Electrically evoked myoelectric signals in back muscles: effect of side dominance

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Merletti, Roberto, Carlo J. De Luca, and Deepa Sathyan. Electrically evoked myoelectric signals in back muscles: effect of side dominance. *J. Appl. Physiol.* 77(5): 2104–2114, 1994.—This work had two goals, to study the effect of hand dominance on myoelectric signal variables and fatigue indexes in back muscles and to assess the repeatability of the estimates of such variables. Myoelectric manifestations of muscle fatigue were studied in the right and left longissimus dorsi muscles of five right-handed and five left-handed normal male subjects. Myoelectric signals (M waves), evoked by stimulation applied to a muscle's motor point, were detected with surface electrodes. Each test consisted of eliciting a tetanic contraction of 30 s duration with supramaximal stimulation at 25 Hz and was repeated five times on 5 different days for each subject. The mean and median frequencies of the resulting power spectra of the M waves were plotted vs. time, and fatigue indexes were obtained from the time course of these variables. Only two-thirds of the elicited contractions provided signals of sufficiently good quality to obtain reliable estimates of the mean and median frequencies. Criteria for acceptability are described. Analysis of variance and paired comparisons showed a statistically significant effect of side dominance on fatigue indexes in the right-handed subjects but not in the left-handed subjects. Normalized initial slope and other fatigue indexes based on spectral variables demonstrated myoelectric manifestations of fatigue that were greater on the dominant side. We surmise that the differences are related to the fiber type modifications associated with the unilateral usage of the upper limbs and the consequent activation of the nondominant side of the back.

electromyography; electrical stimulation; fiber type; median frequency

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BACK MUSCLE FATIGUE has been of interest to investigators over many years because of its possible relationship to low back pain (29). Assessment techniques based on myoelectric manifestations of localized muscle fatigue during sustained voluntary contractions of limb muscles (11, 12, 23) cannot be as easily applied to back muscles because of the much more complex anatomy of the muscle layers, the subject's inability to selectively activate individual muscle groups, and the likelihood of cross-talk (6, 7, 13, 29). A comprehensive description of the state-of-the-art analysis of surface myoelectric signals generated by voluntary contractions of back muscles is provided in a recent work by De Luca (13).

This paper focuses on a quantitative approach to myoelectric manifestations of muscle fatigue by using electrically elicited contractions of the longissimus dorsi (LD) muscles. This approach has received limited attention until recent years (21, 27). The methodology is based on fatigue indexes derived from the time course of myoelectric signal spectral variables and is the same as that used in a number of previous investigations we have carried out on limb muscles (11, 12, 24).

Continued preferential use of selected muscle groups may be expected to induce anatomic and physiological modifications to the muscle structure and function (17). Subjects with strong right- or left-sided dominance would use their limb and back muscles in an unbalanced way, therefore modifying one side with respect to the other. Back muscles on the nondominant side would be subject to more intense use to compensate for loads and forces applied to the dominant side during daily activities and might therefore show smaller manifestations of localized muscle fatigue, as observed by various authors in dominant-side upper limb muscles. Fugl-Meyer et al. (15) reported a higher percentage of slow-twitch type I muscle fibers in the extensor carpi radialis brevis of the dominant limb compared with the nondominant limb. Tanaka et al. (34) observed slower electrically elicited twitch responses in the first dorsal interosseous (FDI) of the dominant hand than in the nondominant hand. De Luca et al. (14) reported a slower decrease in spectral parameters in the dominant FDI than in the nondominant FDI during sustained voluntary contractions. Zjidewind et al. (35) electrically stimulated the FDI and observed a faster decay of M-wave amplitude in the nondominant FDI and large interexperiment and intrasubject variabilities. However, the only related study on back muscle was presented by Roy et al. (31), who were able to correctly classify 13 port rowers and 10 starboard rowers of a varsity crew on the basis of parameters of the myoelectric signal detected from the longissimus, iliocostalis, and multifidus muscles during voluntary contractions. We have chosen to study electrically elicited contractions rather than voluntary contractions for the following reasons: *1*) the elicited signals are independent of the ability or willingness of the subject to perform a voluntary contraction, *2*) the signal is deterministic rather than stochastic and is therefore easier to analyze, *3*) estimates of amplitude and spectral variables have much smaller variances, *4*) only a single muscle or portion of a muscle can be activated, and *5*) cross-talk problems are avoided. Despite the fact that the electrically evoked myoelectric signal is the summation of the motor unit action potentials that add asynchronously during a voluntary contraction, its nature and spectral characteristics are radically different from those of the voluntary signal.

The primary objectives of this work are *1*) to test the intrasubject repeatability of indexes of myoelectric manifestations of muscle fatigue during electrically elicited contractions and *2*) to test the capability of the technique to detect dominance-related differences between the right and left LD muscles.

METHODS

Five right-handed and five left-handed volunteer male subjects were selected according to two criteria: they had no cardiac or neuromuscular disorders and each was ascertained to have a definitive dominance of one side. This dominance was verified by questioning the subjects about the use of their hands in a number of daily life activities. The age of the subjects ranged from 20 to 33 yr [mean 23.1 ± 3.47 (SD) yr]. Five identical tests were performed on 5 different days on each of the 10 subjects.

Stimulation technique. Each subject read and signed the informed consent statement approved by the local Institutional Review Board. The subjects were asked to lie prone on an examination table modified to provide support for both arms. The subjects were strapped to the table with restraining straps placed across the shoulders and hips to minimize the movement caused at the onset of stimulation of the LD muscles. Electrical stimulation was applied between a small (3 cm diam) moist negative electrode placed on a muscle's motor point and two large (10 × 12 cm) moist positive electrodes placed on the bony prominences of both scapulae and connected together. This particular arrangement was chosen to minimize transthoracic current and possible cardiac risks.

A stimulation-detection system, described in a previous work (19), was used to apply rectangular current pulses of 0.2 ms duration, 25 Hz frequency, and amplitude sufficient either to elicit a maximal M wave or to reach the pain threshold of the subject.

Myoelectric signal detection technique. The myoelectric signal was detected with the four-bar electrode double-differential technique described by Broman et al. (10) and used in previous investigations (11, 23, 24). The probe had four contact surfaces consisting of silver bars 1 mm diam, 10 mm long, and 10 mm apart. A reference strap was fixed to the forearm of the subject. The single-differential signal was obtained from the two central bars and was used to compute the myoelectric signal spectral and amplitude variables. The detection technique provided two double-differential outputs from which the muscle fiber conduction velocity (CV) was estimated. Figure 1*A* shows the typical location of the stimulation and detection electrodes. Slew rate limiting and time windowing (signal blanking) were used to eliminate the stimulation artifact (19). The stimulation and myoelectric signal detection circuits were fully isolated. The three myoelectric signals (1 single differential and 2 double differential) were amplified to a range of 2–5 V peak to peak, low-pass filtered with a cut-off frequency of 480 Hz (120 dB/decade roll-off), recorded on FM analog magnetic tape together with a timing signal from the stimulator, and processed off-line. Figure 1*B* describes the stimulation-detection system (19).

