Distinct Patterns of Motor Unit Behavior During Muscle Spasms in Spinal Cord Injured Subjects

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Thomas, C. K. and B. H. Ross. Distinct patterns of motor unit behavior during muscle spasms in spinal cord injured subjects. J. Neurophysiol. 77: 2847 ± 2850, 1997. Surface electromyograms (EMG) and force were recorded during repeated involuntary spasms of paralyzed triceps surae muscles of four men with chronic cervical spinal cord injury. The firing rates of 78 medial gastrocnemius (MG) motor units also were recorded intramuscularly with tungsten microelectrodes. Spasms typically involved a relatively rapid rise, then a more gradual fall in triceps surae EMG and torque. Motor unit firing rates either increased and then decreased with the spasm intensity (54%) or were relatively constant (26%), firing mainly at 2–10 Hz. The remaining units (20%) produced trains that included one or several doublets. Mean peak spasm firing rates were 18 ± 9 Hz (mean ± SD) for rate modulated units and 11 ± 10 Hz for units with little or no rate modulation. Some motor units fired at rates comparable with those recorded previously during maximum voluntary contractions performed by intact subjects. Others fired at rates below the minimum usually seen when normal units are first recruited (<6 Hz). Doublets (interspike interval <10 ms) often repeated every 123–333 ms, or were interspersed in trains firing at low steady rates (<11 Hz). This study shows that rate coding for many motor units appears to be similar whether descending motor input is intact or whether it has been reduced severely by spinal cord injury. In contrast, rate modulation in other units appears to depend mainly on voluntary motor commands.

METHODS
Individuals with chronic (>1 yr) cervical SCI who lacked voluntary control of trunk and leg muscles as assessed by manual muscle evaluation, whose paralyzed triceps surae muscles were prone to contract involuntarily, and who took no medication to dampen spasms were chosen as subjects. Ethical approval and informed written consent were obtained. The leg most susceptible to spasms during an isometric ramp voluntary contraction of control muscle, both force and electromyograms increase because additional motor units are recruited and/or because there is an increase in the rate at which active cells fire. These motor units usually fire at 6–10 Hz when first recruited (Monter and Chan 1977) and at 15–60 Hz during maximum voluntary contractions. Rates also vary between units, between muscles, and between subjects (Bellemare et al. 1983). Such rate modulation is considered to depend largely on the intensity of descending motor drive reinforced by input from local afferent inputs (Binder et al. 1996). Thus motor unit firing rates are reduced during both maximal and submaximal voluntary contractions after afferent feedback has been temporarily blocked by local anesthesia (Gandevia et al. 1990) or when conduction in central nervous system motor pathways is impaired, as in stroke or multiple sclerosis (Gemperline et al. 1995; Rice et al. 1992).

Involuntary muscle spasm is common in muscles paralyzed by spinal cord injury (SCI; muscles where voluntary EMG is absent). Many subjects can trigger spasms at will by trivial stimuli such as light touch or a minor postural shift. These spasms thus would seem to provide a unique opportunity to examine the extent of motor unit rate modulation in muscles to which maximal voluntary drive fails to produce EMG. To our knowledge, no investigations have monitored motor unit activity during such involuntary spasms. The aim of the current study was to examine motor unit firing rates during spasms of medial gastrocnemius muscles paralyzed chronically by SCI. With largely afferent inputs and spinal circuits to contribute to the excitation of the medial gastrocnemius (MG) motor pool, one might expect to record lower than normal motor unit firing rates when these muscles contract involuntarily. In fact, considerable rate modulation was recorded in approximately half the MG motor units. These findings suggest that inputs that remain years after traumatic injury to the human cervical cord are sufficient to excite one group of spinal MG motoneurons, but that others rely mainly on excitatory drive from higher brain centers for rate modulation. Some of these data have been published as an abstract (Ross and Thomas 1994).

INTRODUCTION
During an isometric ramp voluntary contraction of control muscle, both force and electromyograms increase because additional motor units are recruited and/or because there is an increase in the rate at which active cells fire. These motor units usually fire at 6–10 Hz when first recruited (Monter and Chan 1977) and at 15–60 Hz during maximum voluntary contractions. Rates also vary between units, between muscles, and between subjects (Bellemare et al. 1983). Such rate modulation is considered to depend largely on the intensity of descending motor drive reinforced by input from local afferent inputs (Binder et al. 1996). Thus motor unit firing rates are reduced during both maximal and submaximal voluntary contractions after afferent feedback has been temporarily blocked by local anesthesia (Gandevia et al. 1990) or when conduction in central nervous system motor pathways is impaired, as in stroke or multiple sclerosis (Gemperline et al. 1995; Rice et al. 1992).

