

Computer Simulation of Nerve Transfer Strategies for Restoring Shoulder Function After Adult C5 and C6 Root Avulsion Injuries

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Purpose Functional ability after nerve transfer for upper brachial plexus injuries relies on both the function and magnitude of force recovery of targeted muscles. Following nerve transfers targeting either the axillary nerve, suprascapular nerve, or both, it is unclear whether functional ability is restored in the face of limited muscle force recovery.

Methods We used a computer model to simulate flexing the elbow while maintaining a functional shoulder posture for 3 nerve transfer scenarios. We assessed the minimum restored force capacity necessary to perform the task, the associated compensations by neighboring muscles, and the effect of altered muscle coordination on movement effort.

Results The minimum force restored by the axillary, suprascapular, and combined nerve transfers that was required for the model to simulate the desired movement was 25%, 40%, and 15% of the unimpaired muscle force capacity, respectively. When the deltoid was paralyzed, the infraspinatus and subscapularis muscles generated higher shoulder abduction moments to compensate for deltoid weakness. For all scenarios, movement effort increased as restored force capacity decreased.

Conclusions Combined axillary and suprascapular nerve transfer required the least restored force capacity to perform the desired elbow flexion task, whereas single suprascapular nerve transfer required the most restored force capacity to perform the same task. Although compensation mechanisms allowed all scenarios to perform the desired movement despite weakened shoulder muscles, compensation increased movement effort. Dynamic simulations allowed independent evaluation of the effect of restored force capacity on functional outcome in a way that is not possible experimentally.

Clinical relevance Simultaneous nerve transfer to suprascapular and axillary nerves yields the best simulated biomechanical outcome for lower magnitudes of muscle force recovery in this computer model. Axillary nerve transfer performs nearly as well as the combined transfer, whereas suprascapular nerve transfer is more sensitive to the magnitude of reinnervation and is therefore avoided. (*J Hand Surg* 2011;36A:1644–1651. Copyright © 2011 by the American Society for Surgery of the Hand. All rights reserved.)

Key words Biomechanics, computer simulation, brachial plexus, nerve transfer, shoulder.

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BRACHIAL PLEXUS INJURIES commonly result in avulsion of C5 and C6 nerve roots¹ and impair elbow flexion and shoulder function.^{2,3} Surgical interventions seek to restore shoulder stability and reanimate elbow flexion to provide patients with purposeful arm function. Combined nerve transfers to both suprascapular and axillary nerves are preferred to restore shoulder function, but occasionally only single nerve transfer to either the axillary or suprascapular nerve may be possible owing to limited donor nerve availability.^{4–6} Factors that influence functional outcomes after nerve transfers include overall patient health, injury severity, and surgical technique.⁷ Biomechanically, the magnitude of restored muscle force capacity in reinnervated muscles influences a patient's postoperative ability to perform tasks.

During functional movement, muscles rotate a joint by generating moment as a function of the magnitude of muscle force and the distance from the joint center of rotation (moment arm). Whether muscles generate sufficient moment to perform a functional task is a measure of strength. From a biomechanical standpoint, joint strength is most effectively restored when muscles that generate relatively large joint moments favorable for performing a functional task are preferentially targeted for nerve transfer. Previous analyses considered biomechanical factors such as moment arm and isometric joint strength independently to evaluate the importance of the deltoid and infraspinatus muscles during basic shoulder abduction and external rotation movements.⁵ However, analyses did not simultaneously consider other determinants of muscle force (eg, optimal fiber length, pennation angle, muscle volume), the magnitude of muscle force recovery, or dynamic interactions among muscles and limb segments in the context of multi-joint movement.^{8,9}

