesions (as in the case of complete lower thoracic SCI) or removing fascial barriers between innervated muscles and LMN paralyzed muscles (as in the case of complete CES), CS of motor neurones can be facilitated, leading to increased motor unit size and partial re-innervation of paralyzed muscles. In addition to weeding interventions like this, "seeding" procedures like rerouting an innervated muscle and juxtaposing it against LMN paralyzed muscles are likely to facilitate such reinnervation further, as discussed with examples in the next section.

Evaluation of the hypotheses

CS has been recognized as a mechanism of sensory-motor recovery following peripheral nerve injuries. There are reports of nerve collateral growth and sensate territory expansion across the midline and into surgical flaps.[2,5] Other animal and human publications have found evidence of CS-mediated sensate territory expansion in the PNI scenario.[3,4]

In their meta-analysis of 12 studies on sural nerve biopsy and harvest, Ducic *et al*.[6] reported that all those studies found some improvement in sensory deficit. One of these—a prospective study of nerve biopsy cases by Theriault *et al*.,[13] noted a mean reduction of 91% in the sensory deficit area by 18 months. Based on the time frame and centripetal pattern of recovery, they concluded that CS was the most likely mechanism. Diabetic neuropathy did not have an adverse effect on this.

In their experimental work on CS of motor nerves, Lemaitre & Court state that the Wallerian degeneration environment activates a distinctive transcriptome profile (conducive to CS) in uninjured adjacent neurones.[8] Kuiken *et al*.[9] demonstrated in their pioneering human work on targeted muscle reinnervation that motor nerves can take over and innervate new territories by implanting various upper limb motor nerves into denervated strips of pectoralis major muscle in a case of bilateral shoulder disarticulation amputee. This has been reproduced by others since then. However, this concept has not been extended so far to CS-mediated motor territory expansion of intact nerves in cases of proximal neuraxial lesions (SCI, stroke & CES).

There is no certainty about the extent and benefit of CS as a nerve regeneration mechanism. Based on the work of Inbal *et al*.[3]

