PAMELA

Surgical Techniques for Prevention and Treatment of Phantom Limb Pain

Learning Objectives

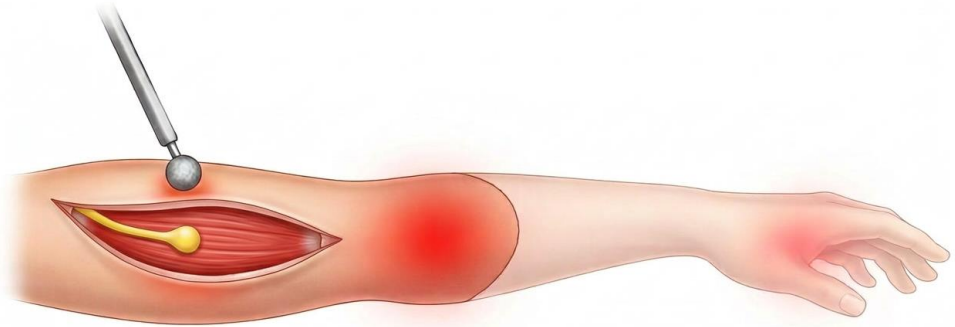
1. Pain Types after Amputation
2. Surgical Techniques for the prevention and treatment of Phantom limb Pain
3. Post Operative Care
4. Consideration Combat-Related Amputations

Pain Types After Amputation

A) Neuroma Pain (NP)
Neuropathic pain from severed nerves

B) Residual Limb Pain (RLP): Pain in the stump

C) Phantom Limb Pain (PLP): Pain in the absent limb



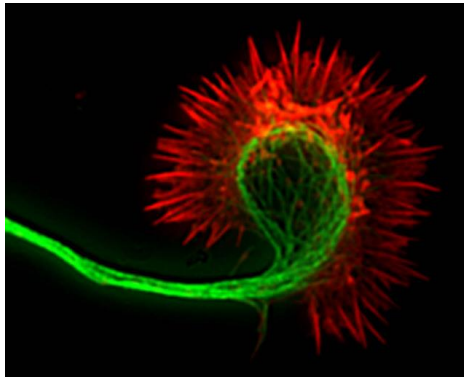
Up to 79.9% report PLP; 67.7% report RLP/NP [11]

Figure modified from Pettersen et al., 2023 [12]

A) Neuroma Pain (NP)

Peripheral nerves lose contact with their target organs when a limb is lost. Following a traumatic nerve amputation, a complicated process that triggers the nerve cell's capacity for regeneration is started close to the site of the amputation.[13] While Waller degeneration causes the distal axon to break down and degrade due to loss of contact with the nerve cell, proximal degeneration typically only occurs to a very limited degree, typically up to the next Ranvier's cord.[14]

Throughout the process, each individual axon starts to spread out proximally once more in an attempt to find a matching target organ. The so-called **"growth cone,"** a specialized, mobile structure from which multiple finger-like projections emerge, is located at the tip of the regenerating axon. The regeneration should ideally occur in the direction of the distal nerve stump, and this is determined by the growth cone. In the event of an amputation, the distal nerve stump is lost, so the regenerating axons typically do not find a corresponding "target." This causes the nerve fibers to grow in an uncontrolled manner, which ultimately results in the development of neuromas.



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A) Neuroma Pain (NP)

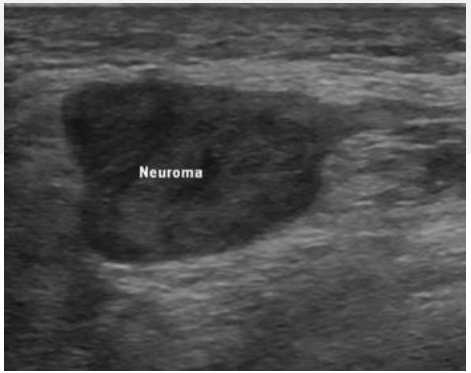
The neuropathic pain that results from a neuroma can be explained by the fact that the nerve fibers inside of it are demonstrably highly sensitive and have the ability to fire on their own.15–17

Symptoms of a neuroma pain:

- Allodynia: a pain sensation triggered by stimuli that do not normally cause pain
- Hyperalgesia: an increased pain sensation in response to painful stimuli
- Positive Hoffmann-Tinel sign: discomfort triggered by tapping on the nerve radiating into the area supplied by the nerve[1]

Second Step:

- Visualization of the neuroma by ultrasound.
- Diagnostic ultrasound-guided infiltration with a local anesthetic.
- A positive result is a temporary reduction or elimination of pain.[1]



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A) Neuroma Pain: Diagnostic Criteria

All three of the following criteria must be met

- Pain exhibiting at least three of the following characteristics: burning, cutting, shooting, electrifying, paraesthesia, numbness, or cold intolerance
- Symptoms confined to a specific neuroanatomical region
- A history of an actual or suspected nerve injury

Additionally, at least one of the following criteria must be met:

- Positive **Hoffmann-Tinel sign** (for cutaneous nerves)
- Response to infiltration with a local anesthetic
- Confirmation of a neuroma through imaging (neurosonography, MRI)

German S3 guideline on the treatment of peripheral nerve injuries[18], outlined in Chapter 9

B) Residual Limb Pain

Residual limb pain is localised in the residual limb and is felt as pain via nociceptors.

Neuroma pain (NP) is also categorised as RLP

In light of recent evidence, it is important **to distinguish RLP from PLP**, as there has been a potential shift in the treatment approach for amputation-associated pain.

While surgical interventions were once deemed ineffective in treating PLP, recent research suggests otherwise, thus highlighting the need for further investigation and clinical consideration of the relationship between RLP and PLP.[2–4]

C) Phantom Limb Pain: Origin



The precise underlying mechanism driving the development of phantom limb pain remains under current investigation and **has not yet been definitively established**[5].

Research suggests that PLP is caused by peripheral, spinal and central pathomechanisms leading to **maladaptive cortical reorganisation** followed by the perception of pain or discomfort in a limb that is no longer there.

Non-painful perceptions of the amputated body part are called **phantom sensations.**[1]

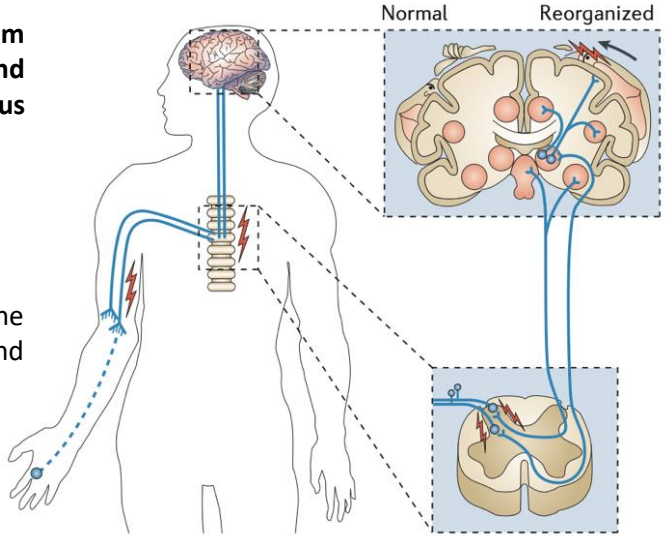
Phantom sensation, unlike phantom limb pain, does not typically require specific treatment interventions.

However, it is important to provide patient education in addressing phantom sensation to promote understanding and address potential concerns related to this experience.

