Appendix I

A Manual for the Neurophysiological Assessment of Motor Control

The Brain Motor Control Assessment (BMCA) Protocol

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CONTENTS

1. INTRODUCTION

The Brain Motor Control Assessment (BMCA) is a functional electromyography (fEMG) method that records electrical activity from several appropriately selected muscles through surface EMG (sEMG) electrodes during the performance or attempted performance of standard volitional and reflex motor tasks. The method is used to characterize impaired motor control and has a rich history of theoretical and technological development through contributions made by many researchers from laboratories located around the world. Initially designed to confirm paralysis and provide evidence of translesional conduction in severe spinal cord injury (SCI), the BMCA protocol and the analytical tools associated with it have evolved into an objective and quantitative measure of essential motor control components for use in assessing all neurological disorders known to impair motor function.

Protocols have been developed for the assessment of neck, shoulders, arms, hands, trunk, and lower limbs that contain the common components of relaxation, voluntary excitation via reinforcement maneuvers (Jendrassik, etc.) and specific movement tasks, reflex responsiveness, and volitional modification of reflex excitability. The validity and utility of data collected under any of these BMCA protocols depend on adherence to standards that control the technical quality of the recording instrumentation, condition of the skin–electrode interface, rigorous administration of the protocol of motor tasks, and the ability of the examiner to control the recording environment, recognize and control artifactual signals, and manage the understanding and cooperation of the person being tested.

2. STANDARDS FOR RECORDING fEMG BMCA PROTOCOLS

1. The recording instrument specifications must meet published standards for sEMG recording including a minimum bandpass of 10 Hz to 500 Hz with high common mode rejection ratio for differential amplification.
2. The condition of the recording instrument and its settings are confirmed by recording a short segment of calibration into the data file as the first data collected with filter and amplification settings used for the BMCA data collection.
3. The frequency bandpass for BMCA is at least 30 Hz to 500 Hz, and digitizing sample rate is at least 1000 Hz. The frequency composition of sEMG is 10 Hz to 450 Hz (ISEK). Electrode and wire artifacts are found in the lower end of that range and need to be reduced as much as is possible. Therefore, the 30 Hz high-pass setting may be used to stabilize the baseline and reduce such low-frequency artifacts without appreciably diminishing sEMG information content.
4. Display sensitivity is the same for all sEMG channels, 50 μV per display unit. This allows the examiner to perform continuous quality control and to recognize minimal motor unit activation. During recording, it is more important to monitor low-amplitude noise and motor unit activity than the large sEMG patterns.
5. The examination is carried out with the test subject in the supine position on a comfortable examination table or bed. Padding or mattress compliance and bedding must not impede performance of volitional tasks by weak individuals.
6. Electrodes are placed in pairs for differential recording, oriented parallel to the long axis of each muscle, centered on the muscle belly for a standard set

of muscles predetermined by protocol (Table I–1). The wider the spacing, the larger will be the volume of muscle recorded. Some electrodes on the market are manufactured as attached pairs providing consistent spacing. More recently, electrodes with preamplifier circuitry located directly on the electrodes have become available. Such electrodes provide improved performance and eliminate cable-movement artifacts.

7. Skin at the location of the electrodes is prepared to provide intraelectrode impedances of less than 5 KΩ. This preparation is performed by cleaning the skin with alcohol and gentle abrasion using commercially available conductive pastes commonly used in EEG laboratories. "Active" electrodes with built-in pre-amplification require only alcohol cleaning of the skin.
8. Electrodes, regardless of type, must be well-fixed to the skin to minimize movement of their recording surfaces relative to the skin. Such movement generates large high-energy artifacts and low-frequency instability that contaminate the desired signals significantly.
9. Electrodes are connected to the appropriate input channel of the device as specified by the standard protocol. (Polarity, distal electrode into the negative input, is observed when transcranial motor cortex, spinal cord, or peripheral nerve stimulation is to be applied as additional test items to expand beyond the standard volitional and reflex sections of the BMCA protocol.)
10. Connections of electrodes to appropriate channels are confirmed through recording into the data file a short "electrode test" segment in which artifacts are induced in each channel in sequence by mechanically disturbing the electrodes (Figure I–1). It may be necessary to reduce the high-pass filter setting to allow this relatively low-frequency artifact to be registered. The high-pass filter setting must be restored before continuing data collection.
11. Data signal quality is monitored throughout the recording, and artifacts such as those radiated by the power-line or that result from electrode failures must be addressed immediately whenever encountered (Figure I-2).
12. The data acquisition is continuous and stored in a single recorded file. It starts from testing the electrodes (item #9 above) and continues until the end of the protocol of tasks as determined by standard protocol (Table I–2).
13. Annotations are placed into the record throughout the recording to label protocol tasks and describe extra-protocol events.
14. An audible and/or visible (for use in hearing-impaired subjects) cue, operated by a button held by the examiner, is tested, and the subject's ability to hear or see the tone or light is confirmed before beginning the examination. This cue is also recorded as an event marker in the data file.
15. All protocols begin with quiet relaxation for five minutes in the supine position. For expanded protocols described later, when in the upright suspended position, five minutes are also recorded; but for sitting or standing-unsupported protocols, only one minute is required.
16. Subjects are carefully instructed using recommended scripts and encouraged to make their best effort. Instructions and tasks can be

repeated as necessary to acquire the minimum number of "best-effort" trials specified for the particular protocol segment being presented, usually three trials. The examiner must remain vigilant and confirm that the instructions are understood by the test subject and provide re-instruction when judged necessary.

17. A brief cue (tone or light) and event mark is given to begin and end the five-minute relaxation section for data reduction and analysis purposes.
18. *Reinforcement* tasks are cued with a three-second tone/light. *For this and subsequent sections of the recording, complete sEMG silence is obtained or 30 seconds is allowed to pass before tasks are repeated or a new task is begun (referred to as the "relaxation standard").* This section requires that three repetitions, separated by a minimum of five seconds each, be performed for each task.
19. *Voluntary* movement tasks are cued and marked with a five-second tone/light for each phase of the movement. The relaxation standard is observed, and three "best-effort" trials are recorded for each voluntary task.
20. *Passive* movements are individually denoted with a brief mark at the beginning and end of each phase but are not audibly or visually cued. The relaxation standard is observed, and three repetitions of each task are recorded. It may be necessary to repeat the relaxation instructions. Tasks should be repeated, with re-instruction, if the examiner perceives assistance during the movement.
21. *Tendon taps* are delivered manually at approximately one per second, 10 times, for each location examined. The relaxation standard applies.
22. Attempts to manually elicit *clonus* are repeated three times for each joint tested, and the relaxation standard is observed.
23. *Vibration* is delivered for 30 seconds to each site tested, and the relaxation standard applies.
24. *Plantar stimulation* is delivered using the handle of the tendon tap hammer to perform the J-shaped stroke used to elicit Babinski's sign. The handle tip is moved along the plantar surface, beginning on the heel, up toward the toes, and across the ball of the foot. Three trials are performed on each side. The series is then repeated after instructing the subject to suppress the response by enforced relaxation, not stiffening, of the limbs.
25. *Additional segments can be added to the end of this protocol to examine specific stimulus-related responses, control of sitting, standing, and walking, or other questions of interest to the clinician or clinical researcher.*
26. Following any additional protocol segments, the electrodes are removed and the skin is cleaned of conductive paste and examined for irritation. Irritated skin should be treated with antibiotic ointment.

