Evaluation of the lower motor neuron integrity of upper extremity muscles in high level spinal cord injury

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Purpose: To evaluate the lower motor neuron (LMN) integrity of upper extremity muscles of persons with high tetraplegia (C1–C4) in order to determine muscles available for stimulation.

Methods: Fourteen subjects (23 arms) were evaluated for LMN integrity. Muscles that elicited a functional response (grade 3 or better) to surface electrical stimulation were considered to have intact LMN and good candidates for FES. Strength-duration (S-D) curves were generated on muscles that showed weak (less than grade 3) or no response to surface stimulation. Muscles were considered denervated if S-D curves were discontinuous or depicted steep, increasing amplitude for pulse durations greater than 1 m.

Results: Muscles for grasp and release had intact LMN in 19 of 23 (83%) arms. The wrist extensors and flexors and pronator were excitable in 17 (74%), 20 (87%) and 19 (83%) arms, respectively. The supinator demonstrated LMN lesion in 80% of the arms. Over 90% of the biceps muscles were unresponsive to electrical stimulation and 85% and 87% of the deltoid and supraspinatus muscles, respectively, were not electrically excitable. The latissimus dorsi and triceps muscles were typically innervated (78% and 91%, respectively) and slightly more than half (52%) of the pectoralis major muscles were excitable.

Conclusion: These data suggest that application of FES in high tetraplegia for hand and arm function would require augmentation because of the inability to stimulate the elbow flexors, deltoid and rotator cuff muscles. These data also show that several paralyzed proximal muscles with intact LMN that have been historically transferred to address shoulder paralysis in other patient populations are available for transfer and stimulation in the population with high level spinal injuries.

Keywords: tetraplegia; functional electrical stimulation; tendon transfers; upper extremity reconstruction

Introduction

Over the past three decades, considerable technological development has greatly improved the ability of functional electrical stimulation (FES) to restore movement following spinal cord injury (SCI), including upper^{1–3} and lower^{3–5} extremity movement, bladder and bowel function^{6,7} and respiratory capacity.^{8,9}

Successful application of any FES system requires that the lower motor neuron (LMN) and muscle fibers it supplies are intact and capable of responding to stimulus pulses of short duration.¹⁰ Although denervated muscle is capable of responding directly to stimulus pulses of long duration, the forcefulness of the contraction is usually insufficient for functional applications because only the muscle fibers in the vicinity of the stimulating electrode will respond. Through sufficient excitation of an intact LMN,

repeatable and forceful contraction of all portions of the muscle supplied by the nerve can be obtained.

With the exception of injuries to the cauda equina, the concomitant LMN damage that commonly occurs within two levels caudal to the level of SCI often goes unrecognized and has been a focus of few studies.^{11–15} Campbell and colleagues^{16,17} described denervation patterns in 24 persons with SCI between C5 and L3; 45% of those with thoracolumbar (T12–L3) lesions and over 7% of those with thoracic (T1–T11) lesions demonstrated LMN impairment. The number in each subgroup was not reported. In a study conducted by Peckham, *et al*,¹⁸ peripheral innervation to the muscles required for stimulated prehension and release was intact in the majority of 24 clients with SCI between C4 and C7. In a prior study from our institution¹⁹, 40% of 113 children and adolescents with SCI demonstrated LMN impairment; slightly more than 20% of 61 children with mid-cervical (C5–C7) tetraplegia had LMN impairment to key muscles for stimulated hand function and 70% of children with

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paraplegia had LMN lesions that inhibited their use of FES for standing and walking.

