Myoelectric signal versus force relationship in different human muscles

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LAWRENCE, J. H., AND C. J. DE LUCA. *Myoelectric signal versus force relationship in different human muscles.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 54(6): 1653–1659, 1983.—An analytic study was initiated to investigate whether the normalized surface myoelectric signal vs. normalized force relationship varies in different human muscles and whether it is dependent on training level and rate of force production. The data were obtained from experiments that involved the biceps, deltoid, and first dorsal interosseous of three pianists, four long-distance swimmers, three power lifters, and six normal subjects. The elite performers (among the world's best) were chosen because they exhibited varying degrees of fine motor control, endurance training, and power training in different muscles. Approximately 200 isometric linearly force-varying contractions peaking at 80% of the maximal voluntary contraction level were processed. The results indicated that the myoelectric signal-force relationship was primarily determined by the muscle under investigation and was generally independent of the subject group and the force rate. Whereas this relationship was quasilinear for the first dorsal interosseous, it was nonlinear for the biceps and deltoid. Several possible physiological causes of the observed behavior of the myoelectric signal-force relationship are discussed.

electromyography; athletes; biceps; deltoid; first dorsal interosseous; exercise

PRESENTLY, NO PHYSIOLOGICAL MODEL exists which accurately describes a relationship between the amplitude of the surface-recorded myoelectric (ME) signal and the measured force output of different muscles in various contraction modes. Various theoretical analyses generally suggest that the amplitude of the ME signal should increase as the square root of force generated if the motor units contract independently (1, 24, 27, and others). Surprisingly, few experimental results support or approach the theoretical square root relationship. Most investigators report a linear relationship, (21, 22, 25, 30, and others) while other investigators (2, 18, 25, 32, and others) report a nonlinear relationship with the ME signal increasing more than force.

Previous investigations have been characterized by great variability in the muscles examined, the type of contractions performed (for example isometric or isotonic), and the quantities derived from raw data to represent the amplitude of the ME signal. These considerations are important because each muscle has unique physiological properties and anatomical structure and may possibly be controlled by different motor schemes

(7, 8, 19). Furthermore, the degree of synergistic action of other muscle groups and the varying amounts of cocontraction among antagonist muscle groups may alter the force contribution of the muscle under investigation to the measured net force on a joint. It is conceivable that any or all of these factors as well as others could influence the ME signal-force relationship.

In addition, variability in recording and data processing techniques may explain some of the inconsistencies in the reported ME signal-force relationship for specific muscles. Three types of electrodes, viz., surface, indwelling needle, and wire electrodes, have been used in both monopolar and bipolar configurations. The filtering properties of bipolar electrodes are a function of their orientation relative to the active muscle fibers (9), the size of the recording contacts (13), the distance between the contacts (20), and the chemical properties of the metal-electrolyte interface (5). Amplifier and filter specifications may also influence the final form of the processed ME signal (5). Most importantly, a variety of parameter measures of the amplitude of the ME signal have been used; they include the smoothed rectified amplitude (30), mean rectified (22), or root-mean-square (rms) (31) amplitude, and several versions of integrated amplitude (2, 18, 21). The great physiological and technological variability so far described has made comparison of experimental results and reproducibility of experiments extremely difficult. Beyond these methodological inconsistencies, the absence of normalization of the data often constitutes a deficiency in many reported investigations that have compared or averaged groups of subjects.

For a more comprehensive review of this topic, the reader is referred to the recent work of Perry and Bekey (26).

The present study has been initiated to investigate whether the normalized surface-recorded ME signal amplitude vs. normalized force relationship varies in different muscles and whether it is dependent on exercise level. Another objective is to determine how much variability exists among the same muscles of different individuals. The data were obtained from experiments that involved the biceps brachii, deltoid, and first dorsal interosseous of pianists, long-distance swimmers, power lifters, and normal subjects during voluntary isometric linearly force-varying contractions. This inquiry presupposed that if type of training influences the normalized surface recorded ME signal-force relationship or if the relationship is muscle-dependent, it will t e revealed through the

elite performers, who exhibited widely varying degrees of fine motor control, endurance training, and power training in three different muscles.