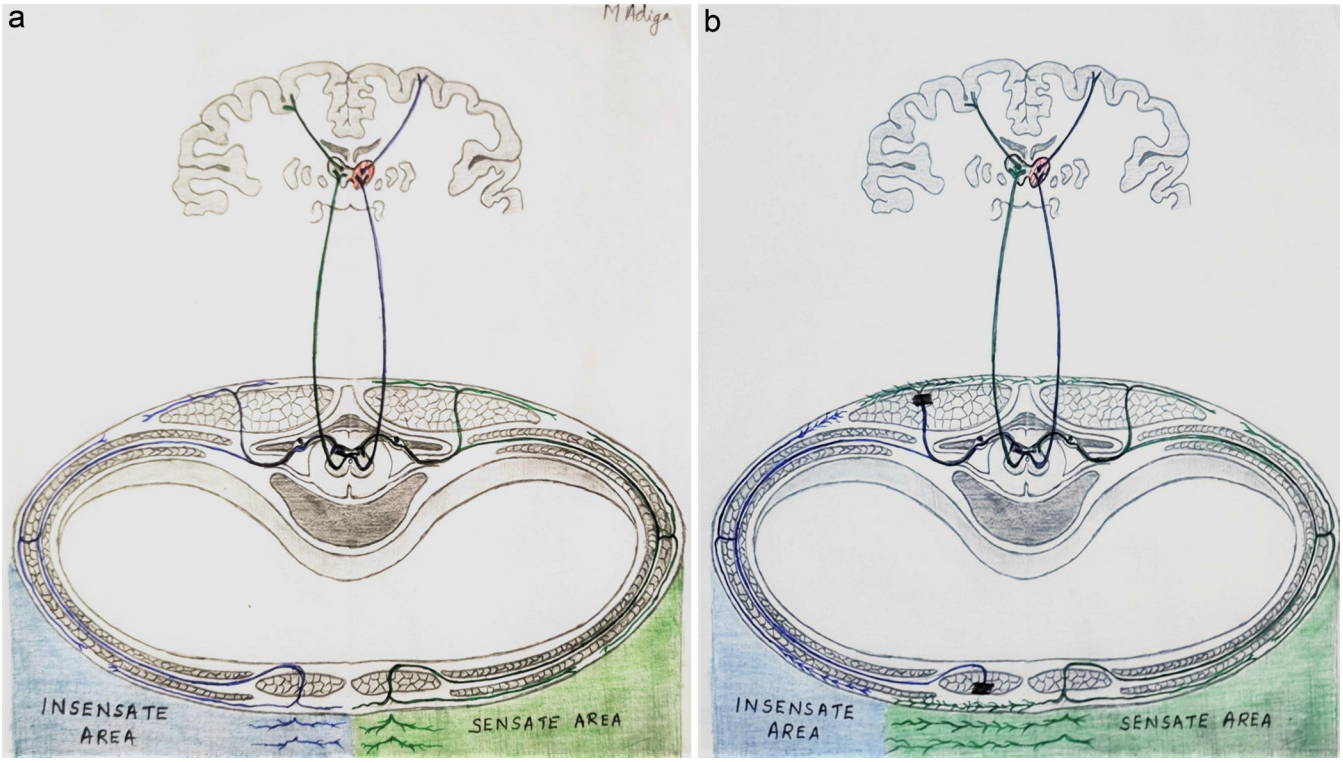

Fig. 2. Depiction of rerouting of sensory conduction to the brain in a complete right hemi-anaesthetic stroke (left thalamic infarction) case. (a) The intact sensory pathway (in green) from the left hemi-body to the right sensory cortex; the pathway (in blue) from the right hemi-body to the left sensory cortex is disrupted due to complete left thalamic infarction. The intact distal continuity of first-order sensory neurones (FSN) on the right side, from its cell body in the dorsal root ganglion (DRG) to the sensory end organs (SEO) in the skin, opposes any attempts of collateral sprouting mediated territory take-over across the midline by the left hemi-body nerves. Hashed area in red: left thalamic infarct. Blue shaded area on the right side of the body: insensate skin; Green shaded area on the left side of the body: sensate skin. (b) The same case after the neurectomy (depicted as black blocks anteriorly and posteriorly) of the cutaneous branches closest to the midline. Now sensory nerves from across the midline extend collateral sprouts into this newly denervated territory, thus expanding their sensate territories. Additionally, there is a growth of "weeds" – insensate but intact FSN on the right side through the lateral cutaneous branches, unless these are also sectioned. The newly acquired sensory territory on the right hemi-body is now connected to the right (ipsilateral) sensory cortex through the left hemi-body nerves and the right spinothalamic tract (in green). Therefore, the newly restored sensation on the right side of the body is felt by the brain as arising on the left side of the midline. Solid black rectangles: transection of anterior and posterior cutaneous branches of the segmental serve. Branching green lines: new collateral sprouts from sensate nerves across the midline. Branching blue lines: new "weed" growth from the lateral cutaneous branch of the intact FSN on the right, insensate through the left thalamic stroke. Blue shaded area on the right side of the body: insensate skin, shrinking away from the midline; Green shaded area: sensate skin on the left hemi-body, now expanding across the midline.

and Theriault *et al*.,[13] one may estimate recovery up to four inches over several weeks to months, though it is hard to conclude that it is the maximum limit. If the sensate expansion of such magnitude can be achieved over the face (oral cavity), hand, or perinium, it can be very beneficial to patients.

