Early Functional Outcomes of Intercostal-to-Musculocutaneous Nerve Transfer for Elbow Flexion Restoration After Traumatic Brachial Plexus Injury

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Abstract

Background: Traumatic brachial plexus injury (BPI) in adults frequently results in profound upper limb dysfunction, with loss of elbow flexion representing one of the most disabling deficits. Restoration of active elbow flexion is universally considered the primary reconstructive priority because it enables positioning of the hand in space and facilitates performance of essential activities of daily living. Among the available nerve transfer strategies, intercostal-to-musculocutaneous nerve transfer has become an established and reliable option, particularly in cases involving root avulsion or absence of suitable proximal donor nerves. Over the past decades, refinements in microsurgical technique and rehabilitation protocols have improved functional recovery and expanded indications for this procedure.

The aim of this review is to critically analyze the early functional outcomes of intercostal-to-musculocutaneous nerve transfer for elbow flexion restoration in adult patients with traumatic BPI. Special focus is placed on the timeline of motor recovery, strength outcomes, predictors of success, surgical technical considerations, and donor-site morbidity. In addition, the role of postoperative rehabilitation and cortical re-education in facilitating functional integration of transferred intercostal nerves is emphasized.

Current evidence indicates that meaningful recovery of elbow flexion, often defined as Medical Research Council grade 3 or greater, can be achieved in a substantial proportion of appropriately selected patients. Early signs of reinnervation are typically observed within several months after surgery, with progressive gains occurring during the first postoperative year. Outcomes are strongly influenced by patient age, delay to surgery, severity and pattern of injury, and the number of intercostal nerves transferred. When performed within optimal timeframes and combined with structured rehabilitation, intercostal nerve transfer offers reproducible early functional improvement with relatively low donor-site morbidity.

In conclusion, intercostal-to-musculocutaneous nerve transfer remains a dependable reconstructive strategy for early elbow flexion restoration in traumatic brachial plexus injury. Careful patient selection, meticulous surgical technique, and coordinated rehabilitation are essential to maximize early functional outcomes and long-term success.

Keywords: *Functional Outcomes, Intercostal-to-Musculocutaneous Nerve Transfer, Traumatic Brachial Plexus Injury*

Introduction

Traumatic brachial plexus injury (BPI) represents one of the most devastating peripheral nerve injuries encountered in reconstructive microsurgery, most commonly affecting young adults following high-energy trauma such as motorcycle accidents. The resulting paralysis of the upper limb produces profound functional, psychological, and socioeconomic consequences. Among the various functional deficits, loss of elbow flexion is considered the most disabling, as it compromises the ability to position the hand in space and perform essential activities of daily living. Consequently, restoration of elbow flexion is widely regarded as the first and most critical objective in brachial plexus reconstruction algorithms. [1]

Historically, management of BPI evolved from nerve grafting techniques toward nerve transfers, particularly in cases involving root avulsions where proximal nerve stumps are unavailable. Nerve transfers provide the advantage of shorter regeneration distances, earlier reinnervation, and more predictable outcomes. Among extraplexal donor options, intercostal nerves have been extensively utilized as reliable motor donors to reinnervate the musculocutaneous nerve or directly the motor branch to the biceps. The modern application of intercostal-to-musculocutaneous nerve transfer was popularized in the late twentieth century and remains a cornerstone technique in adult traumatic BPI reconstruction. [2]

Intercostal nerves offer several theoretical and practical advantages. They are anatomically accessible, contain a substantial motor axon load, and can be harvested without significant long-term respiratory compromise in most patients. Their proximity to the axilla allows relatively direct coaptation to the musculocutaneous nerve, especially when two or three intercostal nerves are mobilized. Furthermore, in cases of total brachial plexus palsy with multiple root avulsions, intercostal nerves may represent one of the few viable donor sources for early elbow flexion reconstruction. [3]

Despite its widespread use, reported outcomes following intercostal nerve transfer vary considerably across studies. Differences in patient selection, timing of surgery, number of intercostal nerves transferred, technique of coaptation (direct versus with graft), and rehabilitation protocols contribute to heterogeneity in early motor recovery. In addition, contemporary practice increasingly incorporates alternative nerve transfers—such as spinal accessory, medial pectoral, or double fascicular (Oberlin-type) transfers—raising important questions regarding comparative early functional results. [4]

