

Estimating Contraction Level Using Root Mean Square Amplitude in Control Subjects and Patients With Neuromuscular Disorders

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Objectives: To assess the utility of the surface electromyographic signal as a means of estimating the level of muscle force during quantitative electromyography studies by examining the relationship between muscle force and the amplitude of the surface electromyographic activity signal; and to determine the impact of a reduction in the number of motor units on this relationship, through inclusion of a sample of patients with neuromuscular disease.

Design: Cross-sectional, cohort study design.

Setting: Tertiary care, ambulatory, electromyography laboratory.

Participants: A volunteer, convenience sample of healthy control subjects (n=10), patients with amyotrophic lateral sclerosis (n=9), and patients with Charcot-Marie-Tooth disease type X (n=5).

Interventions: Not applicable.

Main Outcome Measures: The first dorsal interosseous (FDI) and biceps brachii muscles were examined. Force values (at 10% increments) were calculated from two 4-second maximal voluntary contractions (MVCs). Surface electromyographic activity was recorded during separate 4-second voluntary contractions at 9 force increments (10%–90% of MVC). Additionally, a motor unit number estimate was derived for each subject to quantify the degree of motor unit loss in patients relative to control subjects.

Results: The relationships between force and surface electromyographic activity for both muscles (controls and patients) were best fit by a linear function. The variability about the grouped regression lines was quantified by 95% confidence intervals and found to be $\pm 6.7\%$ (controls) and $\pm 8.5\%$ (patients) for the FDI and $\pm 5\%$ (controls) and $\pm 6.1\%$ (patients) for the biceps brachii.

Conclusions: These results suggest that the amplitude of the surface electromyographic activity signal may be used as a means of estimating the level of muscle force during quantitative electromyography studies. Future studies should be directed at examining if the variability associated with these

force and surface electromyographic activity relationships is acceptable in replacing previous methods of measuring muscle force.

Key Words: Electromyography; Motor neurons; Neuromuscular diseases; Rehabilitation.

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DECOMPOSITION-BASED quantitative electromyography has been developed as a method for obtaining quantitative electrophysiologic data pertaining to the organization of the motor unit pool within a given muscle in both health and disease.¹ These electrophysiologic data, derived from surface and intramuscular electromyographic recordings, can be used to assess motor unit complexity and firing rates, and to estimate motor unit size and number.^{1,2} Such information can provide insight for clinicians and researchers into the changes occurring at the level of the motor unit in response to disorders of the motor system. When applied longitudinally, this same information may provide insight about the natural history of these disorders, the efficacy of potential treatments and the course and effectiveness of a given rehabilitation program.²⁻⁴

Recent studies using decomposition-based quantitative electromyography have illustrated that the level of voluntary force at which these studies are performed has a significant impact on the results obtained.^{5,6} Specifically, it was concluded that higher levels of voluntary force yielded larger needle- and surface-detected motor unit potentials (MUPs) and consequently lower motor unit number estimates (MUNEs). These findings, which result from physiologic, electrophysiologic, and technical factors that are not unique to decomposition-based quantitative electromyography, suggest a necessity to control the level of muscle force or activation during these types of studies.^{5,6}

Presently, research studies using decomposition-based quantitative electromyography have used force transducers and dynamometers designed for specific muscle groups to measure and control for the level of voluntary muscle force.²⁻⁶ Although the validity and reliability of this equipment is high, the expense and time required for patient setup is considerable, decreasing the feasibility of their use in a clinical setting and creating a need for an alternate measure of the level of contraction intensity. It is well known that the electromyography signal detected with surface electrodes is strongly related to contractile intensity with a number of studies documenting a linear relationship between the surface electromyography signal and contractile force.⁷⁻¹⁰ Additionally, preliminary investigations into the use of the amplitude of the surface electromyography signal as an alternate means of gauging the level of contraction during studies using decomposition-based quantitative electromyography were positive, with a linear relationship observed in the first dorsal interosseous (FDI) muscle

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between isometric muscle force and the root mean square (RMS) amplitude.⁵

Given these observations, the purpose of the current study was to further examine the relationship between voluntary muscle force and the surface electromyography signal, represented by its RMS amplitude, in the FDI and biceps brachii muscles. The goal was to determine the clinical utility of the RMS amplitude in estimating the level of isometric voluntary muscle contraction. With due regard to previous studies that have attempted to derive the relationship between force and the surface electromyography signal using a variety of methods,⁷⁻¹³ we selected a monopolar (muscle belly and distal tendon) electrode configuration to detect, and RMS amplitude to quantify, the surface electromyography signal. These parameters were selected because they replicate the conditions used during decomposition-based quantitative electromyography data collection. Additionally, given that decomposition-based quantitative electromyography analysis is not limited to the study of healthy control subjects, we sought to determine the nature of the relationship between muscle force and RMS amplitude in a subset of patients with neuromuscular disease that have experienced varying degrees of motor unit loss and subsequent motor unit remodelling through reinnervation. The FDI and biceps brachii muscles were chosen due to their potential differences in force production strategies as well as the importance of establishing these relationships in muscles that represent different segments of the cervical cord, particularly for future studies of patients, who may present with disease onset in different segments.

