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Application of the F-Response for Estimating Motor Unit Number and Amplitude Distribution in Hand Muscles of Stroke Survivors

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Abstract

The F-response was used in this study to assess changes in the first dorsal interosseous (FDI) muscle after a hemispheric stroke. The number of motor units and their sizes were estimated bilaterally in 12 stroke survivors by recording both the compound muscle action potential (CMAP) and F wave responses. These F waves were induced by applying a large number of electrical stimuli to the ulnar nerve. The amplitude distribution of individual motor unit action potentials (MUAPs) was also compared between paretic and contralateral muscles. When averaged across all the subjects, a significantly lower motor unit number estimate was obtained for the paretic FDI muscle (88 ± 13) compared with the contralateral side (139 ± 11) ($p < 0.01$). Pooled surface MUAP amplitude analysis demonstrated a right-skewed distribution for both paretic (kurtosis 3.0) and contralateral (kurtosis 8.52) muscles. When normalized to each individual muscle's CMAP, the surface MUAP amplitude ranged from 0.22% to 4.94% (median 1.17%) of CMAP amplitude for the paretic muscle, and from 0.13% to 3.2% (median 0.62%) of CMAP amplitude for the contralateral muscle. A significant difference in MUAP outliers was also observed between the paretic and contralateral muscles. The findings of this study suggest significant motor unit loss and muscle structural reorganization after stroke.

Index Terms

Hemiparetic stroke; F wave; surface electromyogram (EMG); motor unit number estimation (MUNE); motor unit action potential (MUAP)

I. Introduction

The F wave is an electrophysiological response usually elicited by supramaximal stimulations of a peripheral nerve. It is a late onset low-amplitude potential produced by antidromic activation of a small portion of the motoneuron pool. The F response occurs infrequently and varies in size and latency from trial to trial because different motor units or combinations of motor units are involved [1, 2]. Although its origins are unclear, it provides a useful tool for electrophysiological analysis of motor neuron pool behavior.

The F wave test has been used in clinical neurophysiology for evaluation of the peripheral nerve functions. Measures of F wave latency provide a sensitive and reliable means to examine the conduction properties of proximal segments of motor axons [3, 4]. In addition, the F wave is also a useful tool for assessing the excitability of motor neurons. Changes of F wave characteristics such as increased amplitude, prolonged duration, or higher frequency of occurrence have been reported to indicate enhanced spinal excitability in spasticity [5–8].

One important application of F wave is for motor unit number estimation (MUNE), a technique that was developed based on detection of repeater F waves, which are observed to recur in identical configurations and latency in long series of stimuli [9–11]. It is believed that the repeater F waves reflect single motor unit action potential (MUAP) discharges. Surface MUAP samples (or repeater F waves) evoked by a certain level of submaximal electrical stimulation are considered to represent motor units of different conduction velocities and sizes in the motoneuron pool of a muscle [10, 12, 13].

F wave MUNE has been applied in counting motor units in both intact and diseased muscles [12–17]. For example, several studies using F wave MUNE found reduced number of functioning motor units in paretic thenar muscles after stroke [14, 15, 17]. Other MUNE methods such as multipoint stimulation were also applied for assessing hemiparetic muscles [18–20]. Recently, we have applied a more convenient and clinically applicable motor unit number index (MUNIX) measurement to assess three hand muscles of stroke subjects [21, 22]. However, the possible effect of muscle fiber atrophy on the MUNIX measurement remains a limitation of the study [23].

In addition to motor unit number changes, muscular structural reorganization may take place post stroke as a consequence of muscle disuse, motor neuron degeneration, axonal sprouting and collateral reinnervation [24, 25]. Such changes can usually be captured by the intramuscular electromyogram (EMG) signals, demonstrating larger single MUAP size, longer MUAP duration, increased complexity of the MUAP waveform, increased muscle fiber density and neuromuscular jitter [26–29]. Surface EMG interference analyses are also useful in revealing muscle structural and functional changes post stroke [30–32]. Attempts to apply surface MUAP analysis have also been reported, but no significant difference in MUAP amplitude was observed between paretic and contralateral muscles [15, 32].