A critical appraisal of early functional outcomes is particularly relevant because early reinnervation strongly correlates with long-term muscle strength and functional integration. Factors such as patient age, denervation time, severity of injury (upper versus total palsy), and cortical adaptation mechanisms may significantly influence early recovery trajectories. Moreover, standardized reporting of outcomes using the Medical Research Council (MRC) grading system, dynamometry, and patient-reported measures remains inconsistent across the literature, creating a research gap in comparative evaluation. [5]

The aim of this review is therefore to comprehensively analyze the early functional outcomes of intercostal-to-musculocutaneous nerve transfer for elbow flexion restoration in adult traumatic brachial plexus injury. We focus on surgical indications, technical considerations, motor recovery timelines, predictors of success, rehabilitation strategies, and donor-site morbidity. By synthesizing validated clinical evidence and highlighting existing gaps, this review seeks to clarify the role of intercostal nerve transfer within modern reconstructive algorithms and to identify factors that optimize early functional recovery. [6]

Relevant Anatomy and Physiologic Basis

A comprehensive understanding of donor and recipient nerve anatomy is fundamental to optimizing outcomes following intercostal-to-musculocutaneous nerve transfer. The intercostal nerves arise from the anterior rami of the thoracic spinal nerves (T1–T11), with T2–T6 most commonly selected for transfer in brachial plexus reconstruction. Each intercostal nerve courses along the inferior border of the corresponding rib within the neurovascular bundle, accompanied by the intercostal artery and vein. Proximally, they provide motor branches to the intercostal muscles and contribute to chest wall stability and respiration, while distally they give sensory branches to the thoracic wall. Their mixed but predominantly motor composition makes them suitable extraplexal donors for reinnervating elbow flexors. [7]

From a surgical perspective, the third, fourth, and fifth intercostal nerves are most frequently harvested because they provide an optimal balance between axonal load and acceptable donor-site morbidity. The upper intercostal nerves (T2–T3) may be technically more challenging due to their deeper location and proximity to the pleura, whereas lower levels may increase the distance required for coaptation. Mobilization typically involves dissection anterior to the midaxillary line to gain adequate length,

allowing tension-free transfer toward the axilla. Anatomical studies have demonstrated that each intercostal nerve contains a sufficient number of myelinated motor axons to support functional reinnervation of the biceps when two or three nerves are combined. [8]
The recipient target is most commonly the musculocutaneous nerve or its motor branch to the biceps brachii. The musculocutaneous nerve arises from the lateral cord of the brachial plexus (C5–C7) and provides primary motor innervation to the biceps brachii, brachialis, and coracobrachialis muscles, in addition to sensory supply via the lateral antebrachial cutaneous nerve. For elbow flexion restoration, reinnervation of the biceps is prioritized because of its strong flexion and supination capacity. Some surgeons advocate coaptation directly to the motor branch to the biceps to reduce regeneration distance and potentially enhance early motor recovery. [9]
Physiologically, the success of intercostal nerve transfer depends on adequate axonal regeneration and cortical plasticity. After coaptation, regenerating motor axons must traverse the neurorrhaphy site, advance distally toward the motor end plates, and re-establish functional neuromuscular junctions before irreversible muscle fibrosis occurs. Timely surgery—ideally within six months of injury—maximizes the likelihood that motor end plates remain receptive to reinnervation. Delays beyond this window are associated with progressive muscle atrophy and reduced functional outcomes. [10]
A distinctive feature of intercostal nerve transfer is the initial coupling of elbow flexion with respiration. Because intercostal nerves are physiologically activated during inspiration and forced expiration, early postoperative contractions of the biceps often occur synchronously with deep breathing or coughing. Through repetitive training and cortical reorganization, patients gradually achieve dissociation of elbow flexion from respiratory effort. This adaptive neuroplastic process underscores the importance of structured rehabilitation and biofeedback techniques in facilitating independent voluntary control. [11]
Understanding both the anatomical constraints and neurophysiologic principles of intercostal nerve transfer allows surgeons to refine technical strategies and set realistic expectations regarding early recovery. Adequate donor axon load, tension-free coaptation, minimized regeneration distance, and early rehabilitation collectively determine the speed and strength of motor return. These anatomical and physiologic foundations form the basis upon which early functional outcomes are achieved and interpreted in clinical practice. [12]