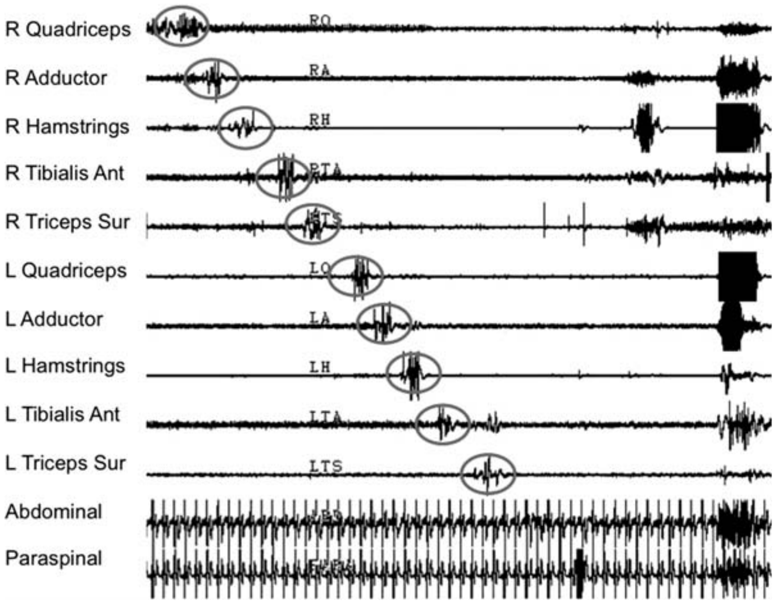
Adherence to these principles and standards allows the calculated parameter values obtained to be reliably compared across repeated BMCA sessions in the same person, across populations of persons with similar diagnoses, across populations of different diagnoses, and across laboratories with different examiners in different geographic locations.

Appendix Table I–1 Example of 16-Channel sEMG Montages for Examining Motor Control in the Upper Limbs, Trunk, and Lower Limbs

Channels	SIDE	MUSCLES		
		Upper Limbs	**Trunk**	**Lower Limbs**
1	RIGHT	Upper Trapezius	Upper Trapezius	Quadriceps
2		Biceps Brachii	Pectoralis Major	Hip Adductor
3		Triceps Brachii	Latissimus Dorsi	Medial Hamstring
4		Wrist Flexors	Intercostal	Tibialis Anterior
5		Wrist Extensors	Rectus Abdominis (para-umbilical)	Triceps Surae
6		Adductor Pol Brevis	External Oblique	Extensor Digitorum Brevis
7		Adductor Dig Quinti	Paraspinal (T12)	Short Toe Flexors
8	LEFT	Upper Trapezius	Upper Trapezius	Quadriceps
9		Biceps Brachii	Pectoralis Major	Hip Adductor
10		Triceps Brachii	Latissimus Dorsi	Medial Hamstring
11		Wrist Flexors	Intercostal	Tibialis Anterior
12		Wrist Extensors	Rectus Abdominis (para-umbilical)	Triceps Surae
13		Adductor Pol Brevis	External Oblique	Extensor Digitorum Brevis
14		Adductor Dig Quinti	Paraspinal (T12)	Short Toe Flexors
15		Open/spare	Open/spare	Open/spare
16		Event Marker	Event Marker	Event Marker

2.1. Study Setup

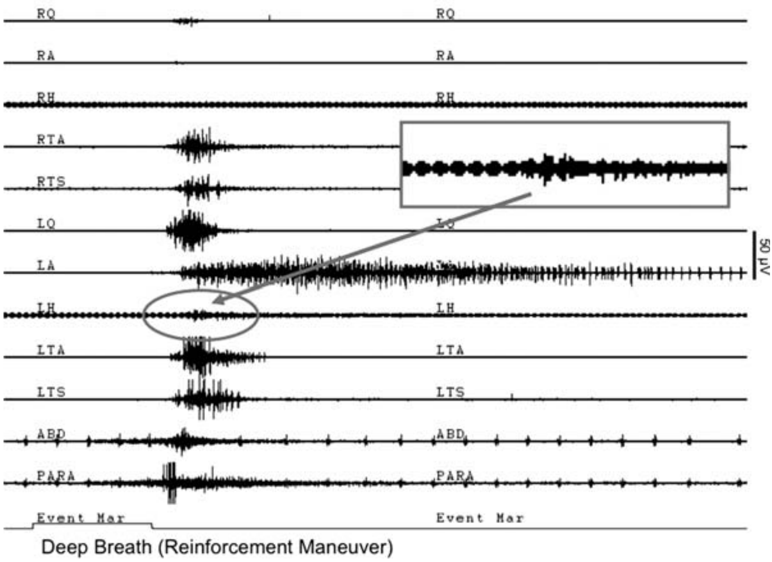
The key to a good recording of surface EMG is the proper preparation of the skin during the placement of electrodes. When using passive electrodes, it is always necessary to clean with alcohol and slightly abrade the skin under the electrodes in order to reach an impedance of 5 KΩ or less between electrodes as is the standard for electroencephalographic (EEG) testing. Otherwise, recorded signals will be contaminated by electrical fields from power lines and electrical devices (Figure I–2). When using active electrodes with pre-amplifiers built into the electrode, simply cleaning with alcohol should be adequate.



Appendix Figure I–1 Verification of sEMG channels and marking channels. Note that this "stripchart" display confirms that electrodes are properly connected to the instrument by recording the movement artifact sequentially induced in each channel by tapping the electrodes with amplifier low-pass filters set to allow such artifacts to pass.

Figure I–1 shows a typical lower-limb recording "stripchart" display of the brief setup segment for electrode testing, with filters set to allow lower-frequency, approximately 1 Hz, movement artifacts to pass. This stripchart display will be used throughout this manual to prepare the reader to recognize electrophysiological patterns in the form in which they will appear during a typical recording session. It is also important to test the manual event marker(s) used by the examiner to both cue the subject and mark points in the recording that will be needed for use by the computer data-reduction software. The examiner must also confirm that the subject can perceive the cuing tone. A visual cue such as a light placed in the visual field of the subject can be substituted for the auditory tone. Any movement-sensors or video recordings should also be verified during this setup section of the BMCA. Once all signals have been verified, the sEMG channel filter settings should be set to 30 Hz to 500 Hz and the subject instructed for the beginning of the examination section of the protocol. The 30 Hz high-pass setting will greatly reduce the movement artifacts recorded during the BMCA examination. If it does not, electrode fixation and wire movement must be examined and controlled. The minimum computer analog-to-digital conversion sampling rate should be 1 KHz to fully represent the 500 Hz bandpass setting on the amplifiers.

Artifact identification and annotation should be carefully performed throughout the recording session. Figure I–2 illustrates the second of the two most common artifacts encountered during the BMCA session. Since the BMCA is often expected to recognize very low sEMG signal levels, 5 μV minimum, such artifacts must be



Appendix Figure I–2 High-impedance electrode pairs pick up radiated power-line interference that can make recognition and quantification of the signal difficult. The event mark denotes the three-second tone used to "cue" the subject. The left hamstring muscle shows such an artifact illustrating the effect on sEMG recognition in the enlarged inset. As with Figure I–1 and for subsequent figures, illustrations were taken from a "scrolling stripchart" display acquired as they appeared during recording, and channel abbreviations are: Right (R) and Left (L) Quadriceps (Q), Adductor (A), Hamstring (H), Tibialis Anterior (TA) and Triceps Surae (TS) along with para-umbilical Rectus Abdominis (ABD) and bilateral T12 Paraspinal (PARA).

controlled. They are usually caused by high-impedance electrode pairs that will pick up radiated power-line and other electrical interference. Other sources may be the location of sEMG signal-carrying cables being too close to power cables. Other sources include powered hospital beds or examination tables. Often, disconnecting such items and other unused electrical devices from power during the recording session is all that is needed to remove these artifacts. A final source can be fluorescent lighting, under some conditions. However, properly prepared electrode impedances should not pick up power-line artifacts from the room lighting unless there are electrical faults in its circuitry. The preceding technical standards for instrumentation setup and record-verification insure that, whatever instrumentation is used to record the BMCA, all inter- and intra-individual differences in motor control patterns recorded are of physiological and not technological origin.