METHODS

Subjects. Sixteen healthy male volunteers representing four distinct types of training participated in this study. These subject groups consisted of six untrained normal subjects, aged 21–34 yr; three pianists with uniquely trained first dorsal interosseous (FDI) muscles, aged 24–52 yr; four 1,500-m swimmers with deltoid and biceps brachii muscles specially developed for endurance, aged 17–19 yr; and three power lifters with biceps brachii and deltoid muscles specially developed for power contractions, aged 20–35 yr. The long-distance swimmers, including a silver medalist from the Montreal Olympics in 1976, were in training for the Moscow Olympics in 1980. The power lifters, including a world record holder, were former US Champions in training for the power lifting World Championships. The pianists, including a member of the Boston Pops Orchestra, had a combined 88 yr of experience.

Experimental procedure. Prior to each experiment, each subject read and signed an informed consent form. The following muscle contractions were studied for the right upper limb: *1)* isometric abduction of the index finger, with the ME signal being recorded from the FDI muscle; *2)* isometric abduction of the upper limb with the forearm fully pronated, with the ME signal being recorded on the surface of the central region of the deltoid muscle; and *3)* isometric flexion of the forearm with the forearm semisupinated, with the ME signal recorded from the short head of the biceps brachii muscle.

The subject generated isometric contractions of the FDI through the attempted abduction of the index finger in a plane parallel to the hand. The force was detected through a pad near the proximal interphalangeal joint by a transducer positioned perpendicularly to the fingers in the plane of abduction. It has been shown by previous investigators (12, 23, 30) that the force thus measured is linearly proportional to the isometric tension developed by the FDI.

The subject generated isometric contractions of the deltoid through the attempted abduction of the upper limb in the coronal plane while supine on a padded table. The arm was fully extended and pronated with the upper limb secured at 45–60° from the sagittal plane. An arm cuff connected to a vertical cable supported the weight of the limb. The force was detected via a cable, and a terminal arm cuff was attached just proximal to the elbow by a transducer positioned perpendicularly to the arm in the coronal plane. For this particular biomechanical orientation, the middle fibers of the deltoid and the supraspinatus are the predominant abductors of the upper limb. Their relative contributions remain approximately constant throughout the complete range of isometric abduction force (6). The force measured was therefore approximately linearly proportional to the isometric tension developed by the middle fibers of the deltoid.

The subject generated isometric contractions of the biceps brachii through the attempted flexion of the elbow in a sagittal plane while supine on a padded table. The elbow was maintained at a 90° angle, and the forearm was semisupinated. The force was detected via a cable, and a terminal arm cuff was placed around the wrist by a transducer positioned perpendicularly to the forearm in a sagittal plane. Since flexion of the elbow is accomplished primarily by the synergistic action of the biceps brachii, brachialis, and brachioradialis, the measured force is not necessarily proportional to the isometric tension developed by the biceps brachii. However, this arrangement provided one of the most direct relationships possible. This point is supported by a recent study of Heckathorne and Childress (15), who reported that in amputees with cineplastic muscle tunnels in the biceps brachii, the force-ME signal relationship was similar to that of the biceps brachii of normals.

For each muscle of each subject, a pair of isometric contractions lasting 5 s was performed 30 min apart to measure the force output of the maximal voluntary contraction (MVC). The larger of the two values was denoted as the MVC and served as a reference value for calibrating the force levels of subsequent contractions. In all cases the two measurements differed by less than 6%. (This may be partially due to the fact that the subjects were requested to come to the laboratory and practice generating MVCs on the previous day.) Then the subjects were required to track a ramp profile appearing on an oscilloscope visually with a trace representing the output of the force gauge. All the contractions reached a level of 80% MVC and were performed at a rate of 10, 20, and 40% MVC/s. Before the beginning of a contraction, the subject was instructed to maintain a small preload (2–5% MVC) on the force transducer to reduce any impulse artifacts at the initiation of tension. Each subject performed each contraction at least twice. The duration of the rest periods between contractions, a minimum of 15 min, was chosen to minimize the effects of fatigue.

