Advanced Assessment of the Upper Limb in Tetraplegia: A Three-Tiered Approach to Characterizing Paralysis

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Background: More than half of all individuals who sustain a spinal cord injury (SCI) experience some degree of impairment in the upper limb. Functional use of the arm and hand is of paramount importance to these individuals. Fortunately, the number of clinical trials and advanced interventions targeting upper limb function are increasing, generating optimism for improved recovery and restoration after SCI. New interventions for restoring function and improving recovery require more detailed examination of the motor capacities of the upper limb. **Objectives:** The purpose of this article is to introduce a three-tiered approach to evaluating motor function, with specific attention to the characteristics of weak and fully paralyzed muscles during acute rehabilitation. The three tiers include (1) evaluation of voluntary strength via manual muscle testing, (2) evaluation of lower motor neuron integrity in upper motor neuron–paralyzed muscles using surface electrical stimulation, and (3) evaluation of latent motor responses in paralyzed muscles that exhibit a strong response to electrical stimulation, using surface electromyographic recording electrodes. These characteristics contribute important information that can be utilized to mitigate potential secondary conditions such as contractures and identify effective interventions such as activity-based interventions or reconstructive procedures. Our goal is to encourage frontline clinicians – occupational and physical therapists who are experts in muscle assessment – to consider a more in-depth analysis of paralysis after SCI. **Conclusion:** Given the rapid advancements in SCI research and clinical interventions, it is critical that methods of evaluation and classification evolve. The success or failure of these interventions may depend on the specific characteristics identified in our three-tiered assessment. Without this assessment, the physiological starting point for each individual is unknown, adding significant variability in the outcomes of these interventions. **Key words**: *assessment, electrical stimulation, electromyographic recording, lower motor neuron, recovery, tetraplegia, upper extremity*

Current statistics show that approximately 17,500 new spinal injuries occur annually, with approximately 58% resulting in complete or incomplete tetraplegia. Therefore, more than half of all sustained spinal cord injuries (SCIs) manifest in some degree of impairment of the upper limb.[1] Such a large comparative proportion of people with tetraplegia warrants increased attention to the evaluation and treatment of the upper limb. Functional use of the arms and hands is of paramount importance to individuals with tetraplegia.[2-5] Fortunately, new interventions and clinical trials directed at restoring upper limb function after SCI are emerging. The purpose of this article is to elucidate a contemporary approach to evaluating the upper limbs of people with cervical SCI. New interventions for restoring function and improving recovery require more detailed examination of the motor capacities of the upper limb. Specifically, characteristics of weak and fully paralyzed muscles deserve more attention early after injury. Two such characteristics include lower motor neuron (LMN) integrity and the presence of latent, or unrecognized, voluntary motor responses in muscles that are clinically classified as paralyzed. These novel characteristics are currently not evaluated as a standard of care in upper limb assessments of people with tetraplegia, however information gained from such evaluations has the potential to influence interventions across the continuum of upper limb care.

There is reason for optimism as there are increasing numbers of trials dedicated toward SCI recovery as well as remediation of effects through rehabilitative interventions. Advancements in numerous potential

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therapeutics and interventions include acute surgical decompression, neuroprotection, neural repair, cell replacement, activity-based rehabilitation, and medical devices requiring surgical implantation such as neuroprosthetics, epidural stimulation, and brain machine–computer interface.[6] From 2012 through 2016, there was a 22% increase in clinical trials utilizing clinical outcome assessments focused on arm or hand function[7] suggesting a greater focus on restoration of the upper limb. Additionally, there are advancements in clinical interventions designed for improving function in the upper limb, such as nerve and tendon transfer procedures.[8-12] Consequently, it is important to address previously underevaluated characteristics of muscles, specifically weak or fully paralyzed muscles, as potential endpoints for determining the extent of neurological recovery resulting from biological or rehabilitative interventions. Researchers are continually challenged to identify refined measures of the impact of research and clinical interventions.