For the core protocol, all maneuvers are attempted in the supine position and repeated three times each. Examiners should be trained to recognize and eliminate artifacts that can and do appear during the recording session. They should also learn to make proper annotations that label event marks and describe extra-protocol events that may occur. It is those annotations that allow anomalous data to be properly interpreted in post-study data reduction and analysis.

Appendix Table I–2 Motor Task Sequence Protocols for Upper Limb, Trunk and Lower Limb Motor Control Assessment

	Protocol		
	Upper Limb	**Trunk**	**Lower Limb**
	Supine position		
	Electrode test		
Relaxation	**5 minutes**		
Reinforcement	Deep breath		
	Neck flexion against resistance		
	Jendrassik		
	Bilateral shoulder shrug		
Voluntary	Unilateral elbow flexion and extension hand pronated	Voluntary cough	Bilateral hip and knee flexion and extension
	Unilateral wrist extension hand pronated	Maximum inspiration (blocked airway - pressure gauge)	Unilateral hip and knee flexion and extension
	Unilateral wrist flexion hand supinated	Maximum expiration (blocked airway—pressure gauge)	Bilateral ankle dorsi- and plantar flexion
	Unilateral grip and release	Unilateral shoulder abduction and adduction	Unilateral ankle dorsi- and plantar flexion
		Unilateral elbow flexion and extension	
		Bilateral hip and knee flexion and extension	
		Unilateral hip and knee flexion and extension	
Passive	Unilateral elbow flexion and extension	Unilateral shoulder abduction and adduction	Unilateral hip and knee flexion and extension
	Unilateral wrist extension hand pronated	Unilateral elbow flexion and extension	Unilateral ankle dorsi- and plantar flexion

Appendix Table I–2 (Continued)

	Protocol		
	Upper Limb	**Trunk**	**Lower Limb**
	Unilateral wrist flexion hand supinated	Unilateral hip and knee flexion and extension	
Tendon taps	Biceps brachii		Quadriceps (Patellar)
	Triceps brachii		Triceps surae (Achilles)
	Wrist extensors		
	Wrist flexors		
Vibration	Biceps brachii		Quadriceps (Patellar)
	Triceps brachii		Triceps surae (Achilles)
	Wrist extensors		
	Wrist flexors		
Clonus	Wrist extension		Quadriceps (Patellar)
			Triceps surae (Achilles)
			Unilateral plantar surface stimulation
			with volitional suppression
		Sitting position—unsupported	
		30 sec Quiet sitting	
		10 sec Lean forward	
		10 sec Lean right	
		10 sec Lean left	
		Standing position—unsupported or supported	
		(Optional)	
		Quiet standing—3 minutes	
		Lean forward—10 seconds	
		Lean right—10 seconds	
		Lean left—10 seconds	
		One step forward (lead right)	
		One step forward (lead left)	
		5 steps (in place, self-paced)	

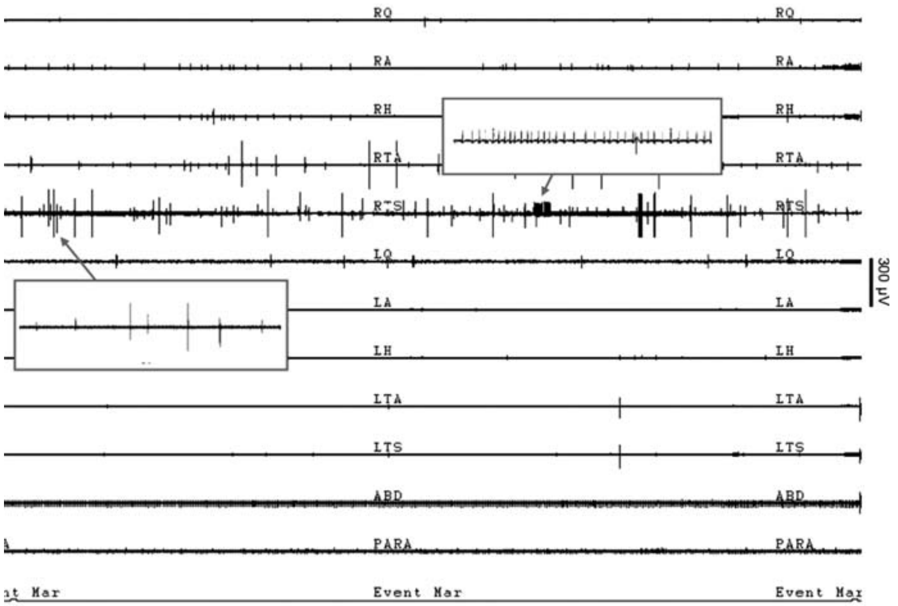
3. SEQUENCE OF MOTOR TASKS (TABLE I–2)

For all recordings, the protocol sequence begins with five minutes of relaxation in the supine position followed by reinforcement maneuvers, which include deep breath, Jendrassik, and neck flexion against resistance. Next, subjects attempt a series of bilateral and unilateral, single- and multi-joint voluntary movements. Regardless of their ability to accomplish the requested motor task, they should be encouraged to do their best, as sEMG is very sensitive and can record even trace activity. These voluntary tasks were chosen because they are simple to instruct and perform and are common movements performed by everyone during normal activities of daily living. Passive movements are then performed, followed by tendon and vibration reflexes. Attempts are made to manually elicit clonus. This series completes the upper-limb protocol. For lower-limb studies, plantar surface stimulation to elicit cutaneomuscular reflexes is performed and repeated with instructions to relax and suppress the response. At this point, before the study is ended or the subject is brought to the sitting or standing position (trunk protocol), transcranial magnetic or electrical stimulation may be applied as an option to acquire threshold and conduction-time data from the corticospinal system. The standard trunk protocol continues with sitting and standing tasks. Standing tasks may be added to the lower-limb protocol as well. Descriptions of the lower-limb protocol tasks, instructions to test subjects, and examples of typically recorded events follow.

4. RELAXATION

Five minutes of relaxation in the supine position begins and ends with a silent event mark to trigger automated analysis. *The test subject is told: "Please place your arms on your chest and relax. Are you comfortable? Do you need a cover for warmth? Please try to relax to the best of your ability. Try not to fall asleep, but should you do so, it will not be a problem. It is important that you relax and keep any voluntary movement to a minimum until I tell you that the five minutes have elapsed. Do you have any questions? Please begin the relaxation period."* It is important to note that the instructions for the BMCA must be cognitively simple and easily reproduced. However, the instructions may be repeated and rephrased or translated as needed for the test subject to understand and respond to the best of their true ability.

Motor events recorded during the relaxation period are of two basic varieties: episodic and continuous. Episodic events include fasciculation potentials (Figure I–3) and withdrawal-like "spasms" (Figure I–4) that can continue into other segments of the BMCA recording (Figure I–5). The first of these patterns are suggestive of denervation as seen in peripheral nerve injury. This form of background activity is distinct from spasms and other episodic events seen in relaxation, which appear as interference patterns, made up of composite motor unit activity. The occurance of "spasms" or multi-muscle sequenced activation patterns that are not annotated as volitional movements can take the general form of the reinforcement response (Figure I–4). The other such "spasm" that is commonly seen in the relaxation segment presents with a multi-muscle pattern and clinical movement resembling the cutaneomuscular reflex that brings whole-limb flexion (Figure I–5). This event can occur randomly or with great regularity, as if pacemaker timed, as seen in the illustration. When this



