Effects of electrode location on myoelectric conduction velocity and median frequency estimates

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ROY, SERGE H., CARLO J. DE LUCA, AND JOCHEN SCHNEIDER. *Effects of electrode location on myoelectric conduction velocity and median frequency estimates.* J. Appl. Physiol. 61(4): 1510–1517, 1986.—The effect of surface electrode location on the estimates of the median frequency and conduction velocity of the myoelectric signal was investigated. The locations were identified with respect to the innervation zone and the tendonous portion of the tibialis anterior muscle. Considerable modifications in the median frequency and conduction velocity parameters were noted. The highest values of the median frequency occurred at the region of the innervation zone and tendonous insertion of the muscle, and decreased proportionally with distance from these areas. The rate of change of median frequency was not effected by electrode location. Estimates of conduction velocity were most stable in a region between the distal tendon and the adjacent innervation zone. This region also provided the best linear fit when comparing conduction velocity to median frequency estimates. The implications for signal detection procedures are discussed.

surface electromyogram; electrode array; spectral analysis; innervation zone; motor point

POWER DENSITY SPECTRUM analysis of the myoelectric (ME) signal has been used extensively in clinical research and ergonomics to quantify localized muscle fatigue in humans [for a review, see De Luca (8)]. The development of this technique is based on the observable fact that the power density spectrum of the ME signal detected on the surface of the skin undergoes a shift towards the lower frequencies as a function of time during a sustained muscle contraction. It has been suggested by others (16) as well as by our group (23) that this phenomena is related to the conduction velocity (CV) of the muscle fibers and other time-dependent processes that are associated with localized muscle fatigue.

There is a growing interest in studying the behavior of spectral parameters with respect to the physiological, anatomical, and biochemical events within a muscle (10, 15, 19, 20, 22). If the relationships between these parameters can be clearly defined, then this technique may also provide insight for augmenting our understanding of localized muscle fatigue processes. However, most of the results to date are preliminary and require further substantiation because of the numerous and complex processes associated with muscular fatigue. Furthermore, recent studies have presented conflicting results when comparing power spectral parameters at different force levels to estimates of the muscle fiber CV (2, 5, 21). In some instances, the reports could not confirm the linear relationship between CV and spectral measures as first proposed by simplified mathematical models of the ME signal. Hence, basic questions have been raised as to whether the spectral changes observed during fatigue are the result of processes other than conduction velocity. These possibilities include changes in the discharge statistics of motor units or the recruitment of other motor units.

A confounding factor that adds to the difficulty of interpreting the results of these studies is the sensitivity of the spectral and CV estimates to the placement of the electrode. Because these techniques rely upon surface electrodes to detect the signal, alterations in the shape of the signal can occur as a result of differences in the location of the electrode with respect to such factors as the innervation zone or conductivity of the tissue beneath the electrode. These effects are well described mathematically (8, 16) for idealized muscle models. The spectral content of the signal and its CV are altered by changes in the observation distance from the signal source, the direction of the signal and the conductivity of the muscle fiber. The effects of these methodological factors in vivo may not be the same, or of the same magnitude, as in the theoretical model. Numerous factors related to the nonhomogeneous and anisotropic properties of muscle may modify these results (7, 12).

No empirical studies are available in the literature that describe the sensitivity of ME spectral parameters and estimates of CV to the location of the detecting electrode. For this reason, we studied the sensitivity of a frequency spectrum parameter, the median frequency (MF), and a CV estimate to different locations of surface electrodes along the length of a muscle. Our interest was directed at observing modifications in these parameters when the location of the electrode was changed with respect to the innervation zone(s) and tendonous portions of the muscle.

METHODS

Subjects. Ten healthy male volunteers, age 21–53 yr, participated in the first part of this study. Six healthy male volunteers, age 23–40 yr, participated in the second part of this study.

Experimental procedure. Prior to an experiment, each subject read and signed an informed consent form. Subjects were seated in a modified dental chair during the experiments to secure their hip, knee and ankle joints at

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approximately right angles. The right foot and ankle were fixed to a device equipped with a force transducer (stiffness = 3 × 10 N/m) to measure the net force output during isometric contractions of the tibialis anterior muscle. The maximal voluntary contraction (MVC) was obtained by requesting the subject to produce three maximal dorsiflexions of the ankle spaced 3 min apart and choosing the highest value.

The innervation zone(s) of the muscle were then located using superficial electrical stimulation to find the motor points (24). Briefly, this technique applies low-amplitude current pulses (in the range of 5–10 mA) to stimulate a series of brisk contractions. During this procedure, a stimulating probe 1 cm in diameter is systematically moved over the skin above the muscle to identify the area(s) that respond with the strongest contraction at stimulating intensities near the threshold of excitation. This response is evident by the most minute, visually perceivable, skin deflections caused by twitching of the underlying muscle fibers. Biopsy studies by other investigators have confirmed that the motor points of this muscle can provide a satisfactory indication of the location of the innervation zones (6). These zones were verified later by observing the region in which action potentials were inverted.

