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Received: 28 July 2025 | Revised: 6 June 2026 | Accepted: 4 August 2026

DOI: 10.1002/pmrj.70221

ORIGINAL ARTICLE

PM&R

# Percutaneous peripheral nerve stimulation as an ancillary treatment following nerve repair surgery

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**Funding information**
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## Abstract

**Background:** Neuropathic pain after peripheral nerve injury severely degrades quality of life. Peripheral nerve stimulation (PN-Stim) is cleared by the U.S, Food and Drug Administration for the treatment of acute and chronic pain. This broad indication supports its potential use at the time of peripheral nerve repair in patients reporting neuropathic pain preoperatively.

**Objective:** To explore the safety and therapeutic effects of PN-Stim on neuropathic pain in patients with severe peripheral nerve injuries undergoing surgical nerve repair.

**Methods:** We analyzed 16 consecutive patients 18 years and older who received PN-Stim implantation at the time of nerve repair surgery. Patients younger than 18 years of age, pregnant, and those without preoperative pain associated with nerve injury were excluded from our study. The primary outcome was pain score reduction, which was evaluated by Visual Analog Scale. The secondary outcomes included motor functional recovery and opioid usage, which were evaluated by manual muscle testing (MMT) and Morphine Milligram Equivalents quantification, respectively. Statistical analyses used paired two-tailed *t*-tests and Wilcoxon sign tests, contingent on data normalcy.

**Results:** Pain scores decreased significantly post-PN-Stim implantation (mean preplacement: 7.35, postplacement: 2.56; $p < .05$). MMT scores showed improvement in 13 patients, with 2 achieving the maximum MMT score ($p < .05$). Chronic opioid usage was observed to decrease in six of seven patients who were using them ($p < .05$). No significant adverse effects were seen after implantation.

**Conclusion:** In this case series of 16 patients with various peripheral nerve injuries who each underwent peripheral nerve repair surgery and concomitant placement of a temporary peripheral nerve stimulator, there were no adverse effects attributable to the peripheral nerve stimulator.

Shyam Maisuria and Antonio Mondríguez-González contributed equally to this study.

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## INTRODUCTION

Conservative estimates indicate that peripheral nerve injuries (PNIs) affect between 200,000 and 2,000,000 people annually in the United States.[1,2] Despite peripheral axons having some capacity for regeneration, PNIs frequently result in incomplete functional outcomes. In the most severe cases, PNIs can lead to irreversible muscle paralysis and debilitating neuropathic pain, severe enough to make patients consider limb amputation as a treatment.[3,4] Neuropathic pain is a particularly common and difficult-to-treat consequence of PNIs.[1] It frequently presents as severe burning, tingling, or shock-like sensations and can profoundly diminish a patient's daily functioning and engagement in daily activities. Current treatment options for neuropathic pain are inadequate for many patients.[3] For instance, pharmacological therapies have limitations due to their side effects, potential for dependence, and reduced efficacy over time. Thus, there is an urgent need for alternative strategies to manage this condition, particularly in patients recovering from nerve repair surgery.

Peripheral nerve stimulation (PN-Stim) has emerged as a promising approach for managing chronic pain, including neuropathic pain.[5] Multiple studies have demonstrated its effectiveness on different types of conditions, including headaches, postamputation pain, chronic pelvic pain, chronic back pain, lower extremity pain, and postsurgical pain.[6] Despite its growing use for pain management in general, the role of PN-Stim in addressing neuropathic pain after PNI and in combination with nerve repair surgery is not well defined. It has been hypothesized that the therapeutic effect of PN-Stim relates to the gate control theory, in which nonpainful stimuli can inhibit the transmission of pain signals via A-delta and C-fibers.[7] Additionally, PN-Stim may prevent the depolarization of nerve cell membranes, thereby reducing the excitability of pain-transmitting fibers.[7]

In this study, we explore the effects of PN-Stim on neuropathic pain in patients with severe PNI with concomitant surgical nerve repair by examining changes in pain scores, motor function, and opioid usage. In this cohort of 16 consecutive patients, PN-Stim was implanted at the time of nerve repair surgery. We aim to provide evidence that PN-Stim has the potential to provide substantial pain relief while also being safe and not interfering with functional recovery in patients undergoing concomitant nerve repair surgery.