C) Phantom Limb Pain: Origin

The pain experienced in a phantom limb involves both peripheral and central components of the nervous system (CNS)

- The residual limb
- Dorsal root ganglion
- Spinal cord
- Supraspinal centers such as the brainstem, thalamus, cortex, and limbic system.[20]



Central changes
- Unmasking
- Sprouting
- General disinhibition
- Map remodelling
- Loss of neurons and neuronal function
- Denervation
- Alterations in neuronal and glial activity
- Sensory–motor and sensory–sensory incongruence

Peripheral changes
- Structural changes in neurons and axons
- Ectopic impulses
- Ephaptic transmission
- Sympathetic–afferent coupling
- Down- and upregulation of transmitters
- Alterations in channels and transduction molecules
- Selective loss of unmyelinated fibres

Copyright: Nature Publishing Group, 2006; “Phantom limb pain: a case of maladaptive CNS plasticity?” by Herta Flor (2006)[20]

C) Phantom Limb Pain (PLP): Treatment

For decades, surgical interventions for phantom limb pain (PLP) and neuroma pain have shown limited efficacy.

In recent years, **targeted muscle reinnervation (TMR)** and **regenerative peripheral nerve interface (RPNI)** have emerged as promising techniques for enhancing prosthetic control and reducing pain.[6]

The TMR and RPNI approach requires additional skills and operating time, careful evaluation of its indication and potential benefits is essential.



Despite the increasing interest in these techniques, comparative studies and randomized controlled trials (RCTs) are currently lacking to determine the relative effectiveness of each approach.

In response to the need for evidence, a double-blind RCT[12] (NCT05009394) has been initiated to compare the effectiveness of TMR, RPNI, and an active control (neuroma excision and muscle burying) in alleviating residual limb pain, neuroma pain, and phantom limb pain. The trial, spanning multiple countries, aims to follow patients for a period of 4 years. This aligns with the imperative to address phantom limb pain, which affects a significant proportion of major limb amputees, profoundly impacting their quality of life. Distinguishing between phantom pain and neuroma pain is crucial, as both types of pain have unique characteristics and require tailored interventions.

2. Surgical Techniques for the Prevention and Treatment of Phantom Limb Pain

Innovative surgical techniques as

A) Targeted Muscle Reinnervation (TMR)

B) Targeted Sensory Reinnervation (TSR)

C) Regenerative Peripheral Nerve Interface (RPNI)

give a specific purpose to the severed nerve endings, providing a clear direction for their growth and potentially preventing their disorganization.

2. Surgical Techniques

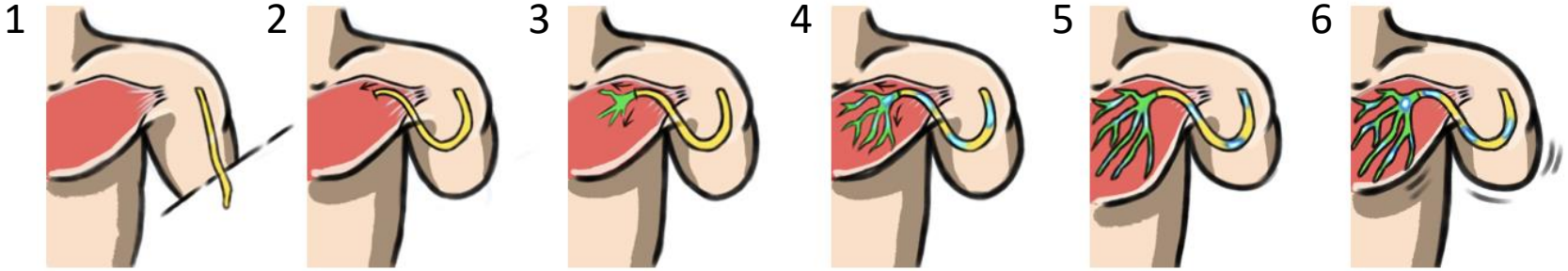
A) Targeted Muscle Reinnervation (TMR)

2. Surgical Techniques: TMR

The principle of Targeted Muscle Reinnervation (TMR) involves redirecting affected proximal nerve stumps to a smaller motor nerve branch that leads to an intact muscle. This denervated muscle is then reinnervated through primary end-to-end coaptation at the nerve entry point, allowing the sprouting axons to enter the motor nerve branch and subsequently reinnervate the denervated muscle tissue or motor end plates.

1. Identify the donor nerve under blunt dissection and gently isolate the donor nerve under loupe magnification using microsurgical instruments as needed. Mobilize the donor nerve for as long as necessary to reach the recipient site.
2. Identify all motor nerve branches to the target muscle by blunt dissection. Transfer the donor nerve to the target muscle and coapt the distal nerve end of a transected motor nerve by end-to-end neurorrhaphy.

3.-6. This provides the nerve with a guide structure via which it grows into the muscle and reinnervates it.



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2. Surgical Techniques: TMR

Initially developed for bionic prosthetics, this technique entailed coapting blind-ending nerves to selected muscle branches to increase the number of individually motorized signals used for prosthetic control. An incidental benefit observed was a very low rate of painful neuroma formation and a reduction in PLP. Subsequent studies have shown excellent results for both pain qualities.[6,29,30]

The targeted muscle reinnervation (TMR) method is not exclusively intended for macrostump treatment, it can also be utilized for addressing painful finger neuromas. TMR represents an improved therapeutic approach compared to surgical resection alone or simple nerve burial within the muscle.[8]

2. Surgical Techniques: TMR

A standardized surgical protocol has been published recently and is summarized below.[32]

1. Presurgical preparations

1. Diagnose the painful neuroma(s): For neuroma pain, **physical stimulation** in the form of digital pressure (e.g. Tinel's sign test) will be used to elicit pain where the neuroma is suspected. No physical stimulation will be used to elicit residual limb pain or PLP; rather, participants will be asked to close their eyes and localize the pain in order to distinguish between the two types. In cases where gentle skin indentation results in RLP, the area can be locally anaesthetized to reduce it and uncover neuroma pain during the physical stimulation. Neuroma pain can also be distinguished by the distally referred painful sensations it elicits in the phantom limb during physical stimulation. At least one of the following methods should be applied to document the presence of neuroma pain: compatible symptomatology, Tinel's sign test, imaging (ultrasound or MRI), or nerve block.[12]
2. Conduct a thorough physical assessment to detect potential muscle targets and evaluate the flexibility of the soft tissue surrounding the nerve. Perform an EMG evaluation of those target muscles in case muscle contraction is hardly assessable.
3. Plan the skin incisions depending on the results from steps 1.1 and 1.2

TERMS

- **Donor nerve**: a nerve with a painful neuroma to be transferred to a recipient residual or "target" nerve.
- **Recipient residual nerve:** the transected segment of a nerve (freshly prepared nerve stump) natively innervating a target muscle.
- **Target muscle:** a viable muscle supplied by the recipient residual or "target" motor nerve in or near the residual limb.

2. Surgical Techniques: TMR

2. Preparation of the donor nerve

1. Perform either regional or general anesthesia without the use of muscle relaxants to allow for effective nerve stimulation. Depending on the planned amputation or site of the painful neuroma, place the patient in a supine or prone position. For the upper extremity, use a surgical arm board to place the arm.
2. Carry out the skin incision using a scalpel. The length and shape of the skin incision depend on the available soft tissue or location of the painful neuroma.
3. Identify the donor nerve or the painful neuroma under blunt dissection.
4. Gently isolate the donor nerve or the neuroma under loupe magnification using microsurgical instruments as needed.
5. Mobilize the donor nerve for as long as necessary to reach the recipient site, considering that the following nerve sutures are free of tension in all range of motions in the proximal joints. Transect the neuroma or transect the nerve using a commercial nerve cutting/preparation set.
6. Repeat steps 2.4-2.6 for each nerve with an identified painful neuroma in the current exposed area.

NOTE
The type of anesthesia depends on the site of the procedure.