Experimental protocol. The preparatory phase for the first test consisted of the following steps. *1*) Identification by palpation of the intravertebral spaces between T_7 and L_5. *2*) Identification and selection of the "best" motor point on the right and left LD muscles. This point was usually found at the T_8-T_{10} level (Fig. 1*A*). The entire area between T_7 and L_5 on either side of the spine was probed using a selective stimulation electrode to identify motor points of the LD muscles. Because there was usually more than one point that could elicit a muscle response, the preferred point was chosen as the one that activated only the LD muscles, had the lowest threshold, and provided a response that could be felt by palpation at the sacrospinalis tendon. *3*) Identification and selection of the best detection location on the right and left LD muscles. This location was usually at the T_{11}-L_1 level (Fig. 1*A*). The single- and double-differential signals were displayed on an oscilloscope, and the position of the detection probe was adjusted to obtain the largest single-differential signal and the double-differential signals that were most similar in shape while having the maximal relative delay. Efforts were made to prevent the placing of the detection electrodes on or near motor points or tendon areas where signals of poor quality would be obtained (16), but this was not always possible, apparently because of the short fiber length. Test contractions of only a few seconds were performed to minimize fatiguing of the muscles. *4*) Placement of the stimulation and detection electrodes, execution of the test, and marking of the electrode locations on the skin at the end of the test.

A 5-min interval was allowed for recovery between the preparatory and test phases. The latter consisted of two 30-s contractions, one on each side, separated by a 5-min interval. During each contraction the subject was asked to relax and hold his breath to minimize breathing and movement artifacts in the muscle response. Despite the straps, some movement took place at the application of stimulation, so the contractions were not rigorously isometric during the first 1 or 2 s. Because myoelectric signal variables are affected by temperature (26, 28), a digital thermistor probe was placed near the detection electrodes and the skin temperature was controlled during the experiment to within ±0.5°C by turning a heat lamp on or off as necessary.

The test was repeated five times on each subject on 5 different days. The locations of the stimulation and detection electrodes were marked after the first test so that on different days they could be identified and electrodes could be repositioned within ±2 mm. Stimulation parameters were identical in the five experiments except for cases in which the subject could not tolerate the same stimulation intensity used in a previous experiment. In such cases the stimulation intensity was reduced to the level of pain tolerance. After the last test, the skinfold was evaluated by taking and averaging repeated (6–8) measurements with a skinfold caliper in the location of the detection electrodes.

Signal acquisition and processing. The recorded single- and double-differential myoelectric signals were sampled at 1,024 Hz and were converted into 12-bit words. The signals were divided into 30 1-s epochs, and the 25 responses elicited during each epoch were averaged. The average response was zero padded up to 0.5 s, and the power spectral density was calculated with a resolution of 2 Hz. The mean and median frequencies (MNF and MDF, respectively) of the power spectrum were calculated for each of the 30 1-s epochs and were plotted vs. time.

Muscle fiber CV was estimated from the two double-differential signals as described in previous work (23, 24). In most contractions, it was not possible to obtain sufficiently similar and properly delayed double-differential M waves. The delay was usually much shorter than the expected 2.5 ms (corresponding to a CV of 4 m/s), and it showed large fluctuations during the contraction. The number of contractions from which a reasonable value of CV could be estimated was too small to allow any statistical analysis of this variable and its parameters. This was attributed to the limited distance between the motor point and the fiber ends, as observed in previous investigations and predicted by modeling (16). As a consequence, the CV information was not used in the statistical data processing.

In most cases the single-differential signal showed the expected progressive M-wave widening during the contraction, as indicated in Fig. 2*A*. In about one-third of the contractions, however, the single-differential signal showed great instability and no clear pattern of change, as indicated in Fig. 2*B*. A rejection criterion, described in the APPENDIX, was defined to remove these cases from the pool of valid data.

The time course of all myoelectric signal variables showed a transient during the first 1–2 s. This transient was attributed to the relative movement of the stimulated muscle with respect to the electrodes. To avoid any effect of such a transient on the

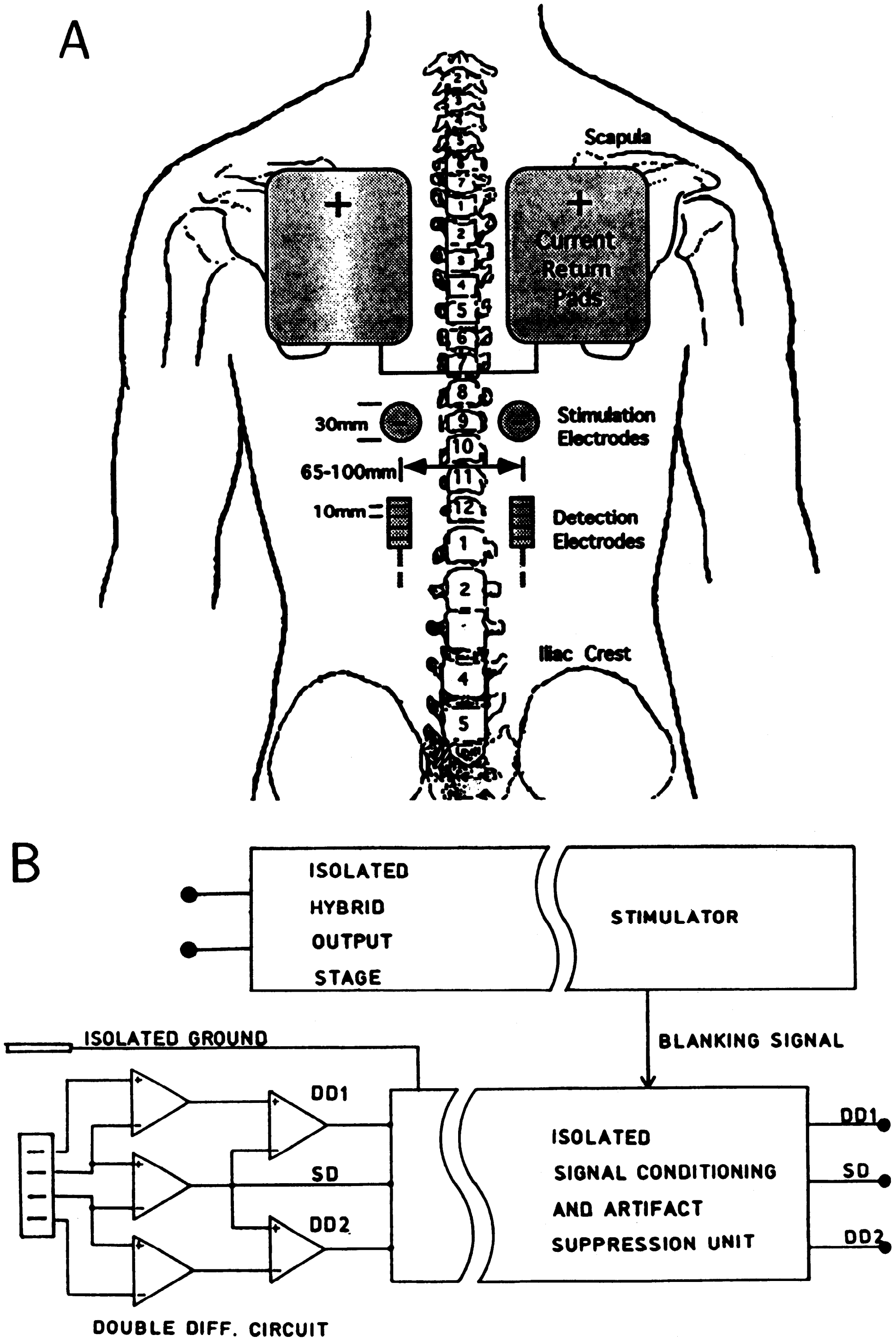

FIG. 1. *A*: stimulation and detection electrode locations on right and left longissimus dorsi. Stimulation electrodes were applied over motor points usually found at T_8-T_{10} level. Detection electrodes were usually placed at T_{11}-L_1 level. Both electrodes were ~35–50 mm lateral with respect to midline of spinal cord. *B*: experimental setup. Stimulation and detection circuitry were optically isolated. Rectangular current pulses of 0.2 ms width and 25 Hz were used. Intensity was adjusted to produce maximal single-differential M wave. SD, single-differential myoelectric signal; DD, double-differential myoelectric signal.

estimates of parameters, the first two data points were removed and each contraction was considered to start after 2 s of stimulation.