Limitations in the brain's ability to correctly match the newly rediscovered sensation with the correct skin territory can present significant challenges and opportunities for future research. In cases of SCI, CES & pBPI, the procedures suggested here utilize the sensory and motor donors from the ipsilateral nerves. Therefore, it is likely to be less challenging for the brain to correctly reallocate sensory or motor controls, as both the donor and the recipient body parts are represented on the same side (contralateral to the body part affected) sensory or motor homunculus, often in close proximity to each other (Fig. 1). Timing of the procedure may be important, as cortical plasticity is most likely to be very active early in the recovery period, indicating that early intervention is preferable. Baldassarre *et al*.[14] have conducted a detailed review of various aspects of cortical plasticity following nerve injury and surgery; this has included successful trans-hemispheric communication and control when the contralateral C7 nerve root was used to reconstruct brachial plexus injury. Such principles outlined here may also apply to the scenarios where CS is the mechanism to re-innervate the insensate skin and paralyzed muscles, as suggested here. There is hope of cortical plasticity working even in those cases where sensory collateral growth across the midline is the most practical way to achieve reinnervation of insensate areas. Socolovsky *et al*.[15–17] have studied brain plasticity following brachial plexus surgery in neonates and adults. While cortical plasticity is better in the younger age group, a proportion of adults also demonstrated significant plasticity in neurological recovery. Such studies may apply to the scenario of healing by CS too and helpful in case selection and pre-operative counseling for the interventions described here.

To determine whether this is a novel concept, a literature search was conducted using Medline & Embase databases (Embase <1974 to 2024 Week 05> and Ovid MEDLINE(R) ALL <1946 to February 02, 2024>) looking for a combination of search terms relating to these three categories – proximal neuraxial lesions, nerve or muscle interventions, and nerve regeneration/CS. The