NOTE
Isolation of the neuroma is optional

NOTE
Resection of the neuroma is optional when challenging.

2. Surgical Techniques: TMR

3. Motor point identification

1. Identify all motor nerve branches to the target muscle by blunt dissection.
    1. Set a hand-held-nerve stimulator at 0.5-1.0 mA, put it in contact with the nerve branches, and stimulate each of them. During stimulation, the nerve that provides the largest muscle contraction is the one that will be used as the recipient nerve. In the following Table (Table 1), target muscles are suggested for each nerve at a specific amputation level.
    2. Use the known most proximal innervation points when possible.
    3. Denervate the target muscle completely when possible.
2. Once active contraction is confirmed, transect the nerve using straight microscissors without tension as close as possible to its entry point. Aim for less than 1 cm.
3. Transpose the proximal nerve end of the transected recipient nerve proximally away from the coaptation site without any specific management.

2. Surgical Techniques: TMR

Level	Donor nerve	Suggested target muscle(s)
Shoulder disarticulation	Musculocutaneous	Pectoralis Major – Clavicular Head
	Median	Pectoralis Major – Sternal Head
	Ulnar	Pectoralis Major – Split Sternal Head
		Pectoralis Minor
		Latissimus Dorsi
		Serratus Anterior
	Radial	Latissimus Dorsi
		Pectoralis Major -Split Sternal Head
		Serratus Anterior
Transhumeral	Musculocutaneous	Biceps Brachii – Long Head
	Median	Biceps Brachii – Short Head
	Ulnar	Brachialis
		Biceps Brachii – Short Head
	Radial – Distal branch	Triceps Brachii – Lateral Head
	Radial – Proximal branch	Triceps Brachii – Long Head
Transradial	Median	Flexor Digitorum Superficialis
		Flexor Digitorum Profundus
	Ulnar	Flexor Carpi Ulnaris
		Flexor Pollicis Longus
	Radial – Superficial branch	Extensor Carpi Radialis
		Flexor Digitorum Profundus
		Brachioradialis

Level	Donor nerve	Suggested target muscle(s)
Hip disarticulation	Sciatic	If posterior thigh flap is preserved: Semimembranosus
		Semitendinosus
		Biceps femoris
		If medial thigh flap is preserved:
		Gracilis
		Adductor longus
		Adductor magnus
		Adductor brevis
	Femoral nerve	Sartorius (if present) or obturator nerve transfer
		Rectus femoris
		Vastus lateralis
	Saphenous	Sartorius (if present) or obturator nerve transfer
	Obturator	Preserved into the flap
	Lateral Femoral Cutaneous	Semimembranosus
		Semitendinosus
		Biceps femoris
		Sartorius
	Posterior Femoral Cutaneous	Semimembranosus
		Gracilis
		Adductor Longus
		Adductor Magnus
		Adductor Brevis

Level	Donor nerve	Suggested target muscle(s)
Transfemoral	Sciatic - Peroneal Component	Biceps Femoris
	Sciatic - Posterior Tibial Component	Semitendinosus
		Semimembranosus
	Saphenous	Vastus Medialis
	Posterior femoral cutaneous	Biceps Femoris - Distal motor branch
Transtibial	Posterior tibial	Soleus
		Medial Gastrocnemius
		Flexor Digitorum Longus
	Common peroneal	Lateral Gastrocnemius
		Medial Gastrocnemius
	Deep peroneal	Tibialis Anterior
	Superficial peroneal	Extensor Digitorum Longus
		Peroneus Longus
	Medial sural	Flexor Hallucis Longus
		Medial Gastrocnemius
	Lateral sural	Lateral Gastrocnemius

Table 1: Target muscles are suggested for each nerve at a specific amputation level.[32] Adaptation determine by the individual patient case are always possible.

2. Surgical Techniques: TMR

4. Nerve-to-nerve coaptation

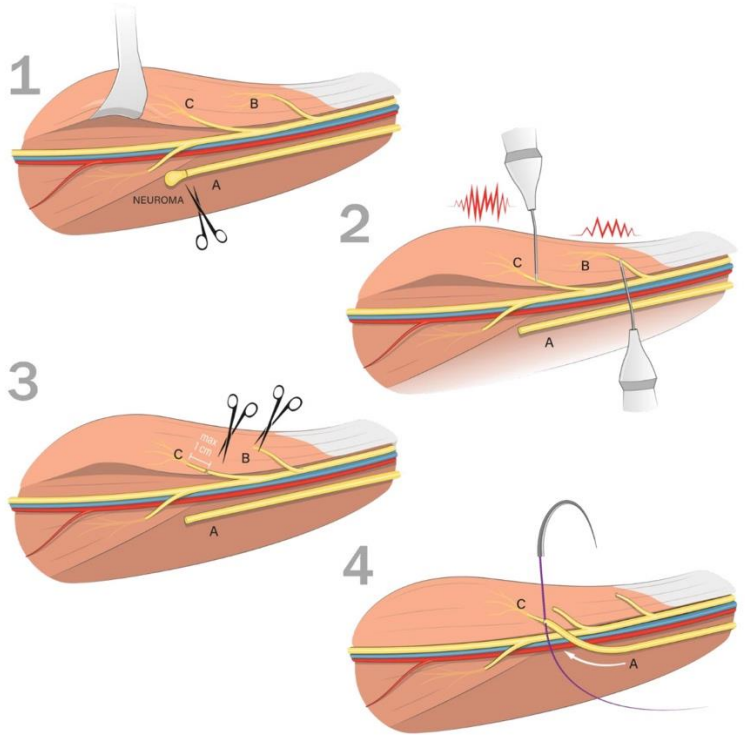
1. Suture the donor nerve to the recipient residual or "target" motor nerve with an 8 - 0 non-resorbable monofilament suture, placing the stitch in the center of the donor nerve.
2. Reinforce with two or three 8 - 0 non-resorbable monofilament sutures that secure the donor nerve epineurium to the fascia and epimysium that surround the recipient nerve. Ensure that the coaptation is performed with neither tension nor excessive redundancy.
3. Close the surgical wounds in layers.

NOTE

Each donor nerve is larger in caliber with more fascicles than the recipient motor nerve. Significant mismatch is usually encountered

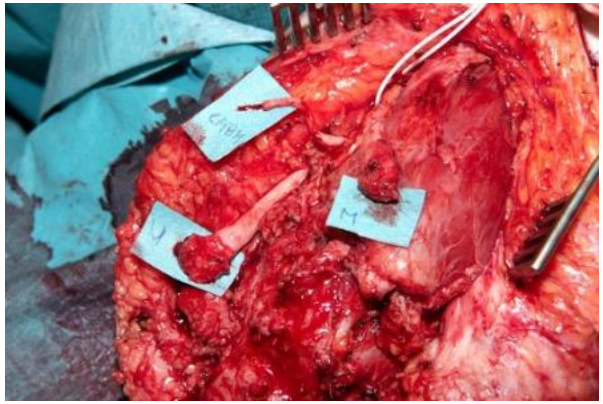
2. Surgical Techniques: TMR

1) Identify and isolate the donor nerve with the painful neuroma (A). Mobilize the donor nerve and transect the neuroma up to healthy neural fascicles.
2) Identify motor nerve(s) to the target muscle and confirm muscle contraction using a hand-held nerve stimulator.
3) If several motor branches are identified, choose the motor branch that results in the largest contraction (C). Transect the nerve without tension as close as possible to its entry point (maximum 1 cm). Dennervate other identified motor branches to the same muscle when possible (B).
4) Suture the prepared donor nerve to the recipient residual or "target" nerve with the stitch placed in the center of the donor nerve. Reinforce with two or three microsutures that secure the donor nerve epineurium to the fascia and epimysium that surrounds the recipient nerve.