## MATERIALS AND METHODS

### Study design and participants

This study is a retrospective chart review of 16 consecutive adult patients who underwent intraoperative implantation of a commercial percutaneous PN-Stim device (SPRINT PNS System, SPR, Cleveland, OH, USA) at the time of surgical nerve repair (Table 1). Sixteen patients were identified from an interdisciplinary complex nerve injury clinic at an academic rehabilitation hospital (Shirley Ryan AbilityLab, Chicago, IL, USA). All surgeries were performed by a neurosurgeon (K.N.S.) at an affiliated academic tertiary care hospital (Northwestern Memorial Hospital, Chicago, IL, USA). A clinical diagnosis of neuropathic pain was present preoperatively and served as the indication for implantation of the PN-Stim device in all patients at the time of surgical nerve repair. This intervention was routinely offered to patients undergoing peripheral nerve repair surgery who reported neuropathic pain preoperatively. The decision to implant the temporary PN-Stim device at the time of nerve repair was based on the clinical judgment of the treating surgical and rehabilitation team, with preoperative neuropathic pain always serving as the primary indication. The PN-Stim device is designed for temporary use (60 days), and then the leads were removed by provider using traction. In all cases, the device leads were secured at or proximal to the site of nerve repair with the intention of providing orthodromic neuromodulation of dorsal root ganglion via peripheral axons (Table 1). The study was approved by the Institutional Review Board of Northwestern University.

### Study outcomes

The primary outcome of this study was the Visual Analog Scale (VAS) postoperative pain score following PN-Stim implantation with nerve repair surgery. Pain reduction was assessed by comparing the patients' worst pain scores reported preoperatively in clinic visit prior to PN-Stim placement with their worst pain scores after PN-Stim placement. Secondary outcomes included changes in manual muscle testing (MMT) scores, and changes in opioid usage, measured in Morphine Milligram Equivalents (MME) before and after PN-Stim implantation. These were analyzed to determine if there were any detrimental impacts due to PN-Stim.

### Data collection

Pain scores were collected using the VAS (ranging from 1 to 10) and in instances where the VAS was not available in the chart ($n = 7$), the pain score from the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire was used instead, which uses a Likert scale from 1 to 5. To maintain consistency across data sources, DASH scores were categorized as "no pain," "light pain," "moderate pain," and "severe pain" and then converted to a 1 to 10 scale for comparison with the VAS scores by multiplying the score by a factor of

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**TABLE 1** Patient demographics, injury characteristics, and surgical interventions.

| # | Age, y (gender) | Race or ethnicity | Injury mechanism | Nerve injury site | PN-Stim site | Surgical procedure | F/U (d) |
|---|---|---|---|---|---|---|---|
| 1 | 70s (M) | White | Compression | Right ulnar | Right elbow | Ulnar nerve decompression + PN-Stim placement at the elbow | 246 |
| 2 | 60s (M) | White | Stabbing | Left brachial plexus and ulnar | Left elbow | Resection of ulnar neuroma and sural graft repair + PN-Stim. Also, neurolysis of brachial plexus | 146 |
| 3 | 30s (M) | White | Laceration | Right median and ulnar. | Right elbow | Resection of ulnar neuroma and sural graft repair + PN-Stim. Also, neurolysis of median. | 561 |
| 4 | 60s (M) | White | Compression | Left median and musculocutaneous | Left forearm | Brachialis-to-anterior interosseus nerve transfer + PN-Stim. Also, neurolysis of musculocutaneous and median in arm. | 71 |
| 5 | 30s (F) | White | Compression | Left radial | Left arm | Radial nerve neurolysis + PN-Stim. | 230 |
| 6 | 30s (F) | White | Motor vehicle crash | Left brachial plexus | Left shoulder | Spinal accessory to suprascapular nerve transfer + PN-Stim. Also, radial to axillary, ulnar to brachialis transfers. | 57 |
| 7 | 30s (M) | Black | Motor vehicle crash | Right brachial plexus | Right shoulder | Sural graft of C5 to suprascapular nerve + PN-Stim. | 382 |
| 8 | 20s (M) | Black | Gunshot injury | Right sciatic | Left thigh | Resection of peroneal neuroma and sural graft + PN-Stim. Also, neurolysis of sciatic and tibial. | 100 |
| 9 | 20s (M) | Black | Motor vehicle crash | Right brachial plexus | Right shoulder | Spinal accessory to suprascapular nerve transfer + PN-Stim. Also, radial to axillary, ulnar to brachialis transfers. | 370 |
| 10 | 60s (M) | White | Iatrogenic (cervical spine surgery) | Right C5 nerve root | Right shoulder | Radial-to-axillary nerve transfer + PN-Stim. | 373 |
| 11 | 50s (F) | White | Iatrogenic (hip surgery) | Left femoral nerve | Left thigh | Obturator to femoral nerve transfer + PN-Stim. | 365 |
| 12 | 30s (M) | White | Motor vehicle crash | Right brachial plexus | Right shoulder | Spinal accessory to suprascapular nerve transfer + PN-Stim. Also, ulnar to brachialis transfers | 179 |
| 13 | 60s (M) | White | Iatrogenic (cervical spine surgery) | Right C5 nerve root | Right shoulder | Radial-to-axillary nerve transfer + PN-Stim. Also, ulnar neurolysis at elbow. | 57 |
| 14 | 70s (M) | White | Compression | Left peroneal nerve | Left fibular head | Peroneal nerve neurolysis at fibular head + PN-Stim. | 57 |
| 15 | 60s (F) | Hispanic | Compression | Left peroneal nerve | Left fibular head | Peroneal nerve neurolysis at fibular head + PN-Stim. | 152 |
| 16 | 60s (M) | White | Compression | Right ulnar nerve | Right elbow | Ulnar nerve decompression at elbow + PN-Stim. | 202 |