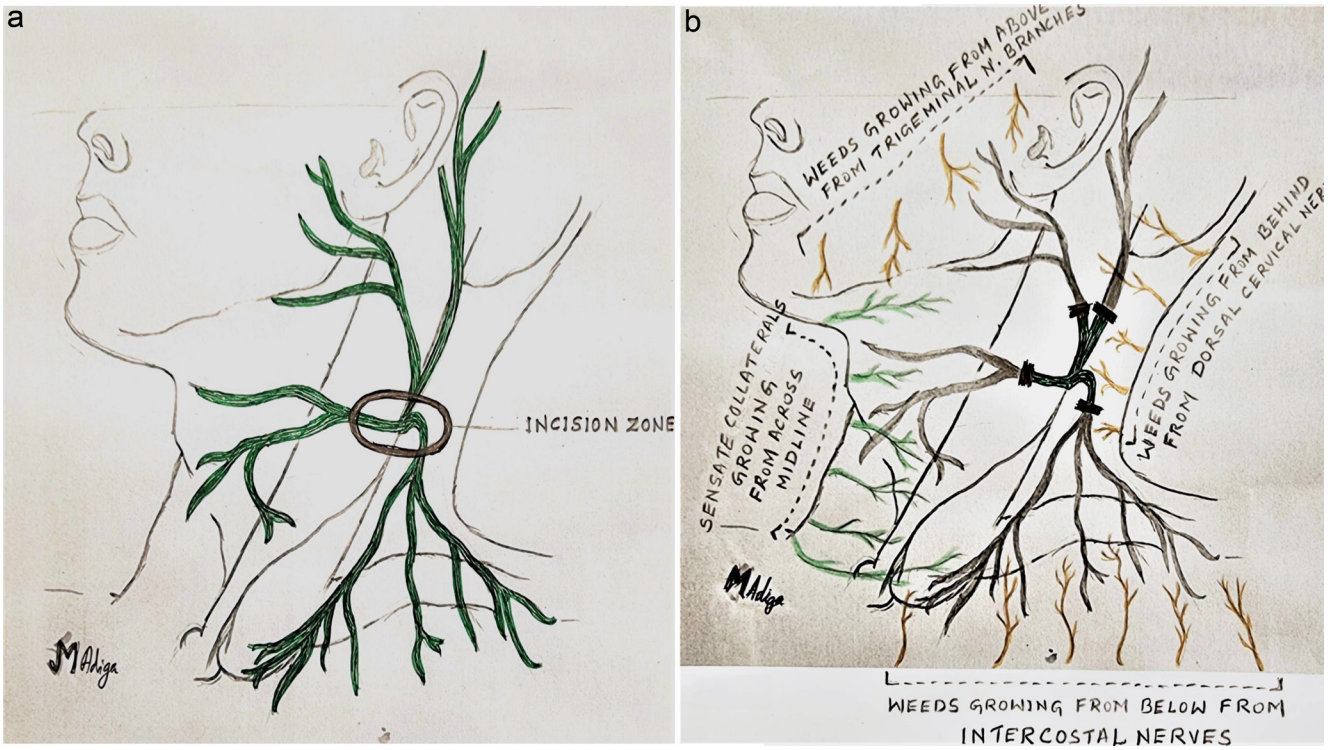

Fig. 3. Suggested test intervention - cervical plexus neurectomy in a thalamic stroke case with hemisensory loss. (a) Depiction of cervical plexus, showing all cutaneous branches supplying a wide field, surfacing through the deep fascia in a small area, allowing transection in the subcutaneous plane through a short incision on already anaesthetic skin. (b) After the nerve section. Cutaneous nerves have degenerated distal to the cut; and new collaterals grow from all around into this newly denervated territory. Those from the antero-medial aspect (shown in green) are the sensate collaterals coming from across the midline. The rest are "weeds" – collaterals from nerves not connected to the brain (due to the thalamic lesion). Once this trial proves the concept by demonstrating a new sensate zone anteromedially, further interventions can be considered over other areas, especially perineal cutaneous branches and trigeminal nerve branches serving the face (including oral mucosa), where regained sensation might be of significant value.

output from this search was then studied further through abstract screening, with the intention of performing a full-text review with cross-reference checking on the final selection. The search strategy is summarized briefly as follows: (Stroke OR SCI OR CES OR pBPI) AND ("collateral sprout" OR (Nerve AND regeneration)) AND (Neurectomy OR neurolysis OR (nerve AND (section OR ablation)) OR fasciectomy).

The search yielded 861 results, reducing to 749 articles with English language abstracts after removing duplicates; on abstract screening, all those were unrelated to the hypotheses concerned and hence not suitable for further processing. This suggests that these are indeed novel concepts. PNI literature suggests the viability of these hypotheses by providing evidence of CS as a potent and useful nerve recovery mechanism for expanding sensory and motor territories.

Consequences and applications of the hypotheses

These principles are already at work in nature. For instance, partial recovery of sensation and motor control at the zone of partial paralysis in SCI may be CS mediated, as some LMN and FSN injury is likely at and just below the NLI. Similar motor unit expansion is likely to take place in cases of incomplete PNI and poliomyelitis.

As the ultimate evaluation of these hypotheses involves performing practical tests in an animal or human setting, a few novel and deliberate applications of this principle are considered now, for minimizing sensory and motor deficits following proximal discontinuity in the nervous system, using distal nerve or muscle interventions to facilitate CS-mediated expansion of the sensory and motor territories of adjacent nerves.

Sensory system applications

Here are a few examples of potential "weeding" interventions applying this hypothesis, aiming to reduce sensory deficits resulting from proximal neuraxial injuries.

Stroke (Pure sensory or complete sensory-motor)

Here, the proposed intervention is to section cutaneous nerve branches on the head, neck, and torso, close to the midline; an easy test intervention, for instance, is to target cutaneous branches of the cervical plexus – supraclavicular, transverse cervical, greater auricular, and lesser occipital nerves. These nerves can all be accessed on a superficial plane through a single, short incision on insensate skin over the sternomastoid muscle (Fig. 3). These neurectomies facilitate sensory take-over from across the midline. After proving the concept by performing such test interventions, further neurectomies close to the midline can be considered – such as transecting skin and mucosal branches of the trigeminal nerve, cutaneous branches of brachial, intercostal, lumbar and sacral cluneal, ilio-hypogastric, ilio-inguinal, genitofemoral, obturator, pudendal and anterior, lateral and posterior femoral cutaneous nerves. The expanded sensory territory is now connected to the brain through the nerves from across the midline with their intact

connection to the brain (Fig. 2). Therefore, sensory pathway interruption from the stroke does not affect this expansion of the sensate area. However, the brain will interpret this new sensation arising from the affected side of the body as coming from the unaffected side (at least early on).