The experimental protocol consisted of two studies. For the first study, the length of the tibialis anterior muscle was divided into 10 equidistant locations. For comparison between subjects, this distance was normalized to the distance between the lateral malleolis and the fibular head. The boundaries of the muscle and location of the tendons were assessed by palpation. A surface electrode with four parallel bars 1.0 cm apart was placed at the marked locations over the muscle, starting at the most distal site. Figure 1 shows a schematic diagram of this electrode that was specially designed for estimation of CV by a cross-correlation technique. The two second differential outputs represent the ME signal at two locations a known distance apart. The CV is estimated by detecting the time delay between these two signals. A more detailed description is given by Broman, Bilotto and De Luca (2). The first differential output of the middle electrode pair is routed to a device called the Muscle Fatigue Monitor. This device measures the MF

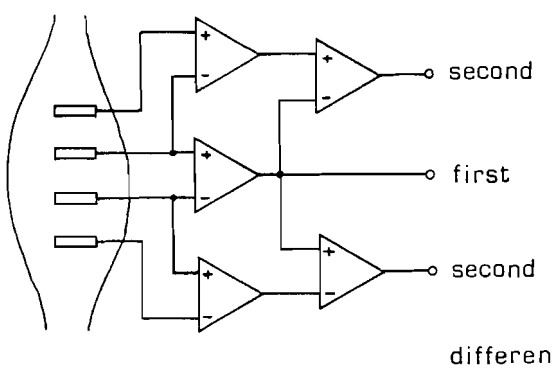

FIG. 1. Schematic representation of surface electrode configuration for conduction velocity estimates. A 4-bar electrode unit with a distance of 1.0 cm between bars is placed on skin over muscle during isometric contractions. Three myoelectric signals, 1 first differential and 2 second differentials, are recorded for further off-line processing.

of the power spectrum using voltage controlled analog filters and a feedback technique to divide the spectrum into two parts with equal power. The device has been described by Gilmore and De Luca (13).

A reference ground strap was attached near the ankle. The subject was asked to perform a 20% MVC contraction of the muscle. To help the subject maintain a constant force, the output of the force transducer and a target line at the 20% MVC level were displayed on an oscilloscope. Subjects maintained the contraction for 10 s, during which the ME signal was recorded. The electrode was then moved to the next marked location and the procedure was repeated until all locations were sampled. To ensure that no cumulative fatigue effects would be introduced by this protocol, a series of contractions for the same duty cycle were tested without moving the location of the electrode. No detectable shifts in the frequency component of the signal were observed during this set of contractions.

For the second part of the study, the instrumentation and positioning of the subject were the same as in the first part. Because CV was not estimated during the second part of the study, a differential electrode with only two parallel bars 1.0 cm apart was used. This electrode is a modification of an electrode unit developed by De Luca et al. (9). An array of these surface electrodes were used concurrently to detect the ME signal from different locations on the muscle. The ME signal was differentially amplified with a bandwidth of 2–550 Hz. The electrodes were placed at the motor points and tendonous portions of the muscle and at 1.5-cm intervals between these locations. The protocol for this part of the study required the subject to generate three 20% MVC contractions and three 80% MVC contractions. For the lower-force-level contractions, a 4-min rest period between contractions was required. For the higher force levels, a 20-min rest period with the subject leaving the apparatus was chosen to reduce the effects of fatigue between contractions. Previous studies on this muscle (unpublished observations) have determined that this is the minimal time period for recovery of the MF-time relationship.

Data processing. All ME signals and the analog signals representing the MF and the force level were recorded on a multi-channel frequency-modulated tape recorder (Honeywell 5600B). To process the data for the first study, the recorded signals were played back, low-pass filtered and digitized by a microcomputer (DEC Micro-11) with sampling rates of 1.0 kHz for the ME signals and 10 Hz for the MF. The digitized data was stored on disk file.

The CV was computed by obtaining 64 samples from both second differential ME channels. These data were multiplied by a windowing function (Hamming window) and 32 cross-correlation values were computed: half of them for negative and the other half for positive delays. To reduce the stochastic behavior of this cross-correlation function, calculations were averaged for eight consecutive time intervals (containing 64 samples each), resulting in a maximum cross-correlation value and a corresponding conduction velocity value for every 0.512

s of experimental data. To improve the estimation of the delay time, the maximum cross-correlation value was interpolated by multiplying the peak of the cross-correlation function by $\sin(x)/x$ function and locating the maximum between the points. This approach was used because it does not alter the relative frequency content of the frequency spectrum of the cross-correlation function. It is equivalent to uniformly spreading the frequency spectrum.

