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Nerve Transfer Surgery: A Systematic Review of Current Practices, Outcomes, and Future Directions

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ABSTRACT
Peripheral nerve injuries remain a significant clinical challenge because they can result in permanent motor and sensory dysfunction, reduced independence, and impaired quality of life. Nerve transfer surgery has emerged as an advanced reconstructive approach that redirects functional donor nerves to damaged recipient nerves to restore neurological function. This study aimed to systematically review current practices, clinical outcomes, influencing factors, and future directions of nerve transfer surgery across various neurological conditions. A systematic review method was applied following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Relevant studies were identified from scientific databases, including PubMed, Scopus, ScienceDirect, and Web of Science, based on predefined inclusion and exclusion criteria. The findings indicated that nerve transfer surgery provided significant improvements in motor recovery, sensory restoration, and functional performance, particularly in patients with brachial plexus injuries, spinal cord injuries, facial paralysis, and complex peripheral nerve injuries. However, successful outcomes were strongly influenced by surgical timing, injury severity, donor nerve selection, surgeon expertise, and postoperative rehabilitation. The review also highlighted that objective functional improvements did not always correspond with patient-reported recovery, indicating the need for comprehensive outcome assessments. In conclusion, nerve transfer surgery represents a transformative advancement in peripheral nerve reconstruction; however, further large-scale clinical studies and innovative regenerative strategies are required to optimize long-term functional outcomes and expand its clinical applications.

INTRODUCTION

Nerve transfer surgery represents a sophisticated reconstructive procedure designed to restore function following specific types of nerve injuries. This complex surgical intervention involves the precise rerouting of a healthy, functional nerve, known as the "donor nerve," to establish a connection with a nonfunctional or damaged nerve, referred to as the "recipient nerve" (Johns Hopkins Medicine, n.d.). The conceptual framework of this process is often compared to a railway switch, in which signals are redirected to new destinations to facilitate the restoration of neural pathways (Johns Hopkins Medicine, n.d.). The primary objective of nerve transfer surgery is to restore lost function, particularly by re-establishing movement in paralyzed muscles or sensation in areas of skin that have become denervated due to nerve damage (Johns Hopkins Medicine, n.d.). The underlying biological mechanism relies on the capacity of nerve fibers, known as axons, from the healthy donor nerve to regenerate and grow through the newly connected recipient nerve. This regeneration process re-establishes the neural pathway, enabling the transmission of motor and sensory signals to the target muscles or skin (Johns Hopkins Medicine, n.d.).

Historically, nerve transfers were primarily limited to the management of highly complex injuries, particularly those involving the brachial plexus (SCIRE Professional, n.d.). However, over recent decades, this technique has undergone substantial development, emerging as a valuable alternative to traditional reconstructive procedures, such as tendon transfers. This advancement has been particularly significant in improving hand and upper extremity function following spinal cord injuries (SCIRE Professional, n.d.).

The evolution of nerve transfer surgery from a specialized technique to a more widely applied and integral component of peripheral nerve reconstruction represents a major transformation in reconstructive strategies. Although the fundamental principles of nerve transfer were established as early as the 1960s, widespread adoption and integration into clinical practice have occurred more recently after overcoming a period of limited utilization (The Miami Project to Cure Paralysis, n.d.). This expansion has been driven by several factors, including advances in microsurgical techniques that allow more precise nerve coaptation, improved understanding of neuroanatomy, refined patient selection criteria, and increasingly effective postoperative rehabilitation strategies. Collectively, these developments have enhanced the clinical relevance of the procedure and expanded its applications (Andreu-Perez et al., 2015; Pesapane et al., 2018).

The advancement of nerve transfer surgery has transformed peripheral nerve reconstruction by extending its application beyond traditional brachial plexus injuries. Contemporary nerve transfer techniques are increasingly utilized in patients with spinal cord injuries, facial paralysis, upper extremity paralysis, and complex peripheral nerve defects. Improvements in microsurgical accuracy, neuroanatomical knowledge, patient selection, and rehabilitation protocols have contributed to improved functional outcomes. Previous clinical evidence has demonstrated that nerve transfers can restore meaningful motor function, including elbow flexion, shoulder movement, wrist extension, finger function, and facial expression. For instance, studies involving brachial plexus reconstruction have shown that many patients achieve Medical Research Council (MRC) grades indicating functional muscle recovery following nerve transfer procedures. These findings demonstrate that nerve transfer surgery has progressed from a specialized reconstructive technique to an important component of modern peripheral nerve surgery.