Computer-generated, dynamic musculoskeletal models are a compendium of mathematical representations of experimentally derived anatomical properties, strength measurements, and joint kinematics. Computational models of movement use fundamental mechanics to describe physiologic musculoskeletal behavior. A benefit of simulation is that muscle model properties can be altered to represent clinical scenarios and evaluate the influence of individual biomechanical factors in isolation on movement. For example, dynamic simulation has been used to assess contributions of shoulder and elbow muscles to wheelchair propulsion¹⁰ and the influence of muscle strength on pinch force after brachioradialis transfer.¹¹

This study sought to elucidate biomechanical consequences of nerve transfer strategies targeting the axillary nerve, suprascapular nerve, or both, using dynamic simulation. The goal was to evaluate (1) the minimum restored force capacity of reinnervated muscles required to perform a characteristic upper-limb functional task, and (2) the effect of compensations after nerve transfer on movement effort. Limb strength, movement effort, and muscle coordination were not considered in previous biomechanical analyses of shoulder nerve transfers but may have important clinical implications for upper-limb movement after brachial plexus injury. This study hypothesized that task performance following combined shoulder nerve transfer will be more similar to an unimpaired upper limb than single nerve transfer to the axillary or suprascapular nerve, and that muscle coordination will change as less muscle force is recovered after transfer to compensate for muscle weakness.

MATERIALS AND METHODS

This study used a 3-dimensional computer model of the upper-limb musculoskeletal system¹² to simulate movement of the upper extremity after various nerve transfers. The computer model was designed as a platform for a broad range of neuromuscular and clinical simulations, capable of dynamic simulation,^{10,13} and implemented in the OpenSim open-source modeling environment (Stanford University, CA).¹⁴ Five physiological degrees of freedom at the shoulder and elbow (shoulder abduction, shoulder flexion-extension, shoulder rotation, elbow flexion, and forearm pronation-supination) were represented (Fig. 1). We constrained the movement of the scapula and clavicle to account for stabilizing physiological action of the trapezius, serratus anterior, and pectoralis minor during movement of the shoulder girdle.¹⁵ We defined the architecture and origin-to-insertion paths of 23 muscles and muscle compartments crossing the elbow and shoulder joints (Table 1) based on anatomical data from previous studies.^{16–20} Muscle fiber lengths and moment arms for each simulated muscle compartment were calculated as a function of the joint postures. We used a mathematical model of the muscle-tendon unit to calculate the total force a muscle could produce passively when stretched, and actively when contracted during neuronal excitation.²¹ Active forces depending on the cross-sectional area, length, and shortening velocity of the muscle-tendon unit were allowed to vary from inactive to fully active levels according to the coordination pattern needed to produce the movement. Passive forces generated by stretched muscles were independent of muscle activation.