Involuntary muscle spasm is common in muscles paralyzed by spinal cord injury (SCI; muscles where voluntary EMG is absent). Many subjects can trigger spasms at will by trivial stimuli such as light touch or a minor postural shift. These spasms thus would seem to provide a unique opportunity to examine the extent of motor unit rate modulation in muscles to which maximal voluntary drive fails to produce EMG. To our knowledge, no investigations have monitored motor unit activity during such involuntary spasms. The aim of the current study was to examine motor unit firing rates during spasms of medial gastrocnemius muscles paralyzed chronically by SCI. With largely afferent inputs and spinal circuits to contribute to the excitation of the medial gastrocnemius (MG) motor pool, one might expect to record lower than normal motor unit firing rates when these muscles contract involuntarily. In fact, considerable rate modulation was recorded in approximately half the MG motor units. These findings suggest that inputs that remain years after traumatic injury to the human cervical cord are sufficient to excite one group of spinal MG motoneurons, but that others rely mainly on excitatory drive from higher brain centers for rate modulation. Some of these data have been published as an abstract (Ross and Thomas 1994).
FIG. 1. Distinct patterns of involuntary medial gastrocnemius motor unit activity recorded during same spasm (A and B) or a different experiment (C) performed by 1 subject. Insets: superimposed traces of consecutive potentials of units identified. Note 2 units are shown in A, 1 of which has a linked potential (right). Large potentials have been truncated (B) to show smaller potentials. Dips in torque probably reflect activation of muscles other than triceps surae.

two to five attempts to voluntarily contract these muscles. A single magnetic pulse at 100% intensity was applied to the cortex at C7 during another 5–10 attempted voluntary contractions. Triceps surae surface EMG was recorded as described above.

All signals were amplified, filtered and sampled on-line (DC-100 Hz and 400 Hz, 30–3,000 Hz and 3,200 Hz, 100–10,000 Hz and 12,800 Hz for force, surface, and intramuscular EMG, respectively) and analyzed off-line. Surface EMG was rectified, then integrated every second before and after the peak MG surface EMG (relative time zero, Fig. 1). Signals from LG and soleus also were analyzed in the same way. Force was measured at the same time points, then converted to torque. Potentials in the intramuscular EMG record were identified as originating from a single unit using amplitude and wave shape criteria (Zoom, Physiology Department, University of Umeå, Sweden). Sometimes it was possible to identify single unit wave-forms from identified MG units to illustrate their unitary nature, instantaneous firing frequencies, and raw motor unit potentials recorded intramuscularly. The firing rate of most motor units (Fig. 1A, n = 42, 54%) increased and decreased up to and after the spasm peak intensity over a frequency range similar to that seen in ramp-force voluntary contractions of intact subjects (Monster and Chan 1977). The wave-forms are also like those recorded during voluntary contractions. However, 20 units (26%) behaved differently, and showed little or no rate modulation (Fig. 2B). Torque and MG surface EMG during spasms recorded from one person on two different days are illustrated in Fig. 1, A–C, each of which shows (top to bottom): torque, rectified MG surface EMG, super-imposed sequential wave-forms from identified MG units to illustrate their unitary nature, instantaneous firing frequencies, and raw motor unit potentials recorded intramuscularly. Descriptive statistics (mean, median, standard deviation, sample number) are used to describe motor unit firing rate data.

RESULTS

Data were recorded from four men (26–39 yr) who had chronic SCI (6–20 yr) at C5 or C6 from diving accidents. All the test triceps surae muscles were paralyzed in that each scored zero on manual muscle evaluation, and no surface EMG was recorded during attempted voluntary contractions or when high-intensity magnetic cortical stimulation was delivered during these voluntary efforts.

Torque and MG surface EMG during spasms recorded from one person on two different days are illustrated in Fig. 1, A and C. The EMG and torque typically increased relatively rapidly and then declined more gradually. Mean spasm rise and fall times were 3.0 ± 1.5 s and 11.2 ± 10.3 s, respectively (n = 33). Peak spasm torque was 13 ± 7 Nm (n = 13) which was <20% of that evoked by 20-Hz stimulation of soleus muscles paralyzed by chronic SCI (Shields 1995). Thus the present spasms of paralyzed triceps surae muscles were weak.