Indications, Patient Selection, and Timing

Intercostal-to-musculocutaneous nerve transfer is primarily indicated in adult patients with traumatic brachial plexus injury in whom proximal nerve roots are unavailable for grafting, particularly in cases of preganglionic root avulsion. In such scenarios, intraplexal donor options are limited or absent, making extraplexal donors essential for reconstruction. Total brachial plexus palsy and upper plexus injuries (C5–C6 or C5–C7) with nonviable proximal stumps are classic indications for intercostal nerve transfer to restore elbow flexion. Because elbow flexion is prioritized in reconstructive sequencing, this procedure is often performed as an early cornerstone intervention. [13]
Patient selection must consider age, mechanism of injury, associated trauma, and overall medical condition. Younger patients generally demonstrate superior axonal regeneration and cortical adaptability, translating into improved early functional recovery. High-energy mechanisms, such as motorcycle accidents, frequently produce root avulsions that favor extraplexal transfers. However, polytrauma patients may present additional considerations, including thoracic injuries, rib fractures, or pulmonary compromise, which could influence donor-site safety. Careful preoperative evaluation of respiratory function is therefore advisable when planning intercostal nerve harvest. [14]
Timing of surgery is a critical determinant of early and long-term outcomes. Denervated muscle undergoes progressive atrophy, fibrosis, and motor end-plate degeneration over time. Most authors advocate performing nerve transfers within 3 to 6 months following injury to optimize reinnervation potential. Early referral to specialized centers significantly improves candidacy for nerve reconstruction. Delays beyond 9 to 12 months are associated with diminished functional recovery and may necessitate alternative strategies such as free functional muscle transfer. [15]
The pattern of brachial plexus injury further influences donor selection. In isolated upper trunk injuries

with intact lower plexus elements, intraplexal transfers such as the double fascicular (Oberlin) technique may provide faster and stronger elbow flexion recovery. Conversely, in complete plexus palsy where intraplexal donors are compromised, intercostal nerves remain a reliable and reproducible option. Thus, intercostal transfer occupies a particularly important role in global plexus injuries and in delayed presentations where proximal grafting is not feasible. [16]

Another important consideration is the number of intercostal nerves transferred. Most contemporary series recommend using two or three intercostal nerves to increase motor axon input and enhance the likelihood of achieving antigravity elbow flexion (MRC ≥3). Although single intercostal transfer has been described, outcomes tend to be less predictable. The balance between maximizing donor axonal load and minimizing donor-site morbidity must be carefully weighed during surgical planning. [17]

In summary, appropriate indications and timely intervention are central to optimizing early functional outcomes following intercostal-to-musculocutaneous nerve transfer. Ideal candidates are medically stable adults with traumatic brachial plexus injury—particularly root avulsions—who present within the early post-injury window and lack suitable intraplexal donors. Thoughtful patient selection, injury pattern analysis, and adherence to optimal timing principles substantially influence the probability of meaningful early elbow flexion recovery. [18]

Surgical Technique and Technical Considerations (Plastic Surgery Perspective)

The surgical success of intercostal-to-musculocutaneous nerve transfer depends on meticulous technique, precise anatomical dissection, and strategic intraoperative decision-making. The procedure is typically performed with the patient in a supine position, allowing simultaneous access to the chest wall and axilla. A curvilinear incision is made along the inframammary or submammary crease to expose the selected intercostal spaces, most commonly the third, fourth, and fifth intercostal nerves. Careful subperiosteal dissection along the inferior border of the rib enables identification of the neurovascular bundle, with protection of the pleura to avoid pneumothorax. [19]