In the current study, F wave recordings were applied to examine motor unit number alterations and structural reorganization of muscles after a hemispheric stroke. The first dorsal interosseous (FDI) muscle was tested. We estimated the number of motor units using

the F wave MUNE technique and examined whether motor unit population in paretic FDI muscles was significantly reduced compared with the contralateral muscles, and how such alterations were associated with compromised hand functions. We also used F wave responses to evaluate alterations in surface MUAP distribution pattern, as a result of structural reorganization of hemiparetic muscles post stroke.

II. Methods

A. Subject Information

Twelve subjects with hemiparetic stroke (4 Female, 8 Male, age: 64 ± 2 years, stroke duration: 10.2 ± 2.5 years, mean $\pm$ standard error) participated in the study. They were recruited through the Clinical Neuroscience Research Registry at the Rehabilitation Institute of Chicago (Chicago, IL). The clinical history of each subject was prescreened. Subjects were free of other neurological disorders or symptoms including neuropathy, radiculopathy, cervical spondylosis, or hyperglycemia. Other exclusion criteria included arm pain, numbness or paresthesia. All subjects gave signed consent approved by the Institutional Review Board of Northwestern University (Chicago) prior to any experimental procedure. Subjects' functional status was evaluated using strength measurement of grip force and pinch force, the Fugl-Meyer test and the Chedoke-McMaster assessment (performed by a physical therapist). The subject demographic and clinical information is presented in Table 1.

B. Experiment

Subjects were seated in an upright posture with the examined arm in a natural, resting position on a height-adjustable table. The examined hand and forearm maintained a supinated position and were restrained by Nylatex® wraps (4" width). Muscle responses were recorded from the FDI muscle using Sierra Wave EMG system (Cadwell Lab Inc, Kennewick, WA, USA). The active electrode (Ag-AgCl electrode, 1.0 cm diameter) was placed over the motor point of the FDI muscle. The reference and ground electrodes were positioned at the metacarpophalangeal (MCP) joint of the thumb and the dorsal side of the hand respectively. A standard stimulating bar electrode was placed over the ulnar nerve, 2 cm proximal to the wrist crease. The cathode of the electrode was oriented distally.

After placement of the electrodes, single stimulation impulses of 200 μ s in duration were delivered at an incremental intensity of 2 mA per step (starting from approximately 10 mA). The amplitude of M wave increased with stimulation intensity till a maximal compound muscle action potential (CMAP) was reached. Then a supramaximal electrical stimulation, equal to approximately 120% of the final intensity, was further applied to ensure activation of all the motor axons innervating the examined muscle.

Once the CMAP was obtained, electrical stimulation intensity was then decreased to evoke M waves of 30% of the CMAP amplitude [13, 17]. At this intensity, a total of 300 stimuli were applied continuously at 1-Hz frequency to the ulnar nerve. Subjects were instructed to remain relaxed and sedative throughout this submaximal stimulation period. Both the paretic and contralateral muscles were examined during the experiments. The order of hands for test

was randomized. All the signals were sampled at 12.8 kHz and band-pass filtered at 1 Hz – 3 kHz. A thermostat showed a steady temperature of approximately 72 degrees Fahrenheit in the laboratory.

C. Data Analysis

All data analysis was implemented offline in Matlab (MathWorks Inc, Natick, MA, USA). F wave responses were often superimposed over the positive afterpotential of the M wave. To approximate a true F wave response, estimation of baseline displacement was performed by means of linear regression algorithm for a period of 5 ms before the onset and 5 ms after the offset of the F response [13]. The estimated segment was then subtracted from the original F response to eliminate the superimposed potential.