*Note*: This table summarizes the demographic information, injury mechanisms, specific nerve injury sites, the location of percutaneous PN-Stim placement, and the surgical procedures performed for each patient. Surgical procedures detail the nerve repair (decompression, neurolysis, graft, transfer, and/or resection) that occurred concurrently with or prior to PN-Stim implantation. Abbreviations: F/U, follow-up; PN-Stim, peripheral nerve stimulation.

two (e.g., 1 = 2, 2 = 4, 3 = 6, 4 = 8, and 5 = 10). This approach allowed pain scores from both sources to be analyzed on a common scale. Pain scores were collected before and after PN-Stim implantation at multiple follow-up medical, physical therapy, and occupational therapy appointments for these patients, and these values were compared to assess pain reduction in the patient population.

To assess opioid usage, prescription records were reviewed to document the use of opioids before and after PN-Stim placement at follow-up appointments with physicians, physical therapy, and occupational therapy. The dates of prescription refills were used to determine if patients were still using opioids, and MME were calculated for those who were prescribed opioids. The MME values from before and after PN-Stim placement were compared to evaluate changes in opioid consumption following the procedure at patient follow-up appointments. To minimize the potential effect of the surgical procedure itself in the pain experienced, only chronic opioid use, and not those prescribed for acute postoperative pain, were considered in this analysis.

MMT scores were retrieved from documentation, either by physicians or physical therapists before and

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after PN-Stim treatment. MMT scores were categorized into six levels: "no movement," "flicker," "severely reduced," "moderately reduced," "mildly reduced," and "normal movement." Each category was assigned a corresponding numerical value, ranging from 0 for "no movement" to 5 for "normal movement." These numerical scores were used to assess and compare motor function before and after intervention.

## Statistical analysis

Due to the sample size of 16 patients, the normality of the data could not be assumed. Instead, kurtosis was used to assess the normality of pain scores, MMT scores, and MME values. Based on the distribution of the data, both parametric and nonparametric tests were employed. A two-tailed paired *t*-test was used to compare the mean pain, MMT, and MME scores before and after PN-Stim placement. For data that was not normally distributed (ie, MME), the Wilcoxon signed-rank test was used as an alternative. The significance level (alpha) was set at .05 for all comparisons. The dataset was assessed for normality, revealing that both pain scores and MMT scores followed a normal distribution, with kurtosis values between −2 and 2, whereas the MME data displayed a nonnormal distribution. For the pain and MMT scores, the data were reported as a mean ± SD. For MME, the data were reported as a decrease from the patients' original MME before the PN-Stim implant.

# RESULTS

Pain scores before and after PN-Stim placement are shown in Figure 1. All 16 patients experienced a reduction in pain following PN-Stim implantation (Figure 1A). The mean pain score before PN-Stim placement was 7.38 ± 2.09, which decreased to 2.56 ± 2.09 after the procedure demonstrating a statistically significant reduction ($p < .05$) (Figure 1B). Importantly, none of the patients experienced adverse effects or elected to have the implant removed before the full treatment period was completed (60 days).