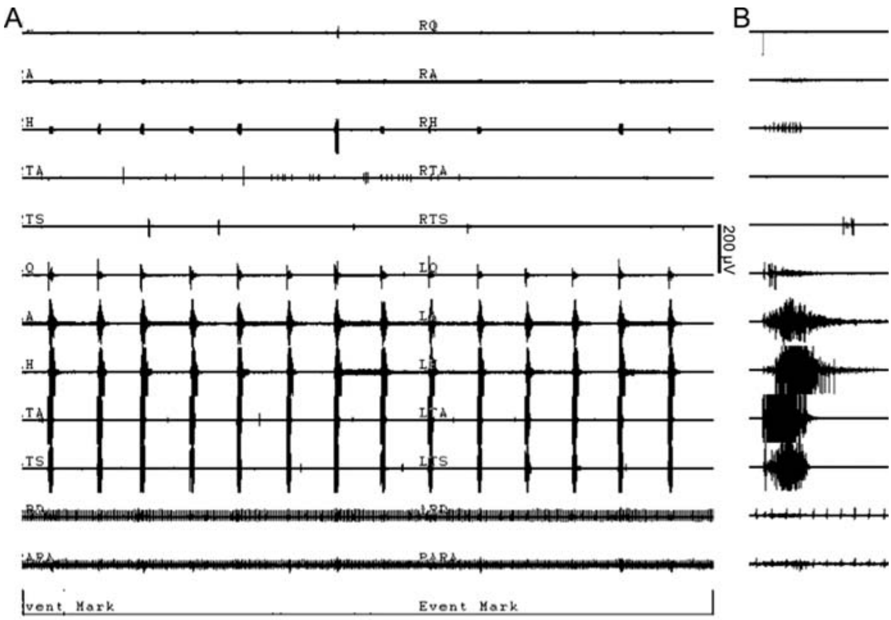
Appendix Figure I–3 Examples of sEMG recording taken from the "scrolling stripchart" display showing the full five minutes of relaxation with time-expanded insets (*boxes*). Although most subjects are able to achieve sEMG silence during the five-minute relaxation period, numerous electrical events can be seen. This stripchart segment was taken from a T12 incomplete SCI subject with a partial cauda equina lesion. The random spontaneous activity seen here is thought to be the surface-recorded version of the denervation potentials seen in needle EMG testing.

pattern is present, the examiner should reposition the subject to change and reduce the peripheral input to the spinal cord that drives the event. These repeating "spasms" can persist beyond the relaxation period and can produce inaccurate results in quantification when not recognized.

5. REINFORCEMENT MANEUVERS

The cuing tone or light and event mark with a preset duration of three seconds is used for this section (Figure I–6). The first instruction given is to wait for the tone before beginning any of the motor tasks. *The test subject is told: "In a moment, you will hear a tone (or see a light). When you do, please take a deep breath. At the end of the tone blow it out forcefully and relax. Please be sure to wait for the tone before you start and relax after it ends. Do you understand?"* Verbal encouragement from the examiner during reinforcement and voluntary movement attempts is appropriate, especially if there is no sEMG activity seen. If errors are made that suggest inadequate understanding of the instructions or cognitive confusion, trials should be repeated with additional instruction. Notes should be entered into the recorded file describing the reason for repeating the trials.

The Relaxation Standard: sEMG channels must achieve complete electrical silence, or 30 seconds is allowed to pass before the next trial or task is begun. It is appropriate

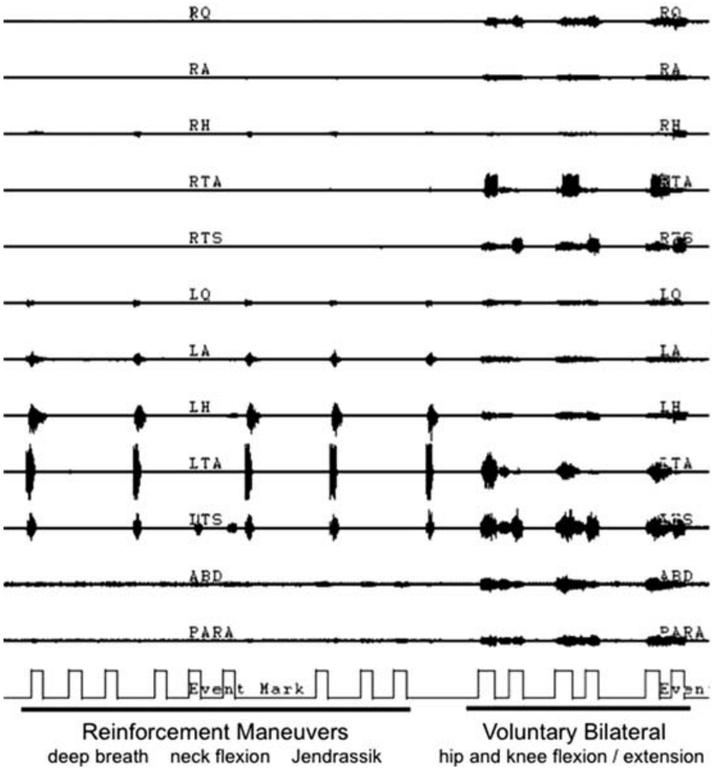


Appendix Figure I–4 Episodic events recorded during the five-minute relaxation period (*A*) can include regularly-repeating flexion events (*B*). Note that the Left Tibialis Anterior (LTA) activates before the Left Hamstrings (LH) helps to produce ankle dorsiflexion and knee flexion. Furthermore, it can be seen that the event "irradiates" to involve muscles of the contralateral limb. Since this pattern resembles the cutaneomuscular reflex seen with plantar surface stimulation, it is important for the examiner to reposition the limbs in an attempt to reduce peripheral input to the spinal cord.

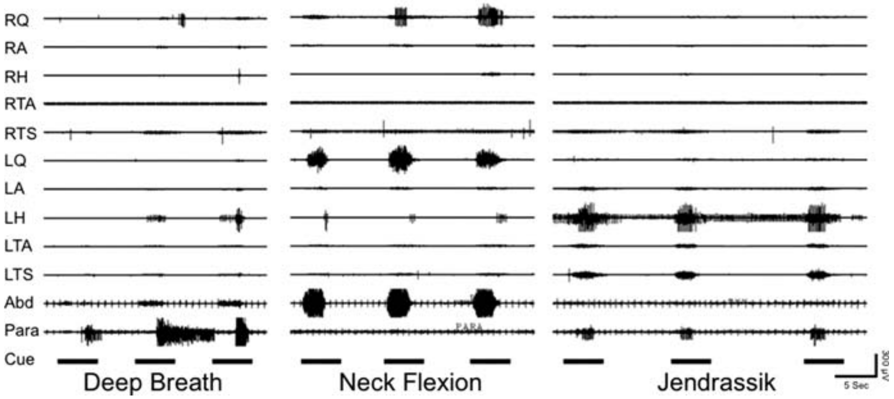
to instruct the test subject to relax, and to be specific about which muscle or muscles need relaxing. For purposes of post-recording data reduction, at least five seconds must pass before another trial is attempted. And each reinforcement maneuver is repeated three times. It is common for these maneuvers to elicit long-lasting activity in many muscles that will appear clinically as flexion and extension spasms.

The other reinforcement maneuvers are: neck flexion against resistance; Jendrassik; and shoulder shrug. Subject instructions are similar. For neck flexion, the subject is asked to lift their head against resistance applied at their forehead by the examiner. To perform the Jendrassik maneuver, the subject is asked to grasp their hands together and pull strongly without releasing their grip. The shoulder shrug maneuver is performed when the test subject "lifts" their shoulders (toward their ears in the supine position). For all of these reinforcement maneuvers, the subject is instructed to begin when they hear the tone and continuing to hold until the tone ends, at three seconds.

The presence of reinforcement task responses in paralyzed individuals is indicative of a "discomplete" lesion in which some long-tract fibers remain functional. In incomplete paralysis or paresis, such responses can indicate other aspects of control, including the impairment of inhibitory control, as responses are absent in neurologically intact people.



Appendix Figure I–5 Repeating episodic bursts of withdrawal-patterned activity (Figure I–4) continue past the end of relaxation, do not synchronize with reinforcement maneuver attempts, but were suppressed by voluntary movement task attempts. If unrecognized as a spontaneously repeating event, this activity would have been quantified and represented as a response to reinforcement, and if not ended by volitional attempts, would be erroneously counted when analyzing other segments of the recording.