In the context of an increasing number of individuals living with tetraplegia combined with advancements in upper limb SCI management, it is increasingly important that methods of upper limb evaluation evolve. This article will describe the relevance of assessing LMN integrity and latent motor responses in people with cervical SCI during acute inpatient rehabilitation. These characteristics of muscle function can be evaluated noninvasively by occupational and physical therapists who are experts in voluntary muscle testing. Early assessment of LMN pathology and the potential existence of latent voluntary motor responses should be a standard of care that contributes to mapping future interventions for full maximization of upper limb function in individuals with tetraplegia.

Evidence Supporting the Importance of Characterizing Paralysis

LMN pathology in tetraplegia

A common approach to most SCI interventions and research aimed at restoring motor function is a singular focus on creating strong voluntary muscles. Of course, it is vital to focus on strengthening, especially throughout the rehabilitation process. However, such attention to strengthening muscles that exhibit fair to moderate strength often means less attention to muscles that are completely paralyzed or extremely weak. Information obtained from specialized evaluation of paralyzed muscles provides valuable information with implications for guiding treatment decisions, developing recovery prognostics, and conducting analyses of interventional outcomes.

SCI is often considered primarily a central nervous system disorder impacting only the upper motor neuron (UMN), with less attention paid to LMN damage. However, in addition to UMN damage, direct trauma to the ventral horn, nerve root, or axon upon exit from the intervertebral foramen generally results in LMN damage as well. This damage to the LMN, masked by the paralysis caused by UMN damage, is permanent.[13] It is important to note that permanency of LMN damage refers specifically to direct spinal cord trauma and may not apply to root avulsions or brachial plexus injuries.[14,15] LMN damage is not specifically evaluated by most clinicians, outside of clinical observations of hypertonicity or flaccidity, which offer clues about LMN status. For example, the clinical characteristics of paralyzed muscles such as hyporeflexia, hypotonia, and longer term muscle atrophy are indicative of LMN pathology. As such, following the period of spinal shock, clinicians may observe sustained flaccidity or absence of spasticity in these paralyzed muscles as compared to persons with an intact LMN. A variety of electromyographic (EMG) testing is available to characterize nerve responses after SCI,[16,17] however they are not currently employed as a standard of care for all individuals with cervical SCI. Beyond observation of these clinical characteristics of paralyzed muscles, there is not a formal differentiation between these mechanisms of paralysis during acute rehabilitation because, in a practical sense, the muscles are no longer under voluntary control. However, the status of the LMN can be assessed with relative ease using surface electrical stimulation.[14,17-19] This approach is beneficial as a preliminary test of LMN integrity.

Latent motor responses in tetraplegia

An additional characteristic of upper limb paralysis that deserves further exploration is the existence of latent motor responses in individuals classified with motor complete SCI. Latent, or *existing yet clinically undetected motor responses*, can be detected through surface EMG recording. Historical electrophysiological studies have supported the presence of descending control below the injury level after complete SCI.[20,21] Recent studies reveal that individuals with motor complete cervical SCI can generate latent motor responses in lower limb muscles.[22-24] Moss and colleagues[24] describe preliminary results from 12 participants (24 lower limbs) with chronic motor complete cervical SCI. All participants were at least 1-year post injury with a median time post injury of 6 years. Surprisingly, significant repeatable activity in response to volitional movement attempts was recorded in at least 10 of 16 muscles below the knee (bilaterally) in *each* of the 12 participants. In other words, statistically detectable muscle activity in response to volitionally attempted movements was identified in 89% of the muscles evaluated in this study even though every muscle had been classified grade 0. This study was expanded to a cohort of 24 subjects (48 lower limbs) using more stringent statistical criteria for identifying surface EMG signals that were correlated with voluntary attempts to move.[22] Using these more stringent criteria, residual voluntary motor function was still found in 50% of all limbs and 67% of all participants. The possibility exists that, in some cases, responses were due to sensory-mediated reflexes or other indirect activation. However, in the majority of cases, the participant was able to turn on *and turn off* the myoelectric activity on command, a strong indicator of a direct voluntary connection. These results demonstrate that some, if not a majority, of individuals with motor complete SCI retain voluntary muscle activity in muscles previously determined to be clinically paralyzed. The activity in these muscles is generally not sufficient to produce functionally useful movements and no visible or palpable movement could be observed in 98% of the muscles tested. As a result, *this ability is overlooked in a standard clinical examination*, which relies on visible or palpable movements. These observations were made in people with chronic tetraplegia, leading to the question of whether more functional voluntary muscle responses would have ultimately been achieved had latent motor responses been detected in the acute stage of injury and been the focus of targeted rehabilitation. Studies to examine latent motor responses in paralyzed upper limbs of people with cervical SCI are currently underway at this center.