Several previous studies have investigated the effectiveness and outcomes of nerve transfer procedures. A systematic review by Fox et al. demonstrated that peripheral nerve transfers provide significant functional improvements in patients with upper extremity nerve

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injuries, particularly when performed within an appropriate therapeutic window. Another systematic review examining nerve transfers following cervical spinal cord injury reported consistent improvements in targeted muscle strength, with most patients achieving clinically meaningful motor recovery. Research by Bertelli et al. also highlighted the effectiveness of nerve transfer strategies in restoring shoulder and elbow function among patients with traumatic brachial plexus injuries. Furthermore, studies investigating facial nerve transfer procedures have shown improvements in facial symmetry, smiling ability, and functional expression. Collectively, these studies support the clinical potential of nerve transfer surgery across various neurological conditions .

However, despite promising functional outcomes reported in existing studies, several limitations remain within the current evidence base. Many previous investigations have focused on specific injury categories, such as brachial plexus injuries or spinal cord injuries, rather than providing an integrated evaluation of nerve transfer applications across diverse clinical conditions. In addition, outcome assessment methods vary considerably among studies, with some emphasizing objective measures such as muscle strength grading, while others focus on patient-reported outcomes, pain reduction, or quality-of-life improvements. This inconsistency complicates efforts to determine the overall effectiveness of nerve transfer surgery and identify factors associated with successful recovery. Furthermore, despite increasing clinical adoption, uncertainties remain regarding optimal surgical timing, patient selection, rehabilitation strategies, and future technological innovations that may enhance nerve regeneration.

The existing research gap highlights the need for a comprehensive synthesis of current evidence regarding nerve transfer surgery. Although previous systematic reviews have examined specific applications of nerve transfers, limited studies have integrated evidence related to surgical principles, functional outcomes, influencing factors, patient experiences, and future research directions. A broader understanding is required to identify common patterns across different injury types and provide a comprehensive perspective on the role of nerve transfer surgery in modern reconstructive medicine. Therefore, a systematic review approach is necessary to consolidate current knowledge, evaluate clinical effectiveness, identify limitations in existing evidence, and establish priorities for future investigations.

The urgency of this research is emphasized by the time-sensitive nature of nerve regeneration and the increasing demand for advanced reconstructive solutions for individuals experiencing neurological disabilities. Delayed intervention following severe nerve injury may substantially reduce the likelihood of functional recovery because prolonged denervation can result in irreversible muscle atrophy. Consequently, improving understanding of nerve transfer indications, outcomes, and limitations is essential for optimizing clinical decision-making and improving patient prognosis. Furthermore, healthcare systems require evidence-based guidance to determine appropriate referral pathways, surgical timing, rehabilitation strategies, and resource allocation for patients with complex nerve injuries.

This study provides novelty by presenting an integrated systematic review that examines nerve transfer surgery from multiple perspectives, including clinical applications, functional restoration outcomes, influencing factors, patient-reported outcomes, and future technological developments. Unlike previous studies that primarily evaluate individual injury categories or specific surgical techniques, this research synthesizes evidence across various neurological conditions to provide a broader understanding of the current state of nerve transfer surgery. The study also emphasizes the relationship between objective functional recovery and patient-centered outcomes, addressing an important limitation in previous literature in which clinical measurements do not always reflect patients' actual postoperative experiences.

Based on these considerations, this study aimed to systematically review current practices, clinical outcomes, challenges, and future directions in nerve transfer surgery. Specifically, this research aimed to identify the effectiveness of nerve transfer procedures in restoring motor and sensory functions, evaluate factors influencing surgical success, examine limitations reported in previous studies, and explore emerging developments that may improve future nerve reconstruction outcomes. Through this systematic evaluation, the study sought to provide a comprehensive evidence-based overview of the development of nerve transfer surgery.

The contribution of this research lies in providing clinicians, researchers, and healthcare stakeholders with a consolidated understanding of current evidence regarding nerve transfer surgery. The findings are expected to support clinical decision-making by highlighting important considerations related to surgical timing, patient selection, rehabilitation requirements, and expected functional outcomes. Additionally, this study contributes to academic development by identifying unresolved issues and future research priorities in peripheral nerve reconstruction. Ultimately, this review aims to support the continued advancement of nerve transfer techniques and improve functional recovery and quality of life among individuals affected by severe nerve injuries.