Appendix Figure I–6 Multiple-muscle lower-limb activity, reinforcement maneuver responses (RMR) recorded from a motor-complete chronic spinal cord injured subject. Note that all tasks are performed three times.

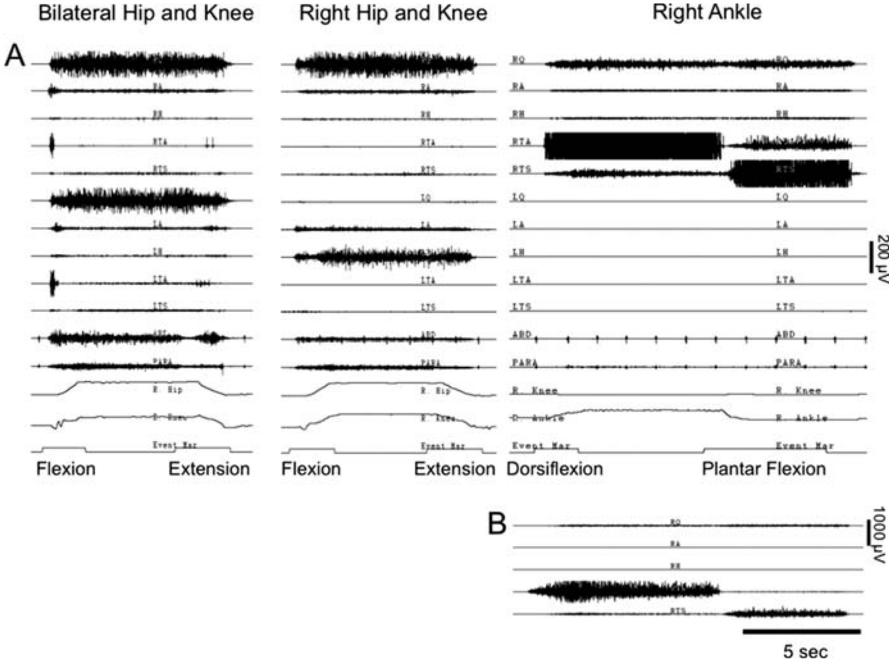
6. VOLUNTARY MOVEMENT

Using the same criteria for cuing as with the preceding reinforcement maneuvers, one bilateral and two unilateral voluntary motor tasks are presented (Figure I–7). All voluntary tasks in the BMCA protocol have two phases, flexion and extension, with the first phase held until the cuing tone ends and the second phase and cue presented following a brief pause, less than one second. For this and following manually marked events, both the cuing tone and marker length are controlled by the examiner. This allows the examiner to mark the end of the movement for each phase by releasing the marker button. This also provides feedback to the subject that the hold phase of the two-phase task has been reached. This hold phase duration and the beginning of the second phase of the task can be adjusted by the examiner to allow for different performance speeds while allowing the recorded data to meet processing criteria for analysis window lengths of at least five seconds after a command tone begins. Analysis of this segment of the BMCA quantifies parameters of motor control that include the recruitment rate of the agonist muscle and co-activation of antagonistic and muscles not activated by neurologically intact subjects for the presented tasks.

For the purpose of limiting the length of this manual, only selected representative tasks from the lower-limb protocol will be described from this point onward. Bilateral hip and knee flexion and extension are paired to form the first two-phase task tested. *The test subject is told: "As before, please wait for the tone to begin what will be a series of voluntary movements that we will ask you to attempt. Please try your best even though you may not feel any movement. Remember that we can pick up very small muscle activation. Each movement will be repeated three times, and the first one is to lift both of your knees to your chest, hold them there until you hear second tone, and then push them out straight, and relax when the tone ends. Do you have any questions? All right,* (tone), *lift both of your knees to your chest, hold them there, hold them . . .* (second tone), *push them out straight* (tone ends), *and relax."* Note that there is no instruction with regard to whether or not to dorsiflex the ankles at the same time as they flex the hips and knees. The analysis of this task allows either strategy to be used.

Again, re-instructing and repeating first trials when instructions appear to have been misunderstood by the subject/patient is recommended. The parallel instruction and tone cue delivery during performance of the task is recommended as it provides encouragement and confirms the task to the subject/patient. The second and third voluntary tasks are unilateral hip and knee flexion and extension, right side three times followed by the left side three times. Ankle dorsiflexion and plantar flexion tasks also begin with a bilateral series and then moves to the right side. *The test subject is told: "With the tone, please pull your toes up, bending only the ankle. Hold that position until you hear the second tone. With the second tone, please push your toes down, and relax when the tone ends."*

Analysis of this section of the BMCA quantifies the co-activation of antagonistic and inappropriate muscles during each of the tasks to characterize the degree of disordered motor control in comparison with healthy subject controls. Movement sensors and video recordings can serve to prove that movement has occurred, and measure the range and rate of movement. However, no standards have been published for such sensors or the analysis of the data they produce. The multi-muscle patterns recorded will range from no spinal motor output as in paralysis, through the

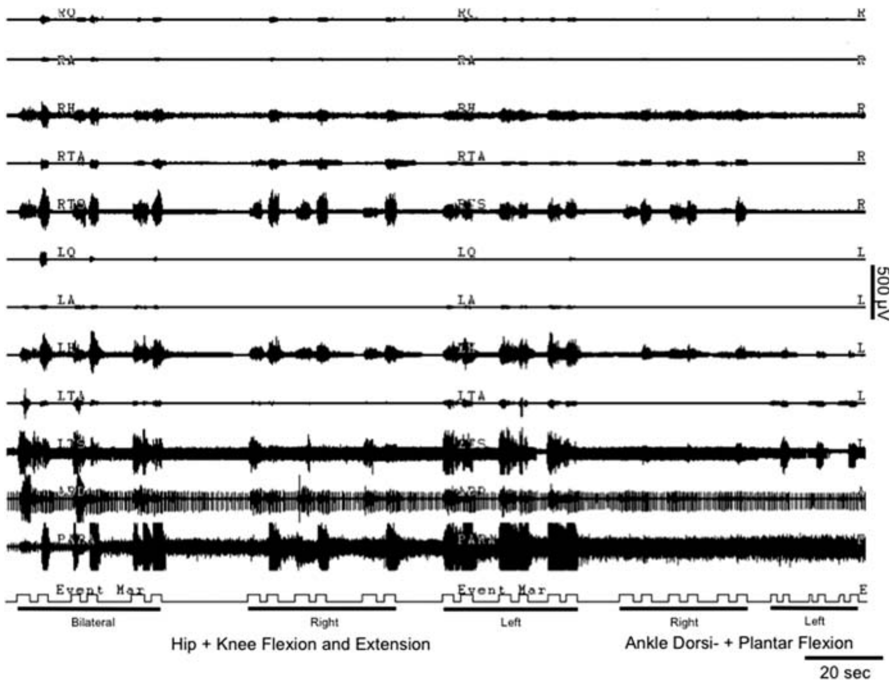


Appendix Figure I–7 Voluntary motor tasks performed by a healthy subject. (*A*) Bilateral and unilateral hip and knee flexion and extension and unilateral ankle dorsi- and plantar flexion showing the typical multi-muscle patterns recorded for these simple, self-paced motor tasks. (*B*) Decreased amplification shows the envelope shape of the agonist muscle for the ankle dorsal and plantar flexion tasks. During the recording session, a sensitive display is maintained to monitor recording quality changes and recognize low-amplitude events.

co-activation of multiple muscles antagonistic or usually uninvolved in performing the requested motor task (Figure I–8), to properly sequenced reciprocal activation needed for controlled single- and multi-joint movement (Figure I–9). However, in contrast to neurologically intact subjects who perform these voluntary tasks by producing multi-muscle patterns that are quite similar across trials and individuals, patients present for testing with relatively individualized degrees of disrupted motor control and wide variety of multi-muscle patterns. However, even in those with damaged control, patterns for each task should be quite similar to oneanother across three trials within each individual (Figure I–10).