The literature describing the occurrence of LMN lesions in persons with high tetraplegia (C1-C4) is even more limited. Doerr and Long²⁰ found LMN lesions in the biceps muscle in three of four persons with C4 SCI. Peckham¹⁸ identified LMN lesions in one of three subjects with C4 SCI; he suggested that similar LMN lesions of proximal shoulder muscles should also be anticipated, and may greatly reduce the benefits of FES for persons with C4 level SCI unless an additional power source can be provided. Reports by Hoshimiya and Nathan support Peckham concerning the need for alternative power sources. Hoshimiya²¹ required a balance forearm orthosis (BFO) to provide proximal stability when he employed intramuscular stimulation controlled by sip and puff sensors for hand grasp and release and elbow extension and flexion. Nathan²² utilized an overhead sling for shoulder support when he applied surface stimulation activated by voice control for hand and arm function. In both studies, FES, combined with orthotic support at the shoulder, enabled several clients with high tetraplegia to perform simple table top activities such as writing, drinking and eating. Our pilot work on FES and high tetraplegia^{23,24} also confirmed the presence of LMN lesions in muscles innervated at C5 and reaffirmed the need for alternative power sources at the elbow and shoulder. We performed a bipolar muscle transfer of the paralyzed but electrically excitable latissimus dorsi to overcome the inability to stimulate the elbow flexors. In conjunction with an overhead sling, stimulated elbow flexion and FES for grasp and release enabled an adolescent with a C4 level SCI and C5 LMN impairment the ability to perform hand-to-mouth activities after set-up. The limitation of the FES system for this adolescent included lack of voluntary or stimulated shoulder external rotation and the cosmesis, awkwardness, poor reliability and set-up difficulty associated with the overhead sling.

The frequency of LMN lesions in the population with SCI justifies careful evaluation especially when applications of FES are being considered. While the nature of LMN lesions of muscles of the hand in persons with mid-cervical tetraplegia (C5-C7) has been formally explored, little has been done to determine the tendency of LMN lesions of proximal muscles of persons with high level spinal injuries (C1-C4). The purpose of this study was to evaluate the nature and tendency of LMN lesions in select upper extremity muscles in young people with high tetraplegia, to determine muscles available for stimulation. The significance of the study is derived from gains realized by persons with mid-cervical SCI who have been outfitted with the Freehand System[®] (NeuroControl Corporation, Cleveland, Ohio, USA) an 8-channel totally implantable FES system designed to restore hand function to persons with C5 SCI^{1,2}, and its potential to provide upper extremity function to persons who have sustained high level spinal injuries.

Methods

Subjects

Fourteen subjects (23 arms) with high level tetraplegia (C1-C4) were evaluated. As shown in Table 1, each subject sustained a traumatic onset spinal injury and, at the time of evaluation, were at least 1 year post injury. So as not to skew the data, subjects were excluded from this study if the nature of their injury was viral (ie: transverse myelitis), vascular or iatrogenic (ie: tumor removal; cardiac surgery); these types of pediatric SCI almost always result in some degree of LMN lesion. One subject (two arms) had a C2 level SCI and two subjects (four arms) had C3 level injuries; the remaining 11 subjects (17 arms) had injuries at the C4 level.

Test procedure

Muscle responses to surface electrical stimulation were evaluated using the UltraStim[™] (Neuromedics, Inc., Clute, TX, USA). For each muscle, a biphasic waveform was applied with a pulse duration between 0–200 us, frequency of 12 or 16 hertz and a current adjusted to elicit a muscle contraction. Each muscle that elicited at least a grade 3 stimulated response to surface stimulation was considered to have intact lower motor neuron. For each muscle that elicited a weak (less than grade 3) or no response, a strength-duration (S-D) curve^{25,26} was generated using amplitudes that elicited a visible twitch response to pulse durations of 100, 50, 10, 3, 2, 1, 0.8, 0.6, 0.4, 0.3 and 0.1 m, S-D curves were generated using the Dynatron 438 (Enraf-Nonius, West Germany). Muscles were considered denervated if S-D curves were discontinuous or depicted a steep, increasing amplitude for pulse durations greater than 1 m. The shape of the S-D

Table 1 Subject profiles

Subject	Age in years	Cause of injury	Asia classification	
			Lue	Rue
1	5	MVA	C2	C2
2	17	football	C3	C3
3	8	MVA	C3(incomplete)C3(incomplete)	
4	11	gymnastics	C4	C4
5	16	diving	C4	C4
6	12	MVA	C4	C4
7	17	diving	C4	C4
8	18	MVA-pedestrian	C4	C4
9	16	MVA	C4	C4
10	14	MVA	C5*	C4
11	16	fall	C5*	C4
12	17	MVA	C5*	C4
13	11	diving	C5*	C4
14	16	MVA	C4	C5*