For the second study, each of the recorded ME signals were processed by the Muscle Fatigue Monitor. Median frequency and force as a function of time were recorded on a dual-channel strip-chart recorder. From these recordings, the initial value of the median frequency (IMF) and the rate of decrease of the MF were determined, as illustrated in Fig. 2. The IMF is defined as the median frequency value occurring at the moment the target force level is achieved and appears stable. The rate of decrease of the MF is calculated by taking the slope of a straight line fitted to the first 5 s of data by a least-squares method. Although some of the data appeared to decay exponentially, the time constants were always long. A comparison of fits between an exponential decay and a linear decay revealed that the linear approximation provided the better fit. The results for the IMF and slope were calculated using the mean value for the three consecutive contractions at either 20 or 80% MVC.

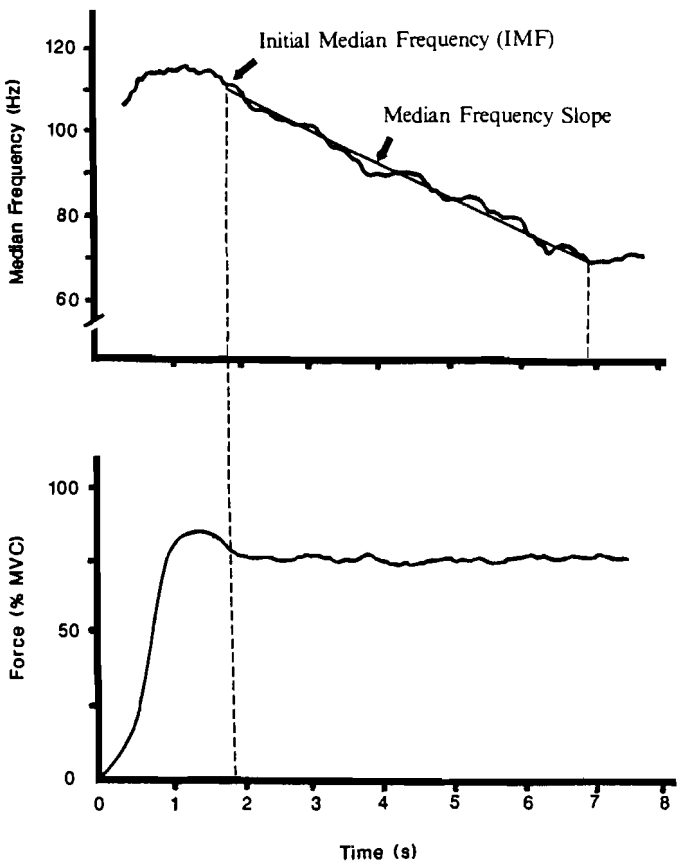

FIG. 2. Procedures for determining median frequency spectral parameters. Initial median frequency (IMF) is indicated in *upper curve* at a point in time corresponding to onset of a steady target force output. Median frequency slope is computed by calculating the slope of a straight line fitted to 5 s of data beginning with IMF.

RESULTS

The number of motor points for the tibialis anterior muscle varied from one to five (mean = 2.44) in the subjects tested. Locations of motor points were highly variable as well. In spite of this variability, the highest MF value always occurred at the region of the motor point and decreased proportionally with distance from the motor point. When the tendonous portion of the muscle was approached, the MF value increased. Figure 3 illustrates these changes for a typical subject tested in the first part of the study. The behavior of the CV estimates and cross-correlation values are also plotted as a function of electrode location in this figure. The sharp discontinuities in the values between adjacent segments reflect the movement of the electrode to a new location. Relatively high CV estimates were found at the most distal location of the muscle (tendonous portion) in 8 out of 10 subjects, if the estimation technique was not made impossible there by low signal amplitudes. High correlation coefficients, and therefore higher quality CV estimates, were derived just proximal to this site for all subjects tested. Distal motor points were always associated with a sudden change in the sign value of the CV. Proximal motor points were associated with unsteady