7. PASSIVE STRETCH

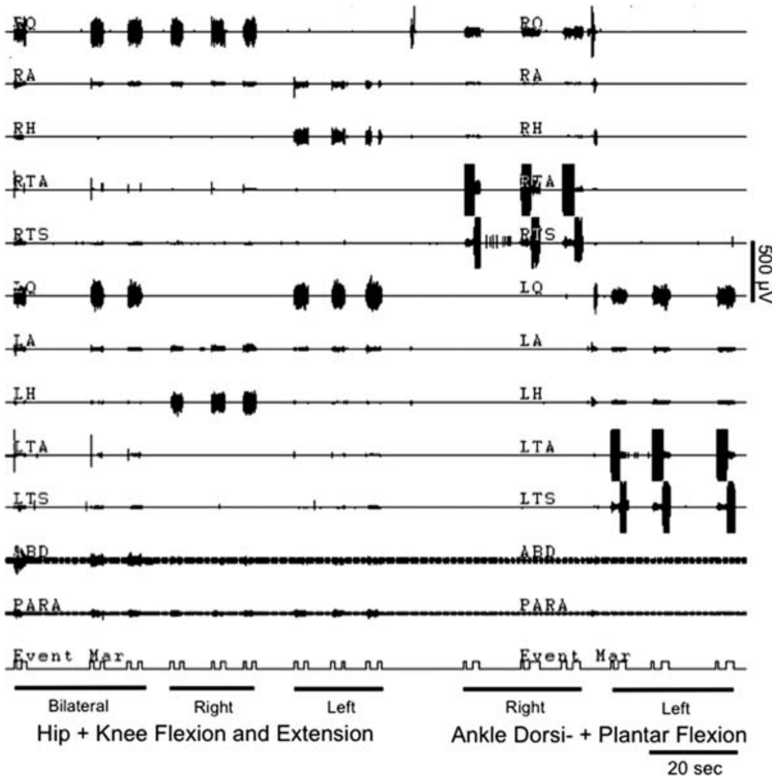
At this point in the recording, the cuing tone is turned off. Silent event-marking will be used for the remainder of the protocol. The unilateral motor tasks presented in the previous segment of the BMCA protocol are repeated passively. Again, three trials of each task are collected in the same sequence as above. *The test subject is told: "Please relax as completely as you can and allow me to do all of the work. I am going to move*



Appendix Figure I–8 Nearly four minutes of stripchart display showing the voluntary motor task segment of a BMCA recorded from a C5 AIS-C SCI subject. Seen is the typical lower amplitude sEMG and lack of appropriate multi-muscle patterning characteristic of altered motor control. Note the generally similar patterns recorded for the very different motor tasks attempted. Also, background activity seen here was verified during the recording to be sEMG. This individual was clinically spastic, showing dystonia-like continuous activity and considerable co-activation of inappropriate muscles for each of the tasks.

your legs through the same movements you did or attempted a few minutes ago." Touch of the leg can bring activation of spasm activity in many patient categories, so the BMCA standards include waiting after the initial touch while monitoring the sEMG for a response. If a response occurs, it must dissipate before the trial can begin. Also, if the examiner perceives "help" from the subject, re-instruction and retrial is necessary, but only for the first trial of each task. Again, it is important to achieve sEMG silence between trials and the two phases of each task.

In persons with altered motor control, passive stretch can elicit spinal motor output patterns that range from activation of the muscle stretched to complex combinations of muscles (Figure I–11). Healthy subjects are able to relax completely and suppress spinal motor output during this passive manipulation (Figure I–12). If activity is recorded during this section in healthy subjects, it can take the spatiotemporal pattern of voluntary activation assisting with the task. The examiner will perceive assistance with the movement and must re-instruct the subject and repeat. Such a pattern is clinically termed a "shortening response" and is exaggerated and uncontrollable in patients with Parkinson's disease or other movement disorders (Figure I–11), and can occur on the so-called unaffected side in stroke patients.



Appendix Figure I–9 Records of all voluntary motor task trials the healthy subject illustrated in the previous Figure I–7—showing three repetitions of for each of the five "paired" tasks. Note the highly repeatable multi-muscle patterns within each task.

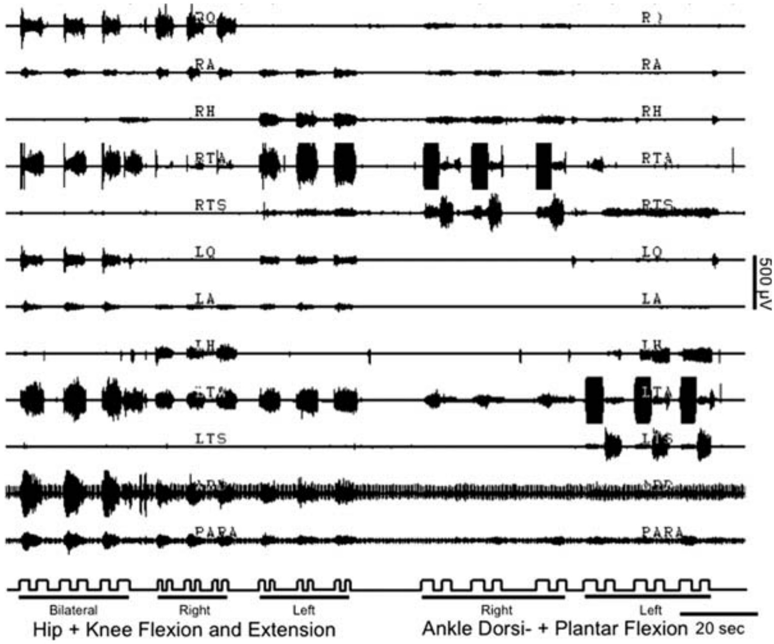
8. TENDON TAP REFLEXES

The right and left patellar (lower pole) and Achilles tendons are tapped manually, ten times each at a rate of approximately 1 Hz in the lower-limb protocol. Taps should be delivered by a standard clinical hammer, preferably instrumented with an accelerometer to mark the recording event channel with a pulse of preset amplitude or one that represents its force.

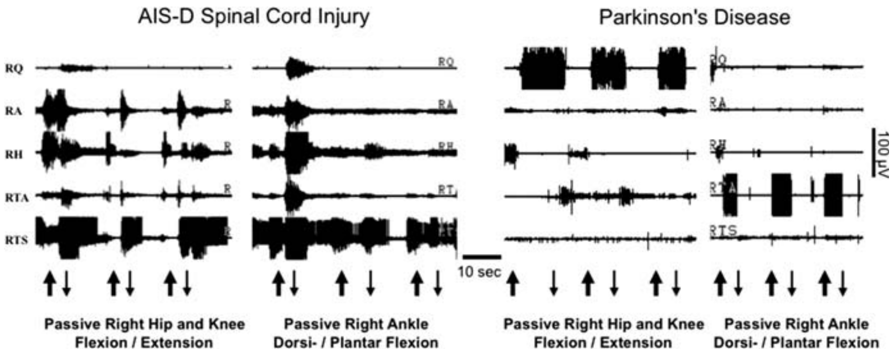
This segment of the protocol confirms the presence of a functioning stretch reflex arc and indicates peripheral nerve sparing. In addition to the elicited t-waves, after-discharge characteristics are recorded from the muscle tapped and other ipsilateral and contralateral muscles (Figure I–13). Irradiation to other muscles and the presence of after-discharging are uncommon in neurologically intact subjects.