Opioid usage data, shown in Figure 2, revealed that seven patients were prescribed opioids before their nerve repair surgery. Following intervention, six patients reduced their opioid consumption to 0 MME, and one patient showed no reduction in opioid use (Figure 2A). Data analysis revealed a statistically significant reduction in opioid use ($p < .05$) (Figure 2B).

As shown in Figure 3, before PN-Stim placement, four patients demonstrated "no movement," one patient showed a "flicker," seven patients showed "severely reduced movement," three patients had "moderately reduced movement," and two patients showed "mildly reduced movement." (Figure 3A). After PN-Stim placement, three patients showed no improvement, five

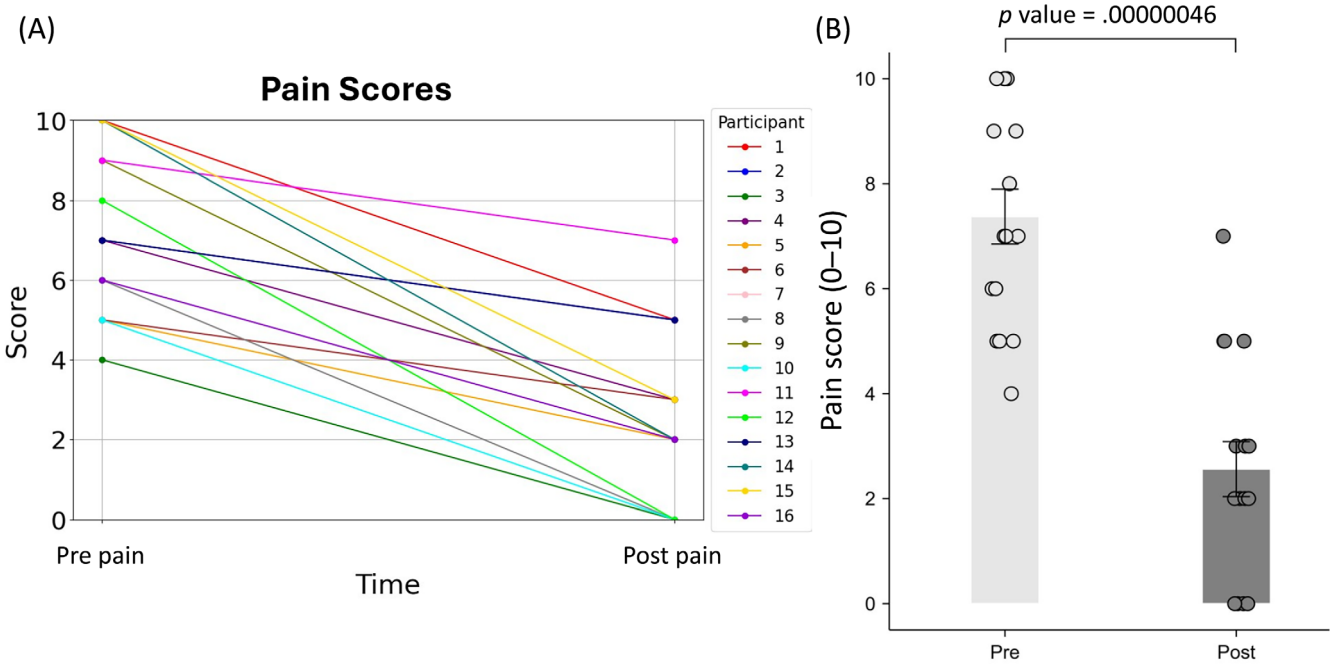



**FIGURE 1** Effect of nerve repair and PN-Stim placement on pain scores. (A) Individual pain scores of 16 patients before and after nerve repair and PN-Stim placement, measured using the Visual Analog Scale from 1 to 10, where higher scores indicate greater pain intensity. (B) Average pain scores across all patients before and after nerve repair and PN-Stim placement, demonstrating a significant reduction in pain intensity post treatment. PN-Stim, peripheral nerve stimulation.