Subsequent to the preprocessing procedure, surface MUAPs were detected from the F responses. To determine that an individual surface MUAP was present, an F wave was required to have peak-to-peak amplitude larger than 40 μ V and recur with an identical shape, size and latency among the 300 trials. An automatic program for detection of surface MUAPs from F waves was developed. Details of the algorithm can be found in [12, 13]. Briefly, an F wave was randomly picked from the extracted F wave pool as a template. The Euclidean distance (ED) between the template and each of the remaining F waves was calculated and then normalized to the area of template waveform. In addition, the difference of onset latency between the template and the other F waves was computed. A repeater F wave was determined as the ED of the F wave smaller than a preset threshold and the latency difference less than 100 μ s. If the repeater F wave(s) were found, the template and all repeater(s) were removed from the F wave pool. Otherwise, only the template was removed from the F wave pool. This process was repeated as a new template was randomly selected from the remaining F responses. The program stopped after all the repeaters were identified, or the size of F wave pool was reduced to 1. Selection of the ED threshold was associated with baseline noise level and inversely proportional to the waveform area of the template. As a result, the threshold was set lower for large-amplitude templates, and larger for small-amplitude templates because small-amplitude templates are more likely affected by noise. Further determination of a surface MUAP required at least 2 occurrences for an F wave repeater whose amplitude was lower than 100 μ V. For larger amplitude or polyphasic F wave repeaters, a minimum count of 3 occurrences was required. Several examples of the superimposed F waves (from 60 stimuli) and the extracted MUAPs are presented in Figure 1.

Surface MUAP samples identified from the population of F responses at relatively low intensity stimulation were considered to represent motor units of different conduction velocities and sizes in the motoneuron pool of a muscle [12]. For each subject, the number of functioning motor units was estimated in the paretic and contralateral hand FDI muscles based on the CMAP and detected surface MUAPs. The amplitude of CMAP and surface MUAP was measured from baseline to negative peak of the waveform. The number of motor units was estimated as the CMAP amplitude divided by the mean surface MUAP amplitude. In addition, ratios of CMAP and MUNE were calculated as values in the paretic side divided by those in the contralateral side.

Comparison of surface MUAPs between paretic and contralateral muscles was performed via the amplitude distribution analysis. Surface MUAPs were normalized to the CMAP amplitude of the same muscle ($\text{MUAPs}/\text{CMAP} \times 100\%$) before they were pooled. The MUAP amplitude distribution in the paretic and contralateral muscles were plotted and the normality of the distribution was examined by the normal plot method. The kurtosis value was calculated to measure the shape of the distribution, which is defined as the fourth centered moment of the data. A high kurtosis value indicates a sharper peak in the distribution.

The outliers of surface MUAPs in the paretic and contralateral muscles were examined further. Outlier MUAPs were selected as the large surface MUAPs whose amplitude was higher than the threshold defined in [33]:

$$\text{OAmp} = Q3 + k * \text{IQR} \quad (1)$$

where $Q3$ is the 75th percentile of the MUAP amplitude data and IQR is the interquartile range. Since the interquartile range of the paretic MUAPs was twice larger than that of the contralateral side, the coefficient k was selected as 1.0 in the paretic side and 1.5 in the contralateral side to ensure that there were comparable outlier numbers chosen from the two sides.

D. Statistical Analysis

Paired T test was applied to compare the differences of mean CMAP amplitude, the MUNE, grip and pinch force between the paretic and contralateral muscles. The surface MUAPs representing outlier MUAPs of large amplitude selected from the MUAP pool are not normally distributed. Therefore, a nonparametric test, the Mann-Whitney U test, was used to assess the differences of the outlier values between paretic and contralateral muscles. In addition, regression analysis was performed to examine any relation between electrophysiological measures (such as the CMAP amplitude, MUNE values, and ratios of CMAP or MUNE) and clinical measures including Chedoke score, Fugl–Meyer score, duration of stroke, pinch force in the paretic muscles, and ratio of pinch force between paretic and contralateral hands. Statistical significance was defined as $p < 0.05$. Results were reported in mean $\pm$ standard error format.