SCI (lower thoracic, complete)

Post-ganglionic lesioning of nerve roots at multiple consecutive levels, beginning immediately below the NLI, is proposed to facilitate sensory and motor expansion from the last intact root above. In this instance, the hypothesis extends to the possibility of motor territory (posterior spinal and abdominal wall muscles) expansion. This is due to many abdominal walls and posterior spinal muscles being laid out as continuous sheets or straps, spanning across multiple segmental nerve territories, without fascial barriers between myotomes. Therefore, downward expansion of the lowest intact motor innervation territory (at the NLI) can be facilitated by creating LMN lesions below the NLI (by transecting spinal nerves for a few levels below the NLI). This intervention also severs FSN continuity distal to the DRG, preparing cutaneous and parietal peritoneal territories for sensate expansion over the lower abdomen, pelvis, and adjacent areas of the lower limbs and genitalia.

Complete CES

Ablation of DRGs below the NLI can facilitate CS-mediated sensory territory take-over by cutaneous branches of the lumbar plexus innervating sensory territories adjacent to insensate areas. For example, a case of central disc prolapse at the L5-S1 (lumbosacral) level can be considered, with complete sensory, motor, and autonomic dysfunction below the level, with no recovery. After confirming that there is no return of function, lesioning DRGs of sacral nerve roots (or cutaneous nerve transections distally) is proposed to facilitate sensory territory take-over by neighboring intact sensory nerves connected to the brain through lumbar roots as detailed below: The saphenous nerve (L4, a branch of the femoral nerve), innervating the medial border of the foot, is now able to expand its territory into the sole of the foot (S1, tibial nerve), thus providing valuable sensory feedback whilst standing (Fig. 1).

Branches of obturator nerve (L2-3), lateral femoral cutaneous nerve (L2), and lumbar cluneal nerves (L2-4) can now expand onto the skin over the ischium (S3, posterior femoral cutaneous nerve & dorsal sacral sensory branches). This provides useful sensory feedback during sitting.

Branches of the ilio-inguinal, genitofemoral, and obturator nerves can expand toward ano-genital regions after transecting the pudendal nerve. This can be valuable, providing early warning of any urinary or fecal leaks.

Preganglionic BPI

In complete long-standing BPI, where nerve repair or reconstruction is no longer considered, after confirming that it is preganglionic injury (using magnetic resonance imaging scan or nerve conduction studies), complete brachial plexus neurectomy in a post-ganglionic location is proposed. This facilitates sensory territory take-over of the proximal upper limb skin by adjacent nerves from the neck, chest, and back: The C5 dermatome on the outer aspect of the upper arm can now be innervated by the expansion of the C4 root territory (supraclavicular branches of the cervical plexus). The T1 dermatome over the inner aspect of the upper arm can now be taken over by T2-3 roots, through intercostal nerve branches supplying the skin of the axilla and adjacent chest. Once such sensory expansion takes place, it will make further reconstructive procedures such as shoulder arthrodesis and above-elbow (trans-humeral) amputation more functional, providing a sensate, mobile stump that can accept and tolerate prosthetic fitting and use.

Motor system applications

Motor system procedures are best considered at a later phase of investigating and validating these concepts, as these would be more invasive. If sensory system procedures aiming to shrink insensate areas prove successful and beneficial, patients may express their willingness to undergo motor system procedures. A clear understanding of risks and potential benefits is essential. Some of these may be considered opportunistically, along with sensory interventions. An example would be to consider juxtaposing the gracilis muscle against the gluteus maximus in a case of complete CES when performing neurectomies in the gluteal region (posterior femoral cutaneous and pudendal nerves) to facilitate sensory field expansion of adjacent sensate nerves.