Sample consists of 14 subjects (23 arms) with high tetraplegia. *Denotes motor level of mid-cervical level SCI and was excluded from analyses

curve is considered diagnostic of LMN integrity because a point is reached at which denervated muscle is not capable of responding with a twitch while an innervated muscle can.^{25,26,27} As shown in Figure 1, in a normally innervated muscle, no increase in the stimulus amplitude beyond rheobase (the amplitude at which a threshold motor response is obtained when an essentially infinite pulse duration is applied) is needed to elicit a threshold response for pulse durations from 1–100 m. In contrast, a denervated muscle (Figure 1) will require increased amplitude to elicit a threshold response for pulse durations shorter than the rheobase duration and will not respond to durations shorter than 1 m. Discontinuous curves, indicative of partial denervation (Figure 1), reflect elements of both an innervated and denervated muscle S-D profile.^{25,26,27}

The authors chose to employ the S-D test (rather than electromyography (EMG) for several reasons. First, S-D testing has been shown to be a reliable means to determine LMN integrity in children with SCI.²⁸ Strength-duration testing is non-invasive and can be conducted by trained and licensed physical or occupational therapists as part of the comprehensive physiological evaluation. In addition, a thorough EMG analysis requires volitionally controlled low-level and maximum contractions by the patient. The subjects in this study lacked voluntary control over the muscles under investigation.

Eleven muscles were tested in the proximal arm or shoulder including the biceps, brachioradialis, brachialis, middle deltoid, supraspinatus, triceps, pectoralis major and latissimus dorsi. In addition, key hand and forearm muscles for grasp and release, forearm rotation and wrist motion were also tested.

One therapist (primary author) experienced in FES and electrodiagnostic testing using surface electrical stimulation performed all of the evaluations. For several muscles that demonstrated inconsistent responses to stimulation or yielded results indicative of partial denervation, interpretation of S-D curves were confirmed by a physical therapist who is a neurology certified specialist.

Results

Tables 2 and 3 show, for each subject, the innervation status of the tested distal and proximal muscles, respectively. The muscles for grasp and release (finger and thumb flexors and extensors and thumb adductor and abductor) were stimlatable in 19 of 23 (83%) arms. In three hands (13%), all of the muscles for grasp and release had LMN lesion involvement; one hand tested partially denervated in the finger and thumb extensors. Similarly, the wrist extensors and flexors and pronator teres were stimlatable in 17 (74%), 20 (87%), and 19 (83%) arms, respectively. The supinator demonstrated LMN lesion in all but five arms (79%). As shown in Table 3, over 90% of the biceps muscles were unresponsive to electrical stimula-

tion and 85% and 87% of the deltoid and supraspinatus muscles, respectively, were not electrically excitable. The implications of these LMN lesions to the application of FES for persons with high tetraplegia are described in Table 4.

Discussion

The results of this study support earlier findings^{18,20,21,22} suggesting a relatively high tendency for LMN lesions of proximal arm muscles following high tetraplegia, especially C3 and C4 level SCI. In this series of 24 arms, LMN lesions of the elbow flexors and proximal shoulder muscles were present in 91% and more than 80% of the cases, respectively. For the subjects with C3 and C4 SCI, the inability to stimulate these muscles was anticipated since the muscles are supplied by C5, just caudal to the SCI. Conversely, LMN lesions caudal to C5 were few; only one subject (#5) would be excluded from FES for grasp and release due to the inability to excite distal forearm and hand muscles. Unfortunately, however, little is gained if stimulated hand function is restored in the absence of elbow flexion and proximal stability.