III. Results

All participants showed reduced muscle grip force in the paretic hand compared with the contralateral side (paretic: 19.38 ± 3.4 kg; contralateral: 38.48 ± 2.99 kg; $p < 0.001$; Table 1). Two subjects had higher pinch force in the paretic hand and four subjects showed comparable pinch force in the paretic side (ratio of pinch force between paretic and contralateral sides higher than 0.8). Despite that, statistical analysis indicated a significant reduction of pinch force in the paretic side (paretic: 6.53 ± 0.89 kg; contralateral: 9.04 ± 0.49 kg; $p < 0.01$).

Myoelectric measurements included CMAP amplitude and F wave responses, using submaximal stimulation (that elicited M responses of 30% CMAP amplitude). The upper plot of Figure 1 depicts a series of raw F responses collected from the paretic FDI muscle of Subject 9 in raster mode. Among the 60 trials, 4 MUAPs (3 had two repetitions and 1 had three repetitions) were determined and each MUAP had identical onset, size and morphology of the waveform. The lower part of the figure showed superimposed mode of the repetitions of the 4 MUAPs after removal of baseline displacement.

For each subject, the amplitude of CMAP and extracted surface MUAPs were measured for both the paretic and contralateral muscles. Ten subjects showed lower CMAP amplitude in the paretic FDI muscle and the other two subjects showed higher CMAP amplitude in the paretic hand. Comparison of muscle response revealed significant difference in CMAP amplitude between the paretic and contralateral sides across all subjects (paretic: 11.55 ± 0.94 mV; contralateral: 13.96 ± 1 mV; $p < 0.01$; left portion of Figure 2). The number of functioning motor units was estimated based on the CMAP amplitude and the averaged value of the surface MUAPs. A significantly lower motor unit number was observed in the paretic FDI muscle compared with the contralateral side (paretic: 88 ± 13 ; contralateral: 139 ± 11 , $p < 0.01$; right portion of Figure 2). Regression analysis was performed to examine the relations between clinical scores and electrophysiological measures. We observed a significant linear relation between the ratio of MUNE (paretic MUNE/contralateral MUNE) and the ratio of CMAP (paretic CMAP/contralateral CMAP) ($R^2 = 0.45$, $p < 0.02$, Figure 3). In addition, there was a linear relation between the ratio of MUNE (paretic MUNE/contralateral MUNE) and the ratio of pinch force (paretic pinch force/contralateral pinch force) ($R^2 = 0.26$, $p = 0.09$). No other linear relations were observed between the clinical measures (duration of stroke, Fugl-Meyer score, and Chedoke score) and the electrophysiological observation (CMAP amplitude and MUNE values) ($p > 0.3$ for all).

Surface MUAP analysis was based on the pooled data from all the subjects. A total of 197 surface MUAPs were extracted from F responses of the paretic muscles and 181 surface MUAPs were extracted from the contralateral muscles. Individual surface MUAPs were normalized to the CMAP amplitude of the same muscle. We observed right-skewed distribution of surface MUAPs and curves in the norm plot for both paretic and contralateral muscles. In particular, distribution of surface MUAP amplitude ranged from 0.22% to 4.94% CMAP amplitude with a median of 1.17% CMAP amplitude in the paretic FDI muscle and from 0.13% to 3.2% CMAP amplitude with a median of 0.62% CMAP amplitude in the contralateral muscle as illustrated in Figure 4. Calculation of the kurtosis value further confirmed the difference of surface MUAP distribution patterns between the paretic and contralateral muscles, which indicates a broader range and less sharp peak of surface MUAP distribution in the paretic muscle (paretic kurtosis: 3.0; contralateral kurtosis: 8.52).

Outlier MUAPs were selected from the two MUAP groups representing paretic and contralateral sides. Based on the threshold defined in Equation (1), 12 outliers were selected in the paretic side ranging from 3.57% to 4.94% CMAP (median: 3.79% CMAP) and 10 outliers were selected in the contralateral side ranging from 1.88% to 3.2% CMAP (median: 2.34% CMAP). Since outliers were possibly selected from different subjects, the Mann-Whitney U test was used to compare the outlier MUAP amplitude between the two sides.