As procedures for sensate expansion are likened to weeding, motor procedures can be considered as weeding with or without seeding. Weeding procedures here are of two kinds. The first approach is to disconnect upper motor neurone (UMN) paralyzed muscles from their LMN cell bodies. This is suitable where muscle continuity exists across multiple nerve territories, without fascial barriers in between. The second approach is to excise all fascial barriers between innervated donor muscles and denervated (LMN paralyzed) recipient muscles, as seen in cases of CES. Seeding procedures involve juxtaposing an innervated muscle such as the gracilis or sartorius against paralyzed gluteal muscles, as in cases of CES.

In a complete CES case, from an L4-L5 central disc prolapse where there is no recovery, attempting to reinnervate denervated hip abductor muscles (gluteus medius, gluteus minimus) can be done by stripping all fascia off these muscles and juxtaposing the sartorius muscle (mobilized on its neurovascular pedicle) against these, thus creating an environment conducive for CS-mediated expansion of motor innervation from sartorius to these gluteal muscles, thereby improving hip abduction power.

In a similar case, the gracilis muscle can be brought into the gluteal region on its neurovascular pedicle and juxtaposed against the gluteus maximus muscle, thus permitting CS-mediated reinnervation of the latter, thereby improving active hip joint extension power.

Similarly, in a complete CES case, from an L5-S1 central disc prolapse, most muscles of the posterior compartment of the calf (gastrocnemius, soleus, flexor digitorum longus, and flexor hallucis longus) are paralyzed, as these are supplied by S1 and S2 myotomes. However, the neighboring tibialis posterior muscle is usually spared (nerve supply: L4-L5). As most of these paralyzed muscles (except gastrocnemius) are adjacent to this innervated muscle (tibialis posterior), resection of all fascial barriers between these muscles creates an environment conducive to CS-mediated expansion of motor innervation from tibialis posterior into some of these adjacent muscles, thus helping to partially restore ankle and toe plantar-flexion power. Pre-operative electromyography can confirm that the tibialis posterior muscle is innervated, while recipient muscles around it are in a state of LMN-type paralysis.

These procedures are best performed within a few months of sustaining a complete CES, due to concerns about motor end-plate death around 18 months following LMN-type paralysis.

As mentioned previously, many abdominal wall and back muscles exist as a continuous sheet or strap across multiple nerve myotomes. Therefore, in complete lower thoracic SCI (NLI of

T7-T11) cases, disconnecting UMN paralyzed portions of these muscles from the spinal cord (severing segmental spinal nerves below the NLI) transforms these into an LMN paralysis state, thereby preparing for take-over through CS-mediated downward expansion of the last myotome at the NLI.

Similarly, in a stroke case with persistent UMN facial palsy, selective sectioning of the facial nerve branches supplying the oral sphincter muscle (orbicularis oris) can facilitate the expansion of motor innervation from intact facial nerve branches across the midline, supplying the other half of this muscle. Combined with improved sensation in the lips and cheek, resulting from similar procedures on trigeminal nerve branches, is likely to improve oral sensation and function leading to a reduction of drooling.

Limitations, biases and caveats

As the procedures described here are destructive in nature and performed distally in the nervous system, aiming to address the deficits arising from more proximal lesions, skepticism about the success of such interventions is natural. The author has strived to address such concerns using appropriate pictorial and written explanations.

While CS does work, there are uncertainties about the speed and extent of such recovery as well as the limits of brain plasticity following such peripheral neural procedures. More research is required, including critical analysis of the results of interventions described here, so that appropriate conclusions regarding efficacy and benefits may be arrived at.

The author has seen many cases of CS-mediated sensory recovery following complete peripheral nerve and plexus injuries with a significant reduction in sensory deficits, including complete sensory recovery in a few instances. This might have led to bias in favor of CS-mediated recovery and the benefits thereof.