The time courses of the MDF and MNF were fitted with a least mean square regression line or a least mean square exponential curve, depending on the shape of the data pattern. The curve that showed the lowest residual standard deviation was selected, and its intercept with the *y*-axis was taken as the initial value. The slope of the regression line or the initial slope of the exponential regression, normalized with respect to the intercept (NIS), was taken as an index of fatigue. A second index of fatigue was the area ratio of the MDF or MNF. These indexes are more clearly defined in Fig. 3 and are more extensively discussed by Merletti et al. (25).

Statistical data processing. The initial values and the fatigue indexes obtained from MDF and MNF of the right and left LD muscles of right- and left-handed subjects were tabulated. Statistical data processing was applied to answer two questions: What is the repeatability of these parameters? and Is there a detectable effect of side dominance on these parameters? These two questions are answered by different statistical tests. In particular, the second question leads to two secondary questions: Is there a component of the total data variance that derives from the existence of a dominant side? and Is there a difference between the dominant and nondominant sides that may be detectable by pairwise comparisons? These two secondary questions are answered by different statistical tests.

The classic statistical tool used to assess data repeatability

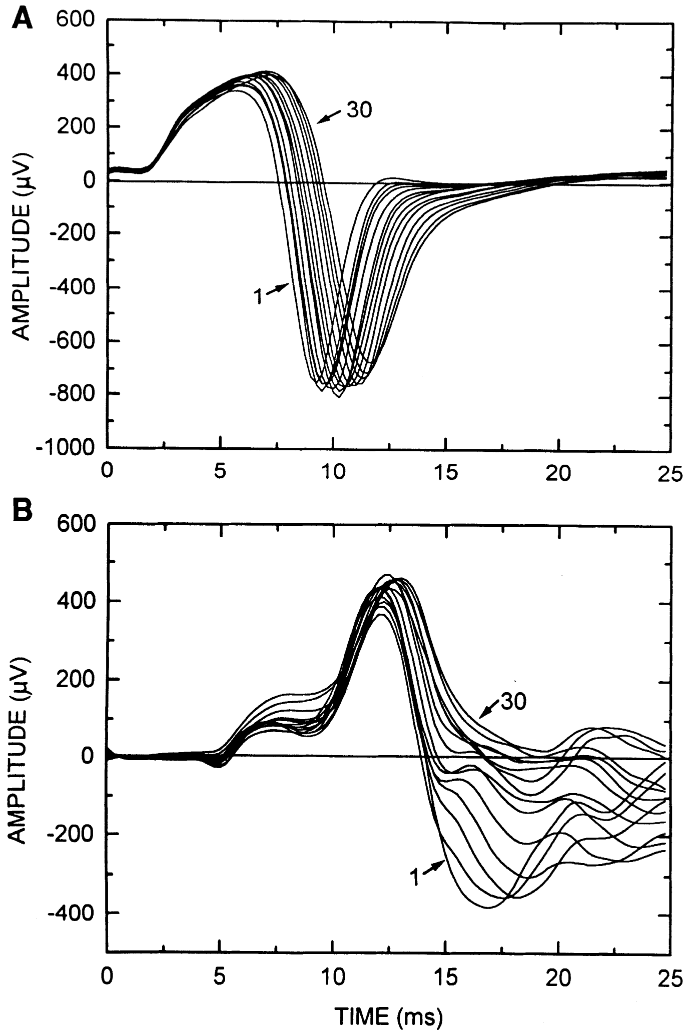

FIG. 2. Example of sequence of averaged M waves detected during accepted contraction and during rejected contraction (see APPENDIX for description of acceptance criterion). Each M wave is average of 25 responses produced during 1 s of stimulation. Every second of 30 average waves is shown. *Wave 1* is average of responses elicited during 1st s, and *wave 30* is average of responses elicited during 30th s of stimulation. Time and amplitude scaling, mostly attributable to changes in muscle fiber conduction velocity, are evident in *A*, and major changes in shape and instability are evident in *B*.

or reliability is the intraclass correlation coefficient (ICC) (2), which, in our design, is defined as

$$\mathrm{ICC} = \frac{\mathrm{V}}{\mathrm{V + E}} = \frac{\mathrm{MS_b - MS_w}}{\mathrm{MS_b - (d-1)MS_w}} \quad (1)$$

where V is true variance (variance attributable to subject-to-subject fluctuations), E is error variance (variance attributable to day-to-day fluctuations), MS_b is mean square value (variance) between subjects, MS_w is mean square value (variance) within subjects, and d is number of days.

A one-way analysis of variance (ANOVA) is used to compute the ICC and to address this problem wherein the one factor considered as the source of error is the day-to-day fluctuation of the parameter in question. An ICC close to unity would indicate that the estimate is highly repeatable (reliable) and the total variance is due mostly to subject-to-subject fluctuations, whereas an ICC close to zero would indicate that the day-to-day fluctuations are much larger than the subject-to-subject fluctuations. It is current practice to accept as "excellent repeatability" ICC values in the range of 0.80–1.00 and as "good repeatability" ICC values in the range of 0.60–0.80 (2).

Two different statistical techniques are applied to answer the two secondary questions above. The two techniques are *1*) a two-way ANOVA wherein the two factors being considered are the side from which the data come (right or left) and the side dominance of the subject (right or left) and *2*) a parametric or nonparametric paired test performed between pairs of values measured on the right and left sides of right-handed subjects, the right and left sides of left-handed subjects, and the dominant and nondominant sides of both right- and left-handed subjects.

Specifically, the two-way ANOVA weights the different sources of variability, whereas the paired tests evaluate the differences between measurements performed on the right and left sides of each subject. These sets of information are different but complementary.