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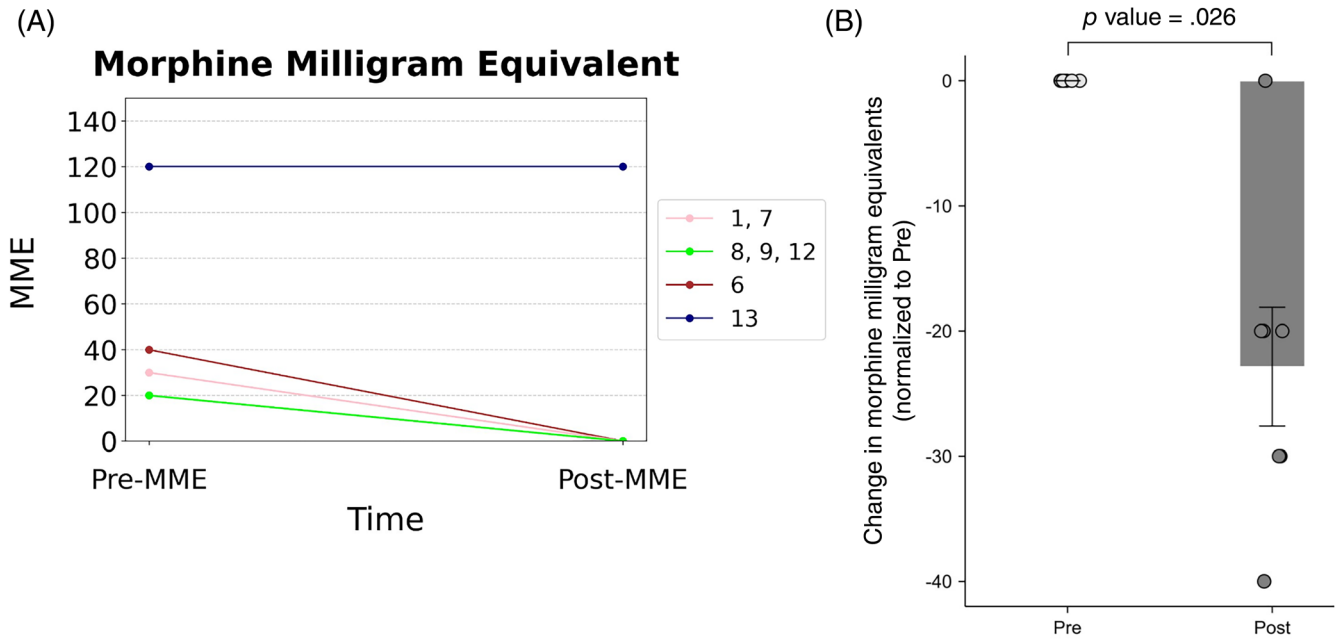



**FIGURE 2** Changes in Morphine Milligram Equivalents. (A) MME of seven patients before and after nerve repair and PN-Stim placement, where higher scores indicate greater levels of required pain control. (B) Average MME changes before and after nerve repair and PN-Stim placement, demonstrating a significant reduction in pain medication utilization. MME, Morphine Milligram Equivalents; PN-Stim, peripheral nerve stimulation.