METHODS

Participants

Nine patients (age, 52 ± 12 y) with clinically probable or definite amyotrophic lateral sclerosis (ALS) as defined by the revised El Escorial criteria¹⁴ and 10 healthy control subjects (age, 27 ± 4 y) volunteered to participate in the study. Three of the 9 ALS patients were unable to perform the FDI portion of the study due to severely atrophied muscles characterized by unrecordable M waves. Due to this limitation, 5 additional patients (age, 37 ± 11 y), with Charcot-Marie-Tooth disease type X confirmed through genetic testing, participated in the FDI portion of the study only. Although the underlying pathophysiology of ALS and Charcot-Marie-Tooth disease type X differ, these 2 patient populations have been grouped for the FDI portion of this study, because both disorders result in decreased numbers of motor units, thereby providing an adequate model to examine force-RMS amplitude relationships in subjects with reduced motor unit numbers. All subjects gave informed consent and our institutional review board approved the study.

Motor Unit Number Estimates

To quantify the extent of motor unit loss in the patients relative to control subjects, we derived MUNE for the FDI (10 control subjects, 6 patients with ALS, 5 patients with Charcot-Marie-Tooth disease type X) and biceps brachii (10 control subjects, 9 patients with ALS) using decomposition-based quantitative electromyography as previously reported.³ Using a series of pattern recognition algorithms in addition to spike-triggered averaging, decomposition-based quantitative electromyography is able to break down both a needle- and a surface-detected electromyography signal, detected simultaneously during a voluntary muscle contraction, into their individual needle and surface-detected MUPs (S-MUPs). Briefly, decom-

position-based quantitative electromyography decomposes the composite electromyography signal detected through a needle electrode into its constituent MUPs using shape and temporal information related to the individual MUP discharges in addition to motor unit firing time statistics. Using these needle-detected MUPs as triggers for spike-triggered averaging, a component of decomposition-based quantitative electromyography, decomposition based spike-triggered averaging, provides a sample of MUPs detected through surface electrodes that are representative of the sizes of the motor units in the underlying muscle of interest. A statistically significant sample of these S-MUPs (≥ 20) is then averaged to determine the mean S-MUP size, which is the electrical representation of the size of an average motor unit within the muscle. Using the same electrodes used to detect the surface electromyography signal, a maximal M wave, which is the summated electrical representation of all of the motor units within a muscle, is obtained through percutaneous electric stimulation of the motor nerve of the muscle under examination. A MUNE is the result of dividing a size-related parameter of the mean S-MUP (ie, negative-peak amplitude) into the corresponding size parameter of the maximal M wave.

Because the level of voluntary force has been shown to influence the results of decomposition-based quantitative electromyography analysis (including MUNE), we maintained consistent contraction intensities throughout the acquisition of the data used to calculate the MUNE values reported here.

Force Measurement

The force measurement protocol used for both the FDI and biceps brachii muscles has been previously reported.^{3,15} For the FDI muscle, subjects were seated during data collection with their right arm pronated and placed in a custom-made force dynamometer. In order to isolate the action of the FDI muscle, the thumb was stabilized with a metal brace at 90° of extension and the lateral 3 digits separated from the second digit with a divider, and immobilized with a medium density sponge placed over the digits and secured with a self-adhesive (Velcro) strap. Additional straps placed just distal and proximal to the wrist joint line secured the forearm and hand position. The isometric abduction force exerted by the FDI was measured in newtons with a force transducer (model FT-10)^a that was anchored to the device and aligned with the proximal interphalangeal joint of the second digit. The output from the force transducer was amplified (model CP 122 alternating and direct current amplifier)^a and converted to digital format by a 12-bit converter (model 1401 plus)^b at a sampling rate of 500Hz and displayed on an analog oscilloscope^c placed in front of the subject.

For the biceps brachii, subjects were supine on a padded table and the right arm placed in a custom-made force dynamometer. The legs were supported on a padded wooden box, with the hip and knee joints flexed to 90° and the right shoulder secured with a padded metal brace. The box and brace prevented the torso from sliding during contractions. The elbow joint was flexed 90° and placed in a padded cup with the forearm fully supinated. The wrist and fingers were prevented from flexing during contraction by a plastic splint that was strapped to the back of the wrist and hand. The ventral aspect of the wrist was secured with a strap to a padded curved bar (11.0×5.2cm) that had a strain gauge^d attached. The output from the strain gauge was amplified (Neurolog models NL 107, NL 126),^e and converted to digital format and displayed on an analog oscilloscope suspended above the subject as described for the FDI.

Electromyographic Data Collection

Surface electromyography signals were recorded using self-adhering electrodes.^f For the FDI muscle, an electrode was cut into 2 strips (1×3cm); as the active electrode, 1 strip was located over the motor point of the muscle, and as the reference electrode, the other located over the first metacarpophalangeal joint. For the biceps brachii muscle, full sized electrodes (2×3cm) were used with the active electrode located over the motor point of the muscle and the reference electrode located over the distal tendon. The motor point of the muscle of interest was identified during acquisition of the evoked maximal M wave. Specifically, the active surface electrode was placed in a position that minimized the time to negative peak of the M wave and maximized the M wave negative peak amplitude in response to supramaximal stimulation. A full sized electrode served as a ground for both the FDI (dorsal aspect of the hand) and biceps brachii (forearm just distal to the elbow crease) measurements. The raw surface electromyography signal was amplified (×100), band-pass filtered (5Hz–5kHz) and sampled at 2kHz (Neurolog model NL 284).^e The intramuscular electromyography signal used to facilitate the calculation of the MUNE was detected with a commercially available, disposable concentric needle electrode^g inserted into the muscle of interest just proximal or distal to the active surface electrode, with band-pass filter settings of 10Hz to 10kHz and a sampling rate of 35kHz using decomposition-based quantitative electromyography software on a Neuroscan Comperio system.^h

Experimental Protocol

We asked subjects to perform 2 tasks, which were the same for both the FDI and the biceps brachii muscles: (1) maximal voluntary contraction (MVC) and (2) constant-force isometric contractions performed at a specific percentage of their MVC force.