Balanced forearm orthoses (BFO)²⁹ or overhead slings²³ are unable to provide the level of proximal stability or arm control necessary to facilitate successful use of a clinical FES hand system by persons with motor complete high tetraplegia.^{21,23} Both types of orthoses are designed to support the weight of the limb so that weak shoulder muscles (typically innervated at C5) can move the arm through a purposeful range;³¹ in the absence of voluntary or FES-excitability muscles both the BFO and overhead sling may simply provide a support to protect the glenohumeral joint. Nevertheless, in our experience, few persons would accept these orthoses on a day-to-day basis because of difficulty in set-up and cosmesis.

Figure 1 Diagram depicting approximate regions on the S-D plot which define the LMN innervation status

Table 2 Innervation status of distal upper extremity muscles

Subject	Level	Supinator C5-6		Pronator C6-7		ECRL C6-8		ECRB C6-8		ECU C6-8		FCU C7-T1		FCR C6-8		EDC C6-8		EPL C6-8		FDS C7-T1		FDP C7-T1		FPL C6-T1		AdP C6-T1		AbPB C6-T1	
		L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
1	C2	I	I			I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
2	C3					I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
3	C3					I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
4	C4					I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
5	C4																												
6	C4					I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
7	C4					I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
8	C4					I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
9	C4					I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
10	C4/5	*				*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I
11	C4/5	*				*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I
12	C4/5	*	I			*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I
13	C4/5	*				*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I
14	C4/5	*	I			*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I	*	I

I - Innervated; Lightly Shaded - Partial Denervation; Heavily Shaded - Denervated; NT - Not Tested; *C5 Motor Level (excluded from study)

I - innervated; Lightly shaded - Partial Denervation; Heavily shaded - Denervated; NT - not tested; *C5 Motor Level (excluded from study)

Table 3 Innervation status of proximal upper extremity muscles

Subject	Level	Supra- spinatus (C4-6)		Biceps (C5-6)		Brachio- radialis (C5-6)		Brachialis (C5-6)		Middle Deltoid (C5-6)		Serratus Anterior (C5-7)		Teres Minor (C5-7)		Latissimus Dorsi (C5-8)		Triceps (C6-8)		Pectoralis Major (C5-8,T1)	
		L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
1	C2	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
2	C3											NT	NT					I	I		
3	C3											NT	NT	I	I	I	I	I	I	I	I
4	C4											NT	NT		NT	I	I	I	I	I	I
5	C4																				
6	C4											NT	NT			I	I	I	I		I
7	C4											I	I	I	I	I	I	I	I	I	I
8	C4											I	I	I	I	I	I	I	I	I	I
9	C4		I										I	I	I	I	I	I	I		
10	C4/5	*		*		*		*		*		*	I	*	I	*	I	*	I	*	
11	C4/5	*		*		*		*		*		*	NT	*		*	I	*	I	*	I
12	C4/5	*		*		*		*		*	I		I	*	I	*	I	*	I	*	
13	C4/5	*		*		*		*		*	I		I	*	I	*	I	*	I	*	
14	C4/5		*		*		*		*	*		NT	*	I	*	I	*	I	*		*

I - Innervated; Lightly Shaded - Partial Denervation; Heavily Shaded - Denervated; NT - Not Evaluated; *C5 Motor Level (excluded from study)

I - Innervated; Lightly shaded - Partial denervation; Heavily shaded - Denervated; NT - not evaluated; *C5 Motor level (excluded from study)

However, principles of traditional soft tissue reconstruction may provide successful techniques to overcome the barriers associated with stimulating muscles with LMN lesions. For example, we^{2,30} and others³² have successfully transferred and stimulated paralyzed but electrically excitable muscles to overcome the problems related to stimulating hand muscles with LMN lesions in persons with mid-cervical level SCI. One adolescent FES user underwent transfer and stimulation of the paralyzed flexor carpi ulnaris to augment stimulated finger flexion.³³ Users of the Freehand System[®], (NeuroControl Corporation, Cleveland, Ohio, USA) routinely undergo tendon transfers and stimulation of paralyzed muscles to take the place of the paralyzed and denervated radial wrist extensors³² and other key muscles for grasp and release.² Transfer of paralyzed muscles for the purpose of FES has been largely influenced by the techniques and principles of tendon transfers for voluntary hand function.^{34–36}