After identification, each intercostal nerve is dissected anteriorly toward the costochondral junction to obtain maximal length while preserving proximal motor branches until the final stage of division. The nerves are then divided distally and mobilized toward the axilla. Adequate length is critical to allow tension-free coaptation. Simultaneously, an axillary incision is used to identify the musculocutaneous nerve or its motor branch to the biceps. Intraoperative nerve stimulation and careful fascicular dissection assist in confirming recipient viability and optimizing coaptation site selection. [20]

A key technical consideration is whether to coapt the intercostal nerves to the main trunk of the musculocutaneous nerve or directly to the motor branch to the biceps. Direct coaptation to the motor branch may reduce regeneration distance and potentially accelerate early reinnervation. However, this approach requires meticulous dissection and precise fascicular alignment. When sufficient length is achieved, direct end-to-end neurorrhaphy without graft interposition is preferred, as it minimizes additional interfaces that could impede axonal regeneration. If tension-free repair is not possible, short autologous nerve grafts may be required, though outcomes may be slightly less favorable. [21]

The number of intercostal nerves transferred remains a critical determinant of motor recovery. Most contemporary surgeons favor transferring at least two, and preferably three, intercostal nerves to increase donor axonal load. The nerves are often sutured together (cable configuration) before coaptation to the recipient to maximize axonal input. Microsurgical technique using epineurial or group fascicular suturing under high magnification, supplemented by fibrin glue, facilitates stable and atraumatic repair. Avoiding excessive manipulation and maintaining adequate vascularity are essential to promote axonal regeneration. [22]

Intraoperative strategies to minimize donor-site morbidity are equally important. Gentle handling of the pleura, meticulous hemostasis, and careful closure reduce the risk of pneumothorax and postoperative pain. Routine chest tube placement is generally unnecessary unless pleural violation occurs. Postoperative monitoring should include respiratory assessment, particularly in patients with prior thoracic trauma. Most patients tolerate the harvest of two to three intercostal nerves without significant long-term respiratory compromise. [23]

From a plastic surgery perspective, surgical planning must integrate reconstructive priorities within the broader algorithm of brachial plexus repair. Elbow flexion restoration is typically addressed first, followed by shoulder stabilization and hand function reconstruction. The surgeon must anticipate the need for additional nerve or tendon transfers and avoid compromising future reconstructive options. Careful coordination with rehabilitation specialists begins immediately postoperatively to optimize early activation and motor retraining. Technical precision, donor selection strategy, and multidisciplinary planning collectively determine the quality and timing of early functional outcomes. [24]

Rehabilitation and Motor Re-education After Intercostal Nerve Transfer

Rehabilitation following intercostal-to-musculocutaneous nerve transfer is not merely supportive but constitutes an integral component of functional recovery. Unlike intraplexal transfers that recruit synergistic motor patterns, intercostal nerves are physiologically linked to respiration. Consequently, early postoperative motor activation of the biceps typically occurs in synchrony with deep inspiration, coughing, or Valsalva maneuvers. Structured rehabilitation is therefore essential to facilitate cortical adaptation and progressive dissociation of elbow flexion from respiratory effort. Early collaboration between the surgical and therapy teams significantly enhances functional integration. [25]

During the immediate postoperative period, immobilization of the arm is usually maintained for approximately three weeks to protect the neurorrhaphy site. Passive range-of-motion exercises are initiated early to prevent joint stiffness and muscle contracture while awaiting signs of reinnervation. Electrical stimulation of denervated muscles remains controversial but may be considered selectively to maintain muscle bulk and enhance local circulation, although evidence regarding its impact on nerve regeneration remains inconclusive. [26]

The first clinical evidence of reinnervation typically appears between 3 and 6 months postoperatively, often detected as flicker contractions (MRC grade 1) during forceful inspiration. At this stage, rehabilitation focuses on reinforcing the connection between respiratory activation and elbow flexion. Biofeedback techniques, surface electromyography, and visual cues may accelerate patient awareness and voluntary recruitment of the transferred nerve input. Repetitive task-oriented training helps strengthen early contractions and promotes synaptic refinement within the motor cortex. [27]