Statistical analysis indicated a significant difference between the paretic and contralateral MUAP outliers (Z score: 3.93; $p < 0.001$).

IV. Discussion

Application of the F response MUNE technique was used in this study to evaluate paretic FDI muscles of 12 chronic stroke survivors. A significant reduction of motor unit number was estimated in the paretic FDI muscles compared with the contralateral side. Regression analysis indicated a strong linear relation between the subjects' relative CMAP change in paretic muscle (i.e. paretic CMAP/contralateral CMAP) and relative reduction of motor unit counts (i.e. paretic MUNE/contralateral MUNE). In addition, there was a strong tendency that relative weakness of the hand pinch strength was associated with reduced motor unit counts. Different MUAP amplitude distribution patterns were also observed between paretic and contralateral muscles, with paretic muscles demonstrating significantly larger amplitude of outlier surface MUAPs.

Evaluation of survival motor units in the paretic FDI muscle was performed in our previous study using the MUNIX technique [22]. Different from the F wave MUNE, the MUNIX technique relies on CMAP and voluntary surface EMG activity at different activation levels to provide an indirect estimation of motor unit number [34]. Evaluation of the MUNIX technique using a simulation approach indicates that there are limitations in applying the MUNIX method to atrophied muscles [23]. For example, MUNIX reduction might be attributed to actual loss of motor units or/and loss of muscle fiber size. In the current study we used the F wave MUNE technique, which is more complex to record, but can overcome the limitations of the MUNIX technique. The results indicated a significant reduction of motor unit number in the paretic FDI muscles.

This finding is consistent with previous reports on other distal hand muscles including those muscles in thenar and hypothenar muscles [14, 15, 17, 19, 20]. Furthermore, it was reported that loss of functioning motor units may begin as early as the second week or earlier after a brain lesion, as evidenced by fibrillation potentials and positive sharp waves recorded during this time [15, 19, 35]. This process can evolve over 2 and 3 months after the onset of stroke and may not show further progress after 3 to 4 months [15, 36]. Besides, Hara and colleagues tracked the same subjects one year after stroke and observed the same extent of motor unit loss in the paretic muscle as recorded 3–4 months after the onset [15]. Our current study examined chronic subjects with duration of stroke ranging from 3 to 33 years. Consistently, we did not discover any tendency that motor unit loss was associated with the time course of stroke, although we were not in a position to assess this factor in an optimal manner.

Most stroke survivors of this study suffered from mild to severe weakness and showed compromised hand and upper extremity functions. Regression analysis indicated a strong tendency between the strength of pinch force and motor unit counts. Increment of voluntary muscle contractions can be achieved either by involving more motor units or by adjusting the firing rate of active motor units. A decrease of MUNE in the FDI muscle indicates less number of motor units being recruited which leads to reduced maximal strength. Other

factors such as decrease of motor unit firing rates can also account for muscle weakness [32, 37–39].

Assessment of the relation between the clinical measures (Chedoke and Fugl-Meyer scores) and MUNE values did not show any clear correlation. This finding is different from a previous study reporting a strong correlation between MUNE and motor function measures [19]. The differences can be attributed to several factors including different muscles under examination, and different motor function measurements or scores. Interestingly, another study tracking F wave MUNE along different Brunnstrom stages disclosed significant loss of motor units through the progressive function recovery stages in stroke [17]. It seems that use of a single parameter such as F wave MUNE may not be sufficient to describe the changes of motor functions. It is also acknowledged that Chedoke or Fugl-Meyer scores measure the overall functional improvements of the hand or upper limb (involving multiple muscles), rather than a single muscle such as FDI.