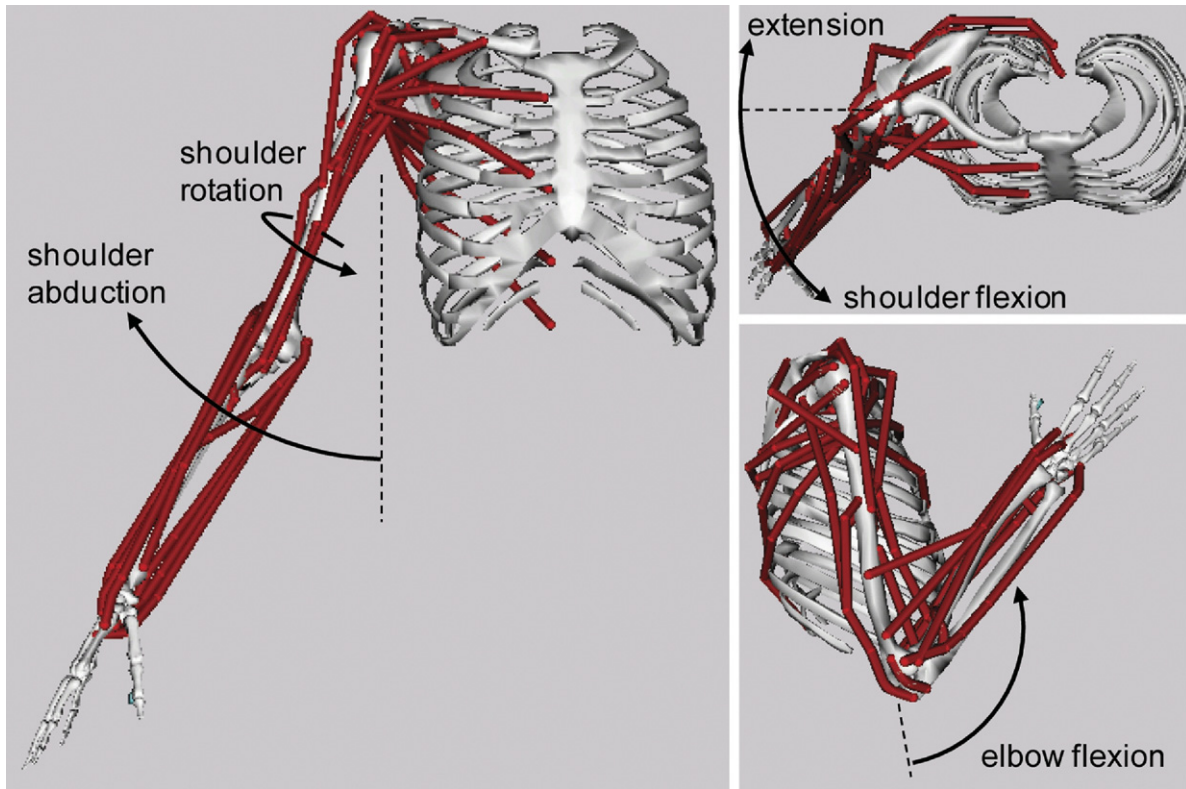


FIGURE 1: The upper extremity model represents 5 degrees of freedom at the shoulder and elbow: shoulder abduction, shoulder rotation, shoulder flexion/extension, elbow flexion, and forearm pronation/supination (not shown). The model is shown with the limb in the initial (left and upper right) and final (lower right) postures of the movement.

TABLE 1. Muscles Represented in Upper Extremity Model

Region	Shoulder	Elbow	Forearm
Muscle	Deltoid	Triceps brachii	Brachioradialis
	Supraspinatus	Biceps brachii	Extensor carpi radialis longus
	Infraspinatus	Brachialis	Extensor carpi radialis brevis
	Subscapularis	Anconeus	Extensor carpi ulnaris
	Teres major	Supinator	Flexor carpi radialis
	Teres minor		Flexor carpi ulnaris
	Latissimus dorsi		Palmaris longus
	Pectoralis major		Pronator teres
	Coracobrachialis		Pronator quadratus

We generated 3 scenarios, each representing a common nerve transfer procedure to the axillary nerve and/or suprascapular nerve for avulsion of the C5 and C6 nerve roots. We generated a fourth scenario representing a normal, unimpaired limb for comparison. Paralyzed muscles and muscles reinnervated by nerve transfer were defined for each scenario based on descriptions of common procedures found in the literature (Table 2).

Brachial plexus avulsion injury of the C5 and C6 nerve roots presents with paralysis of the supraspinatus, infraspinatus, deltoid, teres minor, biceps brachii, brachialis, and brachioradialis.² In all 3 nerve transfer scenarios, the biceps brachii and brachialis were assumed to be reinnervated by a double musculocutaneous nerve transfer.²² The axillary nerve scenario simulated nerve transfer to the axillary nerve with reinnervation of the deltoid and teres minor using the

TABLE 2. Upper Extremity Clinical Cases

Scenario Name	Muscles Paralyzed	Muscles Reinnervated
Unimpaired	None	None
Axillary	SUP, INF, TRIB	DELTA, TMIN, BIC, BRA
Suprascapular	DELTA, TMIN	SUP, INF, BIC, BRA
Combined	TRIB	SUP, INF, DELTA, TMIN, BIC, BRA

SUP, supraspinatus; INF, infraspinatus; DELTA, deltoid; TMIN, teres minor; TRIB, triceps brachii; BIC, biceps; BRA, brachialis; BRD, brachioradialis.

radial nerve branch to the long head of the triceps. The long head of the triceps is denervated as a consequence of this procedure (Table 2).³ The suprascapular nerve scenario simulated nerve transfer to the suprascapular nerve with reinnervation of the supraspinatus and infraspinatus using the spinal accessory nerve (Table 2).⁵ The combined scenario represented nerve transfers to both the suprascapular and axillary nerves (Table 2).