As motor strength progresses toward antigravity levels (MRC grade 3), therapy shifts toward functional strengthening and endurance training. The goal is gradual uncoupling of elbow flexion from respiratory effort, enabling voluntary contraction independent of breathing patterns. Neuroplasticity plays a critical role in this phase; repeated motor practice facilitates cortical remapping and establishment of new motor programs. Younger patients often demonstrate more rapid cortical adaptation, which may partly explain age-related differences in early outcomes. [28]

An additional challenge is preventing compensatory movement patterns that may hinder optimal recovery. Patients frequently recruit shoulder elevation or trunk motion to assist elbow flexion during early phases. Targeted therapy aims to isolate biceps activation while maintaining shoulder stability. Integration of elbow flexion into meaningful activities of daily living further consolidates functional gains and reinforces cortical reorganization. Multidisciplinary follow-up over the first postoperative year is essential to maximize early strength progression. [29]

Overall, successful early functional outcomes after intercostal nerve transfer depend not only on axonal regeneration but also on structured, progressive motor re-education. Rehabilitation bridges the biological process of reinnervation with functional motor control, transforming respiration-driven contractions into purposeful elbow flexion. Without dedicated therapy, even technically successful nerve transfers may fail to achieve their full functional potential. Thus, postoperative rehabilitation should be regarded as a core determinant of early recovery rather than an adjunctive measure. [30]

Early Functional Outcomes: Motor Recovery, Strength, and Predictors of Success

Early functional recovery following intercostal-to-musculocutaneous nerve transfer is primarily evaluated by the return of active elbow flexion and progression along the Medical Research Council (MRC) grading scale. Most clinical series define meaningful early success as achievement of antigravity elbow flexion (MRC grade $\geq$3). Across published cohorts of adult traumatic brachial plexus injury, rates of MRC ≥3 recovery after intercostal nerve transfer generally range between 60% and 80%, depending on injury severity, timing of surgery, and number of donor nerves transferred. These outcomes have established intercostal transfer as a dependable reconstructive option, particularly in total plexus palsy. [31]

The timeline of motor recovery is a critical component of early outcome assessment. Initial signs of reinnervation—often observed as flicker contractions (MRC grade 1)—typically appear between 3 and 6 months postoperatively, reflecting axonal regeneration across the neurorrhaphy site and into the target muscle. Progression to antigravity flexion commonly occurs within 6 to 12 months, although continued strengthening may extend beyond the first postoperative year. Earlier onset of contraction is generally associated with superior final strength, underscoring the importance of minimizing regeneration distance and performing surgery within optimal time windows. [32]

The number of intercostal nerves transferred significantly influences motor strength. Multiple studies have demonstrated improved outcomes when two or three intercostal nerves are coapted to the musculocutaneous nerve compared with a single donor. Increased axonal input enhances the probability of sufficient motor unit recruitment to overcome gravity. However, the incremental benefit between two versus three donors remains debated, and the decision must balance potential gains in strength against operative time and donor-site considerations. [33]

Patient-related factors also play a substantial role in early outcomes. Younger patients consistently demonstrate more robust motor recovery, likely due to superior axonal regenerative capacity and greater cortical plasticity. In contrast, advanced age is associated with reduced regeneration speed and diminished muscle reinnervation potential. The interval between injury and surgery is equally critical; delays beyond six months are correlated with reduced rates of achieving MRC grade 3 or higher, reflecting progressive motor end-plate degeneration and muscle fibrosis. [34]

Injury pattern strongly affects outcome variability. Patients with isolated upper trunk injuries may achieve comparable or superior results with intraplexal transfers such as double fascicular (Oberlin-type) techniques, which provide shorter reinnervation distances. Conversely, in complete brachial plexus palsy, intercostal nerve transfer often represents one of the few viable donor options, and outcomes, although sometimes slightly lower than intraplexal transfers in partial injuries, remain functionally meaningful. Thus, interpretation of early results must account for baseline injury severity and donor availability. [35]

Technical factors further contribute to heterogeneity in early functional recovery. Direct tension-free coaptation without interposition grafting tends to yield earlier reinnervation compared with graft-dependent repairs, owing to reduced regeneration interfaces. Coaptation to the motor branch to the biceps rather than the main trunk of the musculocutaneous nerve may shorten regeneration distance and potentially accelerate early contraction, although definitive comparative data remain limited. Microsurgical precision and preservation of vascular supply at the coaptation site are essential to optimize axonal crossing and minimize scarring. [36]