There was a linear relation between the relative CMAP amplitude and MUNE counts in this study. The CMAP amplitude can thus provide an approximation of the motor unit loss, as long as the average motor unit size remained unchanged after stroke. In this study, a remarkable decrease of MUNE value (36% lower) was observed comparing with relative mild reduction of the CMAP amplitude (17%). This indicates that the F wave MUNE is a more sensitive tool than CMAP amplitude in tracking motor unit number changes. Estimation of motor unit number is primarily affected by motor unit sample size for a given muscle [40]. In particular, estimation error decreases with larger motor unit sample size. The current study extracted an average of 16 MUAPs from the paretic FDI muscle and 15 MUAPs from the contralateral muscle, which can be representative, considering the motor unit population of the FDI muscle.

Surface MUAP analysis was based on the pooled MUAP samples extracted from the F responses. The distribution of surface MUAP amplitude in the contralateral muscle was right-skewed, similar to MUAP size and motor unit twitch force distribution of healthy subjects [12, 13, 41]. The paretic side demonstrated exponential distribution with a wider range and a shift toward larger MUAP amplitudes. Such distribution pattern was also found when analyzing voluntary surface MUAPs or surface EMG peaks of the hemiparetic muscles [31, 33].

The different MUAP distribution pattern in the paretic side indicated that there was muscle structural rearrangement after a stroke. Muscle denervation might occur as a consequence of spinal motor neuron degeneration, as suggested by motor unit loss [42]. The denervated muscle fibers may not survive unless reinnervated by distal axon branches of the remained functioning motor neurons. Such reinnervation may result in the emergence of abnormal large MUAP amplitude and duration, complex MUAP morphology, increased single fiber density and neuromuscular jitter of single-fiber activation, as reported in previous studies using intramuscular EMG recordings [24, 26–29]. Comparison of the surface MUAPs obtained from electrical stimulation or voluntary contractions, however, did not find a significant difference of the MUAP amplitude between the paretic and contralateral muscles despite that larger surface MUAPs were observed in the paretic muscles [15, 31].

Examination of outlier surface EMG peak amplitude at a variety of matched force levels revealed remarkable amplitude increment in the paretic FDI muscles, but it is not clear whether such increased surface EMG peaks are necessarily due to axonal sprouting and collateral reinnervation of the remaining muscle fibers following motoneuron denervation, or due to early recruitment of large motor units [33]. Current observance of larger outliers of surface MUAPs in the paretic hand confirmed previous findings and provided evidence of muscle fiber denervation/reinnervation after a stroke.

Technical Note

There have been various MUNE techniques developed, since its first introduction in 1971 [43, 44]. In addition to F wave MUNE, other major techniques include incremental, multiple-point stimulation (MPS), spike-triggered averaging (STA), decomposition and statistical MUNE (STAT) [43]. The incremental stimulation was the first introduced MUNE method, whose primary limitation lies in higher chances of alternation with stimulating intensity [44, 45]. Other methods were developed to reduce alterations either by stimulating multiple sites along the course of the nerve (MPS), or statistically analyzing CMAP amplitude variation in a number of stimulating intensities (STAT), or identifying surface MUAPs via intramuscular recordings (STA or decomposition STA) [46, 47]. The various forms of MUNE methods also have different limitations. For example, the MPS collects MUAP samples from very low levels of stimulation; the STAT assumes a Poisson distribution of MUAP amplitude; the STA and decomposition techniques rely on invasive intramuscular EMG recording [43]. The F wave MUNE used in the current study usually involves hundreds of stimulation. The technique can be performed using a standard EMG system equipped with F wave protocol. The operating effort for determination of surface MUAPs can be greatly reduced with automatic detection of F wave repeaters.