We assessed functional movement by simulating a task that is characteristic of eating, lifting, or reaching. With the shoulder held in a functional posture of 25° of abduction, 25° of flexion, and 20° of internal rotation, the elbow was flexed from 0° to 120° in 1 second²³ (Fig. 1). The forearm and wrist were held in the neutral position. Whether the model could perform the desired movement accurately depended on the overall strength of the simulated muscle properties in each nerve transfer scenario. We used a computed muscle control (CMC) algorithm²⁴ to calculate the muscle activations that allowed the model to perform the desired movement as accurately as possible while minimizing a physiologically based estimate of the effort (ie, metabolic cost) that muscles exerted to perform the movement.²⁵ This algorithm permits co-contraction of muscles if that pattern of activation satisfies the movement conditions and minimizes the effort cost.

Although we used the CMC algorithm to calculate the actual activation levels of muscles during the movement, there were limits placed on the maximal activation a muscle could experience. This limit was expressed as a percentage of its unimpaired force capacity. Unimpaired muscles were allowed to be fully activated, so these muscles had a force capacity of 100%. Paralyzed muscles were not allowed to be activated and had a force capacity of 0%. We varied rein-

nervated muscle activations among simulations to determine the minimum restored force capacity of reinnervated muscles necessary to perform the movement accurately. For each scenario, we performed a set of simulations in which the restored force capacity of reinnervated muscles was decreased from 100% in 5% increments. In a given simulation, all muscles reinnervated by shoulder nerve transfer had the same activation limit. We assumed passive force properties of reinnervated muscles to be unaffected, whereas paralyzed muscles could produce passive properties only. To fully represent a typical C5-C6 injury while limiting variability across simulations, muscles reinnervated by the musculocutaneous nerve transfer could generate force up to 20% of their unimpaired capacity in all simulations.²⁶

We determined the accuracy of a simulated movement by comparing the resulting joint angles of an unimpaired model with the joint angles in nerve transfer scenarios. A simulated movement that resulted in joint angles with less than 1° of average difference was classified as accurate.

We calculated joint moments for each muscle crossing the shoulder to determine whether muscular compensations were needed after nerve transfer. Moment, a measure of joint strength, is the product of muscle force and moment arm. Because the movement was the same for all successful simulations, the net joint moments were also the same. However, individual muscle contributions could vary based on altered coordination strategies. We evaluated the individual muscle moments for the point in the movement at which the net shoulder moments were maximal for the 3 scenarios, with reinnervated muscles permitted fully restored force capacity (100%) and expressed as a percentage of the net joint moment.

Finally, we evaluated the effort required by each scenario to perform the desired elbow flexion movement while dynamically stabilizing the shoulder, as described earlier. We calculated the movement effort using the effort function that was minimized by the CMC algorithm²⁵ and expressed as the ratio of the movement effort of the nerve transfer scenarios to the movement effort of the unimpaired scenario.