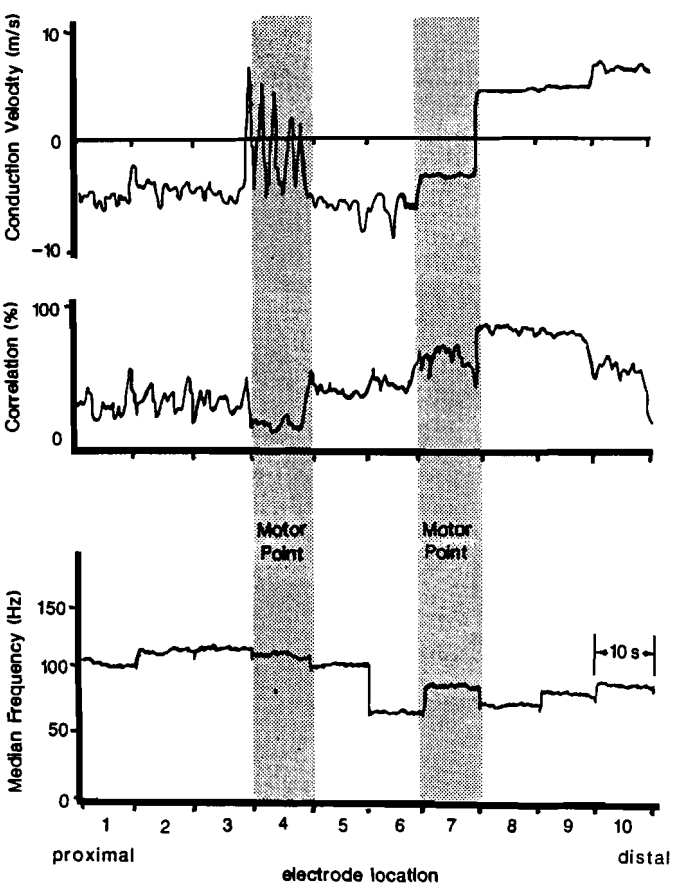

FIG. 3. Plot of conduction velocity, correlation coefficient, and median frequency estimates obtained from an experiment. Length of tibialis anterior muscle of a human subject is divided into 10 equidistant locations. Every 10-s electrode is moved to a new location, from proximal to distal, while subject performs an isometric contraction at 20% maximum voluntary contraction level. Locations of motor points are indicated by *shaded bars*.

estimates of CV that fluctuated repeatedly from positive to negative values. Low cross-correlation values were seen at proximal and distal motor point locations. These results are consistent even in subjects with different number and locations of innervation zones (Fig. 4, *A* and *B*). In these figures, the mean ± SD of each parameter is depicted for data sampled at a specified electrode location.

When comparing the relationship between CV and MF, no correlation was found when data from all electrode locations were included. However, a linear relation with a high correlation coefficient was observed when the data was restricted to electrode locations corresponding to the highest cross-correlation value (Fig. 5). This regression line was calculated as

$$MF = (-0.8 + 23.4\ CV)Hz \qquad (1)$$

where CV is in meters per second and $R = 0.84$.

This regression estimate of the relationship intercepts the MF axis at −0.8 Hz when the CV value is zero. Given that the MF values range from 77 to 108 Hz, the intercept value may be disregarded. This simplification generates an error of less than 1% which is compatible with the