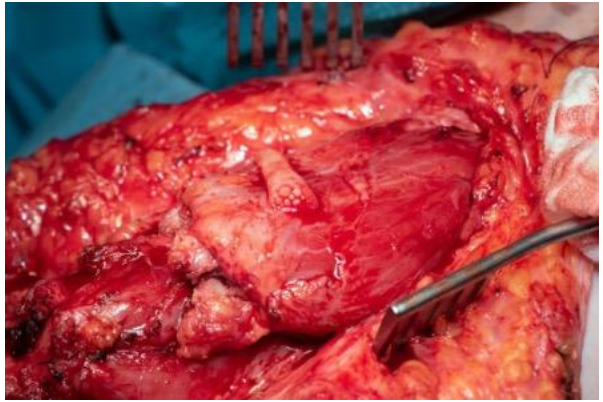


Copyright Pettersen et al., 2024 [32]

2. Surgical Techniques: TMR



Identify the donor nerve or the painful neuroma under blunt dissection. Gently isolate the donor nerve or the neuroma under loupe magnification using microsurgical instruments as needed. Mobilize the donor nerve for as long as necessary to reach the recipient site, considering that the following nerve sutures are free of tension in all range of motions in the proximal joints.

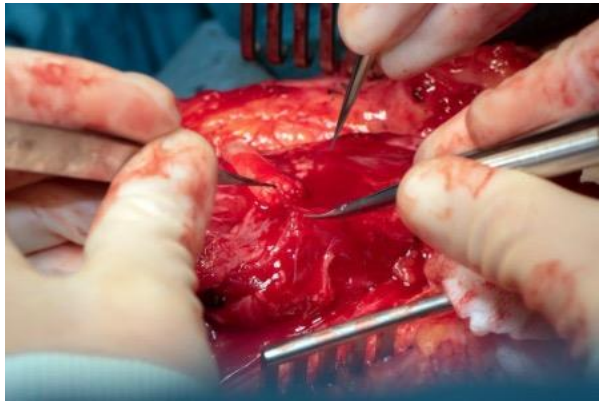


Transect the neuroma or transect the nerve using a commercial nerve cutting/preparation set

2. Surgical Techniques: TMR

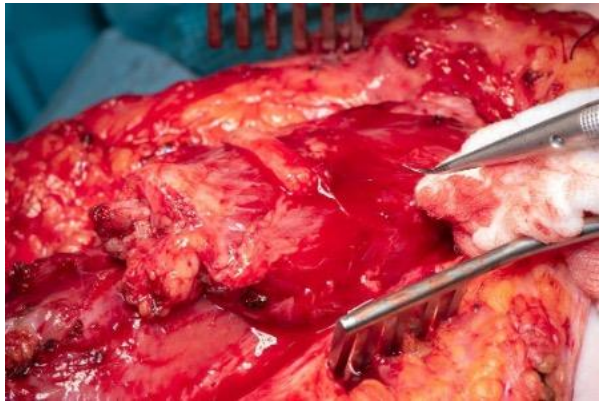


Identify all motor nerve branches to the target muscle by blunt dissection. Set a hand-held-nerve stimulator at 0.5-1.0 mA, put it in contact with the nerve branches, and stimulate each of them. During stimulation, the nerve that provides the largest muscle contraction is the one that will be used as the recipient nerve.

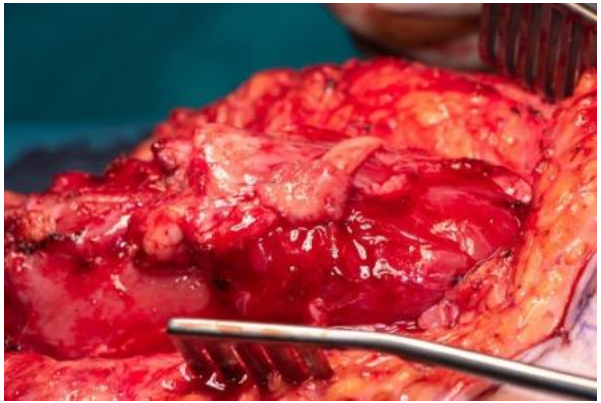


Once active contraction is confirmed, transect the nerve using straight microscissors without tension as close as possible to its entry point. Aim for less than 1 cm. Transpose the proximal nerve end of the transected recipient nerve proximally away from the coaptation site without any specific management.

2. Surgical Techniques: TMR



Suture the donor nerve to the recipient residual or "target" motor nerve with an 8 - 0 non-resorbable monofilament suture, placing the stitch in the center of the donor nerve. NOTE: Each donor nerve is larger in caliber with more fascicles than the recipient motor nerve. Significant mismatch is usually encountered. Reinforce with two or three 8 - 0 non-resorbable monofilament sutures that secure the donor nerve epineurium to the fascia and epimysium that surrounds the recipient nerve.



Ensure that the coaptation is performed with neither tension nor excessive redundancy. To avoid axonal sprouting outside the epineural nerve suture a standard RPNI is wrapped around the coaptation side, please see chapter RPNI. Close the surgical wounds in layers.

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2. Surgical Techniques: TMR

Troubleshooting and Considerations

Felder et al.[33] reported experiences of technical challenges, such as

- nerve redundancy
- size mismatch
- neuroma formation
- the positioning of coaptation sites
- full muscle denervation at the target site
- the selection of the optimal target for prosthetic functionality

2. Surgical Techniques

Targeted Sensory Reinnervation (TSR)

2. Surgical Techniques: TSR

Principles of Targeted Sensory Reinnervation

The impact of sensory feedback on the control of prostheses, along with the associated enhancements in embodiment and alleviation of phantom pain, has been substantiated by a multitude of research studies.[34–36]

The TSR process involves selectively reinnervating a specific area of skin by connecting a sensory donor nerve from the amputation to a defined sensory skin branch. This allows for the stimulation of the skin area in synchronization with the prosthesis function using a sensory feedback system that can be integrated into the socket system.

This technique can provide sensory feedback, and it has been shown to improve functionality and embodiment of the prosthesis.[1,38]

NOTE

During the TMR procedure, the overlying skin is reinnervated by redirecting mixed donor nerves carrying sensor and motor nerve fibers to nearby muscle targets. This facilitates the restoration of sensation and motor control in a non-directed way.[39–41]

2. Surgical Techniques: TSR

Donor Nerve	Recipient Nerve (TSR)	Reinnervated skin area and sensation	Source
Median Nerve	A fascicle of the median nerve was coapted to the intercostobrachial cutaneous (T2)	It innervates the skin covering the medial side of the upper arm	Herbert (2014)
Ulnar Nerve	A fascicle of the ulnar nerve was connected to the cutaneous branch of the axillary nerve	It innervates the skin covering the inferior region of the deltoid muscle (the regimental badge area)	Herbert (2014)
Sural Nerve	Transtibial (TT): Transposition of the ipsilateral sural nerve to the cutaneous territory of the saphenous nerve	It innervates the skin area on the front and medial side of the lower leg	Gardetto (2021)
Sural Nerve	Transfemoral (TF): Transplantation of the contralateral sural nerve as an autologous graft from the distal stump of the sciatic nerve to the cutaneous territory of the lateral femoral cutaneous nerve	It innervates the skin covering the lateral thigh	Gardetto (2021)