Current Status of Upper Limb Assessment and Classification

Current practices for assessing the upper limb in tetraplegia are conducted as part of the International Standards for the Neurological Classification of Spinal Cord Injury (ISNCSCI). This classification has been well described in the literature[25] and is conventionally accepted as the gold standard for classifying injury level and assessing recovery. The International Classification for Surgery of the Hand in Tetraplegia (ICSHT) is used in addition to the ISNCSCI as a more detailed classification of the upper limb for the purposes of planning reconstructive surgeries.[26,27] While there is overlap between the two classification systems, the ICSHT assesses specific muscle motor function, rather than the combined strength of synergistic muscles. For example, the ICSHT requires grading of the two radial wrist extensors (ECRL and ECRB) separately, whereas the ISNCSCI requires grading of wrist extension strength without differentiating between the two extensors. Another difference is related to the strength requirements of the classifications. The ISNCSCI requires grade 3 strength, whereas the ICSHT requires grade 4 strength to attain a classification level. Both classifications provide a useful index of motor function in the tetraplegic upper limb, however attention to characterizing paralysis and measuring latent motor function has the potential to expand these classifications and potentially enhance opportunities to predict recovery.

Expanding the current scope of upper limb motor assessment will complement current classifications for SCI. Evaluating LMN status and latent motor responses represents an evolution of upper extremity assessment that is critical for determining the impact of evolving upper limb interventions for people with tetraplegia. Examination of these characteristics requires attention to the extremely weak and fully paralyzed muscles that are often not the focus of rehabilitative interventions. This comprehensive characterization of the upper limb will contribute important information for guiding and measuring the outcomes of interventions designed to improve function.

Three-Tiered Approach to Upper Limb Assessment

Conventional assessment of the tetraplegic upper limb includes voluntary strength, range of motion, sensation, proprioception, spasticity and tone, pain, and function.[17,18,28] We propose a three-tiered approach for expanding assessment of motor function through a detailed characterization of paralyzed muscles:

- Tier 1: Evaluation of voluntary strength via manual muscle testing (MMT)
- Tier 2: Evaluation of LMN integrity in UMN-paralyzed muscles using surface electrical stimulation/stimulated manual muscle testing (SMMT)
- Tier 3: Evaluation of latent motor responses in paralyzed muscles (MMT grade 0) that exhibit a strong response to electrical stimulation using surface EMG recording electrodes (SMMT grade 3-5).

Occupational and physical therapists are ideally suited to conduct this testing during acute rehabilitation, ideally at the time of admission and prior to discharge. These health professionals have expertise in voluntary muscle assessment and in the use of electrical stimulation, which facilitates their understanding of the processes involved in assessing LMN damage and latent motor responses. We recommend a less invasive approach using surface electrodes for two reasons. First, surface electrical stimulation is a clinically accessible, easy method for identifying whether the LMN is responsive. Second, the use of surface recording electrodes will capture a broader range of residual motor unit potentials under voluntary control compared to precise localization of a needle EMG. This approach is recommended as an initial exploration of LMN pathology and potential latent responses. Additional diagnostic testing can be utilized at the discretion of the clinician.