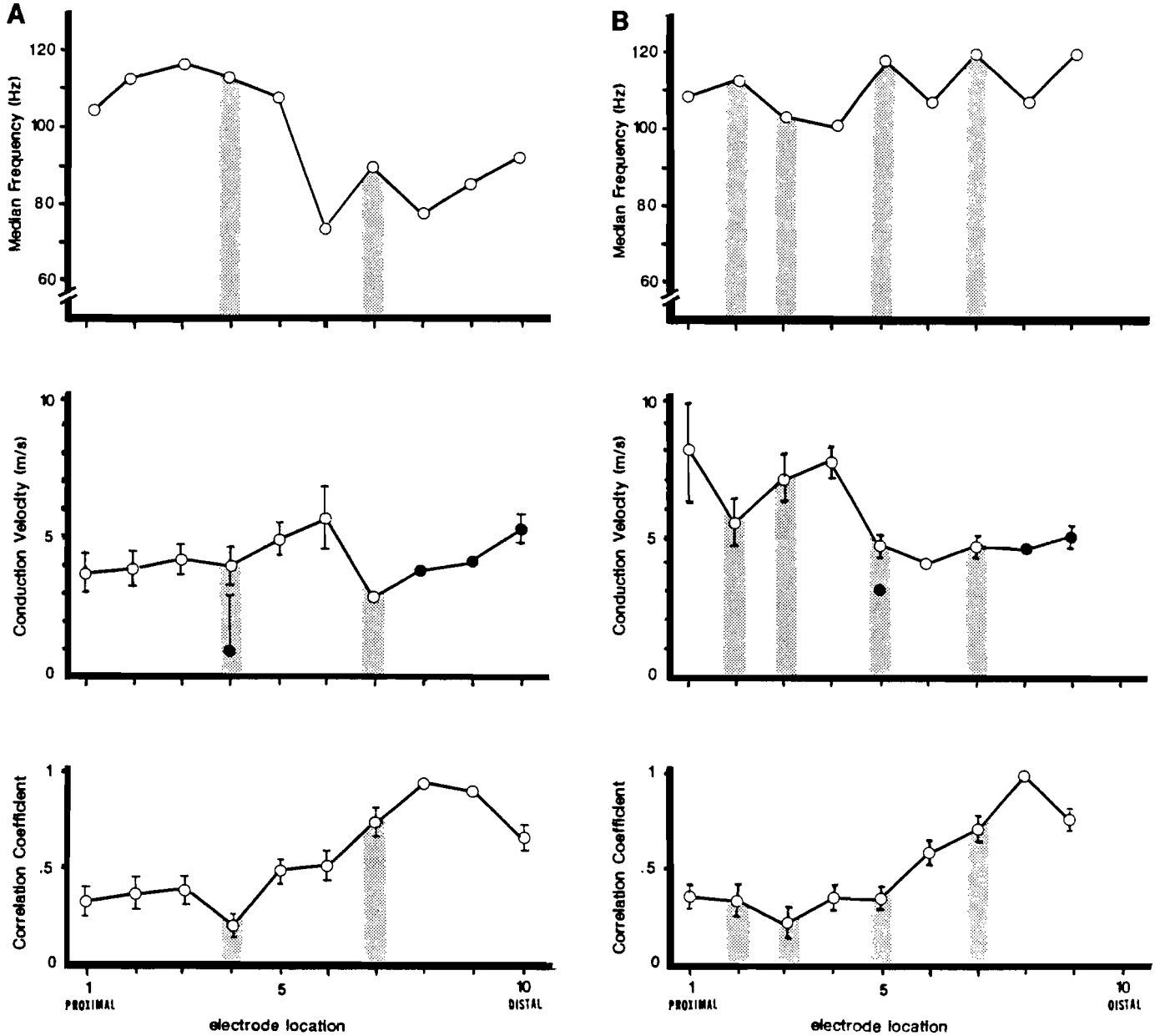

FIG. 4. Estimates of median frequency, conduction velocity, and correlation coefficient as a function of electrode location on tibialis anterior muscle of 2 subjects with different numbers of motor points. Location of motor points are indicated by *shaded vertical bars*. *Open circles* are data averaged for each 10-s contraction. Standard deviations are represented by *vertical bars* (±SD) except in those instances where SD values are less than dimension of *circle*. For conduction velocity data, *closed circles* indicate depolarization spreading in a distal direction; *open circles* indicate a proximal direction. At some motor point locations conduction velocity estimates of both signs are averaged separately. *A*: data of subject with tibialis anterior having two motor points (same subject as in Fig. 3); *B*: data of subject with tibialis anterior having 4 motor points.

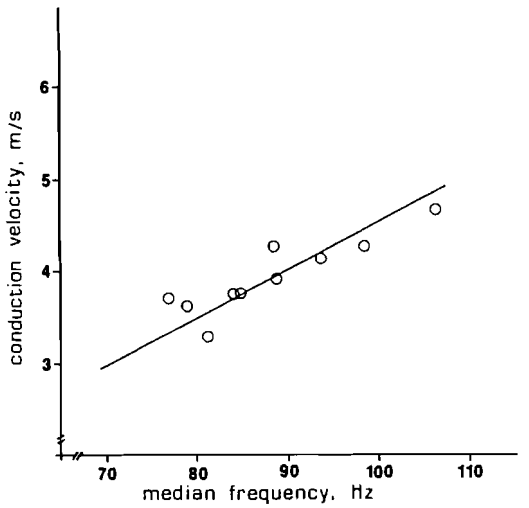

FIG. 5. Relationship between conduction velocity and median frequency for data obtained from electrode site associated with highest cross-correlation values for each subject.

degree of accuracy of the techniques used. Thus, if (0,0) is considered as a data point, the relationship becomes

$$MF = (23.1\ CV)Hz \qquad (2)$$

where CV is in meters per second and $R = 0.98$.

As in the first part of this study, the results for the second part demonstrate the same relationship for MF measurements and location of innervation zones and tendonous portions of the muscle. Increasing the force level of the contraction from 20 to 80% MVC does not appear to effect this relationship except to uniformly increase the value of the MF (Fig. 6). The rate of decrease of the MF during fatiguing (80% MVC) contractions was not sensitive to electrode location (Fig. 7). Contractions at 20% MVC were not included in this analysis because MF curves were typically flat with essentially zero rate of decay.

DISCUSSION

Our finding that as many as five motor points were detected in one tibialis anterior muscle runs contrary to common anatomical beliefs which generally embrace the notion that the majority of muscles have one innervation band. In those subjects with more than two motor points, there did appear to be a 5–10% variability in the threshold levels at which a contraction was elicited for a particular motor point. In addition, there appeared to be differences in the size of the contraction resulting from stimulation of different motor points. Unfortunately, this technique cannot differentiate between the effects of tissue conductivity, depth, or number of endplates in an innervation zone. In one of the few reports that studied the topography of innervation zones from biopsied human muscle, Coers and Woolf (6) describe one innervation zone in muscle fibers that run without interruption from origin to insertion in most of the muscles that they examined. For muscles that appear to contain concatenated muscle fibers, such as the sartorius and gracilis, they found numerous bands of innervation zones scattered throughout their length. According to muscle architecture data for the tibialis anterior muscle, the actual muscle fiber length is approximately one-fourth of the gross muscle length (24). This would suggest either extensive overlapping or concatenation of muscle fibers. The likelihood of finding more than one innervation zone under these conditions should be greater than if the muscle fibers extended from origin to insertion without interruption.