MVC task. After placement in the appropriate dynamometer, subjects were instructed to increase their force output (either abduction of the index finger or flexion of the elbow) from baseline to maximum, with the maximum isometric force output maintained for 4 seconds. During these maximal efforts, subjects received visual feedback of their force output on an oscilloscope and strong verbal encouragement from the examiner. The MVC task was performed twice at the onset of the experiment with a 2-minute rest period separating the efforts and again after a 2-minute rest period at the conclusion of the constant force isometric contractions in order to assess if fatigue developed during the protocol. The peak force of the initial 2 MVC trials was marked on the oscilloscope and designated the MVC.

Constant force isometric contractions. Using this peak value, we calculated force levels corresponding to 10% increments of the MVC and used as the target forces for the constant force isometric contractions. For each contraction, the subject was instructed to increase his/her force output over a 1- to 2-second period until it matched that of a target line marked on the oscilloscope that corresponded to the specified force level, and then to maintain this force output for 4 seconds. After completion of the initial MVC tasks, subjects received a 2-minute rest period and then began the submaximal contractions, with 2 minutes of rest provided between contractions. The order of the constant force isometric contractions was determined prior to the first experimental session and remained the same throughout all sessions. That is, all subjects targeted force levels in the order of 30%, 70%, 40%, 80%, 20%, 90%, 10%, 50%, and 60% of their MVC.

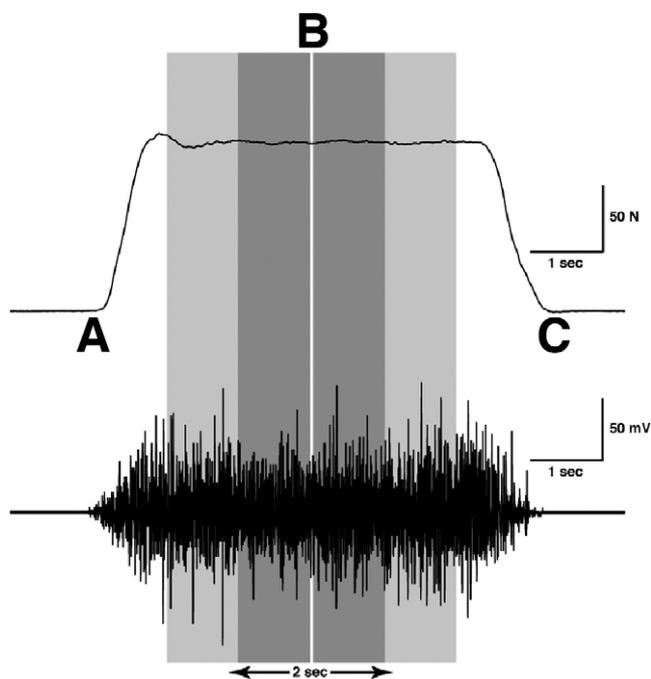


Fig 1. Example of a typical raw force output (upper) and surface electromyography signal (lower) obtained at 40% of MVC in the biceps brachii muscle of a control subject. Force output and surface electromyography signals at rest are shown prior to the (A) onset and (C) after the conclusion of the contraction. The duration of the contraction (4s) is represented by the lighter shaded area, with the darker area representing the 2-second interval (centered on the middle of the force output, point B) over which both the average force and RMS amplitude values were determined.

Both the FDI and biceps brachii protocols (including MUNE) were performed on the same day, with the biceps brachii data collection performed first in all subjects (with the exception of the Charcot-Marie-Tooth disease type X patients who did not have their biceps brachii tested).

Data Reduction and Analysis

We analyzed force and surface electromyography data offline after data collection using a commercially available software package (Spike 2, version 4.5).^b To determine an average force value (in newtons) for each of the specific force levels (including MVCs), a 2-second window from each of the 4-second contractions was averaged. This 2-second window was determined by identifying the center of the force output, located in the middle of the waveform representing the force output and averaging 1 second on either side of this point (fig 1). Using this same 2-second window, the RMS value (in millivolts) of the surface electromyography signal corresponding to the specific force levels was also calculated (see fig 1). To facilitate comparisons within and between groups, force and RMS values have been normalized to maximal values within individual subjects and therefore are presented as a percentage of this value.

Statistical Analysis

Mean values along with their standard deviations (SDs) are presented throughout. A 2-way repeated-measures analysis of variance (ANOVA) was used to compare RMS amplitude values within (effect of force level) and between (control vs

Table 1: Mean MVC and MUNE Data for the FDI and Biceps Brachii Muscles for Control Subjects and Patients

Subjects	FDI				Biceps Brachii			
	MVC (N)	M Wave (mV)	S-MUP NP Amp (μ V)	MUNE	MVC (N)	M Wave (mV)	S-MUP NP Amp (μ V)	MUNE
Controls	25.9 \pm 4.6 (18.9–34.3)	14.5 \pm 2.7 (10.5–17.3)	126.9 \pm 45.2 (66–229)	167 \pm 86 (78–395)	353.9 \pm 65 (259.4–497.7)	11.7 \pm 2.7 (7.1–15.5)	56.9 \pm 18.7 (32.4–91.3)	229 \pm 65 (159–357)
Patients	19.8 \pm 10.4 (5.9–34.8)	6.9 \pm 3.9 (0.4–13.2)	174.1 \pm 101.4 (81.9–392.7)	53 \pm 36 (4–116)	136.8 \pm 80.1 (31.7–270)	4.6 \pm 2.1 (1.2–8.0)	238.2 \pm 451.4 (26.2–1415)	101 \pm 126 (2–419)

NOTE: Values are mean \pm SD (range).