Tendon transfers have also been performed to restore voluntary elbow flexion and shoulder external rotation in persons with a variety of diagnoses including arthrogryposis, poliomyelitis, brachial plexus injuries and traumatic nerve injuries.^{37–44} Surgical restoration of voluntary elbow flexion has been successfully obtained following transfer of the triceps muscle,³⁷ pectoralis major and/or minor muscles^{38–41} and the latissimus dorsi muscle.^{42–44} Voluntary external rotation has also been achieved via transfer of the latissimus dorsi muscle. As outlined in Table 4, this study showed that although UMN lesions were present, LMN integrity was intact in the majority of the latissimus dorsi (78%) and triceps (91%) muscles rendering them available for transfer and stimulation. Slightly more than 50% of the

Figure 2 An adolescent with C4 level SCI and LMN lesion of the biceps. The latissimus dorsi muscle was transferred and stimulated for elbow flexion. Note the support provided at the posterior aspect of the arm to prevent the shoulder from internal rotation

Table 4 Number of stimutable back, shoulder and elbow muscles among the 23 arms studied

<i>Muscle</i>	<i>Innervated (Electrically Excitable)</i>	<i>LMN Lesion (Not Electrically Excitable)</i>	<i>Implications to application of FES</i>
Latissimus Dorsi	18 (78%)	5 (22%)	Stimulatable; can be transferred and stimulated for elbow flexion external rotation
Supraspinatus	3 (13%)	20 (87%)	Not stimulatable; therefore require soft tissue procedure or orthoses for shoulder stability
Pectoralis Major	12 (52%)	11 (48%)	Stimulatable; can be transferred and stimulated for elbow flexion or shoulder forward flexion or stimulated in original position for shoulder adduction
Middle Deltoid	4 (17%)	19 (83%)	Not stimulatable; therefore require soft tissue procedure or orthoses for shoulder stability
Biceps			
Brachioradialis	2 (2%)	21 (91%)	Not stimulatable; therefore require muscle transfer for elbow flexion
Brachialis			
Triceps	21 (91%)	2 (2%)	Stimulatable; can be transferred and stimulated for elbow flexion or stimulated in original position for elbow extension

As expected, the elbow flexors, middle deltoid and supraspinatus were generally denervated (not stimulatable) but the triceps, pectoralis major and latissimus dorsi were innervated (stimulatable). The ability to stimulate the later three muscles is encouraging since for each of them, the muscle can be transferred so that when it is stimulated it can provide elbow flexion or shoulder function

pectoralis major muscles were also electrically excitable and available for tendon transfer.

In our pilot work, we successfully transferred and stimulated the paralyzed but excitable latissimus dorsi to take the place of the paralyzed and unresponsive elbow flexors. With stimulation to the latissimus dorsi, elbow flexion was obtained (Figure 2), enabling an adolescent with C4 tetraplegia to utilize a FES hand system to feed himself.²³ Lack of voluntary external rotation and the inability to stimulate the infraspinatus because of LMN lesion limited the clinical usefulness of FES for this client. Results of the current study provide information on several paralyzed muscles with intact LMN that could be transferred for stimulated shoulder external rotation. For example, the latissimus dorsi could be transferred to the external rotators for stimulated shoulder external rotation and the triceps or pectoralis major transferred for stimulated elbow flexion.

Conclusion

Lower motor neuron lesions of key muscles for stimulated shoulder and arm function may be prevalent in persons with high tetraplegia and therefore, may greatly reduce the potential benefits of FES for this population. However, there was a tendency for some muscles which historically have been transferred to restore voluntary elbow and shoulder motion in other patient populations, to be excitable by electrical stimulation. Transfer and stimulation of paralyzed muscles with intact LMN should be further studied as a means to address LMN lesions of key muscles needed for successful application of upper extremity FES systems in persons with high level tetraplegia.

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