Target muscles

Detailed evaluation of motor function in the tetraplegic upper limb should ideally expand to include muscles that are not represented in current classification systems. A more comprehensive set of muscles would include key muscles/movements included in the ISNCSCI, supplemented by muscles included in the ICSHT, as well as additional key muscles that contribute to functional arm movement and hand grasp (**Table 1**). For example, a therapist evaluating elbow flexion strength would identify the specific contributions of the biceps and the brachioradialis by performing the test with the forearm positioned in supination as well as at neutral. With the forearm at neutral, the brachioradialis can be visualized and palpated to determine its strength in conjunction with the biceps. Similarly, while evaluating wrist extension strength, the therapist would differentiate between the extensor carpi radialis longus and the extensor carpi radialis brevis by noting the direction of pull of the wrist extensor and palpating the tendons at their point of insertion. Additional complementary muscles from the ICSHT include pronator teres, flexor carpi radialis, extensor digitorum communis, extensor pollicis longus, and both flexor digitorum communis and profundus. Additional muscles that are not included in either classification but contribute to upper limb function include the deltoid, supinator, flexor pollicis longus, dorsal interossei as well as abductor pollicis brevis and adductor pollicis. Consequently, the inclusion of additional muscles adds to a more comprehensive and detailed approach to the evaluation of the upper limb. It is noteworthy that the current ISNCSCI allows for documentation of additional, non-key muscles.

Figure 1 displays the three-tiered approach beginning with standard evaluation of voluntary strength in upper limb muscles. Each tier is described in detail below.

Tier 1: Voluntary muscle strength testing

Evaluation of voluntary muscle strength of the recommended muscles should be performed according to conventional MMT techniques.[29]

Table 1. Expanded muscle set

ISNCSCI	+	ICSHT	+	Other key muscles
Elbow flexors (biceps, brachialis)		Brachioradialis		Deltoid
Wrist extensors (ECRL, ECRB)		ECRL		Supinator
Elbow extensor (triceps)		ECRB		FPL
Finger flexors to the middle finger (FDP)		PT		Dorsal interossei
		FCR		AdP
		EDC		AbPB
		EPL		
		FDS		
		FDS and FDP		

Note: AbPB = abductor pollicis brevis; AdP = adductor pollicis; EDC = extensor digitorum communis; ECRL = extensor carpi radialis longus; ECRB = extensor carpi radialis brevis; EPL = extensor pollicis longus; FCR = flexor carpi radialis; FDP = flexor digitorum profundus; FDS = flexor digitorum superficialis; FPL = flexor pollicis longus; PT = pronator teres.