RESULTS

The minimum restored force capacity required by the axillary, suprascapular, and combined nerve transfer scenarios to perform the desired movement accurately was 25%, 40%, and 15%, respectively. The peak net joint moments occurred when the elbow was flexed to

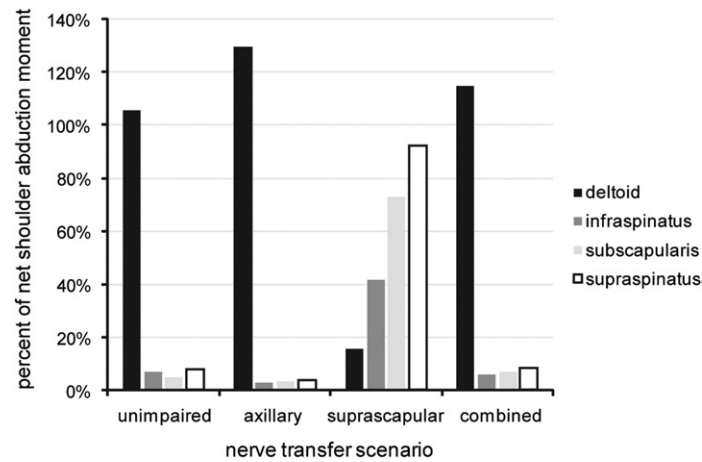


FIGURE 2: Shoulder abduction moment contributions by deltoid, infraspinatus, subscapularis, and supraspinatus at the point in the motion when the net shoulder joint moments were maximal. The moments are shown as a percentage of the net shoulder abduction moment and can exceed 100% owing to the simultaneous action of antagonist muscles. In the unimpaired, axillary, and combined scenarios, the deltoid was the primary contributor to net shoulder abduction moment. When the deltoid remained paralyzed in the suprascapular scenario, the infraspinatus, subscapularis, and supraspinatus muscles were the primary contributors to net shoulder abduction moment.

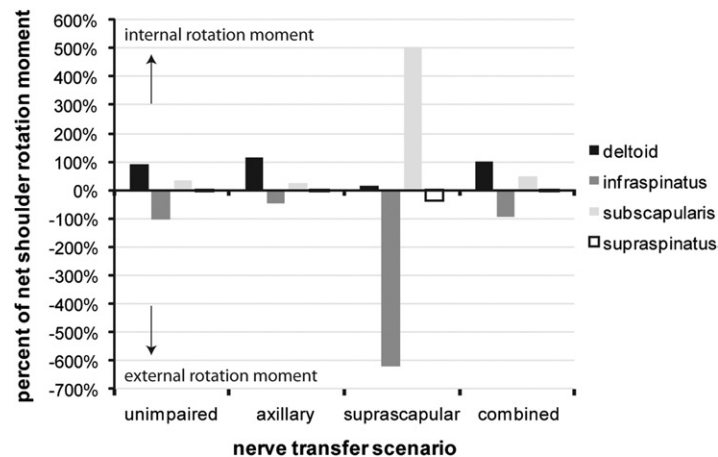


FIGURE 3: Shoulder rotation moment contributions by deltoid, infraspinatus, subscapularis, and supraspinatus at the point in the motion when the net shoulder joint moments were maximal. Shoulder rotation moments are shown as a percentage of net shoulder rotation moment, respectively. Positive values indicate an internal rotation moment, whereas negative values indicate an external rotation moment.

approximately 14°. For the axillary nerve scenario, the ability to perform the task with reduced restored force capacity was limited by the strength of the muscles that contribute to external shoulder rotation moment. That is, below 25% restored force capacity, external rotation moment was not sufficient to maintain the desired posture. In contrast, the suprascapular nerve and combined scenarios were limited by the ability of the muscles to generate sufficient positive shoulder abduction moment.

In the unimpaired scenario, the deltoid, infraspinatus, subscapularis, and supraspinatus were 4 of the primary

muscles that generated moments in the same direction as the net shoulder abduction moment. When restored by axillary or combined nerve transfer, the deltoid generated the largest shoulder abduction moment (Fig. 2). The moment generated by the deltoid exceeded 100% of the net moment for the unimpaired, axillary, and combined scenarios because of the simultaneous action of antagonist muscles (pectoralis major, latissimus dorsi, triceps long head, and biceps short head) that adduct the shoulder. Also in this posture, the restored deltoid generated an internal rotation moment consistent with that developed in the unimpaired arm (Fig. 3).