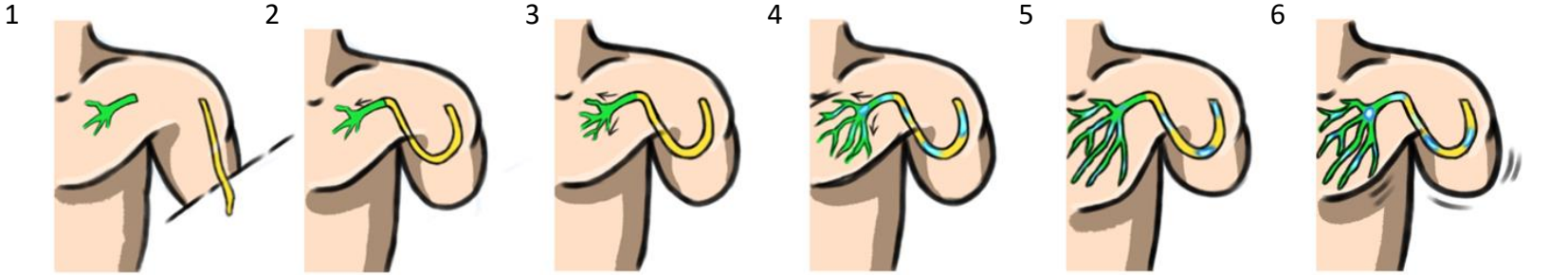
Table 2: Protocols for Targeted Sensory Reinnervation (TSR)

2. Surgical Techniques: TSR

1. Identify the donor nerve under blunt dissection and gently isolate the donor nerve under loupe magnification using microsurgical instruments as needed. Mobilize the donor nerve for as long as necessary to reach the recipient site.

2. Identify all sensory nerve branches to the target muscle by blunt dissection. Transfer the donor nerve to the defined sensitive skin branch and coapt the distal nerve end of the transected sensory nerve by end-to-end neurorrhaphy.

3.-6. This provides the nerve with a guide structure growing into the skin, finding skin receptor and reinnervating the according skin area.



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2. Surgical Techniques: TSR

1. Preparation of the donor and recipient nerve

1. Perform either regional or general anesthesia without the use of muscle relaxants to allow for effective nerve stimulation. NOTE: The type of anesthesia depends on the site of the procedure.
2. Place the patient appropriate to reach the surgical field, depending on the planned amputation or the site of the painful neuroma.
3. Carry out the skin incision using a scalpel. The length and shape of the skin incision depend on the available soft tissue or location of the painful neuroma.
4. Identify the donor nerve or the painful neuroma under blunt dissection.
5. Identify the recipient nerve under blunt dissection.
6. Gently isolate the donor and recipient nerve or the neuroma under loupe magnification using microsurgical instruments as needed.
7. Mobilize the donor nerve for as long as necessary to reach the recipient site, considering that the following nerve sutures are free of tension in all range of motions in the proximal joints. Transect the recipient nerve or transect the painful neuroma using a commercial nerve cutting/preparation set.
8. Transpose the donor nerve end to the distal transected recipient nerve.
9. Bury the proximal end of the transected nerve away from the coaptation site and surface. RPNI can be applied to the proximal end of the transected nerve.

2. Surgical Techniques: TSR

2. Nerve-to-nerve coaptation

1. Suture the donor nerve to the recipient residual or "target" motor nerve with an 8 - 0 non-resorbable monofilament suture or smaller, placing the stitch in the center of the donor nerve.
2. Reinforce with two or three 8 - 0 non-resorbable monofilament sutures that secure the donor nerve epineurium to the surrounding tissue of the recipient nerve. Ensure that the coaptation is performed with neither tension nor excessive redundancy.
3. Close the surgical wounds in layers.

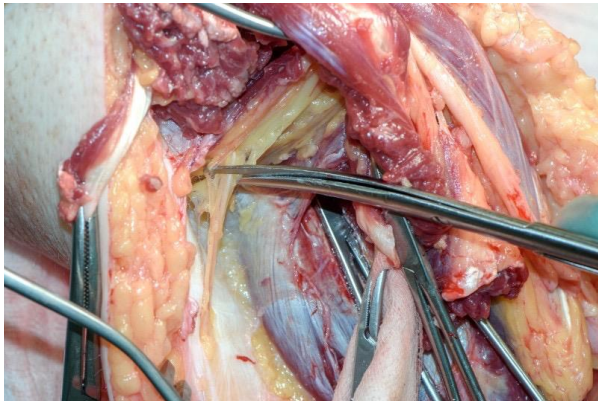
NOTE

Each donor nerve is larger in caliber with more fascicles than the recipient motor nerve. Significant mismatch is usually encountered.

2. Surgical Techniques: TSR

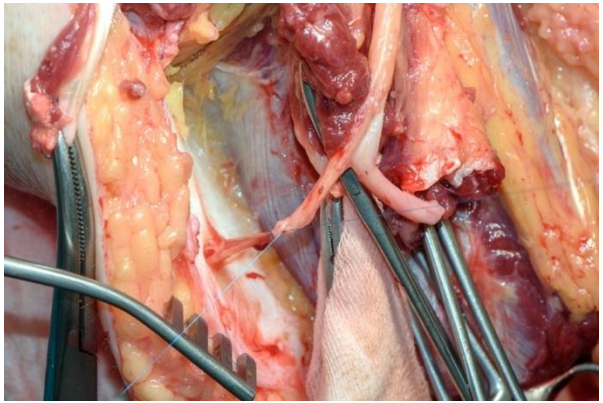


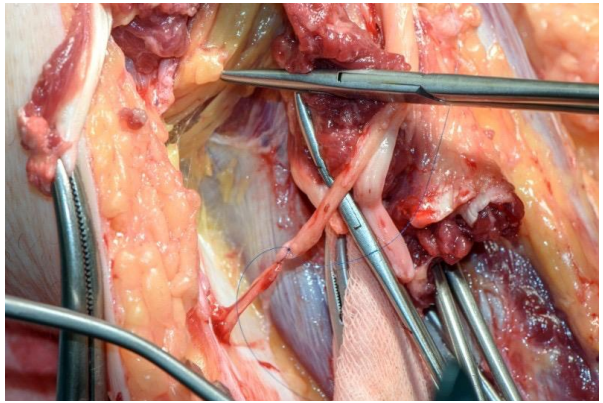
Identify all sensory nerve branches to the target skin by blunt dissection.



Transect the nerve using straight microscissors that cut the nerve at a length allowing for the nerve coaptation without tension. Transpose the proximal nerve end of the transected recipient nerve proximally away from the coaptation site. Bury it in a muscle away from the surface to avoid exposure to pressure or wrap RPNI around it.

2. Surgical Techniques: TSR





Suture the donor nerve to the recipient residual or "target" sensory nerve with an 8 - 0 non-resorbable monofilament suture, placing the stitch in the center of the donor nerve.

NOTE

Each donor nerve is larger in caliber with more fascicles than the recipient motor nerve. Significant mismatch is usually encountered.

Reinforce with two or three 8 - 0 non-resorbable monofilament sutures that secure the donor nerve epineurium to the fascia and epimysium that surrounds the recipient nerve. Ensure that the coaptation is performed with neither tension nor excessive redundancy. Close the surgical wounds in layers.

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2. Surgical Techniques: TSR

Troubleshooting and considerations

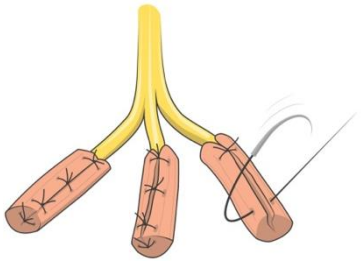
The reported experiences of technical challenges include

- Nerve redundancy
- Donor and recipient nerve distances
- Size mismatch
- Neuroma formation
- The positioning of coaptation sites

- Temporary or full skin denervation at the target site with possible dysesthesia
- Selection of the optimal target for prosthetic and feedback system functionality.[33]

2. Surgical Techniques

Regenerative Peripheral Nerve Interface (RPNI)



2. Surgical Techniques: RPNI

Regenerative Peripheral Nerve Interface (RPNI) also describes as selective nerve transfer

A) The avascular, denervated muscle graft serves as a target for the regenerating axons of the nerve stump.