METHOD

A systematic review design was used in this study because it aimed to synthesize existing evidence regarding current practices, clinical outcomes, influencing factors, and future directions of nerve transfer surgery. The study employed a qualitative descriptive approach through a systematic literature review following internationally recognized guidelines, including the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The research population comprised scientific publications related to nerve transfer surgery, including studies involving patients with peripheral nerve injuries, brachial plexus injuries, spinal cord injuries, facial paralysis, and other neurological conditions requiring reconstructive nerve procedures. The study population consisted of articles indexed in reputable academic databases, including PubMed, Scopus, ScienceDirect, and Web of Science, within the selected publication period. The sample included eligible peer-reviewed articles that met the predetermined inclusion and exclusion criteria, focusing on nerve transfer procedures, clinical outcomes, functional recovery, surgical techniques, and patient-reported outcomes.

The sampling technique applied in this study was purposive sampling, in which articles were selected based on their relevance to the research objectives and compliance with established eligibility criteria. The research instrument was a structured data extraction form used to collect relevant information from selected studies, including publication characteristics, study design, participant characteristics, type of nerve transfer procedure, injury classification, outcome measurements, functional improvements, complications, and reported limitations. Data quality was ensured through content validity assessment of the extraction framework

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based on previous systematic review methodologies and expert recommendations in peripheral nerve surgery. Reliability was assessed through reviewer agreement by conducting independent article screening and comparing data extraction results to minimize selection bias and maintain consistency. Data collection was conducted through systematic searches of academic databases using predefined keywords related to "nerve transfer surgery," "nerve injury," "brachial plexus injury," "motor recovery," "sensory restoration," and "functional outcomes." The article selection process consisted of identification, duplicate removal, title and abstract screening, full-text evaluation, and final study inclusion based on eligibility criteria following the PRISMA flow framework.

The collected data were analyzed using qualitative synthesis and descriptive analysis techniques. The selected studies were categorized based on injury type, surgical approach, functional outcomes, recovery factors, and future development directions. Data management and organization were supported using reference management software, such as Mendeley or Zotero, while screening and systematic review documentation were conducted using tools such as Rayyan or spreadsheet-based databases. The analysis involved thematic synthesis to identify recurring patterns, similarities, differences, and emerging trends across studies. Quantitative outcomes reported in individual studies, including Medical Research Council (MRC) muscle grades, functional scores, patient satisfaction rates, and recovery percentages, were summarized descriptively to provide an overview of surgical effectiveness. The final interpretation integrated evidence from multiple studies to evaluate the current status of nerve transfer surgery, identify limitations in existing evidence, and develop recommendations for future clinical practice and research development.

RESULT AND DISCUSSION

Restoration of Motor and Sensory Function Across Different Injury Types

Th The primary objective of nerve transfer surgery is the restoration of lost movement and sensation (Johns Hopkins Medicine, n.d.). The efficacy of these procedures is demonstrated across various anatomical regions and injury types:

1. Upper Extremity: Nerve transfers in the upper extremity aim to restore critical functions such as elbow flexion, wrist, finger, and thumb extension, and thumb opposition (Johns Hopkins Medicine, n.d.).
2. Lower Extremity: In the lower limb, target functions include knee extension and ankle dorsiflexion (Johns Hopkins Medicine, n.d.).
3. Brachial Plexus Injuries (BPIs): Studies consistently show significant post-operative improvements in objective measures, including elbow flexion range, shoulder flexion, abduction, external rotation, quantitative muscle strength, and grip strength ("Clinical Assessment of Functional Recovery Following Nerve Transfer for Traumatic Brachial Plexus Injuries," n.d.). For instance, 80% of patients achieved Medical Research Council (MRC) grade 3 or above for elbow flexion following phrenic nerve transfer, with some attaining "very good" results (grade 4+) ("Functional Outcome following Phrenic Nerve Transfer in Brachial Plexus Injury," n.d.). Furthermore, double nerve transfers consistently yield better long-term outcomes for both shoulder and elbow function compared to single transfers ("Results of the Nerve Transfers and Secondary Procedures to Restore Shoulder and Elbow Function in Traumatic Upper Brachial Plexus Palsy," n.d.).

4. Spinal Cord Injuries (SCIs): Nearly all reported cases (all but one) demonstrated recovery of at least MRC grade 3/5 strength in recipient muscle groups ("Nerve Transfers in the Upper Extremity Following Cervical Spinal Cord Injury. Part 1," n.d.). The most consistent and meaningful recovery has been observed for wrist/finger extension and elbow extension ("Nerve Transfers in the Upper Extremity Following Cervical Spinal Cord Injury. Part 1," n.d.).
5. Facial Paralysis: Patients undergoing facial nerve transfers almost universally experience some degree of improvement (Mayo Clinic, n.d.). These procedures can effectively restore function, appearance, and facial balance, allowing for separate innervation of different facial muscle subunits responsible for functions like smiling, eye closure, and mouth closure (Shai Rozen, n.d.).