Like other MUNE methods, the F wave MUNE is also affected by a number of factors including the sample size of motor units and the MUAP amplitude distribution [40]. In the current study, the number of motor units extracted in the paretic side was comparable to that in the contralateral side (paretic: 197; contralateral: 181). The paretic side showed a broader range of MUAP amplitude distribution than the contralateral side, which may be accountable to its lower MUNE values. It is likely that a combination of two or more simultaneously activated surface MUAPs may induce the larger outliers of surface MUAPs, particularly given elevated motoneuron excitability after stroke [1, 8]. In the current study a minimum count of 3 occurrences of F wave repeaters was required for determination of a surface MUAP with large amplitude ($> 100 \mu\text{V}$) or complex waveform. Such a requirement can effectively reduce the chance of compound MUAPs from antidromic firing of multiple motor units.

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Biographies

Xiaoyan Li received her B.S. degree in Electrical Engineering from Anhui University, and M.S. degree in Biomedical Engineering from University of Science and Technology of China, both in Hefei, China. She obtained her second M.S. degree in Computer Sciences from Loyola University Chicago in 2002, and her Ph.D. degree in Bioengineering from the University of Illinois at Chicago (UIC) in 2008.

Later she was a Postdoctoral Research Fellow in Institute for Neural Computation of the University of California at San Diego (UCSD), CA, and in Department of Physical Medicine and Rehabilitation of Northwestern University, Chicago, IL, respectively, and a Research Associate at the Sensory Motor Performance Program of the Rehabilitation Institute of Chicago, IL. She became a Research Assistant Professor in Physical Medicine and Rehabilitation of Northwestern University in 2013. She is currently an Assistant Professor in Department of Physical Medicine and Rehabilitation of the University of Texas Health Science Center at Houston. Her research interests focus on motor control, neurological disorders and rehabilitation.

Morris Fisher graduated from Harvard Medical School in 1968. He received his neurology training as well as a Fellowship in Clinical Neurophysiology at the Massachusetts General Hospital in Boston, Massachusetts.

In the past, he has been an Associate Professor of Neurology at both Rush Medical Center in Chicago as well as at the University of Chicago. Since 1992, he has been a Professor of Neurology at Loyola University Stritch School of Medicine in Maywood, Illinois and an Attending Neurologist/Consultant at the Hines VA Hospital in Hines, Illinois. He has been Acting Chief of Neurology at the Hines VA Hospital and has been Director of the Clinical Neurophysiology Laboratories as well as of the Neuromuscular Program. Dr. Fisher has served on the Board of Directors of what is now the American Association of Neuromuscular and Electrodiagnostic Medicine. He has also been on the Board of Directors and served as President of the American Academy of Clinical Neurophysiology. He has been a Director of a Center of Excellence for the Neuropathy Association. Dr. Fisher is an Adjunct Professor in the Department of Physical Medicine and Rehabilitation at the Feinberg School of Medicine at Northwestern University. He is an author of over 100 articles in peer reviewed journals and book chapters. Dr. Fisher has recognized expertise in both central and peripheral clinical neurophysiology, especially in F-waves. He has funded research in the investigation of diabetic neuropathies. His current interests include teaching Neurology as well investigative work in clinical neurophysiology and neuromuscular diseases.

William Zev Rymer is currently researching regulation of movement in normal and neurologically disordered human subjects including sources of altered motoneuronal behavior in hemispheric stroke survivors, using electrophysiological, pharmacological, and biomechanical techniques.

Dr. Rymer serves as Director of the Sensory Motor Performance Program, a position he has held since 1987, and Director of Research Planning at the Rehabilitation Institute of Chicago (RIC). In addition to his research roles at RIC, Dr. Rymer holds appointments as Professor of Physical Medicine and Rehabilitation, Physiology, and Biomedical Engineering at Northwestern University, Chicago, IL.

Dr. Rymer earned his medical degree from Melbourne University and his PhD in Neurophysiology from Monash University, both in Australia. After postdoctoral training at the National Institutes of Health and Johns Hopkins University Medical School, he became an Assistant Professor of Neurosurgery and Physiology at the State University of New York, Syracuse. In 1978, he came to Chicago as an Assistant Professor of Physiology at the

Feinberg School of Medicine at Northwestern University, and he remained as a primary faculty member in Physiology until his appointment at the RIC.