ME activity was detected by two Beckmann silver-silver chloride surface bipolar electrodes oriented parallel to the active fibers of the muscle under investigation and coupled to the skin with an electrolyte gel. The center-to-center interelectrode distance was approximately 2.0 cm. A reference ground strap was attached near the wrist. The ME signal was differentially amplified with a bandwidth of 2 Hz–1 kHz. All force measurements were obtained with an SM250 interface force transducer of low compliance (2.7 μm/kg), which did not compromise the isometric conditions.

Data processing. The ME signal and force data from approximately 200 contractions were processed and analyzed. Both signals were low-pass filtered with a cutoff frequency of 500 Hz and digitized at well over the Nyquist rate to provide finer time resolution and to partly compensate for subsequent data compression routines. The rms values were computed for each ME signal and force data file. The rms value was chosen because it is the parameter that more completely reflects the physiological correlates of the motor unit behavior during a muscle contraction (5, 9). Smoothing was performed using a Hamming window digital filter. The width of this filter

was 400, 600, and 800 ms for the 40, 20, and 10% MVC/s contractions, respectively. The net effect was that the output signal for all three rates of contraction had approximately the same degree of ripple at the peak force. The value of the rms signal was measured at every 4% of MVC interval.

The force level was normalized by the magnitude of the MVC. The ME signal amplitude was normalized by the value of the ME signal corresponding to 72% MVC to avoid the inconsistent variations of the ME signal amplitude at higher force levels. The data were grouped to investigate the effect of the rate of contraction (10, 20, and 40% MVC/s), training (normals, pianists, long-distance swimmers, power lifters), and muscle (FDI, deltoid, biceps).

The first concern was to establish whether the ME signal-force relationship differed as a function of muscle. The most commonly used statistical test of analysis of variance or covariance cannot be used meaningfully in this case, because the data had to be normalized (to allow a reasonable comparison among subjects) and the errors in adjacent points are not independent. Instead, it was decided to test whether the relationships could be considered to be linear or nonlinear. This was done by fitting a zero-, first-, and second-order polynomial to all of the data points of each of the three groups of data (all the experiments on the FDI, deltoid, and biceps). For each polynomial, a goodness-of-fit test was performed to determine the level of confidence that could be associated with how well the polynomial described the data.

The program P5R of the BMDP of the University of California Press (1979) was used to measure the lack of fit of the estimated polynomial at each degree relative to the residual mean square from fitting the polynomial. Thus, a high value of the F statistics would be an indication of a poor fit.

The effect of the force rate and groups could not be tested meaningfully. Due to the dependence and normalization of the data, only weak statistical tests could be performed. Therefore it was chosen to perform only two-tailed t tests at three force levels (20, 40, and 60% MVC). However, it must be emphasized that these t tests provide little confidence above that which may be ascertained simply by looking at the plots and noting the coefficient of variation of the data.

RESULTS

The mean values of the ME signal-force data from the three different muscles are displayed in Fig. 1. These data are an aggregate of all of the contractions performed in the experiments. The standard deviation of the data is not presented in Fig. 1, because of the visual complexity that would result from the overlap; instead, Table 1 presents a brief statistical analysis of the variability of the data characterizing the ME signal-force relationship. The average value of the standard deviation values of the curves was reasonably uniform, approximately 8.5% for all three muscles; this measure provides an assessment of the variability of the data. The quantity was found to be approximately 25% of the mean in each case, indicating that the standard deviation of the ME signal

was relatively constant over the entire force range considered. Table 2 also describes the standard deviation of the ME signal for group-averaged data; however, the "group" is a single normal subject. Each of these subjects performed six or more contractions of one muscle which were then averaged. Apparently there is somewhat less variability in the ME signal when considering one person rather than a group of subjects.