9. MANUAL CLONUS ELICITATION

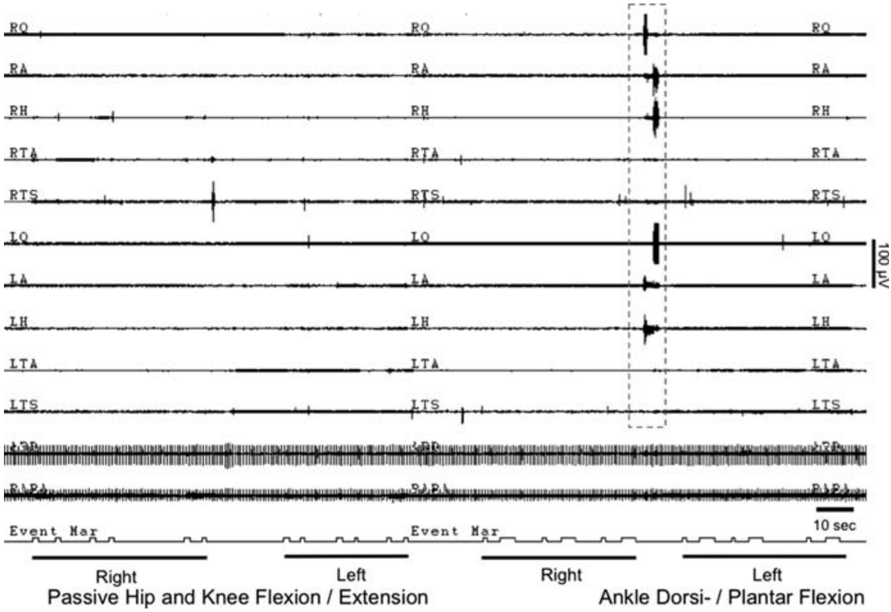
The subject is instructed to relax before three attempts to manually elicit patellar and Achilles clonus are made with manual event-marking held for the duration of any clonic response (8 Hz to 13 Hz) that may appear (Figure I–14). Once elicited, the



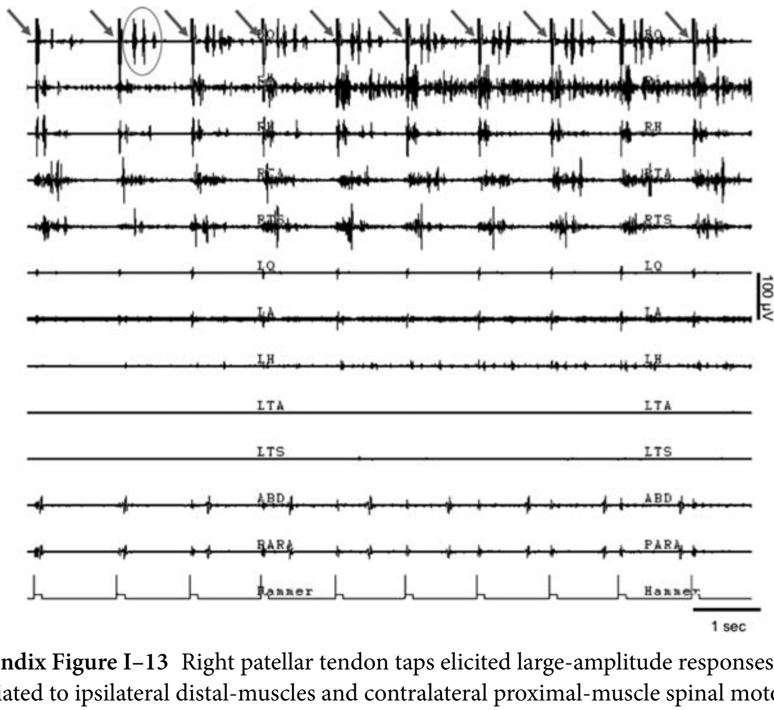
Appendix Figure I–10 sEMG activity during three minutes of standard BMCA voluntary movement tasks taken from an AIS-D subject (ASIA Impairment Scale) whose main motor control finding was asymmetrical hip and knee control. Note that more muscles, spinal motor nuclei, are activated by the attempts in this incomplete SCI example than in healthy subjects (*previous figure*).



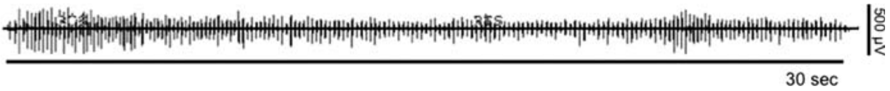
Appendix Figure I–11 Passive flexion (*up arrow*) and extension (*down arrow*) movements elicit complex "stretch" responses from subjects with incomplete SCI (*left*) and "shortening" responses from a person with Parkinson's disease (*right*). Note that more than the muscle stretched activates with passive movement in the AIS-D SCI subject on the left. Also, see that continuous, dystonia-like motor unit activity can be seen in both SCI and Parkinson's disease subjects. The Parkinson's disease subject shows the classic "shortening response" in which the muscle stretched remains inactive, but the muscle shortened is activated. Dotted lines are offered as guides for the visualization of repeating patterns to differentiate between stretched-induced and "spontaneous" spinal motor output.



Appendix Figure I–12 Passive movement segment of BMCA performed in a neurologically intact healthy subject. Subject voluntarily moved to adjust position for comfort (*box*). Note the lack of spinal motor response to passive manipulation of the legs. This is typical of healthy subjects. A possible normal variation is low-amplitude spinal motor output to the muscles shortened by the movement.



Appendix Figure I–13 Right patellar tendon taps elicited large-amplitude responses that irradiated to ipsilateral distal-muscles and contralateral proximal-muscle spinal motor nuclei. Also present are phasic after-discharge patterns (*circle*).

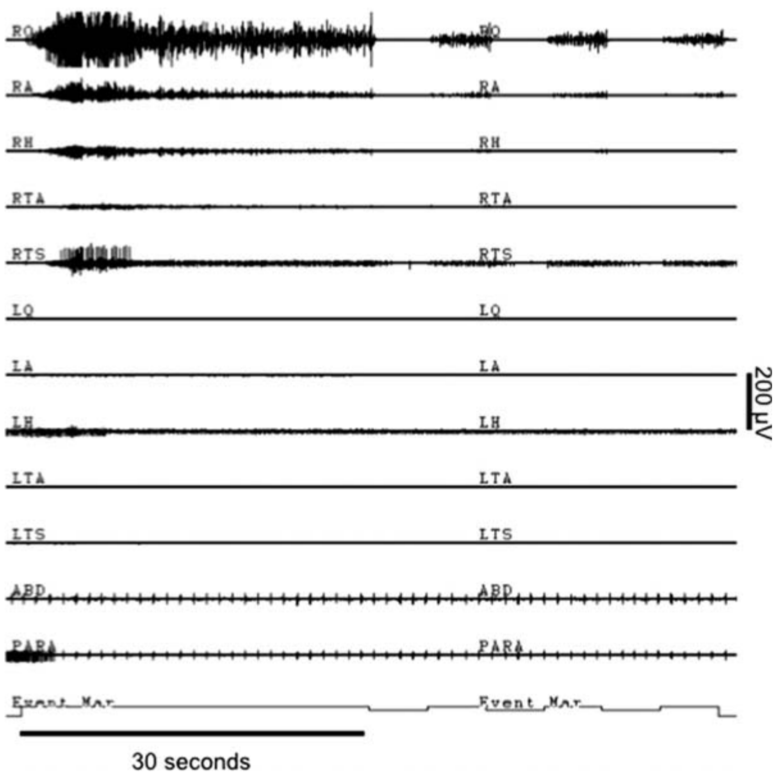


Appendix Figure I–14 Manually-elicited right ankle clonus in a clinically motor-complete SCI subject showing that there remains some translesional connections that support spinal motor excitability and a repetitive-stretch response.

examiner maintains the stretch for up to 30 seconds if the response persists. When the response lasts 30 seconds, it is considered to be evidence of supraspinal facilitation of the spinal motor neurons in persons who are clinically paralyzed.