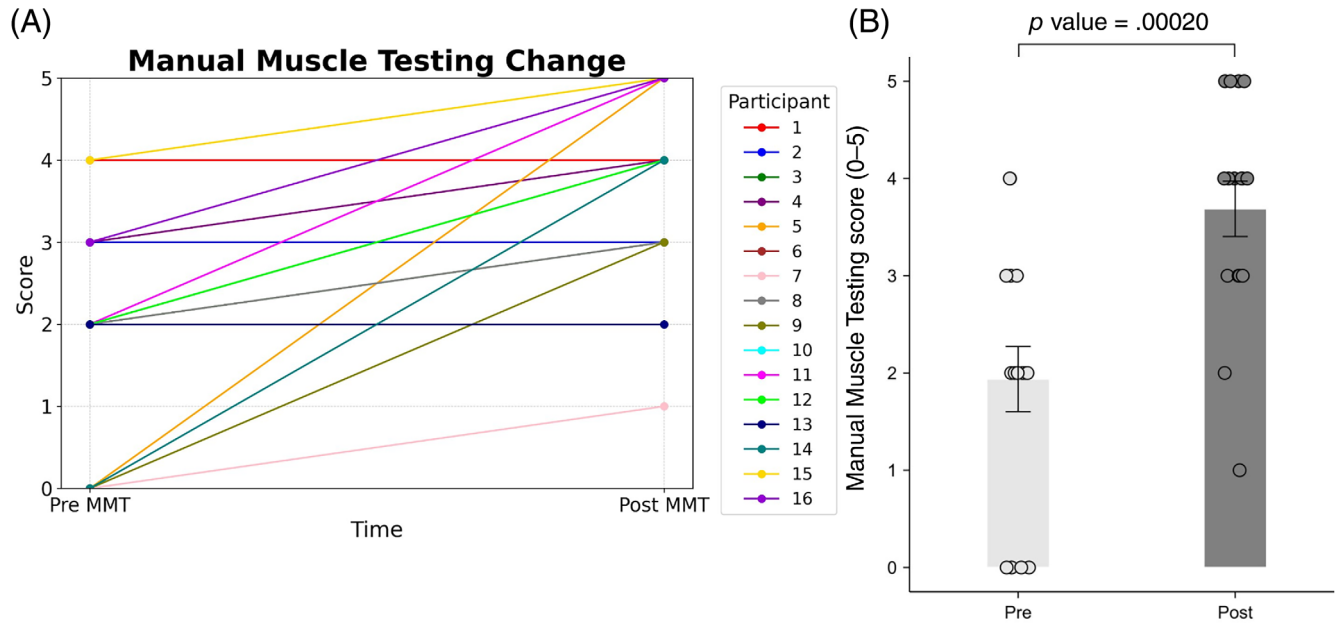



**FIGURE 3** Manual Muscle Testing Change (A) Individual Manual Muscle Testing Score of 16 patients before and after nerve repair and PN-Stim placement, measured using physical exams performed by providers, where higher scores indicate greater muscle strength. (B) Average MMT scores across all patients before and after nerve repair and PN-Stim placement, demonstrating a significant increase in muscle movement. MMT, Manual Muscle Testing; PN-Stim, peripheral nerve stimulation.

patients improved by one category, four improved by two categories, two improved by three categories, one patient improved by four categories, and one patient improved by five categories (Figure 3A). The comparison of MMT scores before and after PN-Stim intervention through a paired two-tailed *t*-test demonstrated a statistically significant improvement ($p < .05$) (Figure 3B).

There were some instances in which PN-Stim's efficacy varied between patients. Interestingly, two patients experienced total pain relief while the PN-Stim

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device was in place, but their pain returned after the implant was removed. Another patient stated that she felt differences in pain when the implant was "on (better)" versus "off." This suggests that the inhibition of pain fibers may not persist post-PN-Stim implant for some patients. It is important to note that none of the patients who underwent PN-Stim had a worsened level of pain during or after the course of treatment was finished relative to their baseline pain level.

## DISCUSSION

Our study indicates that PN-Stim implantation in conjunction with nerve repair surgery can lead to significant reductions in pain and opioid consumption in people with PNI, while also not interfering with the expected improvements in motor function post nerve repair. The significant decrease in VAS pain scores and opioid usage, along with gains in MMT strength scores, underscores the potential of PN-Stim as an effective tool implanted during nerve repair surgery to enhance postsurgical rehabilitation and pain management. These findings align with prior literature examining the role of PN-Stim in pain modulation for other causes of pain, yet this study adds unique insights into both the feasibility and benefits.

A key finding of this study is the demonstration of pain reduction across all patients (Figure 1), with none reporting worsened pain during or after treatment. Notably, six of the seven patients prescribed opioids prior to PN-Stim intervention discontinued opioid use entirely (Figure 2). We chose to focus on opioid reduction because they have shown significantly more detrimental side effects than other analgesics.[8] This reduction in opioid dependence has significant clinical implications, potentially mitigating risks associated with long-term opioid use, such as addiction, respiratory depression, and gastrointestinal side effects.[8] A limitation of this case series is that opioid use typically decreases following surgical recovery. Whether there might be additional benefit of PN-Stim is a hypothesis that should be tested in a future prospective clinical trial.