Beyond objective strength grading, functional integration is increasingly recognized as a critical measure of early outcome. Achieving MRC grade 3 enables the patient to bring the hand to the mouth when gravity is eliminated or partially assisted, restoring essential self-care tasks. However, endurance, coordination, and independent activation without respiratory coupling determine the true functional utility of the transfer. Structured rehabilitation programs significantly influence this transition from raw motor strength to practical arm use. Therefore, early outcome assessment should incorporate both quantitative strength grading and qualitative functional evaluation. [37]

Overall, early functional outcomes following intercostal-to-musculocutaneous nerve transfer demonstrate that a substantial proportion of appropriately selected patients regain antigravity elbow flexion within the first postoperative year. Success is multifactorial, depending on timing, patient age, injury severity, donor axon load, surgical precision, and rehabilitation intensity. Recognition of these predictors allows refinement of patient counseling and optimization of reconstructive algorithms in modern brachial plexus surgery. [38]

Complications and Donor-Site Morbidity

Although intercostal-to-musculocutaneous nerve transfer is generally considered safe and reproducible, awareness of potential complications is essential when evaluating early outcomes. The most immediate intraoperative risk is pleural violation, which may result in pneumothorax. Careful subperiosteal dissection along the inferior rib border and meticulous handling of the intercostal neurovascular bundle significantly reduce this risk. When pneumothorax occurs, it is typically small and manageable with chest tube placement, without long-term sequelae. In experienced hands, the incidence remains low. [39]

Donor-site sensory disturbances are relatively common but usually mild. Because intercostal nerves contain sensory fibers supplying the chest wall, patients may report localized numbness or paresthesia along the corresponding dermatomes. These sensory changes are generally well tolerated and rarely interfere with daily activities. Over time, partial sensory compensation may occur through adjacent dermatomal overlap. Chronic neuropathic pain at the donor site is uncommon but should be discussed during preoperative counseling. [40]

Respiratory compromise is a theoretical concern given the motor contribution of intercostal nerves to chest wall mechanics. However, multiple clinical series have demonstrated minimal long-term pulmonary impairment following harvest of two or three intercostal nerves in otherwise healthy individuals. Objective pulmonary function testing typically shows no clinically significant reduction in respiratory capacity. Caution is warranted in patients with preexisting pulmonary disease, rib fractures, or thoracic trauma, in whom donor harvest may carry higher risk. [41]

Another potential complication relates to insufficient motor recovery despite technically successful transfer. Failure to achieve meaningful elbow flexion may result from delayed surgery, inadequate donor axon load, poor cortical adaptation, or advanced muscle atrophy. While not a complication in the traditional sense, suboptimal recovery represents a significant clinical challenge. In such cases, secondary procedures—including free functional muscle transfer—may be considered if functional goals are not met within an appropriate timeframe. [42]

Scar-related issues and chest wall contour changes are typically minor but may concern some patients, particularly younger individuals. Strategic incision placement along natural skin creases and careful closure techniques help minimize cosmetic impact. In plastic surgery practice, aesthetic considerations remain relevant even in reconstructive contexts, reinforcing the importance of balanced surgical planning. [43]

Overall, donor-site morbidity following intercostal nerve transfer is generally low and acceptable when weighed against the functional benefits of restoring elbow flexion in traumatic brachial plexus palsy. Serious complications are uncommon, and most adverse effects are transient or mild. Thorough preoperative evaluation, precise surgical technique, and postoperative monitoring ensure that complication rates remain minimal while preserving the procedure's favorable risk-benefit profile. [44]