Abbreviation: NP Amp, negative-peak amplitude.

patient) groups. Additionally, MVCs performed by individual subjects before and after the constant force isometric contractions were compared using standard pairwise *t* tests, with all other between-group differences determined through 1-way ANOVA. All statistical analyses were performed using GraphPad Prism 4¹ with an α level of *P* less than .05 denoting significance.

Force and RMS Amplitude Relationships

To determine the nature of the force and RMS amplitude relationship, we plotted individual subject's RMS amplitude values against their corresponding force value and fit with both a linear (first-order polynomial) and curvilinear (second-order polynomial) function using nonlinear regression analysis. Due to the high level of fit between individual data sets and the simple linear function, as determined through the least sum of squares, it was concluded that the relationships were linear in nature, so additional curve fitting (ie, higher-order polynomials) was not performed. Additionally, slope values were determined for individual and grouped (control subjects and patients) force and RMS amplitude relationships using linear regression analysis, with 95% confidence intervals (CIs) calculated to quantify the range of variability for the slope of the regression lines and the RMS amplitude values of the grouped data.

RESULTS

FDI MUNE, MVC, and RMS Amplitude

MUNEs differed significantly between control subjects ($n=10$) and patients ($n=11$, Charcot-Marie-Tooth disease type X=5, ALS=6) (table 1). Despite this difference, the initial MVC values were similar between groups (see table 1). The addition of the Charcot-Marie-Tooth disease type X patients did not alter this finding, because the MVC values of both the Charcot-Marie-Tooth disease type X (21.4 \pm 10.5N) and the ALS (18.5 \pm 11.1N) patients did not differ compared with the control subjects individually. Additionally, the initial and post-contraction MVC values were similar within groups (controls, 25.9 \pm 4.6N, 25.8 \pm 4.4N; patients, 19.8 \pm 10.4N, 21.9 \pm 10.1N). Both groups accurately achieved and maintained the target forces during the constant force isometric contractions, shown by a mean variability in force across all levels of 1.2% (range, .2% [at 70% target force] to 2.5% [at 60% target force]). RMS amplitude increased with force ($P<.05$) in the FDI for both groups with no differences observed between groups (fig 2). Last, mean values associated with the MUNE calculation are shown in table 1, including maximum M wave and surface-detected MUP amplitude.

Biceps Brachii MUNE, MVC, and RMS Amplitude

MUNEs differed between control subjects ($n=10$) and ALS patients ($n=9$; $P<.05$) (see table 1) as did the initial

MVC values ($P<.05$) (see table 1). The initial and post-contraction MVC values were similar within groups (controls, 353.9 \pm 65.1N, 351.1 \pm 58.9N; patients, 136.9 \pm 80.1N, 134.9 \pm 73.5N). Force levels targeted during the constant force isometric contractions were achieved and maintained accurately by both groups, confirmed by a mean variability of 0.7% across all force levels, with a range of variability of 0.2% (30% of MVC) to 1.6% (60% of MVC). RMS amplitude increased with force for both groups ($P<.05$) (see fig 2). Despite a trend toward a difference in RMS amplitude values at lower levels of force (10%–30% of MVC) no differences were observed (see fig 2). Last, mean values associated with the MUNE calculation, including maximum

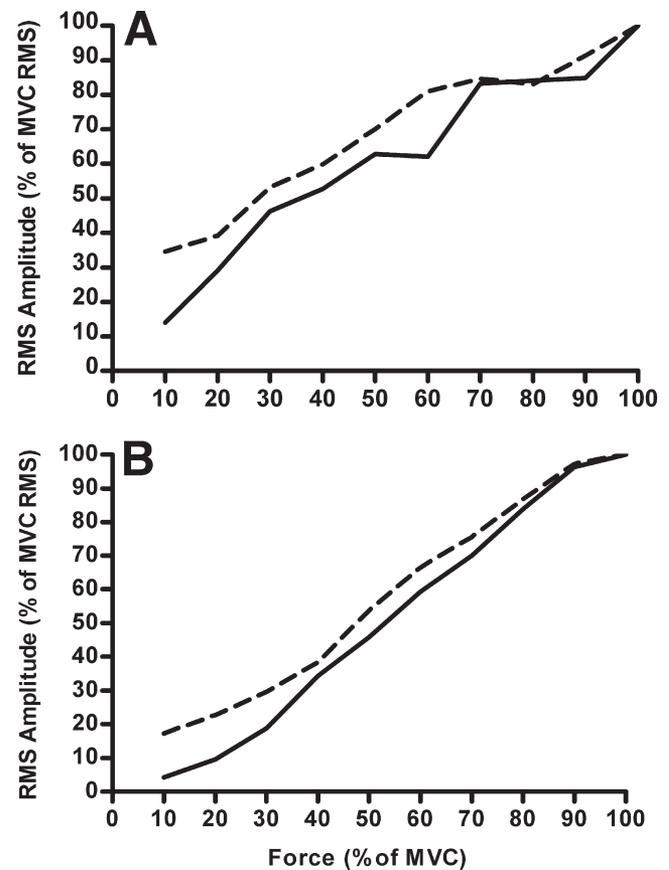


Fig 2. Relationship between force and RMS amplitude for control subjects (solid line) and patients (dashed line) for the (A) FDI and (B) biceps brachii. RMS amplitude increased with force ($P<.05$), with no differences detected between groups ($P>.05$) for both the FDI and biceps brachii.