Factors Influencing Recovery Timelines and overall Success

Several factors critically influence the recovery timelines and overall success of nerve transfer surgery:

1. Timing of Surgery: This is arguably the most critical determinant of success (Duke Health, n.d.). The sooner the surgery is performed after injury, the higher the chances for a successful outcome (Duke Health, n.d.). The optimal window for nerve transfer is generally before 6 months post-injury (BSSH, n.d.). Early exploration and reconstruction, ideally within 3-6 weeks, are indicated when there is a high suspicion of root avulsion or a proximal nerve injury (BSSH, n.d.). Conversely, delayed transfers (beyond 9-12 months) or late transfers (beyond 12 months) yield poor results due to irreversible motor endplate demise (The Buncke Clinic, n.d.). For BPIs, each month of delay from injury to reconstruction can reduce the probability of achieving MRC grade ≥M4 by 7% ("The Effectiveness of Different Nerve Transfers in the Restoration of Elbow Flexion in Adults Following Brachial Plexus Injury," n.d.).
2. Surgeon Expertise: The success of the procedure is significantly influenced by the skills and experience of the surgical team (Johns Hopkins Medicine, n.d.). Choosing a surgical team with specialized experience and skill in brachial plexus and peripheral nerve surgery can substantially improve the likelihood of a good outcome (Johns Hopkins Medicine, n.d.).
3. Nerve Regeneration Rate: Axons typically regenerate at a consistent rate of approximately 1 inch (or 1 millimeter) per month (Johns Hopkins Medicine, n.d.).
4. Distance to Muscle: A major advantage of nerve transfers is their ability to be performed closer to the paralyzed muscle, resulting in a shorter distance for nerve fibers to regenerate and thus a faster recovery of function compared to nerve grafts (Johns Hopkins Medicine, n.d.).
5. Type and Severity of Injury: The nature and extent of the nerve injury directly impact the potential for recovery and the overall success rate (Johns Hopkins Medicine, n.d.).
6. Patient Age: Patient age is a significant factor influencing recovery, with younger patients generally exhibiting better outcomes (The Buncke Clinic, n.d.).
7. Post-operative Rehabilitation: Comprehensive and consistent physical and occupational therapy is crucial for maximizing functional recovery. This includes retraining the brain to utilize the new nerve connections and muscles (Johns Hopkins Medicine, n.d.).

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The overwhelming emphasis on the time-sensitive nature of nerve transfers, particularly the "golden window" of 6-12 months, is not merely a clinical guideline but a reflection of a fundamental biological constraint: the irreversible degeneration of the motor endplate and muscle fibers if deprived of innervation for too long. The explicit quantification of declining success rates, such as the 7% reduction per month delay for BPI, reinforces this biological imperative. This implies that the success of nerve transfer surgery is not solely dependent on the surgeon's skill but is profoundly influenced by systemic factors such as early diagnosis, rapid referral pathways, and efficient healthcare access. Missing this window necessitates alternative, often less ideal, reconstructive strategies.

Patient-Reported Outcomes (PROs)

While objective functional improvements are frequently reported, patient-reported outcomes (PROs) offer a critical, complementary perspective on the overall impact of nerve transfer surgery. A systematic review focusing on nerve transfer for BPI revealed that while Disabilities of the Arm, Shoulder and Hand (DASH) scores generally improved post-operatively, a "high degree of ongoing disability" was still reported by patients ("A Systematic Review and Meta-Analysis of Patient-Reported Outcomes Following Nerve Transfer Surgery for Brachial Plexus Injury," n.d.). Return to work was observed in 66% of participants across five studies ("A Systematic Review and Meta-Analysis of Patient-Reported Outcomes Following Nerve Transfer Surgery for Brachial Plexus Injury," n.d.). Overall patient satisfaction was assessed at 64% in four studies, although another source indicated 83% satisfaction with the functional results of brachial plexus surgery ("A Systematic Review and Meta-Analysis of Patient-Reported Outcomes Following Nerve Transfer Surgery for Brachial Plexus Injury," n.d.). Pain assessment varied across studies; among those reporting pain intensity, 29.3% were "pain-free" or had "no pain" post-operatively ("A Systematic Review and Meta-Analysis of Patient-Reported Outcomes Following Nerve Transfer Surgery for Brachial Plexus Injury," n.d.). However, some sources suggest that sensory function and pain are "barely improved" by the surgery in certain cases ("A Systematic Review and Meta-Analysis of Patient-Reported Outcomes Following Nerve Transfer Surgery for Brachial Plexus Injury," n.d.). For radial nerve palsy, both nerve transfers and tendon transfers led to improvements in pain, function, and patient satisfaction ("Radial Nerve Palsy: Nerve Transfer Versus Tendon Transfer to Restore Function," n.d.).