The presence of more than one motor point must also raise the question of how well surface electrical stimulation can detect innervation zones, particularly for the tibialis anterior muscle where the innervation zone is located deep within the muscle (5). It is conceivable that excitability thresholds from surface stimulation may change along the length of a muscle due to the nonhomogeneity of muscle conductivity rather than the presence of different innervation zones. To preclude this possibility in our data, we looked for an inversion of the ME signal as the surface electrode traversed a suspected motor point location.

The observed behavior of the MF measurements with respect to the proximity of the surface electrode to the innervation zone is consistent with the predictions of theoretical models of the ME signal. Action potentials of different wavelengths propagate in opposite direction from the innervation zone, forming a complex interference pattern (1, 11). The superposition of minutely phase shifted action potentials in the vicinity of the innervation zone provides a relative increase of the high-frequency components of the ME signal (18). This explains the relatively high MF measurements at or near a motor point. The proportional decrease of MF values with distance from a motor point is consistent with the understanding that innervation zones are present as bands of motor end plates that extend with diminishing density beyond the confines of a motor point (6).

When the surface electrode is placed at either end of the muscle fiber, the relatively high impedance of the tendon tissue truncates the action potentials and increases the high-frequency components of the signal. Calculations have shown that this effect is equivalent to that of a high-pass filter where only the lower frequency components of the signal are attenuated (18). This edge effect is empirically demonstrated in our results by the relative increase in MF near the tendonous portions of the muscle.

The uniform increase in MF values at 80% MVC may reflect changes in motor unit recruitment consistent with the "size principle" (14). Larger motor units, containing the larger diameter fast-twitch fibers are recruited at the higher force levels. Theoretically, CV and MF estimates should increase proportionally to the muscle fiber diameter (3). Other studies on the tibialis anterior muscle by Broman, Billoto and De Luca (4) in our laboratory have also demonstrated that CV and MF estimates increase with contraction level.

The fact that no trends were noted for the rate of change of the MF as a function of the surface electrode location indicates that the time-dependent effects of a sustained contraction are invariant in all locations of the muscle. This observation was not surprising considering