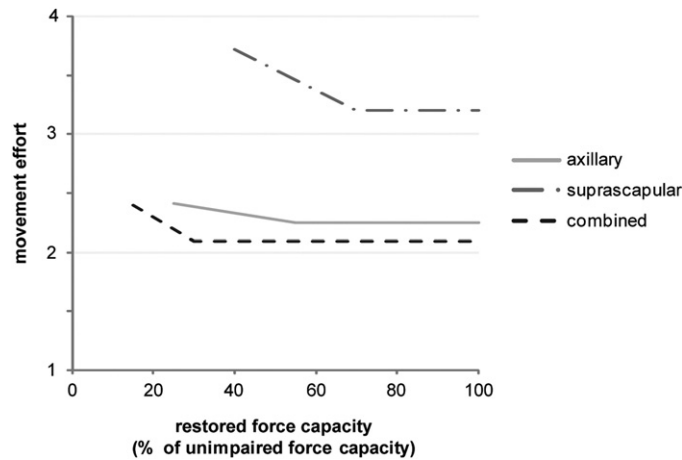


FIGURE 4: Relationship between restored force capacity and movement effort. The movement effort was expressed as the ratio of the effort required by the nerve transfer scenario to perform the desired movement to the effort required by the unimpaired scenario to perform the desired movement. The suprascapular scenario exhibited the highest movement effort, whereas the combined scenario exhibited the lowest movement effort. Movement effort decreased as restored force capacity increased.

When the deltoid remained paralyzed in the suprascapular scenario, the infraspinatus and subscapularis were more highly activated and generated shoulder abduction moments that were higher than those in the unimpaired scenario to compensate for deltoid weakness. However, as a consequence, the infraspinatus generated a large external rotation moment that opposed the net shoulder internal rotation moment and required antagonist action of the subscapularis to maintain the shoulder posture (Fig. 3).

The movement effort increased as the restored activation capacity of muscles in each scenario decreased (Fig. 4). The combined scenario exhibited the lowest movement effort of the 3 nerve transfer scenarios. The movement effort of the suprascapular scenario was approximately 50% higher than that of the axillary and combined scenarios.

DISCUSSION

We simulated 3 shoulder nerve transfer scenarios to elucidate how the magnitude of restored force capacity affects performance of a functional task. The minimum restored force capacity required to perform the intended movement correlates with the extent of muscle recovery achieved by nerve transfers and reinnervation of the target muscles. Nerve transfer scenarios that were able to perform the movement with lower restored force capacity required less muscle reinnervation compared to transfer scenarios requiring higher restored force capacity to perform the movement. The combined axillary and suprascapular nerve transfer required

the least restored force capacity for adequate functional movement. This finding concurs with clinical observations that combined nerve transfers provide enhanced functional recovery compared with single nerve transfers for brachial plexus injuries.^{4,6,27} Of the single nerve transfer scenarios, the axillary scenario outcome required a lower restored force capacity to perform the elbow flexion movement accurately.

We evaluated shoulder joint moments generated by muscles crossing the shoulder to identify the biomechanical role of muscles targeted by nerve transfers during functional movement. In the suprascapular scenario, the infraspinatus and subscapularis were required to contribute larger shoulder abduction moments to compensate for deltoid paralysis. Although compensation enabled the suprascapular simulations to perform the desired movement while the deltoid remained paralyzed, the movement was performed less efficiently. The unique musculoskeletal geometry and muscle architecture of the deltoid allowed it to elevate the shoulder without generating axial rotation moments that required antagonist action to overcome. The muscle properties of the infraspinatus and subscapularis were not as well suited for generating the required shoulder joint moments.

Several limitations of this study should be considered. We used a generic model representing average musculoskeletal properties of an adult male. These properties vary across subjects and with age and gender. Among all simulations, the musculoskeletal properties were held constant while restored force capacity was

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