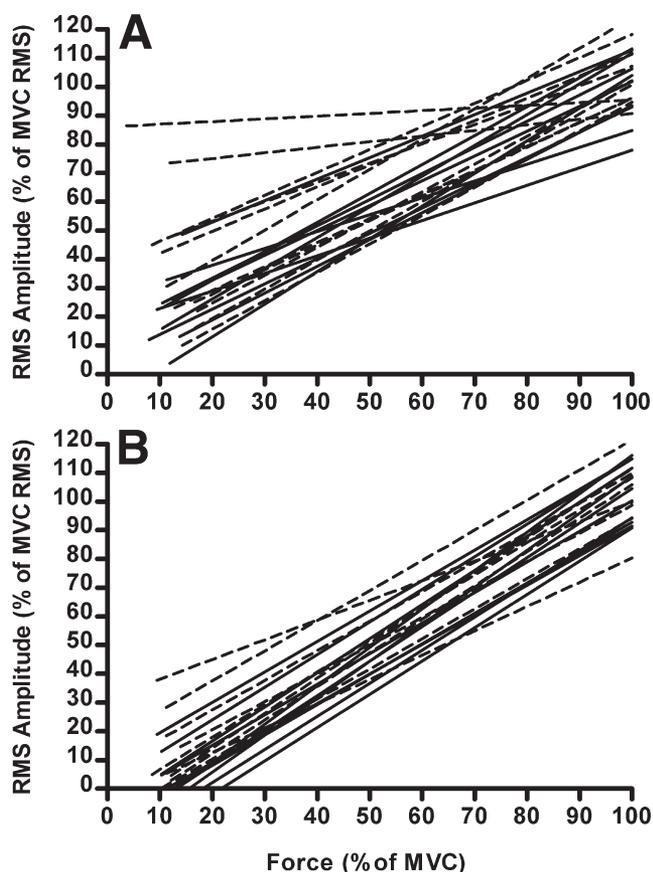


Fig 3. Force and RMS amplitude relationships for the (A) FDI and (B) biceps brachii fit with linear regression for both control subjects (solid lines) and patients (dashed lines). All subjects displayed strong positive linear relationships with the exception of 2 patients (A) (see text for details).

M wave and surface-detected MUP amplitude can be found in table 1.

FDI Force and RMS Amplitude Relationships

Individual relationships were well defined by the simple linear function, with the exception of 2 patients (fig 3), whose force–RMS amplitude relationship did not differ significantly from 0 when fit with either the first- or second-order polynomial, but rather would be best fit by a horizontal line (zero-order polynomial), indicating the absence of a relationship. Based on this finding, these patients were excluded from further analysis, and will be addressed in the latter portion of this report. With these patients excluded, a strong positive association was found between force and RMS amplitude for individual control subjects and patients, with mean R^2 values of $.81 \pm .17$ and $.77 \pm .16$, respectively (see fig 3). Relative to the mean correlation coefficients of the individual subjects, the R^2 values determined for the grouped relationships were slightly lower for both control subjects (.74) and patients (.64). Slope values ($\pm 95\%$ CI) for the regression line of the grouped force–RMS amplitude relationships were lower than those reported for the biceps brachii, but similar between groups (controls, $.88 \pm .11$; patients, $.87 \pm .14$) (fig 4).

Biceps Brachii Force and RMS Amplitude Relationships

Similar to the FDI, force and RMS amplitude relationships for the biceps brachii in individual subjects were well defined

by the simple linear function, displaying a strong positive relationship for control subjects and patients (mean R^2 , $.95 \pm .03$, $.94 \pm .02$, respectively) (see fig 3). Although lower than the mean regression coefficient (R^2) of the individual relationships, the R^2 value observed for the grouped relationships was high for both controls (.88) and patients (.83). Slope values ($\pm 95\%$ CI) for the regression line of the grouped force and RMS amplitude relationship were $1.1 \pm .04$ for the control subjects and $1 \pm .1$ for the patients (see fig 4).

DISCUSSION

The results of this study show that for these experimental conditions, the individual and grouped force–RMS amplitude relationships are best fit by a simple linear function for both the biceps brachii and FDI muscles. These relationships did not differ in comparing a sample of control subjects and patients with neuromuscular disease, in whom substantial motor unit loss and remodelling had occurred. Similar results were found across groups within each of the muscles studied, with higher levels of variability observed for the individual and grouped force–RMS amplitude relationships in the FDI. The linear relationships observed between force and RMS amplitude suggest that RMS amplitude may be used effectively as an estimate of contractile level during quantitative electrophysiologic examinations using decomposition-based quantitative electromyography.

Estimating contraction level using RMS amplitude. The application and subsequent fit of the force and RMS amplitude relationships by a simple linear function affords the ability to consider the use of the RMS amplitude as a means of estimating the level of contraction. Primarily, the use of a simple linear function allows for a basic understanding of the force and RMS amplitude relationship, which enables the relationship to be used in a practical manner. This is in contrast to the use of a higher order function, which by its nature may provide a better fit as defined by a higher regression coefficient (R^2), but at the same time lessens the practicality of the derived relationship.