B) The individual nerves are split interfascicularly to form multiple distinct nerve endings, either to facilitate the passage of more signals or to supply the axons with additional muscle tissue for reinnervation.[44]

C) This process allows the formation of new neuromuscular connections that effectively prevent the formation of new symptoms of neuropathy.

In comparison to TMR, this procedure requires significantly **less time** and can be **performed by non-microsurgeons**.

The use of RPNIs has been shown to reduce **phantom limb pain** by up to 53 percent and neuroma pain by 71 percent.[1,8,42]

2. Surgical Techniques: RPNI

1



1. Identify a healthy donor muscle and harvest a muscle graft.

It is crucial to ensure the gviability of the free muscle raft by limiting its dimensions to a maximum of **30-40 mm in length, 15-20 mm in width, and 5-6 mm in thickness**.[42,44]

2



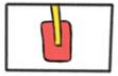
2. Identify and isolate the nerve. Transect possible painful neuroma.

3



4





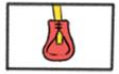
3.-4. Place the fascicle in the muscle graft and secure the nerve with sutures.

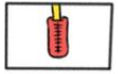
5



6







5.-6. Fold the muscle graft around the fascicle and secure with sutures.

7



8



7.-8. Perform blunt dissection in the residual limb to provide a protected area where each RPNI can lie comfortably and out of weight-bearing surfaces of the limb

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2. Surgical Techniques: RPNI

Surgical Roadmap

A standardized surgical protocol has been published recently and is summarized below.[45]

1. Presurgical preparations

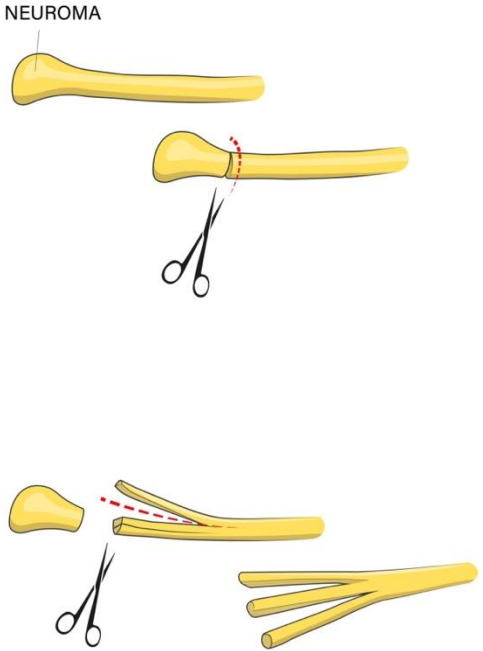
1. Diagnose the painful neuroma(s) if present
2. Plan the skin incisions depending on the results from step 1.1 and depending on the location of each painful neuroma. [46]

NOTE
In principle, any healthy skeletal muscle can be used; however, the muscle graft was originally recommended to be harvested from the vastus lateralis muscle in the thigh.

2. Surgical Techniques: RPNI

2. Preparation of the recipient site

1. Perform either regional or general anesthesia. NOTE: The type of anesthesia varies depending on the site of the procedure.
2. Place the patient in a supine or prone position, depending on the planned amputation or site of the painful neuroma. For upper extremity, place the arm on a surgical arm board.
3. Carry out the length and shape of the skin incision depending on the available soft tissue or location of the painful neuroma.
4. Identify the nerve or the painful neuroma under blunt dissection.
5. Gently isolate the nerve or neuroma with fine instruments. Use loupe magnification if needed. NOTE: Isolation of the neuroma is optional when challenging.
6. Mobilize the nerve and transect or transect the neuroma up to healthy neural fascicles using a commercial nerve cutting/preparation set. NOTE: Resection of the neuroma is optional when challenging
7. Make longitudinal intraneural dissections from the distal end of the nerve for about **2-3 cm with straight microscissors. The number of fascicles will depend on the amputation level and the size of the nerve. Ensure that the diameter of each fascicle is a maximum of 4-6 mm**. For each nerve, a number of neural fascicles that should be prepared are suggested in *Table 3***.**



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2. Surgical Techniques: RPNI

Amputation level	Nerve	Suggested number of neural fascicles
Shoulder disarticulation	Axillary	2
	Musculocutaneous	2
	Median	3
	Ulnar	2
	Radial	2
Transhumeral	Axillary	2
	Musculocutaneous	2
	Median	3
	Ulnar	3
	Radial	2
Transradial	Median	3
	Ulnar	2
	Radial	1*
Hip disarticulation	Sciatic	4
	Femoral	3
	Lateral Cutaneous Femoral	1*
	Obturator	1*
	Posterior Cutaneous Thigh	2
Transfemoral	Sciatic	3
	Tibial	2
	Deep peroneal	1*
	Superficial peroneal	1*
	Sural	1*
	Saphenous	1*
Transtibial	Tibial	2
	Deep peroneal	2
	Superficial peroneal	1*
	Sural	1*
	Saphenous	1*

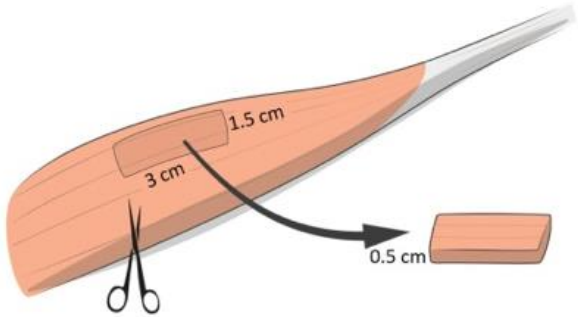
Table 3: Suggested number of neural fascicles specified for each nerve at a specific amputation level. Adaption determine by the individual patient case are always possible.

* Use the nerve entirely

2. Surgical Techniques: RPNI

3. Preparation of the donor site

1. Identify a healthy native donor muscle as a source for obtaining a free muscle graft. Harvest the muscle graft as follows:
    1. Ensure that each graft has the dimensions **3 cm (length) x 1.5 cm (width) x 0.5 cm (thickness**). NOTE: The main axis should be parallel to the muscle fibers.
    2. Dissect the muscle graft using delicate dissecting scissors following the main axis of the muscle fibers. Use magnifying loupes as needed.
    3. Gently excise adipose tissue and the muscle fascia from the muscle graft using dissecting scissors.
2. Keep the harvested muscle in a moist gauze with 0.9% NaCl sterile until utilization in section 4.
3. Repeat steps 3.1-3.2 for each muscle graft, based on the number of nerves and corresponding nerve fascicles to be wrapped with a prepared free muscle graft for an RPNI construct.