Ping Zhou (S'01–M'05–SM'07) received the B.S. degree in electrical engineering and the M.S. degree in biomedical engineering from the University of Science and Technology of China, Hefei, China, in 1995 and 1999, respectively, and the Ph.D. degree in biomedical engineering from Northwestern University, Evanston, IL, USA, in 2004.

From 1999 to 2014, he was progressively a Research Assistant, Research Associate, full time and adjunct research faculty at the Rehabilitation Institute of Chicago, Chicago, IL, USA. From 2006 to 2014, he was an adjunct Research Assistant Professor and later Associate Professor in Physical Medicine and Rehabilitation of Northwestern University, Chicago, IL, USA. From 2012 to 2015, he was also a faculty member in Biomedical Engineering of the University of Science and Technology of China. He currently holds an Adjunct Associate Professor position in Physical Medicine and Rehabilitation at the University of Texas Health Science Center at Houston, TX, USA. He is Director of NeuroMyo Engineering for Rehabilitation in TIRR Memorial Hermann, Houston, TX, USA, and Director of Rehabilitation Engineering for the newly founded Research Institute of the Guangdong Provincial Work Injury Rehabilitation Center, Guangzhou, China.

Dr. Zhou's research interests include biomedical signal (in particular, EMG) processing, motor unit pathophysiology and electrodiagnosis, myoelectric control, and assistive devices for neurorehabilitation.

Figure 1.

An example of four surface MUAPs extracted from F wave responses in the paretic FDI muscle of Subject 9. All detected surface MUAPs have identical size, shape and latency. The F responses were evoked in submaximal electrical stimulation with M wave amplitude 30% of CMAP. Note that upper part shows the raw F responses superimposed on M wave afterpotentials. The displaced baseline was removed in detected surface MUAPs as shown in the bottom.

Figure 2.

Comparisons of the CMAP amplitude and motor unit number estimation (MUNE) between the paretic and contralateral muscles. CMAP amplitude (mean $\pm$ standard error): 11.55 ± 0.94 mV (paretic), 13.96 ± 1.00 mV (contralateral), $p < 0.01$. MUNE: 88 ± 13 (paretic), 139 ± 11 (contralateral), $p < 0.01$.

Figure 3.

Left: plot of ratio of MUNE vs ratio of CMAP amplitude ($R^2 = 0.45$, $p < 0.02$). Right: plot of ratio of MUNE vs ratio of pinch force ($R^2 = 0.26$, $p = 0.09$).

Figure 4.

Surface MUAP amplitude distribution for paretic and contralateral muscles. Surface MUAPs were pooled across all the subjects: 197 MUAPs from paretic side and 181 MUAPs from contralateral side. The MUAP amplitude was normalized to each muscle's CMAP amplitude.

TABLE I

SUBJECT INFORMATION

ID	Sex	Age (years)	Duration (years)	Paretic side	Chedoke	FM	Grip force (kg)		Pinch force (kg)	
							paretic	contra-	paretic	contra-
1	F	60	16	left	3	10	2.6	20.8	1.2	7.3
2	M	64	10	right	4	56	16.9	40.9	7.4	8.0
3	F	60	7	right	4	40	12.4	31.2	3.4	6.5
4	M	72	5	right	7	64	37.0	43.7	9.1	8.0
5	M	63	6	right	6	63	21.8	36.2	6.2	8.6
6	M	71	3	left	7	56	27.3	37.7	7.8	8.4
7	F	55	5	right	6	64	32.0	41.5	10.4	10.0
8	F	70	6	right	5	53	15.9	26.1	4.7	8.8
9	M	50	4	right	6	48	17.3	44.2	10.5	11.2
10	M	67	18	right	2	17	8.0	53.1	4.0	12.1
11	M	59	10	right	5	51	36.6	55.9	9.7	11.0
12	M	73	33	left	2	7	4.7	28.4	4.0	8.6

FM: Fugl-Meyer assessment