Regardless of the high R^2 value provided by the simple linear function, which meets the goals of both goodness of fit and practicality, it would be inappropriate to suggest that the observed relationships be used to precisely predict muscle force. However, the relatively high mean regression coefficients observed for the individual force and RMS amplitude relationships in addition to mean individual slope values nearing a value of 1 for both the biceps brachii (controls, $1.1 \pm .08$; patients, $1.0 \pm .16$) and FDI (controls, $.88 \pm .18$; patients, $.90 \pm .13$) (see fig 3) indicate that these relationships may be a useful tool to estimate submaximal intensities of contraction for individual subjects.

Although it is of interest to study these individual relationships, their use as a means of estimating contractile level clinically lacks practicality, because it is not feasible to determine the force and RMS amplitude relationship of each individual patient prior to a quantitative electromyography examination. Alternatively, combining the data from different muscles of individual control subjects or patients would be more efficient, because a single force and RMS amplitude relationship would then represent the subjects within the group (ie, control subjects or patients).

The grouped force and RMS amplitude relationships in our study displayed slope values similar to those obtained for the individual relationships, shown by the relatively small 95% CIs calculated around the slope of the grouped regression lines (see fig 4). However, the regression coefficients for these grouped relationships are lower compared with the mean values of the individual relationships in both muscles. This finding is not

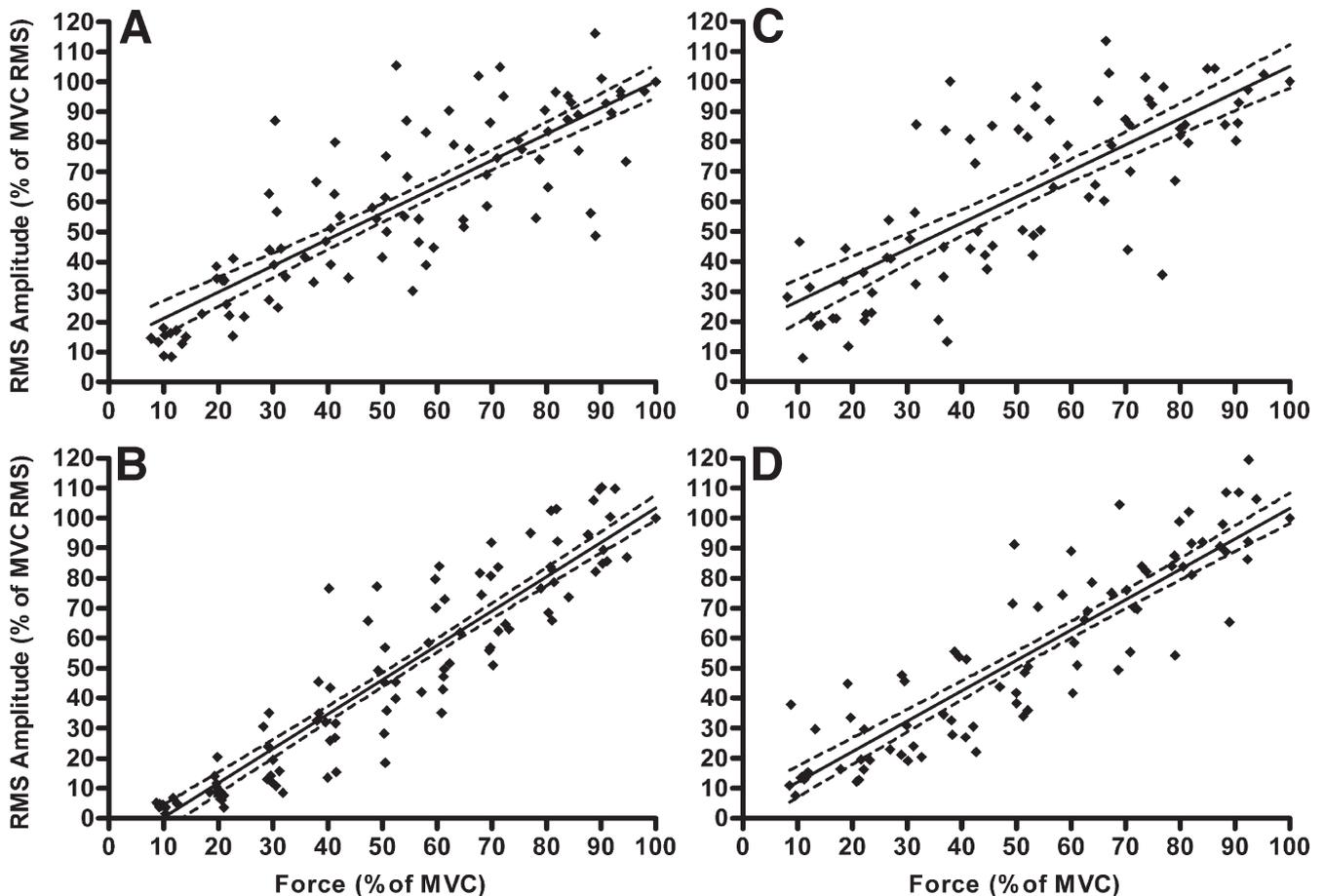


Fig 4. Grouped force and RMS amplitude relationships for control subjects (A, B) and patients (C, D) for the FDI (A, C) and biceps brachii (B, D) fit with linear regression. Slope values of the regression lines $\pm 95\%$ CI (dashed lines) for control subjects and patients are $.88 \pm .11$ and $.87 \pm .14$ for the FDI and $1.1 \pm .04$ and $1 \pm .1$ for the biceps brachii, respectively.