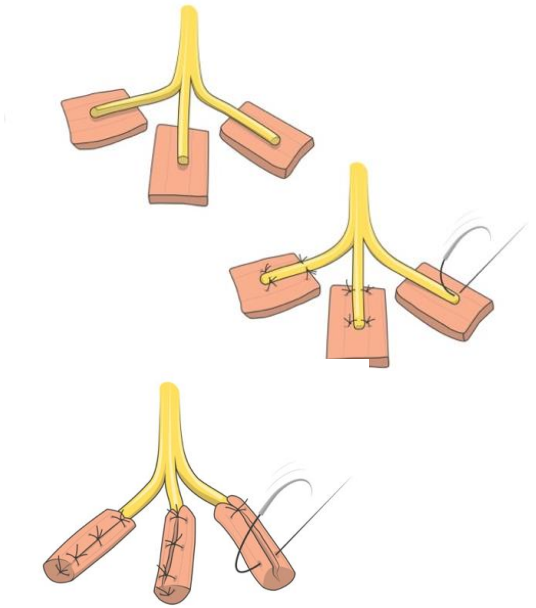


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2. Surgical Techniques: RPNI

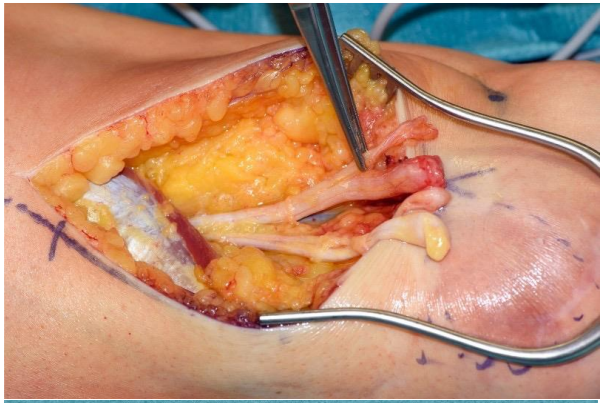
4. RPNI construct fabrication

1. Expose the nerve, already isolated and divided in fascicles.
2. Place the fascicle on the muscle graft so that the distal stump **falls in the central or proximal third of the muscle graft while having its orientation parallel to the muscle fibers.** NOTE: A parallel orientation is preferred to optimize successful axonal reinnervation.
3. Secure the nerve stump in the center of the longitudinal axis of the muscle graft using 6 - 0 non-resorbable monofilament sutures. Add one more stitch to secure the nerve at the proximal edge of the muscle graft. NOTE: Do not suture the nerve end into the muscle graft; the transected portion of the nerve remains free.
4. Fold the muscle graft around the fascicle and secure it with a 6-0 interrupted or continuous non-resorbable monofilament suture.
5. Repeat steps 4.1 - 4.4 for each fascicle.
6. Perform blunt dissection in the residual limb to provide a protected area where each RPNI can lie comfortably and out of weight-bearing surfaces of the limb. Where possible, offset the location of each RPNI in series.
7. Close the surgical wounds in layers.



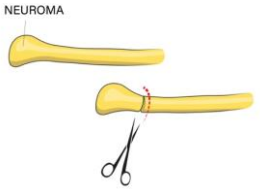
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2. Surgical Techniques: RPNI



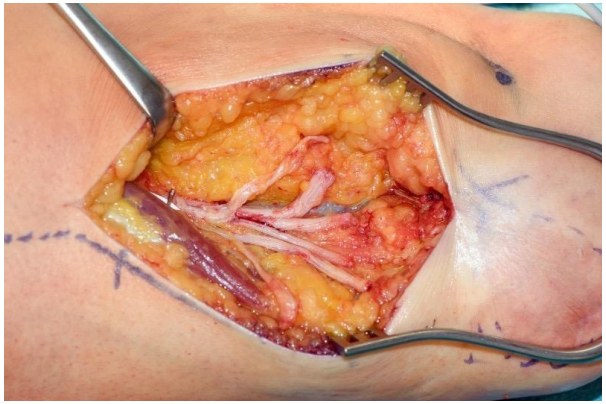


1. Identify the nerve or the painful neuroma under blunt dissection. Gently isolate the nerve or neuroma with fine instruments. Use loupe magnification if needed.



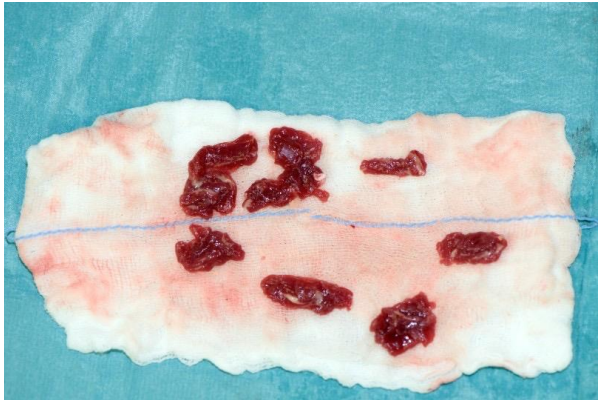
2. Mobilize the nerve and transect or transect the neuroma up to healthy neural fascicles using a commercial nerve cutting/preparation set.

2. Surgical Techniques: RPNI

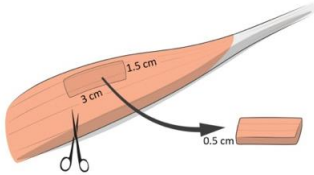


3. Make longitudinal intraneural dissections from the distal end of the nerve for about 2-3 cm with straight microscissors. The number of fascicles will depend on the amputation level and the size of the nerve. Ensure that the diameter of each fascicle is a maximum of 4-6 mm.



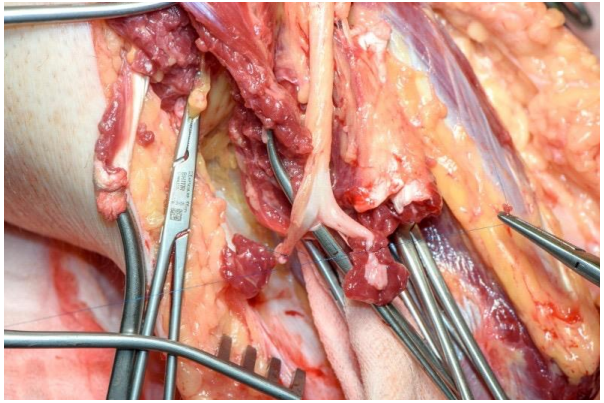


4. Identify a healthy native donor muscle as a source for obtaining a free muscle graft. Harvest the muscle graft as follows: a) Ensure that each graft has the dimensions 3 cm (length) x 1.5 cm (width) x 0.5 cm (thickness). b) Dissect the muscle graft using delicate dissecting scissors following the main axis of the muscle fibers. c) Gently excise adipose tissue and the muscle fascia from the muscle graft using dissecting scissors.

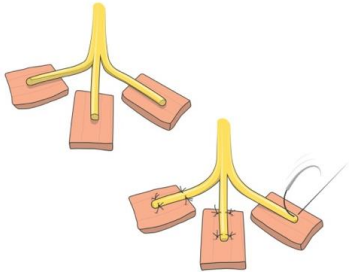


2. Surgical Techniques: RPNI

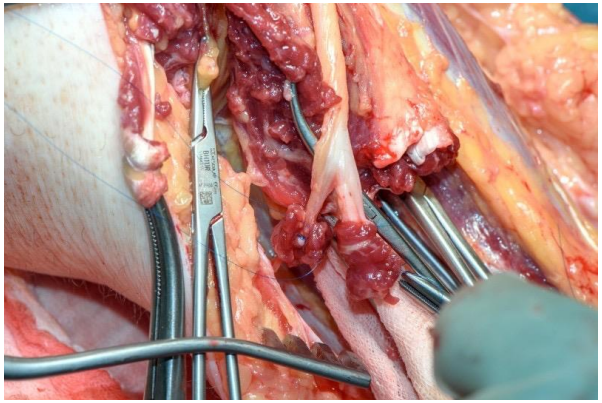




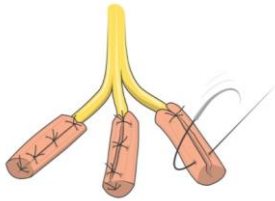
5.-6. Expose the nerve, already isolated and divided in fascicles. Place the fascicle on the muscle graft so that the distal stump falls in the central or proximal third of the muscle graft while having its orientation parallel to the muscle fibers. Secure the nerve stump in the center of the longitudinal axis of the muscle graft using 6-0 non-resorbable monofilament sutures. Add one more stitch to secure the nerve at the proximal edge of the muscle graft.