The results of the polynomial regression fits are presented in Table 3. Neither a first- nor a second-order polynomial is complex enough to fit the curvature of the deltoid and biceps data as indicated by the unacceptably high values of F and low values of P. A straight line is a better fit to the data for the FDI than it is to the other two but still lacks fit in a statistical sense. The second-order polynomial does fit. The estimated first- and second-order polynomial regressions were

$$m = 2.23 + 1.33\ \phi$$
$$m = 1.72 + 1.36\ \phi - 0.00042\ \phi^2$$

where m is the normalized amplitude of the ME signal and ϕ is the normalized force. It should be noted that the
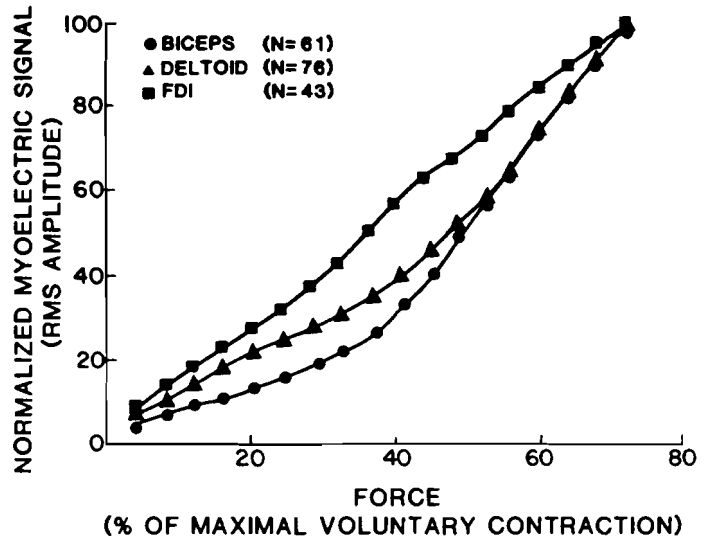

FIG. 1. Effect of muscle on myoelectric signal-force relationship. N, number of contractions averaged.

TABLE 1. *Standard deviation of normalized myoelectric signal for different muscles*

Muscle	N	Avg SD
Biceps	61	8.33
Deltoid	76	8.18
FDI	43	9.14

N, No. of muscles; FDI, first dorsal interosseons.

TABLE 2. *Standard deviation of normalized myoelectric signal for individual normal subjects*

Subj	Muscle	N	Avg SD
MS	Biceps	7	5.98
MK	Deltoid	10	6.23
JM	FDI	6	3.84

N, No. of muscles; FDI, first dorsal interosseons.

TABLE 3. *Goodness-of-fit tests for polynomial regressions*

Muscle	N	Polynomial Deg	F	P
FDI	450	0	1,117.20	NS
		1	3.53	0.03
		2	2.12	0.15
Deltoid	473	0	1,964.20	NS
		1	59.52	NS
		2	10.33	NS
Biceps	460	0	1,187.11	NS
		1	72.54	NS
		2	34.07	NS

N, No. of points; FDI, first dorsal interosseous; P, values for null hypothesis that the polynomial fits. Note that a significant F statistic indicates that a higher degree polynomial should be considered. Data of the first dorsal interosseous muscle appears to be better approximated by a first-order polynomial than that of the deltoid or biceps which are more complicated.

second-degree term does not provide a substantial deviation from the linear expression. For example, for $\phi = 50$, the value of the ME signal amplitude calculated by both equations differs by only 3%. Hence, for practical purposes, a quasilinear relationship is well suited to describing the FDI data.

The ME signal-force curves for group-averaged contractions at different force rates are displayed in Fig. 2 for each muscle. The paired t test results generally indicated no statistically significant effect ($P > 0.05$) due to force rate in the range investigated. A doubling of force rate from 10 to 20% MVC/s or from 20 to 40% MVC/s had almost no effect on the ME signal-force relationship, but a quadrupling of the rate from 10 to 40% MVC/s produced some statistical differences that were mostly significant ($P < 0.05$) at low force levels (20% MVC). Visually the mild effect of rate was evidenced by the rather consistent order of the three curves for a given force level; i.e., the 40% MVC/s curve had the highest mean amplitude ME signal, followed by the 20% MVC/s curve, and then the 10% MVC/s curve. It is also apparent that for each muscle the three force rate curves followed the same contour.