10. TONIC VIBRATORY RESPONSE (TVR)

This segment requires the availability of compressed air and a pneumatic vibrator with which to strongly vibrate muscles or tendons. For the lower-limb protocol, the patellar (upper pole) and Achilles tendons are vibrated for 20 seconds each (Figure I–15). Again, instructions to the subject/patient are to relax. The examiner



Appendix Figure I–15 Strong vibration to the upper pole of the patellar tendon induced a sustained tonic vibratory response (TVR) in a motor-complete SCI subject. BMCA protocol standards require that five-second periods of on and off vibration follow sustained responses to test habituation. Note the irradiation of activity to other muscles of the same limb.

manually marks the delivery of vibration, or the vibrator can be equipped with a sensor to indicate when it is running. Response duration in the vibrated muscle is used as an indicator of "central state" modification by the brain in the face of clinical paralysis. When the response is absent in the muscle vibrated or disappears before 30 seconds have elapsed, the subject/patient is instructed to perform the Jendrassik reinforcement maneuver as they did earlier in the BMCA.

It should be noted here that the vibrator used for this segment of the BMCA is custom-constructed from a pneumatic hand-grinder fitted with an offset weight and protective barrel that produces 60 Hz to 120 Hz vibration, depending upon driving air pressure. Electrical vibrators have difficulty developing adequate force and always cause artifacts in the sEMG channels.

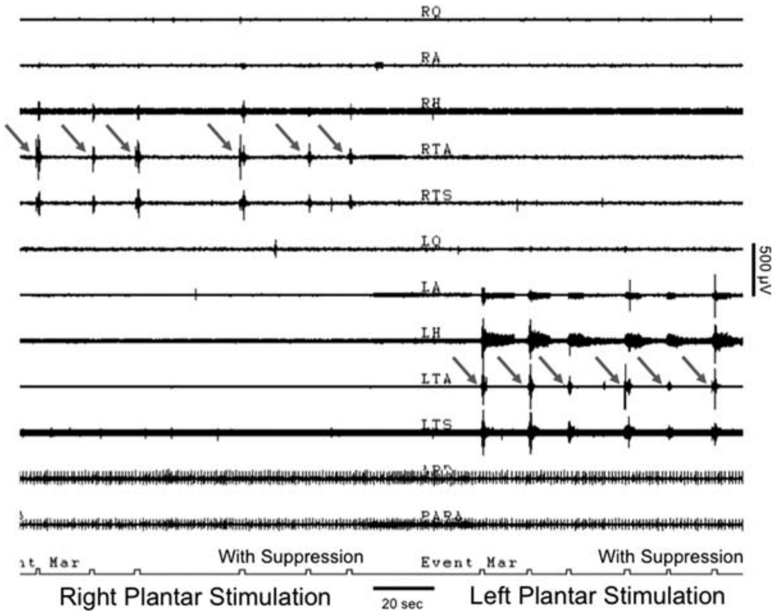
11. WITHDRAWAL SUPPRESSION (PLANTAR-STIMULATION RESPONSE SUPPRESSION–PRS)

This section of the BMCA protocol is stimulus-response based. It uses the manual stroking of the plantar surface as is done to elicit the classic clinical Babinski sign. The stimulus is delivered with the sharp end of a neurological hammer placed on the heel and drawn along the plantar surface toward the fifth toe, turning and traveling medially across the ball of the foot. For three trials on each side, the test subject is instructed to relax and allow the leg to jump, should it do so. Rate of stimulus delivery is determined by background activity and requires at least five seconds between trials. After three trials on each side, *the test subject is told:* "*Relax to prevent the leg from jumping. Do not tense as if to oppose the response but rather relax to prevent it.*" This parameter, the ability to actively inhibit spinal reflex response, is another indicator of residual brain influence over the central state of excitability in paralyzed persons (Figure I–16).

12. OPTIONAL SEGMENT FOR ALL PROTOCOLS

Transcranial magnetic stimulation (TMS) of the motor cortex to elicit a motor evoked response (MEP) can be used to assess threshold and conduction times within the corticospinal system. The best results are obtained in the supine position, because sitting (even reclining) or standing increases the resting excitability of the system. Important information obtained includes the threshold or minimum stimulus strength at which a response can be elicited. Also, the conduction time from the motor cortex to the muscle can be measured. MEPs can be obtained from all skeletal muscles in neurologically intact subjects. Delayed or high-threshold responses are indicative of damage to the corticospinal system. In neurologically intact persons, TMS is usually not considered to be uncomfortable at motor threshold levels. However, a caution must be issued here: stimuli will become uncomfortable at some intensity in all people with clinically complete or incomplete paralysis.

For lower limb muscles, TMS is delivered through a 110-degree double-cone coil (9 cm diameter each). For the upper limb muscles, a flat 9 cm diameter coil is used. In both cases, they are placed centered over the scalp vertex (Cz using the International 10–20 system for EEG electrode placement). The dual-cone coil is oriented so that



Appendix Figure I–16 Right and left plantar-stimulation withdrawal reflex response in a spinal cord injured individual during three repetitions without, and then with, instructions to suppress movement through relaxation. Note the asymmetry in the number of muscles activated and their amplitude of activation. The plantar response suppression (PRS) marker of incompleteness is present but better on the right than the left in this AIS-D example.

current flow inside the brain is counterclockwise in the left hemisphere and clockwise in the right hemisphere. The posterior-to-anterior current flow from the two coils overlaps in the region of the lower limb muscle representations of the motor cortex. For upper-limb muscles, the flat coil will produce high flux density at its edge, which is over the motor cortex hand representations for the right and left hemispheres. As with other segments of the BMCA protocol, pre-stimulus relaxation is required. The process begins with single pulses at minimum stimulator output. Each intensity is tested three times. In paralyzed persons, a paired-pulse paradigm using an inter-stimulus interval of 15 msec to 25 msec may be required (Figure I–17). Stimulus intensity is advanced in 10% increments until maximum single-pulse output is reached. If MEPs are not observed by the examiner, the second stimulus is added, beginning again at 40% for both stimulators. Both pulses are increased together until all recorded muscles respond or maximum stimulator output is reached. The delivery of single or paired stimuli must be separate by at least five seconds.

Finally, to complete the TMS section of the protocol, voluntary activation against a 2 kgm load will increase the MEP amplitude in those with incomplete lesions and allow the recording of TMS-induced silent periods under standard conditions. Stimulus intensity will be threshold, determined earlier, plus 10% of stimulus output. The duration of the silent period has been linked to corticospinal system dysfunction and can be used as an indicator of recovery.

Appendix Figure I–17 Examples of records during three repetitions of paired-pulse transcranial magnetic motor cortex stimulation (TMS). Display scale should be adequate to recognize a 5 μV p/p response. Single-pulse stimulation was not adequate to evoke motor evoked potentials; however, paired pulses with 25 ms inter-stimulus interval successfully elicit motor evoked potentials (MEPs) in the right and left quadriceps, adductor, and hamstrings muscles (*circled*). Also note the MEPs in the abdominal and paraspinal muscles. This AIS-D individual was capable of voluntary hip and knee flexion and extension but could not voluntarily move either ankle.

13. SITTING AND STANDING

The standard trunk protocol includes sitting and standing sections in which 30 seconds of quiet sitting and three minutes of quiet standing are followed by 10-second periods of leaning forward, back, right, and left. When standing, gait initiation and stepping in place are recorded. All of these tasks are cued with beginning and ending tones and event marks and are repeated three times each. Analysis of these segments is focused on asymmetrical activation of muscles, slow or absent responses to position changes, and instability within the multi-muscle activation patterns. Initiation of gait and stepping provide insight into the control of sequenced activation within multi-muscle patterns.

Data collection is ended with the removal of electrodes, cleaning of the skin, examination for skin irritation, and treatment of any irritation with antibiotic ointment. The examiner should express gratitude to the subject for their cooperation and explain to them how they may obtain results from the testing. Different laboratories have different policies regarding who may tell patients the results of testing that must be observed. Regardless, the subject should be told that quantitative results will only be available after some time for analysis.