For the two-way ANOVA technique, the sources of variability are *1*) the side from which the data come (right or left), *2*) the side that is dominant (right or left), *3*) subject-to-subject fluctuations, and *4*) day-to-day fluctuations. The first two sources are the factors we want to study, and the last two sources are errors or "experimental noise." This test indicates the relative importance of each source of fluctuation and the importance of their interaction; that is, it indicates whether for

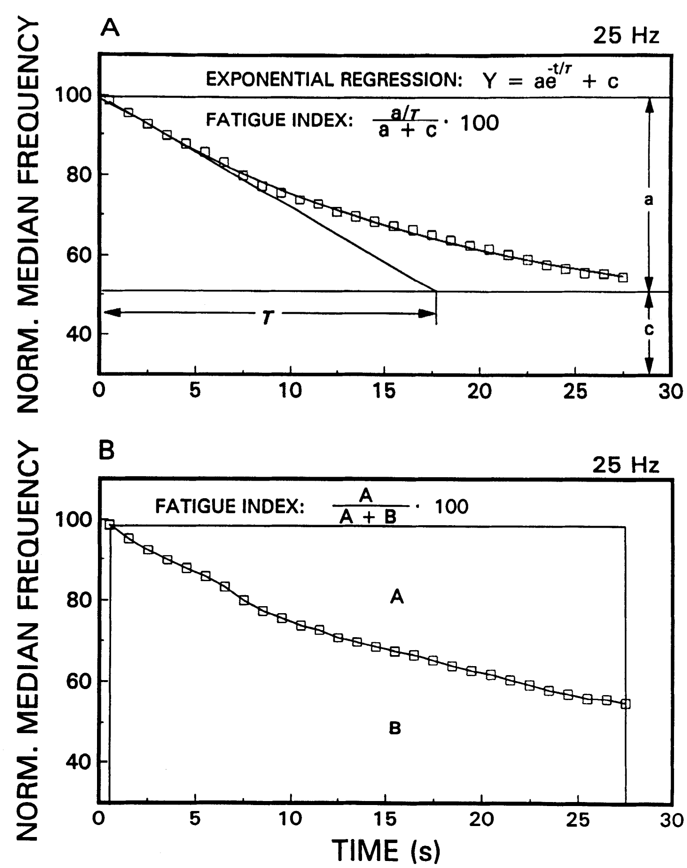

FIG. 3. Definition of initial values and fatigue indexes. *A*: time series of mean or median frequency values (MNF and MDF, respectively) was fitted either with regression line $y = h - kt$ or with regression exponential $y = ae^{-t/\tau} + c$, where h is intercept, k is slope, and t is time. Initial value is h for linear model and $a + c$ for exponential model. Normalized initial slope was defined either as $100k/h$ or as $(a/\tau)/(a + c) \times 100$, depending on regression model considered most appropriate. a, c, and τ are defined in figure. *B*: 2nd (regression free) fatigue index was defined as $A/(A + B) \times 100$ where A and B are areas defined in figure. This index is referred to as area ratio and is discussed by Merletti et al. (25).

any level of *factor 1* there is an effect of *factor 2* and vice versa. A source causing a small but consistent difference between pairs of measurements may not be detected with this technique if sources of fluctuations larger than such a difference are present.

On the contrary, the paired test technique uses the a priori information about the fact that the data come in pairs from the right and left sides of each subject. A consistent difference between one side and the other would be detected even if it were much smaller than other sources of fluctuations affecting both elements of each pair. Both the paired "classic" parametric *t*-test and the paired "robust" Wilcoxon nonparametric tests (3) were performed to see whether within-pair differences could be detected. This technique, however, provides no information about the weight of experimental noise. Both the ANOVA and the paired tests are necessary in this study because they address different questions.

RESULTS

It was the purpose of this work to test the repeatability of estimates of initial values and fatigue indexes of myoelectric signal spectral variables and to test the hypothesis that such indexes are affected by side dominance. To reach the second goal it was first necessary to ensure that the experimental conditions were the same across experiments and that the procedures did not favor one side with respect to the other. Although any unbalance in favor of one side would become evident from the statistical tests, a preliminary level of analysis was performed on the stimulation intensity values and on the M-wave amplitude applied to and detected from, respectively, the dominant and nondominant sides. Neither the paired or unpaired Wilcoxon test nor the *t*-test showed statistically significant differences between the two groups. It can therefore be assumed that the experimental procedure was not biased. This assumption was verified through other tests.

It is interesting to observe that the M-wave amplitudes detected on the LD muscles, in the range of 0.2–1.5 mV peak to peak, were considerably lower than the 1–4 mV peak to peak commonly observed for limb muscles (e.g., tibialis anterior or biceps). This difference implies a poorer signal-to-noise ratio. Therefore, the averaging procedure described in METHODS is particularly important when analyzing signals from the back muscles because it improves the signal-to-noise ratio.

As indicated in our previous work (25), an index of myoelectric manifestations of muscle fatigue on the basis of spectral variables is an indicator of progressive spectral compression, reflecting metabolic changes in the active motor units. This concept of fatigue index becomes fuzzy if the pool of active motor units is unstable during a sustained contraction. In such cases, indeed, it would no longer be clear what "fatigue" is, since some of the fatiguing motor units may be activated intermittently or become inactive. In such cases, the shape of the M wave would be unstable and the time courses of MNF or MDF would be irregular and show fluctuations that would invalidate the linear or exponential regression and therefore the very definition of the fatigue indexes. On the other hand, a stable motor unit pool undergoing a progressive change in CV would be associated with a myoelectric signal with a spectrum that displays progressive compression with a minor or no change in shape. As a consequence, we decided to discard trials that produced obvious changes in shape in the power spectrum of the myoelectric signal during the contraction. Two criteria were adopted; one was subjective and based on visual examination of the spectral shape and the other was objective and based on the relationship between MNF and MDF.

TABLE 1. *ICC values for IV, NIS, and AR of MNF and MDF of M wave power spectrum*

Parameter	Intersubject Variance (ICC), %	Error Variance, %
MNF		
IV	80.0	20.0
NIS	32.7	67.3
AR	48.6	51.4
MDF		
IV	74.7	25.3
NIS	30.4	69.6
AR	58.8	41.2

ICC, intraclass correlation coefficient; MNF, mean frequency; MDF, median frequency; IV, initial value; NIS, normalized initial slope; AR, area ratio.

Details about the two criteria and the acceptance and rejection regions adopted in this work are provided in the APPENDIX. (For examples of accepted contractions from either side of a right-handed subject, see Figs. 2*A* and 6. For examples of a rejected contraction, see Figs. 2*B* and 7.) The accepted contractions are very likely to have a stable motor unit pool and therefore provide meaningful fatigue indexes.

A total of 100 contractions (25 contractions for each side of either the right- or left-handed subjects) were performed. After application of the selection criterion, we accepted 13 contractions from the right side and 21 from the left side of the right-handed subjects and 16 from the right side and 21 from the left side of the left-handed subjects. They formed only 25 pairs, 12 for right-handed subjects and 13 for left-handed subjects. Statistical tests were applied to these selected contractions.

Reliability analysis (ICC and 1-way ANOVA). The values of ICC computed for the accepted contractions are given in Table 1. These results indicate that the day-to-day intrasubject variations are comparable to or larger than the intersubject differences. From a signal processing point of view, the intersubject variance may be considered as the information of interest (signal power) and the error variance as experimental noise (noise power). The high level of noise power, much greater than the signal power for NIS, indicates that individual measurements are meaningless and that repeated measurements are necessary to reach conclusions. The initial value is the parameter least sensitive to experimental noise (high ICC) followed by area ratio and NIS. MDF and MNF are approximately equivalent in this respect.

Table 2 provides a summary of the results. Nonpaired *t*-tests indicate differences between right- and left-side values significant for NIS ($P < 0.05$) and marginally significant for area ratio ($P = 0.07$) for right-handed subjects and marginally significant for NIS ($P = 0.07$) and not significant for area ratio for left-handed subjects.