Regarding changes in patients' MMT scores, 13 patients showed motor function recovery by at least one category (Figure 3). In fact, one patient with a femoral nerve transfer and no prior movement before PN-Stim implantation regained full movement after the conclusion of treatment (Patient 11). It is worth mentioning that none of the patients' MMT scores worsened after PN-Stim, reassuring us that PN-Stim does not have a detrimental effect on motor function or nerve integrity, thus supporting its safety in those undergoing nerve repair. Future studies incorporating electrophysiological assessments or imaging could provide greater clarity regarding the effects on motor recovery. Notably, acute electrical stimulation has actually been demonstrated to improve peripheral axon regeneration in preclinical and several single-center clinical trials recently reviewed by Ni et al.[5] A more recent meta-analysis of rodent models by Koopman et al. demonstrated similar findings, in which they found that brief, intraoperative electrical stimulation performed by many different investigators improved nerve regeneration compared with nerve repair alone.[9]

Our findings are consistent with previous studies that have examined the effects of PN-Stim on pain. For instance, one case series consisting of patients with chronic lower back pain conducted by Gilmore and colleagues demonstrated a significant reduction in patients' pain scores 1 year after PN-Stim treatment.[10] The difference in these clinical scenarios is that our intervention occurred during nerve repair surgery, whereas other studies use PN-Stim after recovery. This is a potential application of PN-Stim that could be explored in nerve injury patients without preoperative pain with the goal of reducing postoperative pain. This reduction in opioid dependence is particularly significant in light of the ongoing opioid crisis, emphasizing PN-Stim's potential to offer a safer, nonpharmacologic alternative for pain management.[8]

Study limitations include the small sample size ($n = 16$) and reliance on subjective measures such as VAS and MMT scores. Although every effort was made to standardize the collection of these data, inherent variability in patient reporting and clinician assessment introduces the potential for bias. Another limitation is the inability to isolate the effects of PN-Stim from those of the nerve repair surgery itself, as all patients underwent both interventions. This makes it challenging to determine the extent to which observed improvements are driven by either procedure. Future studies should compare PN-Stim plus surgery with surgery alone to better differentiate their respective contributions to symptomatic improvement and to clarify how much of the observed benefit can be attributed to the natural course of recovery. Additionally, the absence of long-term follow-up data is a notable limitation. Although all patients demonstrated pain relief during the treatment period, the durability of this effect postimplant removal remains uncertain. Two patients reported the return of pain following device removal, which is consistent with other studies that have demonstrated this occasional variability.[11] These results continue to highlight the need to investigate whether prolonged or repeated stimulation may sustain pain relief and motor improvements. Future research should explore the optimal duration of PN-Stim treatment and assess outcomes at extended intervals post treatment.

Mechanistically, while prior studies suggest that electrical stimulation may promote axonal regeneration through the upregulation of neurotrophic factors like brain-derived neurotrophic factor and its downstream signaling pathway,[1,4,10] our study was not designed to assess these biological factors. Thus, although the

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observed motor functional improvements are encouraging, they should be interpreted within the context of clinical outcomes rather than underlying cellular mechanisms. Further investigations incorporating animal models and/or new clinical biomarkers (imaging, serum brain-derived neurotrophic factor, etc.) could help elucidate the potential regenerative effects of PN-Stim at a mechanistic level.

## CONCLUSION

The PN-Stim shows significant potential as an adjunct therapy for managing neuropathic pain and supporting overall recovery for patients undergoing concomitant nerve repair surgery. The observed reductions in pain and opioid use, coupled with the observed improvements in motor function, highlight its promise as a safe nonpharmacologic ancillary treatment to nerve repair surgery. By addressing pain, regardless of whether it could theoretically improve neurological recovery, PN-Stim may contribute to reducing opioid use postoperatively. Future studies should focus on elucidating its role in axonal regeneration, optimizing treatment protocols, and expanding its application to broader patient populations to enhance rehabilitation outcomes for individuals recovering from PNI. This should include large randomized controlled trials to confirm these results and determine the long-term effects of this intervention.

### ACKNOWLEDGMENTS

S.M. was funded by the Shirley Ryan AbilityLab Externship Program for medical students. C.K.F. would like to acknowledge support from the Belle Carnell Regenerative Neurorehabilitation Fund.

### DISCLOSURE

No conflict of interest.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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**How to cite this article:** Maisuria S, Mondríguez-González A, Pavlos T, Swong KN, Franz CK. Percutaneous peripheral nerve stimulation as an ancillary treatment following nerve repair surgery. *PM&R*. 2026;1-7. doi:10.1002/pmrj.70221

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