The ME signal-force curves for the four groups, viz., normal subjects, pianists, long-distance swimmers, and power lifters are displayed in Fig. 3. The results revealed no statistically significant difference between the normal subjects and the specialists for the FDI except between long-distance swimmers and power lifters at 60% MVC ($P < 0.005$). This discrepancy may be attributed to the erratic course of the long-distance swimmers' curve, which is a compilation of only four contractions. With this in mind, it may be seen that, for the FDI the ME signal-force relationship is generally independent of subject group. In the biceps, the normal subjects developed a smaller ($P < 0.05$) mean amplitude ME signal than the three specialist groups at 40% MVC. Otherwise, the curves for the biceps of all four groups were quite similar statistically. For the deltoid, significant differences were observed between long-distance swimmers and power lifters at high and low forces ($P < 0.005$), between pianists and power lifters below 40% MVC ($P < 0.005$), and less significantly between normal subjects and power lifters
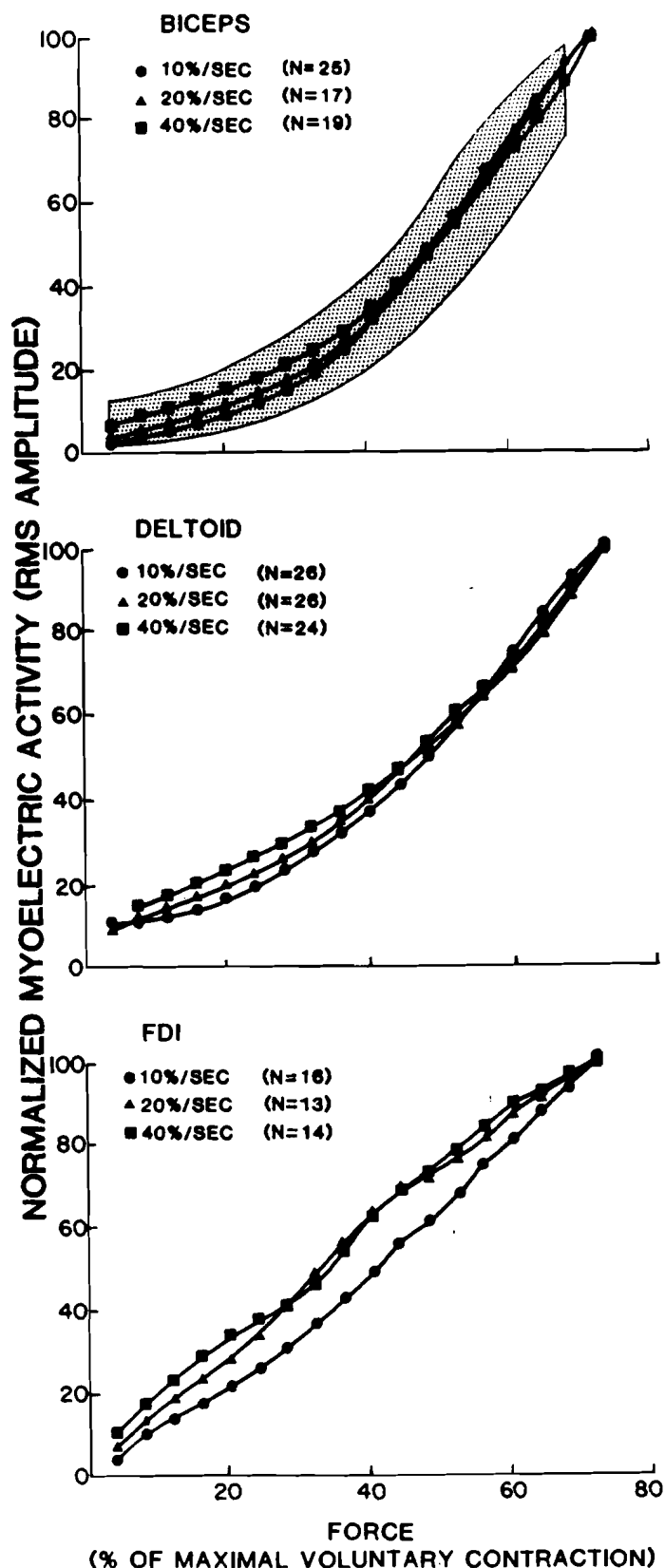

FIG. 2. Effect of force rate on myoelectric signal-force relationship. Standard deviations of raw data are indicated by *shading* in *top graph*. N, number of contractions averaged.

below 40% MVC ($P < 0.05$). Resembling the behavior of the force rate curves in Fig. 2, the four subject group curves for each muscle had a similar shape.