TABLE 2. *Summary of data according to factors 1 and 2 and variable of interest*

Factor 2:	Right-Hand Dominance		Left-Hand Dominance	
Factor 1:	RS	LS	RS	LS
n	13	21	16	21
MDF				
IV, Hz	104.6±28.1	92.1±25.6	67.5±17.3	75.0±20.2
NIS, %/s	3.14±1.6	1.58±0.9	1.5±1.0	2.66±2.4
AR, %	22.3±6.3	17.9±7.0	16.6±7.6	17.3±8.3
MNF				
IV, Hz	118.1±28.3	103.5±26.6	78.7±15.9	86.0±19.0
NIS, %/s	3.28±1.7	1.53±1.0	1.22±1.13	2.1±1.8
AR, %	21.56±6.1	17.1±6.2	16.8±6.2	17.0±5.1

Values are means ± SD; *n*, no. of observations (accepted contractions only). RS, right side; LS, left side.

However, paired tests are in this case more important than unpaired tests and are discussed in the next section. Table 2 also shows an unexpected relationship between the initial values of MDF and MNF and dominance. Because the initial value is related to the tissue filtering function, i.e., to skinfold, the regression between initial value, NIS, and area ratio with respect to skinfold was studied. No clear relationship emerged between hand dominance and skinfold. As expected, the initial value was related to skinfold with a regression coefficient (RC) of −5.1 Hz/mm, which is significantly lower than zero ($P = 0.02$). The area ratio index was also related to skinfold with an RC of −1.5 %/mm, which is significantly lower than zero ($P = 0.015$), whereas NIS was not related.

Two-way ANOVA and dominant/nondominant paired comparison analysis. Results of the two-way ANOVA are reported in Table 3. As expected, the test indicates that the parameters in question do not depend on the stimulated side. Consequently, the experimental procedure does not appear to be biased in favor of a particular side. The test also indicates that the parameters are affected by side dominance. The effect of side dominance reaches the threshold significance level of 0.05 only for the initial value, whereas it is between 0.05 and 0.09 for NIS (MNF only) and area ratio. Considering that *1*) there is interaction between the two factors, i.e., the values on the right side are affected by handedness, as indicated in Table 3, and *2*) the results of the paired tests in Table 4 clearly show the role of hand dominance, we feel comfortable in stating that the "marginal" levels of significance indicated in Table 3 support the effect of dominance indicated by the paired tests reported in Table 4.

TABLE 3. *Results of two-way ANOVA with respect to stimulated and dominant sides*

	IV	NIS	AR
MNF			
Side	Not dependent ($P = 0.51$)	Not dependent ($P = 0.42$)	Not dependent ($P = 0.22$)
Dominance	Dependent* ($P = 0.01$)	Marginally dependent* ($P = 0.08$)	Marginally dependent* ($P = 0.06$)
MDF			
Side	Not dependent ($P = 0.62$)	Not dependent ($P = 0.61$)	Not dependent ($P = 0.30$)
Dominance	Dependent* ($P = 0.01$)	Not dependent* ($P = 0.47$)	Marginally dependent* ($P = 0.09$)

ANOVA, analysis of variance. * Statistically significant interaction between stimulated (*factor 1*) and dominant (*factor 2*) sides ($P < 0.05$).

TABLE 4. *Results of paired comparisons of fatigue indexes from RS and LS of right-handed and left-handed subjects*

Fatigue Index	Alternative Hypothesis (paired comparison)	No. of Pairs	*P* Value	Test
NIS of MDF	RS of RH > LS of RH	12	0.023	Robust
	LS of LH > RS of LH	13	0.290	Robust
	D side > ND side	25	0.072	Robust
			0.001	*t*-Test
NIS of MNF	RS of RH > LS of RH	12	0.012	Robust
	LS of LH > RS of LH	13	0.004	Robust
	D side > ND side	25	0.001	Robust
AR of MDF	RS of RH > LS of RH	12	0.140	Robust
			0.020	*t*-Test
	LS of LH > RS of LH	13	0.190	Robust
			0.020	*t*-Test
	D side > ND side	25	0.020	Robust
AR of MNF	RS of RH > LS of RH	12	0.130	Robust
			0.018	*t*-Test
	LS of LH > RS of LH	13	0.130	Robust
			0.530	*t*-Test
	D side > ND side	25	0.028	Robust

RH, right-handed subj; LH, left-handed subj; D, dominant; ND, nondominant; Robust, "robust" Wilcoxon nonparametric test; *t*-Test, Student's *t*-test. Results of *t*-test are shown when outcome of robust test was marginally significant. Data are from accepted pairs only.

Table 4 shows the results of paired comparisons for the fatigue indexes for the accepted pairs only. NIS of MDF was clearly higher on the dominant side of right-handed subjects, whereas the difference was not significant in left-handed subjects. The area ratio of MDF was not significantly different according to the robust test but was different according to the *t*-test, which indicates a non-Gaussian skewed distribution of results. NIS of MNF was clearly higher on the dominant side of both right- and left-handed subjects. The area ratio of MNF was higher on the dominant side of right-handed subjects according to the *t*-test but not according to the robust test, whereas no significant difference was detected in left-handed subjects. From the above observations it may be concluded that dominance-related differences in fatigue indexes are more clearly evident in right- than left-handed subjects. Furthermore, the fatigue index most sensitive to the dominant side is the NIS of MNF followed by the NIS of MDF. The area ratio index, although less affected by experimental noise (Table 1), appears to be less sensitive than NIS to side dominance. Figures 4 and 5 summarize the results depicted in Table 2.

DISCUSSION

Repeatability. The motor points of the LD muscles were not easy to identify and often consisted of poorly defined areas, which suggested multiple innervation zones. This situation was aggravated by the fact that very little is known about the innervation zones of these muscles (8), and no information could be found in the literature about the length of the fibers and the location of the neuromuscular junctions. It is likely that, in our tests,

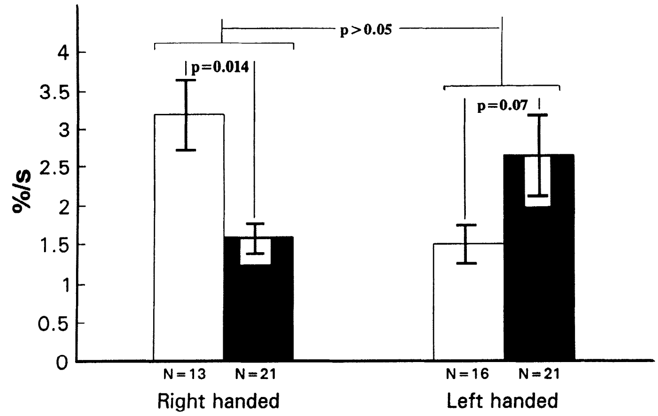

FIG. 4. Normalized initial slope of MDF defined as %decrement/s. Values are means ± SE of mean of this index for accepted contractions; *n*, no. of contractions. Open bars, right longissimus dorsi; solid bars, left longissimus dorsi. *P* values are for unpaired *t*-test.

stimuli applied in one location activated nerve fibers innervating motor units in locations caudal with respect to the stimulation electrode, possibly even caudal with respect to the detection electrodes. This arrangement could cause the poor estimates of CV (due to bidirectional propagation of action potentials underneath the detection electrodes) and the poor repeatability (due to the critical position of these electrodes). This second issue would be particularly important in the case of fibers that are not much longer than the electrode array (16). The fact that we observed poor CV estimates and repeatability supports the hypothesis of scattered innervation and possibly short muscle fibers. Additional factors contributing to experimental noise are related to the variability of muscle structure at the thoracolumbar level (32).