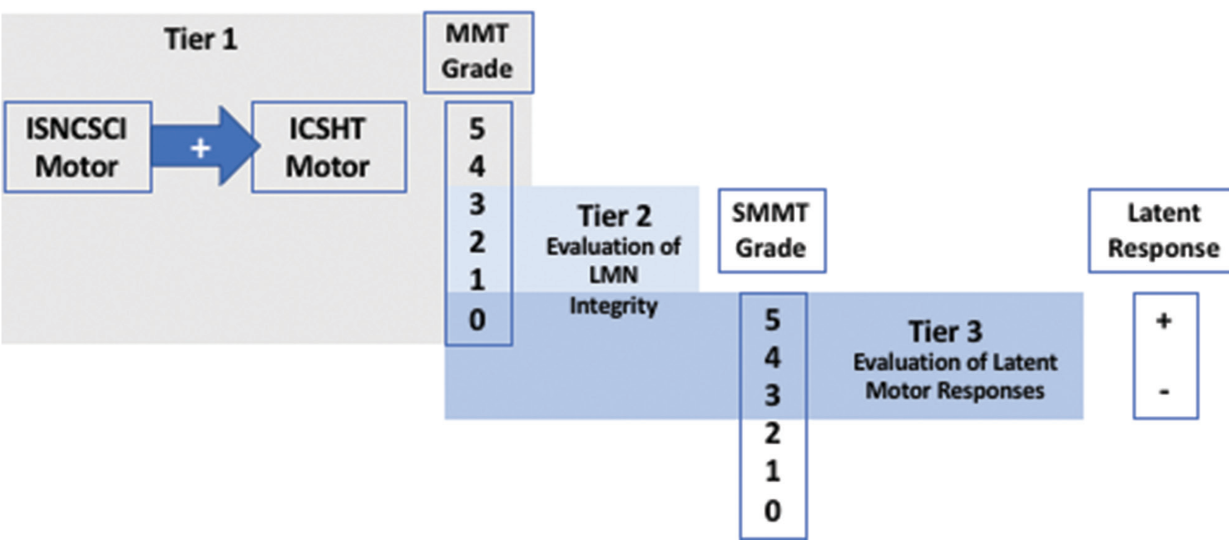

Figure 1. A three-tiered approach to upper limb assessment in tetraplegia. Tier 1 consists of conventional voluntary strength testing. Tier 2 evaluates electrical excitability to identify lower motor neuron (LMN) integrity in muscles that are weak or fully paralyzed (grade 0-3). Tier 3 evaluates the presence of latent motor responses in upper motor neuron–paralyzed muscles (grade 0). ICSHT = International Classification for Surgery of the Hand in Tetraplegia; ISNCSCI = International Standards for the Neurological Classification of Spinal Cord Injury; MMT = manual muscle testing; SMMT = surface electrical stimulation/stimulated manual muscle testing.

Tier 2: Evaluation of LMN integrity (electrical excitability)

Muscles that demonstrate less than good to normal voluntary function (MMT grade 3 or less) should have surface electrical stimulation applied as a secondary approach to characterizing nerve function. Similar to voluntary strength testing, muscle responses to electrical stimulation should be graded using the same guidelines as for MMT, with the exception that electrical stimulation takes the place of voluntary muscle activation. Therefore, each muscle will elicit an SMMT score ranging from 0 to 5. Contraction of all muscles with an intact LMN in the upper extremity can be obtained using a maximum stimulus of 100 mA, 300 µs at 30 Hz from a commercially available neuromuscular stimulator that is available in most therapy departments. Electrode placement is best guided by use of a motor point chart.[29,30]

Individual muscle responses to electrical stimulation can be aggregated to determine specific zones of innervation and denervation. Zones of innervation/denervation have been described by Coulet and colleagues[19] and expanded upon by Bryden and colleagues.[14] **Table 2** demonstrates these zones. Zone 1 represents normal voluntary strength that is expected above the spinal cord lesion. Electrical stimulation responses in these muscles would be strong but would not be indicated due to normal voluntary strength. Zone 2 manifests in a mixture between normal voluntary strength and voluntary weakness expected at the upper bound of the spinal cord lesion. This mixed border zone may have varying responses to electrical stimulation depending on whether there is damage to the LMN. Therefore, weak voluntary muscles that do not demonstrate greater strength with stimulation are presumed to have partial LMN damage, whereas those that display greater strength have an intact LMN despite partial UMN damage. Zone 3, the primary lesion site, is characterized by UMN damage that is likely accompanied by significant LMN damage. Upper motor neuron paralyzed muscles in this zone have no response to electrical stimulation due to the loss of LMN function. Zone 4 represents another border zone consisting of UMN paralysis and varying degrees of LMN damage, as indicated by variable response to electrical stimulation. The expectation for Zone 5 is that all muscles demonstrate UMN paralysis, however the LMN is intact and the sublesional muscles respond strongly to electrical stimulation.

The use of surface electrical stimulation provides a straightforward approach to deeper understanding of upper limb paralysis after SCI by identifying the presence of each of the zones as well as the size of the injured metamere.[19] The size of the zones can be variable across individuals with cervical SCI,[19] and not all people with cervical SCI will present each of the zones. For example, some individuals may not exhibit any LMN damage, and some may display larger areas of mixed innervation. This variability has implications for recovery and functional restoration; therefore it is critical that we include advanced methods of evaluation as a standard of care early after injury to maximize function of the upper limb.

Precautions should be taken when applying electrical stimulation. Contraindications include demand pacemakers and certain cardiac conditions, pregnancy, internal fixators, or open wounds.[31] Some individuals experience adverse sensation from electrical stimulation, however adjustment of electrode placement and stimulation parameters