Distinct patterns of motor unit activity recorded during spasms are illustrated in Fig. 1, A–C, each of which shows (top to bottom): torque, rectified MG surface EMG, super-imposed sequential wave-forms from identified MG units to illustrate their unitary nature, instantaneous firing frequencies, and raw motor unit potentials recorded intramuscularly. The firing rate of most motor units (Fig. 1A, n = 42, 54%) increased and decreased up to and after the spasm peak intensity over a frequency range similar to that seen in ramp-force voluntary contractions of intact subjects (Monster and Chan 1977). The wave-forms are also like those recorded during voluntary contractions. However, 20 units (26%) behaved differently and showed little rate modulation, firing at almost constant rates (either low, 6.1 ± 0.8 Hz, or high, 33.5 ± 6.1 Hz, respectively) despite substantial changes in spasm intensity (Fig. 1B). Another 16 units (20%) had one or more short intervals between potentials (doublets, <10 ms apart) (Bawa and Calancie 1983). These usually occurred near the spasm peak intensity (Fig. 1C). Motor units showing all these discharge patterns, rate modulation, little or no rate modulation, and doublets occurred in every subject during different spasms (Fig. 1, A and C), and even within a single spasm (Fig. 1, A and B).

Figure 2 shows the mean per train, instantaneous firing frequencies recorded during each 2 s for all motor units that increased or decreased rate with changes in spasm strength (Fig. 2A) or showed little or no rate modulation (Fig. 2B). Irrespective of firing pattern, units with high mean rates were generally recorded near spasm peak intensity (taken as time zero). Mean rates within 1 s on either side of time zero were 18 ± 9 Hz (Fig. 2A) and 11 ± 10 Hz (Fig. 2B). The
distribution of mean and median rates were similar. Units showing rate modulation before or after the peak response generally had rates that followed the form of the surface EMG (Fig. 1A; cf. Fig. 2A). Most units showing little rate modulation fired at rates <8 Hz (Fig. 2B), a typical recruitment rate for units during voluntary contractions (Monster and Chan 1977). Doublets enhanced firing rate variability (not shown) and were dispersed in trains of potentials firing at low constant rates (<11 Hz) or fired repeatedly every 123–333 ms.

**DISCUSSION**

Spinal motoneurons fire in response to voluntary commands from higher motor centers and also when excited by local inputs. During maximum voluntary contractions of neurologically intact subjects, motoneuron discharge rates generally range from 15 to 60 Hz (Bellemare et al. 1983). However, Gandevia et al. (1990) have shown that, when motoneurons are deprived temporarily of afferent input by local anesthesia of their motor nerve, maximum voluntary efforts fail to elicit motoneuron firing rates >20 Hz. Thus it appears that normal maximum firing rates can be achieved only when the excitability of motoneurons is enhanced by facilitation from muscle spindles (Hagbarth et al. 1986) and/or other afferent sources. The motor unit firing rates recorded here during spasms of paralyzed triceps surae muscles show what occurs in the reverse situation. That is, afferent and spinal input is intact but the descending voluntary motor drive is reduced to the extent that no palpable contraction or surface EMG was recorded during attempted voluntary contractions of triceps surae muscles or when high-intensity cortical stimulation was given during these voluntary efforts. The changes in surface EMG recorded during spasms of paralyzed triceps surae muscles and the rate modulation behavior of 54% of the MG motor units were similar to those seen in weak voluntary contractions (Monster and Chan 1977). Although some of this rate modulation may reflect alterations in the number, distribution, and effectiveness of synapses with chronic paralysis and/or adoption of fast-type motor unit properties (Cope et al. 1986), such adaptations may not be universal (Thomas 1997). Removal of descending input also lowered the minimum triceps surae unit firing rate to 2 Hz (Fig. 2A). Other triceps surae motor units fired doublets, possibly a reflection of delayed depolarization in motoneurons, as suggested for doublets recorded during weak voluntary contractions (Bawa and Calancie 1983). The remaining triceps surae motor units did not change their discharge rate with torque, behavior not seen during ramp-force voluntary contractions. The present data suggest that afferent input, spinal systems, and any other inputs that remain but that are not accessible to voluntary drive or high-intensity cortical stimulation can induce substantial rate modulation and doublets in a subset of MG motoneurons. The negligible firing rate changes in other motor units, despite changes in EMG and torque, suggest these cells depend more on voluntary drive and/or other afferent inputs for rate modulation.

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