It might be possible to improve the stimulation technique by locating the large positive return electrodes elsewhere. In the present arrangement (Fig. 1*A*), the electrodes are located on the scapulae and current flows underneath the skin from the small to the large electrodes with a progressively decreasing density. Placing the return pads on the chest would imply a faster current density decrease and a greater selectivity but would also reduce the safety for the subject.

Voluntary contractions are presumably less affected by experimental noise, since the issue of stimulation electrode replacement does not exist and muscle activation modalities might be more similar from test to test. However, the available data on this topic are insufficient to prove that this is the case. Roy et al. (29) reported good repeatability of MDF initial values and slopes but only from intraexperiment tests. Biedermann et al. (6) performed a test-retest experiment (5 days apart) and found a correlation coefficient (CC) of >0.90 for the MDF value obtained from electrodes placed on the multifidus and >0.75 for electrodes placed on the iliocostalis muscles. No data are reported by these authors about intertest intrasubject repeatability of fatigue indexes. Kondraske et al. (20) and Standridge et al. (33) studied the time course of MNF and related its slope to the muscle load but did not separate intra- and intersubject repeatabilities. They estimated MNF over 1-s epochs and showed epoch-to-epoch fluctuations on the order of 10%, which indicates that the estimate of slope is highly affected by the number of epochs considered. Roy et al. (31) observed smaller fluctuations in the MDF time course but used a device with an output affected by a time constant on the order of 1 s. As a consequence, in their case, the slope could be estimated with a smaller standard error.

As is obvious from Fig. 6, electrical stimulation produces time patterns of MNF and MDF with very small fluctuations and therefore excellent estimates of regression parameters. However, intrasubject intertest repeatability is poor. Further work is needed to allow comparisons between the techniques based on stimulated and voluntary muscle activation.

Side dominance. A second finding of this work is related to the effect of side dominance on the initial value and fatigue indexes of myoelectric signal variables. Despite the experimental noise, this effect is clearly detected by the paired tests and ANOVA. We attribute this difference to the continued preferential use of muscle groups on the nondominant side of the back to compensate for moments applied to the dominant side in daily life activities. It is generally accepted that exercise modifies the fiber constituency of a muscle, mostly by converting type IIb into type IIa fibers (17), a fact that would result in lesser myoelectric manifestations of muscle fatigue because type IIa fibers have greater fatigue resistance than do type IIb fibers. Also, Tanaka et al. (34) reported that, when electrically stimulated, the FDI on the dominant side displayed a statistically significant slower rise time of the twitch response, which suggests a higher percentage of type I fibers with respect to the nondominant side. Bagnall et al. (1) observed a statistically significant difference between fiber type distribution in muscles on the right and left sides of the dorsal column (multifidus and sacrospinalis). In 12 male subjects, these authors found a higher percentage of type I fibers on the left side than on the right side. Unfortunately, their data were not correlated to side dominance. However, if we make the reasonable assumption that their subjects were mostly right handed, then this finding would be in agreement with the greater use of the muscles on the left side of the spinal cord in daily life activities. As a consequence, greater resistance to fatigue could be developed by back muscles of the nondominant side.

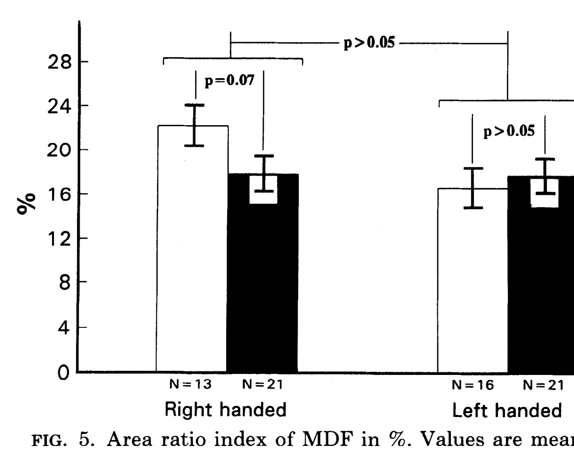

FIG. 5. Area ratio index of MDF in %. Values are means ± SE of mean of index for accepted contractions; *n*, no. of contractions. Open bars, right longissimus dorsi; solid bars, left longissimus dorsi. *P* values are for unpaired *t*-test.