Table 2. Innervation/denervation patterns after spinal cord injury

Zone	Location	Voluntary muscle characteristics	Electrical stimulation responses	Surface EMG utility
1	Supralesional	Voluntary muscles are strong; UMN intact; reflexes intact	Strong, but not indicated	Present, but not indicated
2	Supralesional to upper bound of lesion	Partial voluntary strength; UMN partially damaged; may or may not have LMN damage	Weak response if LMN damage present; stronger than voluntary if LMN is intact	Present, but not indicated
3	Lesion	Voluntary muscle paralyzed; UMN damage; LMN damage	No response	Not indicated since endpoint has LMN damage
4	Sublesional	Voluntary muscle paralyzed; UMN damage; partial LMN damage and partial LMN intact	Weak response	Useful in UMN grade 0 muscles with weak response to stimulation
5	Sublesional	UMN paralysis; LMN intact	Strong response	Useful in UMN grade 0 muscles with strong response to stimulation

Note: LMN = lower motor neuron; UMN = upper motor neuron.

can remediate this effect. Secondary conditions such as spasticity and joint contractures should be carefully evaluated as they may prevent accurate assessment of UMN and LMN status.

Tier 3: Evaluation of latent motor responses in paralyzed muscles

The third element in the characterization of upper limb nerve responses after cervical SCI involves the measurement of latent motor responses in UMN paralyzed muscles with an intact LMN (**Figure 1**). Therefore, this testing should only be conducted in Zone 4 and 5 muscles — muscles that are UMN grade 0 with a moderate to strong response to electrical stimulation. Muscles that have even mixed voluntary function will display surface EMG signals, and muscles that do not respond at all to electrical stimulation indicate LMN pathology and will not display activity even in the presence of preservation of the corticospinal tract. Muscles that are paralyzed but have a fully intact LMN have the capacity to transmit surface EMG signals if there is some preservation of the corticospinal tract.

Electromyographic signals can be recorded using clinically available biofeedback systems, equipment that is already accessible in most rehabilitation facilities. Additionally, equipment for surface EMG recording can also be found in the lay community, offering a less expensive option for resource-challenged facilities. For example, Backyard Brains Spikerbox Pro (https://backyardbrains.com) provides surface recording electrodes and a pre-amplifier that connects to the microphone of a smart phone or tablet. Through a downloadable application, surface EMG signals can be observed and recorded in real time. Clinicians should familiarize themselves with guidelines for conducting surface EMG testing.[32] For the purposes of this clinical exploration of latent muscle function, responses can be recorded as present (+) or absent (-).

Discussion

LMN damage in SCI

The presence of LMN pathology has been under-appreciated by clinicians who treat individuals with SCI. The concept of using electrical stimulation or recording as a diagnostic approach has not been embraced, even among clinicians who utilize therapeutic electrical stimulation treatment. Therapists who are less experienced with electrical stimulation often attribute difficulty eliciting a response from a paralyzed muscle to a lack of skill in locating the motor point rather than LMN damage. However, LMN pathology has been reported by many researchers. Peckham and colleagues used surface electrical stimulation to assess LMN status in the paralyzed muscles of 24 study participants with ISNCSCI motor levels ranging from C4-C6. While the results show that the LMN was intact in the majority of muscles tested, it was fully or partially damaged in 10% of the finger flexor muscles and 26% of the finger extensor muscles. LMN damage was generally limited to one to two muscles in each participant, although one participant demonstrated extensive LMN damage in all muscles tested. The findings of this study are significant for identifying an important pattern of LMN damage in people with cervical SCI. LMN damage is more likely to occur one segment caudal to the site of injury. For example, injuries at C6 are more likely to exhibit LMN pathology in the finger extensors.

Coulet and colleagues further investigated LMN pathology by examining the range of denervation in 43 participants (85 upper limbs) with tetraplegia. Their results show the range of denervation to be variable across participants with same injury level, manifesting in different clinical presentations in hand posture. Gorman and colleagues[33] found that out of 30 people with tetraplegia who would otherwise be a candidate for an upper extremity neuroprosthesis, 13.3% were excluded due to extensive denervation. Similarly, Triolo and colleagues[34] found some degree of upper limb denervation in 28% of people with tetraplegia. Recently Bersch and colleagues[35] found that LMN damage as detected by surface electrical stimulation of the forearm extensor muscles influenced hand position and the development of a tenodesis grasp. Others have advocated for the utility of using surface electrical stimulation to identify LMN pathology.[12,17,36] The presence of LMN pathology in people with cervical SCI is important for clinicians to identify, separate from UMN paralysis, to best determine the course of care for the upper limb.