Comparative Context: Intercostal Nerve Transfer Versus Other Donor Options

In contemporary brachial plexus reconstruction, intercostal-to-musculocutaneous nerve transfer must be evaluated within the broader context of available donor strategies for elbow flexion restoration. In patients with partial plexus injuries—particularly upper trunk lesions—**intraplexal nerve transfers** such as the double fascicular (Oberlin) technique have demonstrated rapid and often superior early motor recovery due to shorter regeneration distances and synergistic donor activation. Transfers utilizing ulnar and median nerve fascicles to the motor branches of the biceps and brachialis frequently achieve MRC grade 3 or higher within a shorter timeframe compared with extraplexal donors. Consequently, when intact intraplexal donors are available, they are often preferred. [45]

However, in cases of total brachial plexus palsy with multiple root avulsions, intraplexal options are typically absent. Under these circumstances, extraplexal donors such as the spinal accessory nerve, phrenic nerve, and intercostal nerves become critical reconstructive resources. The spinal accessory nerve is commonly directed toward shoulder reconstruction (suprascapular nerve transfer), thereby limiting its availability for elbow flexion. The phrenic nerve offers a strong motor donor but carries a greater theoretical risk of respiratory compromise, particularly in polytrauma patients. Intercostal nerves, therefore, often represent the most balanced option in terms of safety and motor potential. [46]

Comparative studies suggest that while intraplexal transfers may yield faster and sometimes stronger early elbow flexion in partial injuries, intercostal transfers provide reliable antigravity strength in global palsy cases where alternatives are limited. The slightly longer reinnervation distance associated with intercostal nerves may delay initial contraction compared with Oberlin-type transfers; however, in complete injuries, the comparison is not directly equivalent because of differing baseline severity. Interpretation of early outcomes must therefore account for injury pattern and donor availability rather than absolute strength values alone. [47]

The phrenic nerve has been proposed as an alternative extraplexal donor for musculocutaneous reinnervation, demonstrating promising motor outcomes in selected series. Nevertheless, concerns regarding diaphragmatic weakness, especially in patients with chest trauma or bilateral injury, restrict its universal application. In contrast, harvesting two or three intercostal nerves rarely produces clinically significant respiratory impairment in otherwise healthy individuals. This safety profile reinforces the role of intercostal transfer as a dependable option in complex trauma settings. [48]

Free functional muscle transfer (FFMT), particularly using the gracilis muscle, constitutes another alternative for restoring elbow flexion, especially in delayed presentations beyond the optimal nerve transfer window. While FFMT can provide strong elbow flexion even after prolonged denervation, it requires microsurgical muscle transplantation and carries its own donor-site morbidity and technical complexity. In early-presenting patients within six months of injury, nerve transfers—including intercostal-to-musculocutaneous—remain the preferred first-line strategy due to lower morbidity and more physiologic reinnervation. [49]

From a reconstructive algorithm standpoint, intercostal nerve transfer maintains a distinct and enduring role. It is especially valuable in complete brachial plexus injuries where intraplexal donors are absent and respiratory reserve permits safe harvest. Although early recovery may be somewhat slower than with double fascicular transfers in partial injuries, functional antigravity elbow flexion is consistently achievable in a substantial proportion of patients. Thus, intercostal nerve transfer should not be viewed as inferior, but rather as context-dependent within the spectrum of modern nerve reconstruction strategies. [50]

Evidence Gaps, Standardization Issues, and Future Directions

A major limitation of the intercostal-to-musculocutaneous (ICN→MCN) literature is heterogeneity in outcome definitions and reporting timepoints, which makes "early outcomes" difficult to compare across cohorts. Many studies rely predominantly on Medical Research Council (MRC) grading without standardized dynamometry, endurance testing, or uniform follow-up windows (e.g., 6 vs 12 vs 18 months). Even in well-cited clinical series, differences in surgical timing, donor number, and rehabilitation documentation introduce confounding that can obscure true predictors of early recovery. Standardized outcome frameworks tailored to nerve transfers in adult traumatic brachial plexus injury would substantially improve comparability and meta-analytic synthesis. [51]

Another gap is the limited granularity of patient stratification by injury pattern and reconstruction context. Outcomes after ICN→MCN in pan-plexus injury (often avulsion-dominant) are not directly comparable to outcomes in partial injuries where intraplexal donors exist. Contemporary systematic syntheses demonstrate that donor choice and injury type (partial versus pan-plexus) materially affect reported strength recovery, emphasizing the need for subgroup-based reporting rather than pooled results that blur clinically distinct populations. Clear differentiation between upper trunk injuries and complete palsies is essential for meaningful early outcome interpretation. [52]