Overall, the statistical tests performed on the data of Fig. 2 and 3 are consistent with the visual interpretation of this data.

DISCUSSION

Even under the careful and controlled conditions of the experiments, the data characterizing the ME signal-force relationship exhibited considerable variability. This variability, expressed by the average standard deviation of the amplitude of the ME signal at a given force, ranged from approximately 7 to 11%; in individual subjects the variability was approximately 25% less. Stulen and De Luca (31) found a similar range of standard deviation during constant force isometric contractions.

Although the MVC was a reliable reference level for force, there was no equally consistent reference quantity for the amplitude of the ME signal. The value chosen, corresponding to 72% MVC, was reasonable, but it was subject to a large standard deviation in the ME signal at high force levels that may have biased the entire normalized ME signal. Furthermore, the normalization procedure did not take into account the time lag between the peaks of the ME signal and force waveforms, which is due to biochemical and electromechanical interactions. The net consequence was to slightly elevate (by approx 2–4%) the normalized ME signal at a given force level for faster contractions. This may have been responsible for the "mild effect" of rate observed in Fig. 2. By fixing a point on the graph (72% MVC, 100% normalized ME signal), normalization inherently limited the excursion of the ME signal-force curve. This procedure may have partially disguised some variability in the data, but it further strengthens the significance of the difference between muscles.

A concern that arises from the experimental paradigm used in this study relates to the accumulated effect of muscle fatigue on the ME signal during the sustained isometric contraction. It is well known (4, 10) that during a sustained constant-force contraction, the amplitude of the surface detected ME signal increases as a function of time; therefore the slower force rate contractions should be more affected. In fact, this phenomenon may be clearly seen in Fig. 2, where for each separate muscle the curves of the three force rates are arranged in a similar orderly sequence. However, the difference in the mean value caused by the fatiguing process is far less than the standard deviation across subjects. Therefore it may not be held accountable for determining the linearity of the relationship and does not explain the conflicting reports in the literature.

The results indicate that the ME signal-force relationship approaches being linear for the FDI and is, with considerable confidence, nonlinear for the biceps brachii and deltoid muscles. The quasilinear relationship in the FDI is in agreement with previously reported observations (3, 22, 30). For the biceps brachii, both linear (21, 25, and others) and nonlinear (3, 18, 25, 32, and others) relationships have been reported.