Utility of measuring LMN status and latent motor responses

Understanding the status of the LMN and possible existence of latent motor responses is important for guiding upper limb interventions for people with cervical SCI. Specifically, an understanding of these characteristics contributes to preventive care, determination of upper limb reconstruction and effectiveness of motor learning-based interventions, and more detailed classification of injury level.[14] For example, LMN damage to the radial nerve innervating triceps has been associated with elbow flexion contractures in individuals with C5 and C6 tetraplegia.[37] Knowledge of LMN pathology early after injury can focus early intervention activity toward prevention of this secondary condition. Baseline recording of LMN responses during acute SCI can also serve to diagnose subsequent chronic issues that can develop in people with SCI, such as a syrinx or spinal instability such as a Charcot spine. Both of these conditions cause damage to the LMN that can be identified not only by weakness in voluntary muscles, but also by a change in response to electrical stimulation in paralyzed muscles.

A working knowledge of LMN status can also guide interventions for neural recovery and upper limb reconstruction. Careful analysis of LMN-paralyzed muscles and possible latent motor responses can indicate eligibility for motor learning-based interventions. A paralyzed muscle with a strong response to electrical stimulation indicates that the LMN is intact. If latent motor responses are present in that same muscle, there may be potential for recovery. Existence of latent voluntary responses will encourage more attention, in the form of increased treatment fostering neural input, to muscles or functions that would not otherwise be targeted for treatment, encouraging a greater focus on motor learning-based rehabilitation interventions rather than compensatory rehabilitation interventions. Further research is needed to identify these characteristics and determine their predictive power for recovery. Conversely, damage to the LMN suggests that individuals may not be a candidate for motor learning-based interventions, since this damage is permanent and not expected to be reversible with increased neural input or exercise.[13] Resources should then be allocated elsewhere to maximize the individual's functional independence.

Reconstructive surgery, including tendon and nerve transfer, can be more effectively implemented with knowledge of LMN status and the existence of latent motor responses. In cases of LMN damage where there is risk of contracture development, a decision for tendon transfer surgery may be made sooner, in advance of permanent joint tightness or contracture. For example, an individual with C5 or C6 tetraplegia with paralyzed and denervated triceps may elect to have a biceps to triceps tendon transfer to restore elbow extension.[11,38,39] Further, the success of nerve transfers hinges on the identification of LMN pathology. Paralyzed muscles with intact LMNs have a greater chance of success from nerve transfers. When LMN damage is present, restoration of control via neuromuscular rescue is possible if intervention occurs before Wallerian degeneration causes permanent paralysis. Therefore, early LMN assessment is critical[14] in order to identify when it is appropriate to employ early interventions.

Detailed characterization of paralysis may be important for reasons yet to be discovered. It is significant that latent motor responses can be detected only if the LMN is intact in the UMN paralyzed muscle. Consequently, there is less optimism for recovery in the presence of LMN damage. However, there may be reason for optimism that biologic or other interventions currently under study may someday have the effect of reversing LMN pathology, and that surface electrical stimulation could be a mechanism for detecting such an effect. We have reviewed how two relatively simple evaluations can provide critical insight into the nature of fully paralyzed or extremely weak musculature. In the current environment of increasing biologic and restorative interventions targeting improved recovery after SCI, it is critical that evaluation techniques evolve to measure the impact of advanced interventions.

An important factor in advancing the three-tiered approach of assessing the upper limb to clinical practice is the development of its psychometric properties. While validity and reliability of MMT has been well-established,[29,40,41] these properties have not yet been established for electrical excitability and latent motor response testing. Electrical excitability testing has the potential for similar validity and reliability to MMT as it uses the same scale, however additional factors involved in testing such as electrode placement, stimulation level, and tolerance of the patient may affect these properties. There are multiple factors that need to be addressed in the measurement of latent motor responses, the two most important ones being EMG electrode placement and minimization of cross-talk between closely located muscles – a particular concern for the distal upper extremity. An important first step toward developing the psychometric properties requires additional training for the therapists and other clinicians who will perform these evaluations. A standardized assessment manual, which is in process at this center, will provide structure and guidance for conducting the testing. More detailed examination of the upper limb, as proposed by this three-tiered approach, can contribute to refined methods of classification and potentially better prediction of motor recovery. Certainly, the precursors to this potential prediction are the development of standardized evaluation techniques, establishment of psychometric properties, and implementation of further clinical studies.