A persistent methodological weakness is inconsistent reporting of timing and biologic readiness: denervation duration, electromyographic evidence of recipient muscle viability, and objective markers of reinnervation (time to first motor unit potentials, time to antigravity strength) are not uniformly captured. When these elements are reported, they reinforce that surgical delay and advanced denervation correlate with weaker early recovery. However, the field still lacks robust prospective datasets that model timing as a continuous variable and integrate clinically meaningful covariates such as associated vascular injury, thoracic trauma, and patient comorbidities. [53]

Rehabilitation is widely acknowledged as essential—particularly because early biceps activation is commonly respiration-coupled—yet published therapy protocols are rarely described with sufficient detail to allow reproducibility. This creates a translational gap between surgical reinnervation and functional independence, and likely contributes to outcome variability between centers. Future investigations should provide standardized descriptions of motor re-education strategies, including biofeedback utilization, frequency and intensity of training, and defined milestones for respiratory uncoupling. Such reporting would enhance interpretation of early functional outcomes beyond MRC grading alone. [54]

An additional area requiring development is the incorporation of patient-reported outcome measures and participation-level endpoints. While achievement of MRC grade 3 elbow flexion represents a clinically meaningful milestone, patient-perceived functionality depends on endurance, coordination, independence from respiratory coupling, and integration into daily tasks. Broader adoption of validated outcome instruments could provide a more comprehensive understanding of early recovery and better inform shared decision-making between surgeon and patient. [55]

Future directions should therefore include prospective multicenter registries with standardized early evaluation intervals (e.g., 3, 6, 9, and 12 months), comparative effectiveness analyses against alternative donors where appropriate, and integration of objective neurophysiologic markers of reinnervation and cortical adaptation. Combining clinical grading systems with electromyographic and functional data may refine prognostic modeling and improve counseling regarding expected early recovery trajectories. Continued methodological refinement will be critical to optimizing reconstructive algorithms in modern brachial plexus surgery. [56]

Conclusion

Intercostal-to-musculocutaneous nerve transfer remains a fundamental reconstructive strategy for restoring elbow flexion in adult traumatic brachial plexus injury, particularly in cases involving root avulsion or global plexus palsy where intraplexal donor options are unavailable. From a reconstructive hierarchy standpoint, elbow flexion continues to represent the primary functional objective, as it re-establishes the ability to position the hand in space and enables meaningful engagement in daily activities. Within this context, intercostal nerve transfer provides a reliable and reproducible solution when applied in appropriately selected patients.

Early functional outcomes demonstrate that a substantial proportion of patients achieve antigravity elbow flexion within the first postoperative year, with initial reinnervation typically emerging within several months. Success is strongly influenced by timing of surgery, patient age, injury severity, donor axon load, and the technical precision of tension-free coaptation. Transfer of two or three intercostal nerves generally enhances motor strength compared with single-nerve transfer, while early and structured rehabilitation plays a decisive role in transforming respiration-coupled contractions into independent voluntary movement.

Although alternative donor strategies—such as double fascicular intraplexal transfers—may provide faster recovery in selected partial injuries, intercostal nerve transfer maintains a critical role in complete brachial plexus palsy and complex trauma settings. Donor-site morbidity is typically low and acceptable when balanced against the functional gains achieved, particularly when meticulous surgical technique and appropriate patient evaluation are employed.

Despite decades of clinical experience, variability in outcome reporting and limited standardization of early assessment metrics continue to challenge direct comparison across studies. Future progress in this field will depend on prospective data collection, uniform functional benchmarks, and integration of objective neurophysiologic and patient-reported outcomes.

In conclusion, when performed within optimal timeframes and supported by dedicated rehabilitation, intercostal-to-musculocutaneous nerve transfer offers dependable early restoration of elbow flexion in traumatic brachial plexus injury. Careful patient selection, surgical refinement, and multidisciplinary follow-up remain the cornerstones of maximizing early functional recovery and long-term success.

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