The interventions suggested here work only in situations where a well-defined contiguity zone exists, with the skin or muscle connected to the brain (donor) on one side meeting FSN-disconnected skin or LMN-paralyzed muscle (recipient) on the other side. On the other hand, if there is a strip of insensate FSN-connected skin or UMN-paralyzed muscle separating the donor and the recipient, acting as a barrier between them, only "weeds" will grow.

Corneal and throat denervation procedures might result in harm due to the possibility of ulceration or worsened pharyngeal/laryngeal reflexes. These are best considered at a later phase of research.

Future directions

The next step would be to practically test these hypotheses for effectiveness and safety. Animal experiments as well as human trials are possible, with ethical and practical issues to be addressed in both. For direct human application, the approach of focus groups consisting of patients and expert clinicians is one way to establish propriety and feasibility. Caution is required to avoid harm by acts of commission; at the same time, individuals living with disabilities should have access to potentially beneficial interventions without undue delays in translating the research idea into clinical application. Otherwise, such patients might be inadvertently harmed through procrastination. As aptly stated by Sterling Bunnell,[18] "To someone who has nothing, a little is a lot". Therefore, exploring this concept further with patients and other stakeholders through focus groups is a good way forward. This helps investigators understand patients' views on whether some surgical risks are acceptable for the possibility of deriving potential benefits from these interventions.

Many unanswered questions regarding nerve recovery through CS and the relearning ability of the CNS may be answered by procedures proposed here, as prospective studies can be planned. These include the speed and extent of recovery, the effect of age and other patient factors, differences in recovery among sensory modalities, the effect of duration on sensory end organ survival and cortical plasticity, medications and other interventions that might help, the likelihood of future fatigue of the neurones taking up larger territories (as postulated in the case of post-polio syndrome), the effect of various rehab strategies, etc.

There are many interesting possibilities for combining the methods proposed here with other therapeutic approaches to obtain better results. Various chemicals and growth factors are being investigated. There are suggestions about electroacupuncture,[19–21] Botulinum toxin,[22] various medications, and other interventions in priming or enhancing peripheral nerve regeneration; these may also apply to the CS situation. Rehabilitation techniques such as mirror therapy and biofeedback may improve cortical reorientation, associating new sensory-motor territories with appropriate parts of the sensory-motor cortex. Thus, weeding and seeding methods outlined here may be supplemented with other aspects of "gardening"—preparing the field, feeding, watering, and protecting the crop, as envisaged from a neurological viewpoint.

The future will see many improvements in brain and spinal cord regeneration and repair. Hopefully, a time will come when it is possible to regenerate damaged parts of the brain and spinal cord, restoring lost function without leaving residual deficits. If and when such a state is reached, the kind of procedures suggested in this article may not be required. Until then, there may be a role for these in selected cases. Additional indications may come up, such as stable cases of multiple sclerosis, incomplete cases of stroke, SCI and CES, etc.

It is hoped that a new body of knowledge will be generated from this line of work in the coming years and decades—about the limits of CS, brain plasticity, factors influencing these, etc. Hopefully, such learnings will have lasting relevance, even in the remote future when there is no need for these interventions anymore.

Conclusions

In proximal neuraxial lesions, FSN and LMN act as custodians of their sensory and motor territories, respectively, opposing any attempts at territory take-over through the CS process by neighboring nerves, thus behaving like weeds in the garden; weeding procedures proposed here facilitate overcoming this resistance and expanding sensate/voluntary motor control territories of adjacent intact nerves. These procedures include creating new FSN/LMN lesions in insensate/paralyzed territories, excising fascial barriers between donor and recipient muscles, and juxtaposing innervated and paralyzed muscles. Future research in this field is likely to provide clarity on various issues such as the speed and extent of sensory-motor recovery through CS, helping and hindering factors, best cases and situations for these procedures, central nervous system plasticity after such recovery, rehab interventions facilitating it, possible effects on pain, and any additional benefits.

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Conflict of interest

None.

Author contributions

SA is the sole author of the article.

Data sharing statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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