A variety of phenomena that may contribute to the muscle-dependent difference in the ME signal-force relationship can be identified. Some of them are 1) motor unit recruitment and firing rate properties; 2) relative
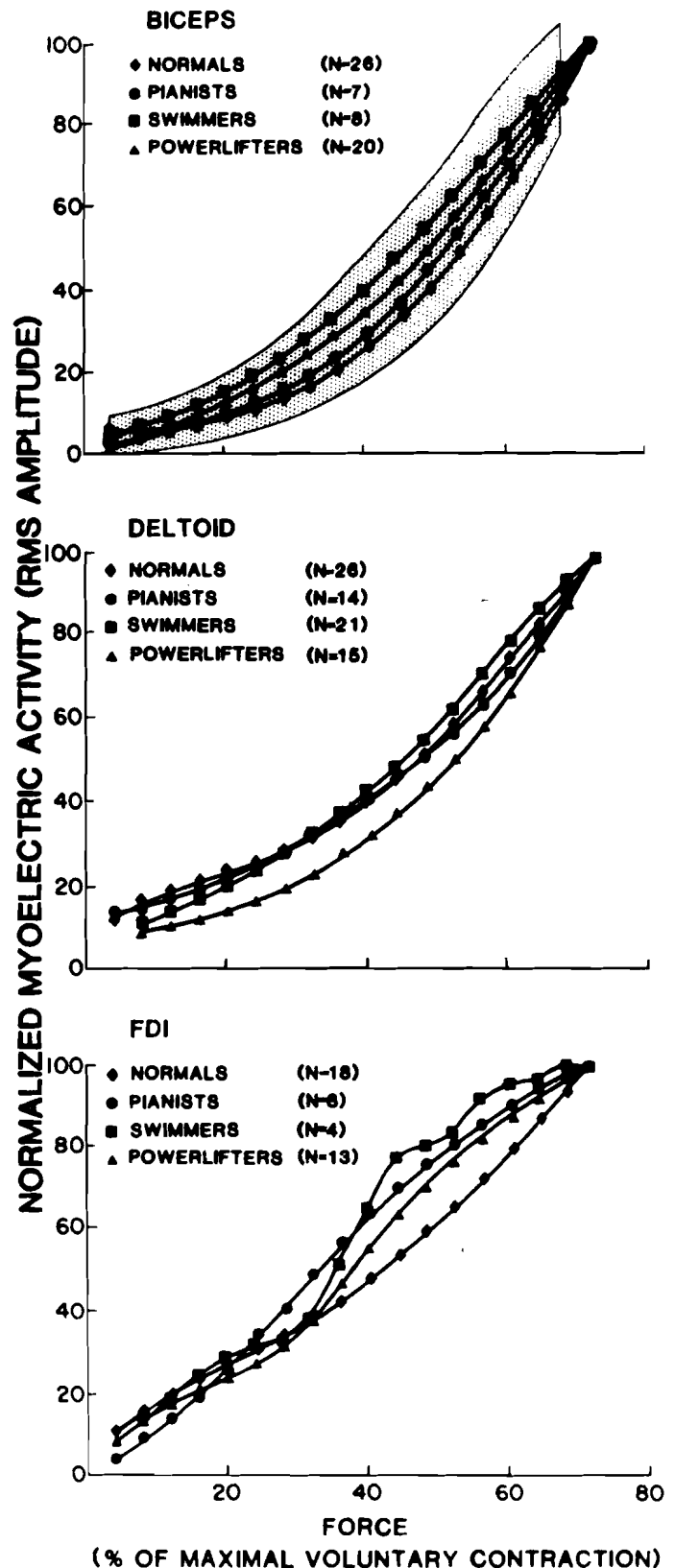

FIG. 3. Effect of subject group on myoelectric signal-force relationship. Standard deviations of raw data are indicated by *shading* in *top* graph. N, number of contractions averaged.

amounts and location of slow-twitch and fast-twitch muscle fibers within the muscle; 3) cross talk from ME signals of adjacent muscles; 4) agonist-antagonist muscle inter-

action; and 5) viscoelastic properties.

The difference in the viscoelastic properties of muscles, although it may be an influential factor, remains difficult to verify. The agonist-antagonist interaction of simultaneously contracting muscles becomes an important consideration during isometric contractions where the joints must be stabilized. In experimental paradigms such as the one used in this study and many others reported in the literature, only the net force resulting from the agonist-antagonist interaction is measured. This net force is customarily assumed to be linear with respect to the agonist muscle of interest. However, this relationship may be altered by numerous factors such as joint angle, limb position, and pain sensation. Hence, the ME signal-force relationship (from the muscle of interest) may be altered. The electrical cross talk from adjacent muscles is unquestionably a possible factor and cannot be eliminated when testing muscles in situ, especially during forceful contractions. In fact, this cross talk may account for the reported difference in the ME signal-force relationships when the ME signal is detected with monopolar or bipolar electrodes (25). These two types of electrodes have considerably different frequency characteristics and detect different amounts of electrical signals from "distant" active muscle tissue (20, 33).

The motor unit recruitment and firing rate properties appear to be related to the behavior of the ME signal-force curve. Such a relationship is predicted by the ME signal model developed by De Luca and Van Dyke (9). Recently De Luca et al. (8) have provided evidence that the recruitment and firing rate properties of the FDI and deltoid muscles are substantially different. The FDI relies mostly on a firing rate increase, which is linear with respect to force, to increase the force output, whereas the deltoid relies mostly on recruitment to increase its force. Kukulka and Clamann (19) found that the biceps brachii, like the deltoid, relies mainly on recruitment to increase its force. The quasilinearity of the FDI curve and nonlinearity of the deltoid and biceps brachii curve in Fig. 1 appears to be a more general manifestation of this fact.