surprising, however, given that the spread of the data is greater when individual subject data are grouped. This variability is illustrated in figure 3, which shows that, despite comparable slope values, there are considerable differences in the elevations of the regression line intercepts across individual subjects. These differences reflect that the scatter in the data is primarily in the RMS amplitude values, because force was held constant for all subjects at each of the testing levels (see fig 4, see results for force data). To quantify the range of this variability, 95% CIs were calculated for the RMS amplitude values about the regression lines of the grouped relationships. This analysis revealed that for any given point on the regression line the RMS amplitude value may vary in the FDI by $\pm 6.7\%$ (control subjects) or $\pm 8.5\%$ (patients), with lower values calculated for the biceps brachii of $\pm 5\%$ (control subjects) and $\pm 6.1\%$ (patients). Given the complexity of detecting and measuring the surface electromyography signal during voluntary contractions, it is not surprising that there is a degree of variability.¹⁶⁻¹⁸ Furthermore, although these results confirm that there is a degree of variability present in these relationships, that fact does not preclude the use of the relationships as a means of estimating contractile level.

Control subjects versus patients. Our finding of similar force and RMS amplitude relationships between groups despite considerable differences in motor unit number is not unex-

pected, given that the control subjects and patients' absolute force and RMS amplitude values were normalized to their respective maximal values. These similarities may be attributed to a decrease in the extent of amplitude cancellation within the surface electromyography signal that occurs when positive and negative phases of different MUPs overlap and summate destructively prior to rectification; a process that seems to be influenced by the number of motor units within the motor system.¹⁹ This was shown in a recent simulation study, which showed that compared with an intact motor system, a system exhibiting a 50% loss of motor units experienced an average of 12.9% less amplitude cancellation across the range of muscle excitation, yet displayed a similar average electromyography activity—excitation level relationship as the intact system when both average electromyographic activity and force were normalized to maximal values.¹⁹

Interestingly, the force and RMS amplitude relationships observed in the current study were similar within muscles and between groups with the exception of 2 patients, who had MUNE values equal to 2.4% (4 motor units) of control subjects and who displayed almost no relationship between force and RMS amplitude (see fig 3). Despite the remainder of their contractions displaying an RMS amplitude value similar to that of the 10% MVC contraction, both patients successfully matched the target forces across the range of their respective MVC values.

The relatively small magnitude of these values, and the absence of a large change in RMS amplitude, suggests a lower threshold of motor unit number at which amplitude cancellation has a greater impact. Specifically, it is expected that higher levels of force result in an increase in the magnitude of the RMS amplitude, even in the absence of the recruitment of additional motor units, due to the higher discharge rates of the active motor units. The absence of this increase in RMS amplitude may be related to the frequency with which the MUPs of these active motor units overlap, resulting in a greater degree of phase cancellation and subsequently reduced RMS amplitude. For the FDI muscle, this lower threshold of motor unit number may lie somewhere below 15% of the number of motor units estimated for the control subjects, because linear force and RMS amplitude relationships were observed in patients with greater than 80% motor unit loss.

Evidence for this lower threshold effect was not apparent in the biceps brachii, despite the fact that 2 patients had MUNE of 4.4 (10 motor units) and 0.9% (2 motor units) of control subjects. The preservation of these linear relationships in the face of severe motor unit loss may be due to the contribution of other muscles that act to flex the elbow joint as a source of both force production and volume conducted electromyography. Last, it could be speculated that differences in the recruitment patterns and discharge frequencies of the motor units in addition to variability in the duration of the individual MUPs could impact on the degree of phase cancellation within the surface electromyography signal and subsequently on the RMS amplitude values obtained. Future investigations into the relevance and potential impact of these possible explanations are warranted.

Biceps brachii versus FDI. Previous studies examining the relationship between force and the surface electromyography signal have reported conflicting results (nonlinear and linear) for the biceps brachii, but consistently reported linear relationships for the FDI muscle.^{5,8,10-12,20} The differences observed between the muscles were attributed to their distinct muscle fiber composition and force production strategies.²⁰⁻²³ Contrary to some of these past findings, our results show that the force and RMS amplitude relationship is best fit by a linear function for the biceps brachii and FDI muscles in both control subjects and patients with neuromuscular disease. The similarity in the relationships observed for the muscles in this study are supported by the results of simulations, which have shown comparable relationships when normalized surface electromyography was plotted as a function of muscle excitation (0%–100%) for both a narrow (FDI) and broad (biceps brachii) recruitment range.^{19,24}

It is possible that the varying relationships observed within experimental studies may be related to methodologic differences, including electrode size, type and configuration, contraction type and the method(s) used to analyze the surface electromyography signal.^{13,16,18,25} Last, the type of analysis used to characterize the relationship between force and surface electromyographic activity should be considered, because many of the nonlinear relationships reported previously may also be well defined by a simple linear function, though not as accurately as by a higher-order, nonlinear function, as described earlier.

CONCLUSIONS

For the experimental conditions described for this study, linear force and RMS amplitude relationships were observed for the biceps brachii and FDI muscles in control subjects and patients with neuromuscular disease. These results are inclusive of the relationships derived for subjects and groups, although the establishment of the grouped relationships and their

corresponding 95% CIs may have greater clinical applicability in estimating the level of contraction because they express the variability associated with a population of similar subjects or patients.

The high level of association observed between force and RMS amplitude in the biceps brachii and FDI suggest that RMS amplitude is an acceptable means of estimating contractile level in studies using decomposition-based quantitative electromyography. However, because there is a degree of variability present in these force and RMS amplitude relationships, it is necessary to determine if this variability is acceptable in replacing the previous methods of measuring force.