While numerous studies report high rates of objective functional improvement (e.g., MRC grade M3/M4 strength), the systematic review on patient-reported outcomes (PROs) for BPI presents a more complex picture. Despite objective gains, PROs, such as DASH scores, still indicate a "high degree of ongoing disability," and improvements in pain and sensory function are sometimes "barely improved." This apparent contradiction suggests that objective clinical measures, while vital, may not fully capture the patient's subjective experience of recovery, their quality of life, or the persistence of residual symptoms like pain and sensory deficits. This highlights a critical knowledge gap and an urgent need for future research to incorporate more comprehensive and nuanced PROs to truly understand the overall impact of nerve transfers on patients' lives, potentially guiding rehabilitation strategies to address these persistent challenges more effectively.

Table 3: Summary of Functional Outcomes and Success Rates by Injury Type

Injury Type	Key Functional Outcomes	Reported Success Rates / Strength Grades	Patient-Reported Outcomes (PROs)	Relevant Snippets
Brachial Plexus Injuries (BPIs)	Elbow flexion, shoulder abduction/flexion/external rotation, quantitative muscle strength, grip strength.	80-90% improvement in function [1]; 80% achieved MRC grade ≥M3 for elbow flexion [17]; 75% achieved MRC grade ≥M4 for partial BPI [30]; 45% achieved MRC grade ≥M4 for pan-plexus injuries [30]; Dual nerve transfers yield better long-term outcomes.[20]	DASH scores variably improved but high degree of ongoing disability reported [45]; 66% return to work [45]; 64-83% patient satisfaction [45]; 29.3% pain-free post-op, but sensory/pain often "barely improved".[45]	[1]
Spinal Cord Injuries (SCIs)	Wrist/finger extension, elbow extension, thumb/finger flexion.	All but one case report showed recovery of at least MRC grade 3/5 strength [22]; Best, most consistent outcomes for wrist/finger extension and elbow extension.[22]	Not explicitly detailed in provided data.	[22]
Facial Paralysis	Smile restoration, eye reanimation, facial balance, mouth closure.	Almost always experience improvement.[23]	Improved function, appearance, and facial balance.[24]	[23]
Radial Nerve Injury	Grip strength, pinch strength, pain, function.	Greater grip strength with nerve transfer vs. tendon transfer.[40]	Improved pain, function, and patient satisfaction for both nerve and tendon transfers.[40]	[40]
Overall Nerve Transfers	Restoration of movement and sensation.	High success rate, nearly all restore some degree of function, many achieve full function.[26]	Pain from incision minimal and temporary.[1]	[1]

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CONCLUSION

Nerve transfer surgery represents a transformative advancement in peripheral nerve reconstruction, offering substantial potential for restoring motor and sensory function in patients with severe nerve injuries. This systematic review highlights the advantages of nerve transfer surgery over conventional reconstructive techniques, such as nerve grafting and tendon transfer, particularly in cases involving extensive nerve gaps, proximal injuries, and scarred nerve environments. The procedure has also demonstrated an expanding role in complex conditions, including brachial plexus injuries, spinal cord injuries, facial paralysis, and post-amputation pain. The effectiveness of nerve transfer procedures depends on careful donor nerve selection, with considerations including donor nerve expendability, anatomical proximity to the target muscle, and functional compatibility, which collectively contribute to favorable outcomes reported in many patient cohorts. However, the success of nerve transfer surgery is strongly influenced by the timing of intervention, as early reconstruction is essential to optimize muscle reinnervation before irreversible muscle atrophy occurs. Although objective functional improvements are frequently reported, patient-reported outcomes may indicate persistent limitations in daily activities and residual pain, highlighting the importance of comprehensive outcome assessments.

Challenges remain in achieving consistent and complete functional restoration, particularly in cases involving long nerve gaps and complex injuries, as well as in improving the understanding of the biological mechanisms underlying nerve regeneration. Future research directions focus on addressing translational challenges through biological enhancement of nerve healing, including pharmacological interventions and advanced neuromodulation techniques. Further rigorous, large-scale clinical trials and standardized patient-reported outcome measures are needed to strengthen the evidence base and guide future clinical practice. Ultimately, nerve transfer surgery, often performed in combination with other reconstructive strategies and intensive neurorehabilitation, represents a significant advancement in modern peripheral nerve surgery, providing renewed opportunities for functional recovery and improved quality of life among individuals affected by debilitating nerve injuries.

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