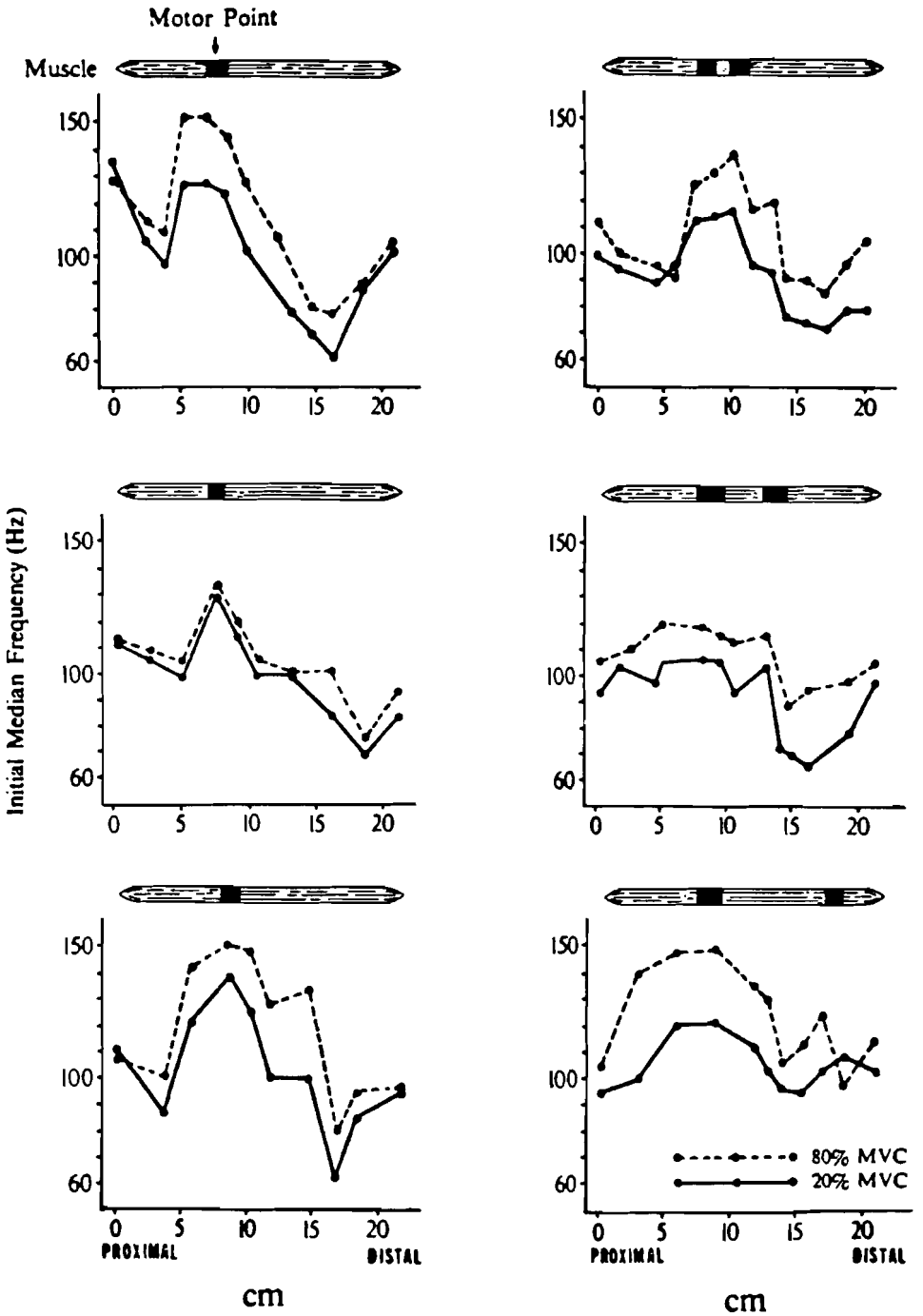

FIG. 6. Median frequency measures from surface electrodes placed along length of tibialis anterior muscle. Each *graph* indicates results from a different subject. *Data points* are average initial median frequency values for 3 sustained constant-force contractions. *Dotted lines* connect data points from tests conducted at 80% maximum voluntary contraction (MVC); *solid lines* connect data points from tests conducted at 20% MVC. Location of tibialis anterior motor point for each subject is indicated above each graph.

that muscle fiber types are spread homogeneously throughout a muscle and that the surface electrode tends to detect a relatively large domain that normally includes many motor unit populations. Furthermore, the lactic acid produced in any segment of the muscle will diffuse throughout the interstitial fluid of the whole muscle. This will influence the membrane properties of the muscle fibers throughout the muscle.

Although we observed similar behavior for CV and MF as a function of electrode location, many of the CV estimates were unstable near motor points. The relatively poor cross-correlation measures near the motor points (Fig. 3 and Fig. 4, *A* and *B*) are most likely the result of ME signals traveling in different directions from the innervation zone. The computed estimates of CV in these instances are severely biased and reflect the high sensitivity of this technique to electrode position. It was surprising to find a consistent difference in the way CV estimates behaved at motor points located distally as opposed to proximally. In all cases, we observed stable CV estimates and a sign reversal near the distal motor point with only moderately decreased correlation coefficient measures. This behavior was detected in a region approximately 3–4 cm in length between the distal motor point and the tendon. In this region, the muscle tapers towards a common tendon providing for a more orderly arrangement of muscle fibers and a more symmetrical propagation of action potentials. This may explain the