Further study is needed to determine the success of assessing LMN integrity and latent motor responses as a standard of care in a clinical setting. First, there may be challenges employing these techniques in higher level patients. For example, it is difficult to rate the response of paralyzed shoulder muscles to electrical stimulation, since the scoring incorporates range of motion. Stimulation to one paralyzed shoulder muscle in the presence of other paralyzed shoulder muscles will not result in active movement, even with a strong response to stimulation, since activation of all of the agonist muscles would be required. However, the muscle response can be scored on a binary scale based upon whether a contraction is present (+) or absent (-). This provides at least preliminary information about LMN integrity to guide appropriate interventions or suggest more detailed testing. Second, clinical characteristics such as spasticity and tone may prevent accurate assessment of voluntary and stimulated muscle responses. Therefore, careful documentation of responses is necessary, and ultimately these assessments may not be appropriate for individuals with significant tone and spasticity. Third, it is always a challenge to incorporate additional testing during acute rehabilitation due to decreasing lengths of stay combined with increasing pressure to increase productivity and profitability. However, these examinations are eligible for coverage under current occupational and physical therapy evaluation billing codes, as the information learned directly contributes to the course of rehabilitation. The feasibility therefore lies in how well this approach is embraced by therapists in clinical practice. Providing education about the benefits of this knowledge will likely increase their enthusiasm and willingness to incorporate these evaluations into clinical practice.

We have proposed a three-tiered approach to assessing motor function in the upper extremities of people with cervical SCI. This approach is an important component of a broader assessment of upper limb function across the continuum of SCI, as guided by the World Health Organization International Classification of Functioning, Disability and Health (WHO ICF).[42] While the three-tiered assessment fits within the ICF domain of body functions and structures, it is important to remember that evaluations of additional functions such as sensation, activity, and participation contribute to a more comprehensive understanding of recovery after SCI. Our recommendation for initiating the three-tiered approach early after injury, during the acute rehabilitation stage, aligns with the tendency for the focus of care to be more heavily weighted in the domain of body functions and structures during that period.[18] However, additional attention should be directed at assessing functional activities and participation as rehabilitation progresses.

Conclusion

The purpose of this article is to emphasize the value of detailed characterization of paralysis through the electrical evaluation of muscle responses after cervical SCI. Given the rapid advancements in SCI research and clinical interventions, it is critical that methods of evaluation and classification evolve. We have reviewed three tiers of motor function that should be evaluated early after SCI. The first tier of voluntary muscle testing is currently a standard of care after SCI, but often muscles outside of the ISNCSCI are not evaluated, especially during acute rehabilitation. We propose two additional tiers of testing across a broader set of muscles, focusing on the characteristics of weak or fully paralyzed muscles. Information gained from this expanded approach to upper limb testing can be utilized to mitigate potential secondary conditions such as contractures, or to target the most effective interventions such as activity-based interventions or reconstructive procedures.

Most importantly, this article serves to challenge current thinking about upper limb assessment and encourage more detailed characterization of nerve responses in preparation for lifetime management of the upper limb. The goal is to encourage frontline clinicians, occupational and physical therapists who are experts in muscle assessment, to think about paralysis after SCI in a more nuanced way. By prioritizing the weak or paralyzed muscle as an important element of upper limb evaluation, we can gain insight as to when it is appropriate to increase neural drive, employ prevention methods, or intervene early with reconstructive procedures. Studies are in process at this center to build evidence in support of the three-tiered approach to upper limb assessment. From a practical clinical perspective, there nothing to lose and much to gain by implementing these new approaches of assessment. It is noninvasive, time-efficient, and has the capacity to generate knowledge that will shape the trajectory of intervention for upper limb management for individuals with tetraplegia.

Conflicts of Interest

The authors declare no conflicts of interest.

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