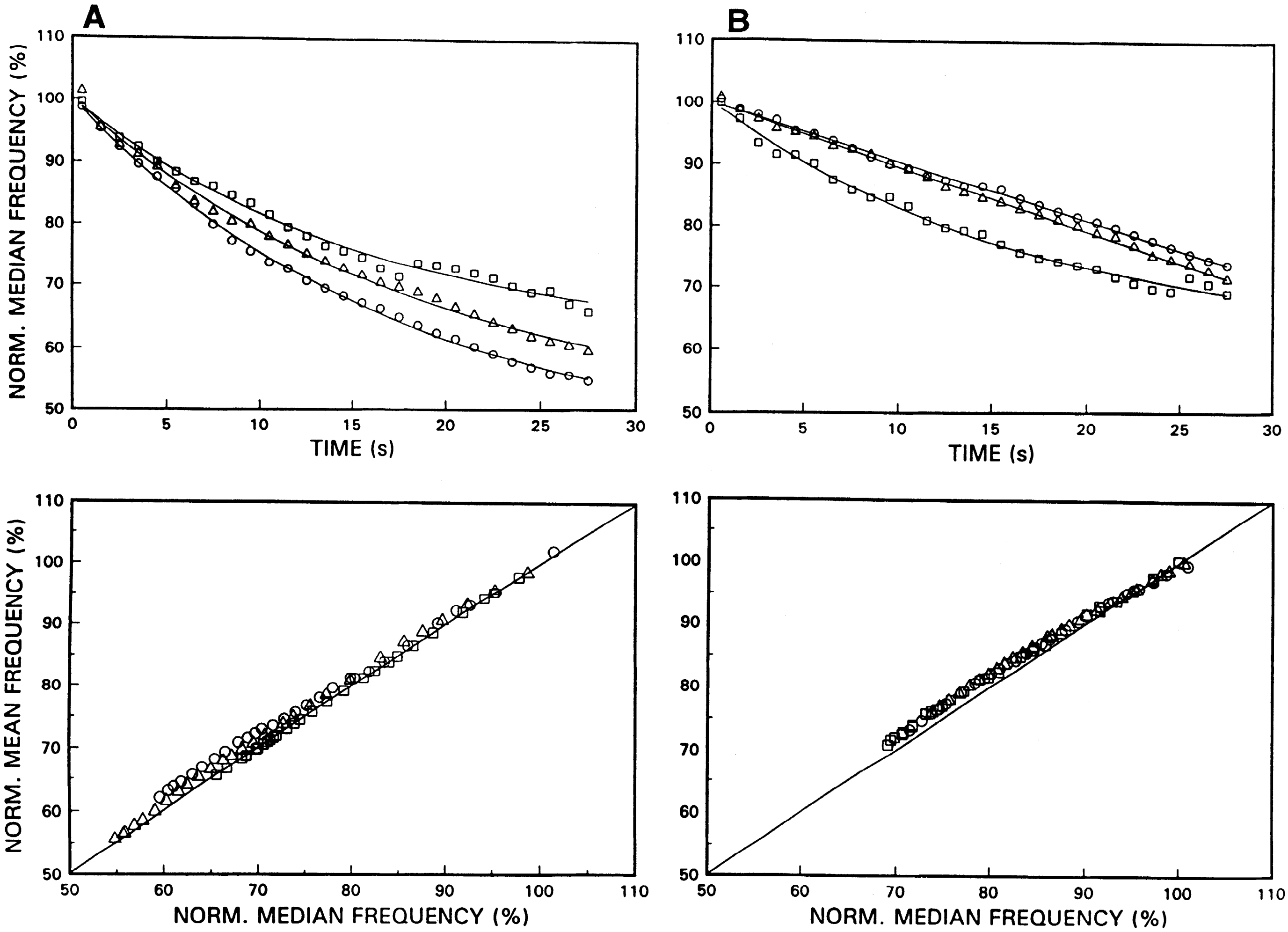

FIG. 6. *A*: examples of MDF vs. time (*top*) in 3 experiments performed on right longissimus dorsi of same right-handed subject on 3 different days. All contractions are accepted because relationship between normalized MNF and MDF is very close to line of unity slope (*bottom*) (see APPENDIX). *B*: left longissimus dorsi of same subject (*top*). All contractions are accepted because relationship between normalized MNF and MDF is very close to line of unity slope (*bottom*) (see APPENDIX). Each symbol refers to 1 day. Difference between 2 sides is clear in 2 of 3 tests.

Tables 2 and 3 indicate that the initial values of MDF and MNF depend on side dominance. This fact may be due to dominance-related differences in the following factors: *1*) tissue-filtering effects, *2*) mean and statistical distributions of CV, *3*) spatial scatter of the neuromuscular junctions, *4*) width of the depolarized zones, and *5*) the manner in which the action potentials become truncated at the end of the fibers (16). A correlation between one-half of the skinfold thickness and the initial values of MDF and MNF was found. For MDF, CC was −0.61 and RC was −10 Hz/mm (significantly different from zero at $P = 0.02$). Similar values were observed for MNF. However, skinfold thickness was not significantly different in the right and left sides of either right- or left-handed subjects, which suggests that *factors 2–5*, rather than *factor 1*, may be responsible for this observation. The most likely factor is the mean and distribution of CV values. If the muscles on the dominant side had a higher portion of a fiber type with higher and/or less dispersed CV values, then the initial values of MDF and MNF would be higher and in agreement with our findings. The relationship between spectral variables and fiber type would, of course, overlap with that between spectral variables and skinfold. In addition, *factors 2–5* may be different in different individuals and may change considerably, even in the same individual, from the thoracic to the lumbar level because of different fiber type constituency in the two regions (32), therefore contributing to experimental noise.

Dominance-related differences in fatigue indexes are less significant in left- than in right-handed subjects. From Table 2 and Figs. 4 and 5 it is clear that fatigue indexes are relatively similar in the right and left sides of left-handed subjects and in the left side of right-handed subjects, whereas they are higher in the right side of right-handed subjects. These findings indicate that the lesser used muscles on the right side of right-handed subjects are more fatigable not only with respect to those of the opposite side but also with respect to those of either side of left-handed subjects. This observation is consistent with the fact that the left upper limb of right-handed subjects is used less than the right limb and than either limb of the left-handed subjects.

Truly left-handed subjects constitute a small percentage of the population. Beukelaar and Kronenberg (5) found that, in a random group of subjects examined for

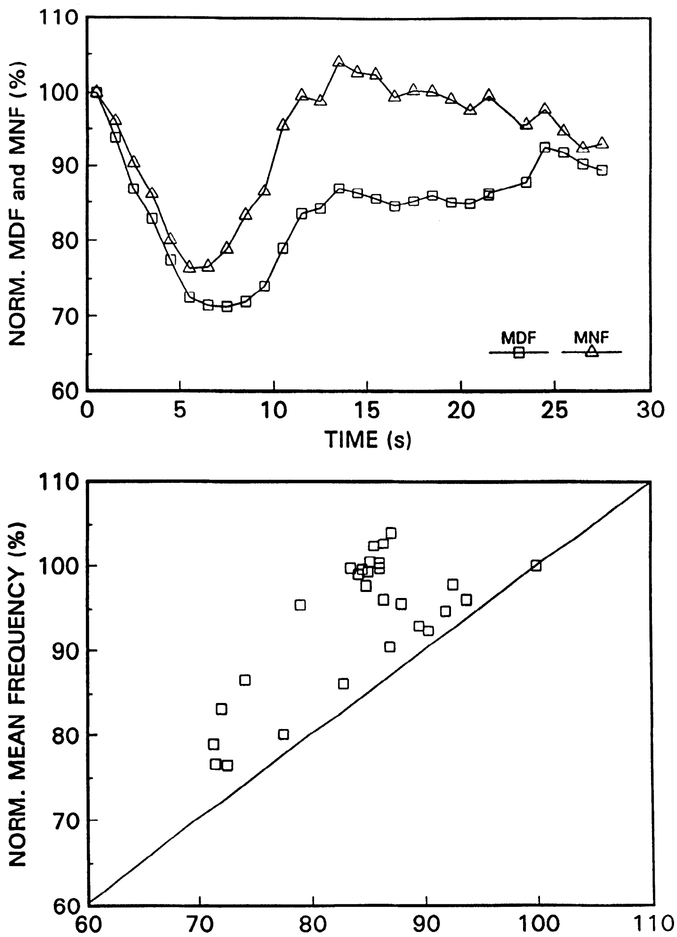

FIG. 7. Example of rejected contraction. Both MNF and MDF show large fluctuations (*top*), and their regression is not close to line of unity slope (*bottom*) (see also Fig. 2).

writing skills, 80% were right handed and 20% were left handed. Nonetheless, 56% of the left-handed subjects were able to write and perform other manual tasks with their nondominant hand while only 0.6% of the right-handed subjects could do the same. This finding indicates that, although hand dominance is well established in right-handed subjects, it is far less defined in left-handed subjects, who appear to be mostly ambidextrous.

TABLE 5. *Acceptability conditions for electrically evoked contractions of LD muscles and no. of contractions satisfying each combination of conditions*

	Condition A	Not *Condition A*	Total
Condition B	68	12	80
Not *Condition B*	4	16	20
Total	72	28	100

LD, longissimus dorsi; *condition A*, visual observation of no changes of shape in M-wave spectrum between beginning and end of contraction; *condition B*, $0.8 < RC < 1.2$ and $CC > 0.9$ where RC is regression coefficient of normalized MNF vs. normalized MDF and CC is correlation coefficient of normalized MNF vs. normalized MDF.

This observation is in agreement with our findings as well as previous findings by De Luca et al. (14), who noticed this fact in the FDI muscle.