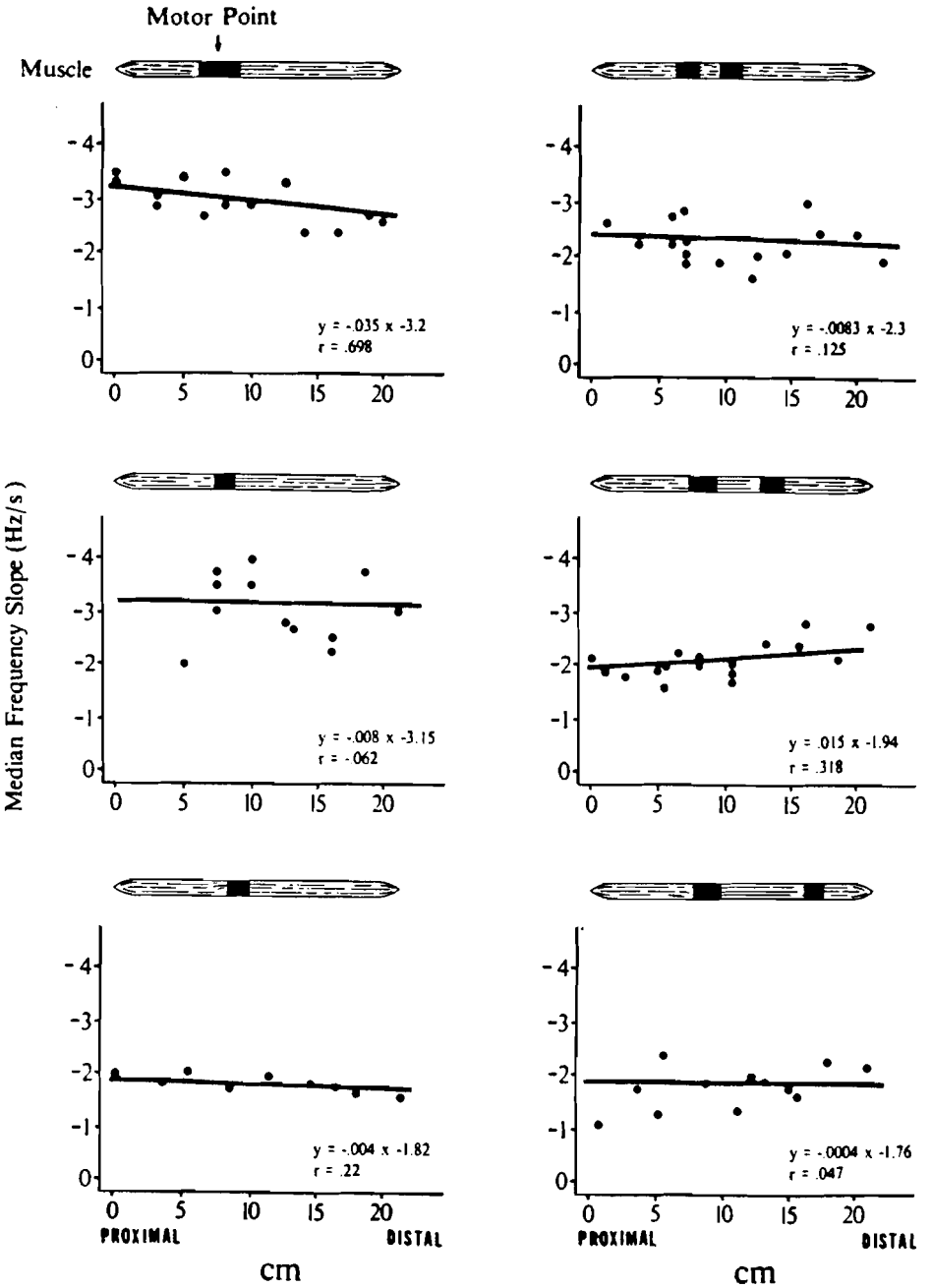

FIG. 7. Median frequency slope values from surface electrodes placed along length of tibialis anterior muscle. Each graph indicates results from a different subject, as in Fig. 6. Data are average value of 3 sustained contractions at 80% maximum voluntary contraction. Linear regression curves were fit to each set of data, and equation and correlation coefficients for each analysis are indicated.

high correlation coefficients found for signals detected in this area.

In the mid to proximal portions of the muscle we consistently found relatively low values of correlation coefficients with correspondingly variable estimates of CV near the motor points. CV estimates fluctuated from positive to negative values during the time period of these recordings. It may be that this behavior is related to the observation that motor points were greater in number and more closely clustered at the proximal section of the muscle than the distal section. Variations in the depth of the motor endplates for a particular innervation zone may also contribute to this difference in CV behavior.

The poor correlation between MF and CV for data obtained from all electrode locations reflects the problem of estimating CV when ME signals are highly disturbed or are traveling in opposite directions. The data obtained from the electrode locations with the greatest cross-correlation measure demonstrate a linear relationship between CV and MF estimates. This linearity is consistent with mathematical models of the ME signal from the literature (17, 23). The larger decrease of the MF measurements than the CV estimates agrees with the reported findings of Broman, Bilotto, and De Luca (5) in the tibialis anterior and Bigland-Richie (2) in the biceps brachii muscles. In contrast to these findings, Naeije and Zorn (21) concluded from their data on the biceps that mean frequency may decrease without a simultaneous decrease in conduction velocity. Considering the implications of our results, this disparity may be attributable to the effects of electrode placement with respect to innervation zone(s). Naeije and Zorn (21) described placement of the electrodes at a set distance from a

motor point; however, it was not mentioned whether other placements were tried. There is evidence from Boon et al. (3) that valid estimates of CV can only be found in a distinct region between the motor end plate zone and the tendon and that, although high cross-correlation values may be found outside of this region, they can still be associated with incorrect estimates of CV. The fact that there was a concomitant decrease in CV and MF for some of their subjects and not others reinforces this suggestion.

In summary, we have presented data from one muscle that demonstrates the sensitivity of CV and MF estimates to the placement of the surface electrode. The location of the surface electrode with respect to the innervation zone and tendonous portion of the muscle influenced CV and MF estimates in a typical pattern. A "stable" zone between the distal motor point and the tendon was observed to produce the most valid estimates of CV. This location also provided the best linear fit when comparing CV with MF. The practical implications of this study reinforces the need to consider the appropriate placement of surface electrodes when detecting ME signals for their spectral content and estimation of conduction velocity. Whether these results can be generalized for other muscles remains an open question.

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