The relative amounts and location of slow-twitch and fast-twitch muscle fibers within the muscle is an important consideration because of the following reasons. The amplitude of the action potential generated by a single muscle fiber is proportional to $d^{1.7}$, where d is the fiber diameter (29). Fast-twitch fibers, which in the human FDI and biceps brachii muscles are generally larger in diameter (28), have higher amplitude action potentials than slow-twitch fibers. Higher amplitude motor unit action potentials result in a higher amplitude rms ME signal (9). However, the amplitude of the motor unit action potential that contributes to the surface ME signal is a function of the distance between the active fibers and the recording electrodes: the greater this distance, the smaller the amplitude contribution. The larger motor units (containing the larger diameter fast-twitch fibers) are preferentially recruited at high force levels according to the "size principle" (16). Therefore the relative location of the fast-twitch fibers within the muscle and with respect to the recording electrodes determines how the electrical signal from these motor units affects the surface ME signal.

The apparent insensitivity of the ME signal-force re-

lationship to the rate of force production evident in Fig. 2 is consistent with the observations of Heckathorne and Childress (15). A possible explanation for this behavior may be found in the results of De Luca et al. (7, 8), who reported that the recruitment and firing rate properties of motor units remain invariant with force rates (in the range considered in this study).

Because the ratio of slow-twitch to fast-twitch fibers varies greatly across subjects and subject groups, the lack of dependence of the ME signal-force relationship on subject group implies that fiber-type composition does not affect the normalized ME signal-force relationship. For example, the ME signal-force curve for the deltoid of the long-distance swimmers, which has an average of 74% slow-twitch fibers (14), did not differ significantly from the deltoid curves for either the normal subjects or the pianists. This lack of invariance among the subject groups with different muscle training regimens is also consistent with the recent results of De Luca et al. (8), who reported that in these very same subjects the motor unit control scheme was uniform and did not alter with training.

One exception was the curve for the deltoid in power lifters, which varied significantly from the deltoid curves for the normals, pianists, and long-distance swimmers. This exception may be attributable to fiber typing and hence fiber diameter. A significantly larger ratio of fast-twitch to slow-twitch fiber area may be present in muscles of power lifters compared with those of normal subjects or endurance athletes such as long-distance swimmers (11). However, the mean areas of the slow-twitch fibers are reported to be comparatively similar in power lifters, endurance athletes, and sedentary subjects (11). Therefore the relatively larger area of fast-twitch fibers in power lifters contributes relatively more to the amplitude of the ME signal at high force levels than does the corresponding smaller fast-twitch fiber area in nonpower lifters. At low force levels the slow-twitch fibers whose mean area does not appear to vary across subject groups are the dominant active fibers, so the relative amplitudes of the ME signal for these groups are similar. The net effect is that, upon normalizing, the amplitude of the ME signal from the deltoid in power lifters is scaled down more than it is for the other groups, thereby shifting the power lifters' curve below the others. This downward shift was not observed for the power lifters' biceps curve, possibly because the biceps of normal subjects has on average approximately 25% more fast-twitch fibers than the deltoid of normal subjects (17). These speculations should be considered tentative due to the wide variation in the fiber type ratio across subjects for a given muscle (17), and the relatively small subject population for each group of this study.

To summarize, for group-averaged data from isometric contractions, the normalized surface ME signal vs. normalized force relationship 1) exhibits a large intersubject variation but smaller intrasubject variation for the same muscle; 2) appears to be independent of the force rate of the contraction over the range of nonballistic contractions from 10 to 40% MVC/s; 3) is generally independent of the subject group and therefore possibly the type of exercise, with the noted exception of some muscles of the powerlifters and the deltoid of the swimmers; 4) is pri-

marily determined by the muscle under investigation; 5) is quasilinear for the first dorsal interosseous muscle; 6) is nonlinear for the biceps and deltoid muscles, with the amplitude of the ME signal increasing faster than force; and 7) may be partially affected by the different motor unit firing rate and recruitment properties of different muscles (7, 8).

We are most grateful to all the subjects and especially to the elite

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