It is interesting to observe that NIS of spectral variables did not appear to be correlated to skinfold. This fact, observed also by Linssen et al. (22) in the biceps, suggests that NIS may be preferred to the absolute slope or the area ratio as an indicator of myoelectric manifestations of muscle fatigue. The correlation between area ratio and skinfold appears to be complex to explain and may be the result of a monodimensional view of a multivariate relationship. In particular, this fact indicates that the time course of spectral variables is curvilinear in most cases (Fig. 6). In fact, in the case of a linear decrease, area ratio and NIS would be equally affected, as demonstrated by Merletti et al. (25).

Data quality. The technique and fatigue indexes used in this work are sensitive enough to allow the detection of side dominance effects even in a relatively small group of subjects. However, the complex anatomy of the back introduces experimental noise, moderate repeatability, and the need to separate valid data from unacceptable data affected by artifacts. In ~30% of the cases the quality of the estimates was not acceptable. This finding indicates a major difference between back muscles and the tibialis anterior. In our previous experience on the latter muscle, all or almost all of the electrically elicited contractions were acceptable (23, 24). Furthermore, in the back muscles, the ICC value was relatively low, especially for the fatigue indexes.

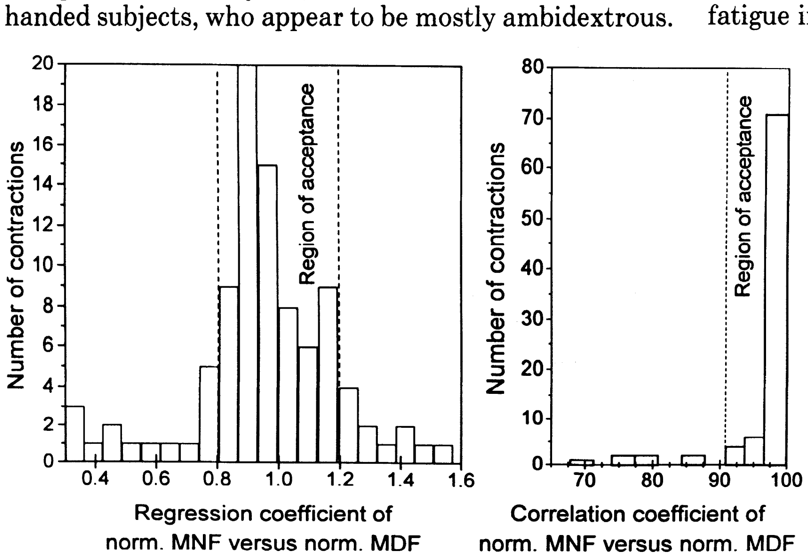

FIG. 8. Histogram of values of regression and correlation coefficients of normalized MNF vs. normalized MDF. A few values are outside depicted range. Regions of acceptance (dashed lines) are $0.8 \leq$ regression coefficient ≤ 1.2 and $0.9 \leq$ correlation coefficient ≤ 1.0. Change in spectral shape was visually evident when values of either regression or correlation coefficients were outside respective acceptance regions.

As a consequence, a single test does not provide sufficient information and repeated measurements are necessary to detect clinically relevant differences. Future clinical applications will then require repeated measurements and on-line data processing for ascertaining the quality of signals and optimization of electrode position. In this regard, criteria for acceptability of a contraction have been proposed.

Conclusions. This work led to the following findings. *1)* The electrically elicited myoelectric signal on the right and left LD muscles may be used to distinguish muscle fatigability and possibly fiber type differences related to side dominance. Such differences are statistically significant in right-handed subjects and less significant or not significant in left-handed subjects. *2)* Fatigue indexes of the right and left LD muscles must be based on spectral variables (MNF and MDF) and not on muscle fiber CV. Because of the complex anatomy of these muscles, estimates of CV based on surface myoelectric signals cannot be obtained reliably with the techniques presently available.

These conclusions are relevant in many fields of rehabilitation medicine such as back pain analysis, back muscle biofeedback research, scoliosis investigations, and assessment of back muscle pathology and performance.

APPENDIX

Criteria for accepting and rejecting contractions. The basic criterion for accepting or rejecting a contraction was related to the invariance of signal and spectral shape during the progressive spectral compression (M-wave widening) taking place during the contraction. In this work the concept of spectral shape variation is defined as a change other than horizontal or vertical scaling. Such a change can be attributed to factors that invalidate the estimates of fatigue indexes based on signal (or spectral) scaling. Fluctuation of the number of active motor units is one of such factors. A general methodology for spectral shape analysis is not yet available, and it is necessary to rely on visual observation to decide whether the spectral shape has changed. However, a well-known property of the Fourier transform states that when a signal expands in time without changing shape its power spectrum is scaled in frequency and the MNF and MDF change by the same percentage (24). This statement implies that a plot of normalized values of MNF vs. normalized values of MDF will provide a straight line with unity slope. This condition, however, is necessary but not sufficient and, by itself, does not guarantee shape invariance because very specific (and unlikely) variations of shape might change MNF and MDF by the same percentage. As a consequence, we decided to adopt the following two conditions for accepting and rejecting contractions. *1)* Visual identification of changes in shape of the power spectrum during the contraction. Spectral shapes at the 3rd s and at the last 1 s of contraction were compared, and if a change in shape was evident the contraction was rejected. The decision was subjective. This is the most logical condition: it is necessary and sufficient; however, it is subjective and cannot be easily implemented numerically, and it requires an additional quantitative and objective condition. *2)* The RC and CC of the least mean square line fitted to the values of normalized MNF vs. normalized MDF. Because spectral compression, with no change in shape, would imply equal changes in the normalized two frequencies, the RC and CC of this least mean square line should both be unity. This condition is quantitative and objective: it is necessary but not sufficient, and it was used jointly with *condition 1.* According to *condition 2,* a contraction was accepted if RC was between 0.8 and 1.2 and CC was between 0.9 and 1.0. These thresholds were set by observing that the histograms of RC and CC showed a main lobe within these windows with small tails outside the windows and that contractions with values outside the windows were all associated with visually evident changes in spectral and M-wave shapes during the contraction (see Fig. 2*B* for an example).

Figure 6 shows cases of accepted contractions. The relationship between normalized MNF and normalized MDF is highly linear. Figure 7 shows MDF and MNF vs. time and the plot of normalized MNF vs. normalized MDF for a rejected contraction. Application of the two conditions to the 100 contractions performed in the 50 tests on our 10 subjects led to the results shown in Table 5. *Condition 2* is necessary but not sufficient to ensure shape invariance, since there could be shape changes in the low- and high-frequency bands that would have compensatory effects on the MNF-MDF relationship. This is consistent with the finding that 12 contractions met *condition 2* but not *condition 1.* The unexpected finding of four contractions that met *condition 1* but not *condition 2* is attributed to the visual verification of spectral shape limited to initial and final epochs. Verification of intermediate spectra in these contractions indicated momentary changes.

Figure 8 shows the histogram of the values of RC and CC and the windows used for the acceptance and rejection criteria. A main lobe with small tails can be clearly identified for both RC and CC but is particularly evident for CC. Trials that were within the acceptance regions showed no visually detectable changes in spectral shape. Therefore, *condition 2* provides an acceptable quantification of *condition 1.*

Table 5 reveals that 68 contractions were accepted out of the 100 that were performed. Only 50 of the accepted contractions formed 25 pairs (1 measurement each on the right and left sides of the same subject); the other 18 were not matched by an accepted contraction on the opposite side.

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