References

1. Doherty TJ, Stashuk DW. Decomposition-based quantitative electromyography: methods and initial normative data in five muscles. *Muscle Nerve* 2003;28:204-11.
2. Boe SG, Stashuk DW, Doherty TJ. Motor unit number estimation by decomposition-enhanced spike-triggered averaging: control data, test-retest reliability, and contractile level effects. *Muscle Nerve* 2004;29:693-9.
3. Boe SG, Stashuk DW, Doherty TJ. Within-subject reliability of motor unit number estimates and quantitative motor unit analysis in a distal and proximal upper limb muscle. *Clin Neurophysiol* 2006;117:596-603.
4. McNeil CJ, Doherty TJ, Stashuk DW, Rice CL. Motor unit number estimates in the tibialis anterior muscle of young, old, and very old men. *Muscle Nerve* 2005;31:461-7.
5. Boe SG, Stashuk DW, Brown WF, Doherty TJ. Decomposition-based quantitative electromyography: effect of force on motor unit potentials and motor unit number estimates. *Muscle Nerve* 2005; 31:365-73.
6. McNeil CJ, Doherty TJ, Stashuk DW, Rice CL. The effect of contraction intensity on motor unit number estimates of the tibialis anterior. *Clin Neurophysiol* 2005;116:1342-7.
7. Inman VT, Ralston HJ, Saunders JB, Feinstein B, Wright EW Jr. Relation of human electromyogram to muscular tension. *Electroencephalogr Clin Neurophysiol Suppl* 1952;4:187-94.
8. Milner-Brown HS, Stein RB. The relation between the surface electromyogram and muscular force. *J Physiol* 1975;246:549-69.
9. Moritani T, deVries HA. Reexamination of the relationship between the surface integrated electromyogram (IEMG) and force of isometric contraction. *Am J Phys Med* 1978;57:263-77.
10. Woods JJ, Bigland-Ritchie B. Linear and non-linear surface EMG/force relationships in human muscles. An anatomical/functional argument for the existence of both. *Am J Phys Med* 1983;62:287-99.
11. Lawrence JH, De Luca CJ. Myoelectric signal versus force relationship in different human muscles. *J Appl Physiol* 1983;54: 1653-9.
12. Lloyd AJ. Surface electromyography during sustained isometric contractions. *J Appl Physiol* 1971;30:713-9.
13. Perry J, Bekey GA. EMG-force relationships in skeletal muscle. *Crit Rev Biomed Eng* 1981;7:1-22.
14. Brooks BR, Miller RG, Swash M, Munsat TL. El Escorial revisited: revised criteria for the diagnosis of amyotrophic lateral sclerosis. *Amyotroph Lateral Scler Other Motor Neuron Disord* 2000;1:293-9.
15. Klein CS, Rice CL, Marsh GD. Normalized force, activation, and coactivation in the arm muscles of young and old men. *J Appl Physiol* 2001;91:1341-9.
16. De Luca CJ. The use of surface electromyography in biomechanics. *J Appl Biomech* 1997;13:135-63.
17. Farina D, Cescon C, Merletti R. Influence of anatomical, physical, and detection-system parameters on surface EMG. *Biol Cybern* 2002;86:445-56.

18. Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG. *J Appl Physiol* 2004;96:1486-95.
19. Keenan KG, Farina D, Maluf KS, Merletti R, Enoka RM. Influence of amplitude cancellation on the simulated surface electromyogram. *J Appl Physiol* 2005;98:120-31.
20. Milner-Brown HS, Stein RB, Yemm R. The contractile properties of human motor units during voluntary isometric contractions. *J Physiol* 1973;228:285-306.
21. Klein CS, Marsh GD, Petrella RJ, Rice CL. Muscle fiber number in the biceps brachii muscle of young and old men. *Muscle Nerve* 2003;28:62-8.
22. Kukulka CG, Clamann HP. Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions. *Brain Res* 1981; 219:45-55.
23. Milner-Brown HS, Stein RB, Yemm R. The orderly recruitment of human motor units during voluntary isometric contractions. *J Physiol* 1973;230:359-70.
24. Fuglevand AJ, Winter DA, Patla AE. Models of recruitment and rate coding organization in motor-unit pools. *J Neurophysiol* 1993;70:2470-88.
25. Solomonow M, Baratta R, Shoji H, D'Ambrosia R. The EMG-force relationships of skeletal muscle; dependence on contraction rate, and motor units control strategy. *Electromyogr Clin Neurophysiol* 1990;30:141-52.

Suppliers

- a. Grass-Telefactor, 600 E Greenwich Ave, West Warwick, RI 02893.
- b. Cambridge Electronic Design, Science Park, Milton Rd, Cambridge, CB4 0FE, UK.
- c. Model 5111A storage oscilloscope; Tektronix Inc, 14200 SW Karl Braun Dr, Beaverton, OR 97005.
- d. Model SST-700-100A; ASTechnology, Haliburton, ON, Canada.
- e. Digitimer, 37 Hyde Wy, Welwyn Garden City, AL7 3BE, UK.
- f. Kendall-LTP, 2 Ludlow Park Dr, Chicopee, MA 01022.
- g. Model N53153; Teca Corp, 12 Skyline Dr, Hawthorne, NY 10532.
- h. Compumedics Ltd, 30-40 Flockhart St, Abbotsford 3067, Victoria, Australia.
- i. Version 4.02; GraphPad Software, 11452 El Camino Real #215, San Diego, CA 92130.