2. Surgical Techniques: RPNI



7. Fold the muscle graft around the fascicle and secure it with a 6-0 interrupted or continuous non-resorbable monofilament suture. Repeat steps for each fascicle.





8. Perform blunt dissection in the residual limb to provide a protected area where each RPNI can lie comfortably and out of weight-bearing surfaces of the limb. Where possible, offset the location of each RPNI in series. Close the surgical wounds in layers.

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2. Surgical Techniques: RPNI

Refresher: Basic principles of peripheral nerve surgery

The basic principles of peripheral nerve surgery include meticulous dissection using appropriate magnification, careful handling, and protection of the nerve.

For coaptation, please reinforce a suture with two or three 8 - 0 non-resorbable monofilament sutures (or equivalent) that secure the donor nerve epineurium to the fascia and epimysium surrounding the recipient nerve. Ensure that the coaptation is performed with neither tension nor excessive redundancy.[7,47–49]

The nervous tissue should lie comfortably and away from the weight-bearing surfaces of the limb. It also entails managing associated soft tissue and bony components to optimize the outcome. Additionally, postoperative protection of the nerve suture for three weeks, rehabilitation, and monitoring are essential components of successful surgery.[7,47–49]

3. Post-Operative Care

Surgical post-operative care

The postoperative protection of the nerve suture for a period of three weeks, rehabilitation, and monitoring are essential components of successful surgery.[7,47–49]

Prosthetic Rehabilitation

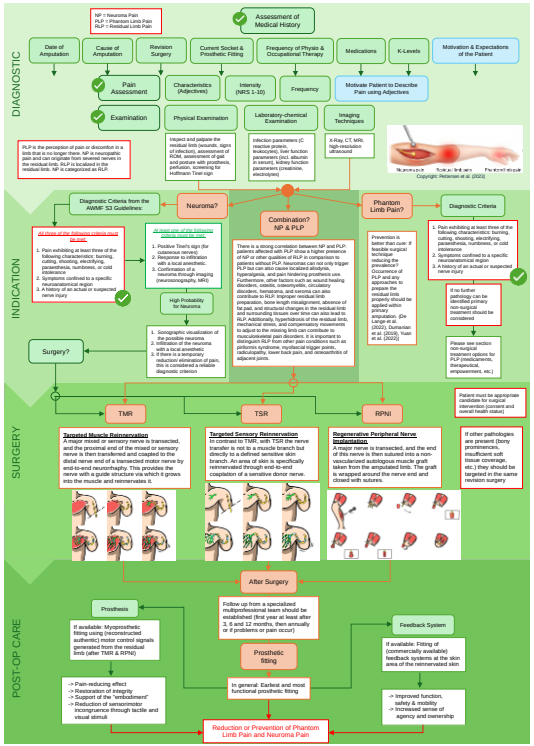
- The use of a prosthesis can ease the reduction of sensorimotor incongruence following an amputation by providing tactile and visual stimuli that are reinforced through the prosthesis itself.
- Wearing and using a prosthesis has a similar pain-relieving effect to mirror therapy's reorganization of the sensorimotor cortex and phantom pain.
- Furthermore, wearing the prosthesis helps the body's "embodiment" process and restores its integrity, both of which can lessen phantom pain.[50]
- Somatosensory feedback enhances embodiment, lessens phantom pain, and improves prosthesis functionality.[51–53]

This beneficial effect, for example, can be achieved by myoelectric prostheses with or without feedback systems integrated into the prosthesis socket.[38] In addition to the previously mentioned advantages, these feedback systems provides sensory feedback to the skin, which has been shown to improve function, safety, mobility, and the skin's sense of agency and ownership.[1,34,38,53,54]

General Rehabilitation

Close long-term follow-up in a multidisciplinary team is crucial for addressing and treating persistently symptomatic limbs, ultimately leading to increased prosthetic use and overall improved outcomes for patients.[10]

3. Post-Operative Care



Algorithm for the diagnosis and treatment of phantom limb pain: download here

(Copyright: Jennifer Ernst, Marlene Arlt, MHH)

4. Considerations Combat-related Amputations

Special Considerations in Combat Surgery

Combat polytrauma presents unique challenges, particularly in the context of injuries sustained from improvised explosive device blasts. These injuries, often compounded by penetrating trauma from small arms fire, manifest as a distinct pattern of wounds characterized by extensive tissue damage and limb loss.[58] The anatomical disruption caused by blast or penetrating injuries can lead to nervous system trauma and subsequent neuropathic pain in various parts of the body.[59,60]

In the realm of combat surgery, time and special considerations are pivotal in striving for optimal outcomes for the affected individuals. Time sensitivity is paramount in the battlefield, where prompt medical attention can be the defining factor between life and death. Further, the constraints of limited resources, challenging working conditions, and the necessity of prioritizing critical cases underscore the criticality of swift and effective decision-making in combat surgical procedures. Medical personnel must be well-prepared, adaptable, and capable of making rapid, sound decisions in order to maximize the prospects of survival and recovery for the injured.[58–60]

4. Considerations Combat-related Amputations

On the battlefield

In the context of combat scenarios, tourniquet education is critical in preventing short amputations. A tourniquet can be used to apply pressure to a limb to control severe bleeding, thereby preventing further damage and reducing the risk of amputation. Proper training in tourniquet application and awareness of the proper timing and techniques for its use can significantly impact the outcome of combat injuries. It is essential for individuals involved in combat situations to be well versed in tourniquet education as part of their medical training to effectively respond to life-threatening situations and minimize the risk of short amputations.[61–63]

The management of post-trauma amputations should prioritize open, length-preserving techniques to preserve residual limb length and viable tissue. The use of atypical flaps is recommended to salvage valuable residual limb length and functional joint levels. Keep viable structures and nerves as long as possible to implement surgical advancements (TMR, RPNI) to primary amputation. Guillotine amputations result in the sacrifice of residual limb length and viable tissue.[10]

Long-term follow-up and potential revision surgery for persistently symptomatic limbs can significantly enhance prosthesis use, function, and quality of life. Additionally, addressing accompanying PTSD and psychological disorders through a multidisciplinary approach is essential for maximizing outcomes. Further advancements, such as osseointegration, has shown to be a viable option for patients who have rejected prosthetic wear due to the high incidence of short residual limbs in war-related amputations. TMR has proven effective in improving the intuitive function of upper extremity prostheses, and TMR and RPNI are beneficial in preventing or treating symptomatic neuromata.[10,64]

4. Considerations Combat-related Amputations

On the battlefield

The energy associated with traumatic injuries often leads to significant soft tissue defects, higher amputation levels, and increased post-amputation pain. Targeted Muscle Reinnervation (TMR), in conjunction with advancements in prosthetic technology and ongoing military research, offers improved outcomes to aid active-duty service members and further war-related (young) amputees in achieving their goals.

The capabilities and applications of TMR and other advancements are rapidly expanding due to its high surgical success rate, technological innovations in prosthetic care, and favorable patient outcomes. As technology continues to evolve to include osseointegration techniques and bidirectional neuroprosthetic devices, the future of amputation surgery holds immense promise, presenting innovative solutions to optimize patient outcomes.[10,64]

Military Rehabilitation

The majority of the military cohort at the time of injury are young, healthy, fit men who work in a specific psychosocial environment.[55] Veterans of the armed forces are a unique population with unique health needs and a distinct culture that includes particular values, ethos, codes of conduct, and obedience to authority.[56] Additionally, compared to the general population, they have been found to use opioid medications more frequently and to be at a higher risk of overdosing.

Mulitiple Choice

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