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Median frequency of the myoelectric signal

Effects of hand dominance

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Summary. A study was performed to investigate the existence of any distinction in the fatiguability of corresponding contralateral muscles in the hand as a function of hand dominance. The first dorsal interosseous muscle was studied. The median frequency of the myoelectric signal was employed to describe the fatigue behavior of the muscle. It was found that during sustained contractions the median frequency decreased faster in the non-dominant hand of right handed individuals, whereas, no statistically significant distinction could be found in left handed individuals. This distinction was evident in both male and female subjects. This study demonstrates that continued preferential usage of a muscle is associated with altered electrical properties of the myoelectric signal and that the median frequency of the signal provides an appropriate measure of the modifications. It is argued that the findings may provide an indication of modifications in the metabolic properties of muscle fibers induced by a lifetime of preferred functional use.

Key words: Fatigue — Muscle — Hand dominance — Myoelectric signal — Median frequency — First dorsal interosseous

Introduction

Continued preferential use of selected muscle groups may be expected to induce biochemical and structural modifications to their muscle fibers. Recent reports have provided evidence of such modifications. Fugl-Meyer et al. (1982) have reported a higher percentage of slow-twitch Type I muscle fibers present in the extensor carpi radialis brevis muscle of the dominant limb, compared to the corresponding muscle in the contralateral limb. More recently, Tanaka et al. (1984) arrived at the same conclusion by noting that the electrically induced twitch response of the first dorsal interosseous (FDI) muscle in the dominant hand had a statistically significant slower rise time. Upper limb muscles may be more predisposed to modifications than lower limb muscles (Schantz et al. 1983) because humans preferentially employ these muscles during certain motor acts. The frequent preferential use of the dominant hand in daily activities may over the years act as a form of endurance training for the muscles of the hand. This behavior most likely explains the observation by Thormgren and Werner (1979) who documented that the dominant hand has greater grip strength than the non-dominant hand. It, therefore, follows that fatiguability of muscles in the dominantly used side may differ from that of corresponding contralateral muscles.

In the past, it has been customary to think of muscle fatigue as the inability of a muscle to maintain either voluntarily or involuntarily a specified force output. This contractile fatiguability of muscles has been related to the muscle fiber types that comprise a muscle. Muscles with predominantly slow twitch motor units are more resistant to contractile fatigue than those that are more evenly mixed with slow and fast twitch motor units (Tesch 1980).

More recently, the concept of muscle fatigue has been considered as a continuous time dependent process throughout the entire contraction. In this sense, the progression of fatigue has been associated with a monotonic shift in the frequency

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spectrum of the myoelectric (ME) signal towards lower frequencies. See De Luca (1985) for a review. This frequency shift has been mathematically associated with a decrease in the intramuscular conduction velocity during sustained contractions (Lindström 1970). This association has been recently demonstrated empirically (Arendt-Nielsen and Mills 1985; Broman, Bilotto, and de Luca 1985). The latter study further associated the changes in the intramuscular conduction velocity with changes in the median frequency of the ME signal. The median frequency had previously been demonstrated to provide the preferred estimate of a single parameter for monitoring the frequency shift (Stulen and De Luca 1982). The median frequency and intramuscular conduction velocity are related to the muscle fiber size and type. Because smaller muscle fibers have been found in women than in men (Prince et al. 1977), males and females should demonstrate different values for the median frequency of the ME signal. Therefore, the effect of handedness and gender on muscle function will be assessed in this study by the technique of monitoring the median frequency of the myoelectric signal.

Methods

A total of 35 normal adult subjects volunteered for this study; 16 were females with an average age 25.6±3.0 years, 19 were males with an average age of 27.3±3.7 years. Eighteen subjects were right-handed and 17 were left-handed. Hand dominance was identified by a subject's indication that they used the dominant hand in most of their daily living activities; including manipulation, writing skills, and other hand and finger activities. The identification of hand dominance was further confirmed when subjects were observed during manipulation of objects in the laboratory and during signing of the informed consent forms prior to beginning the experiments. This observation of hand preference during manipulation was carried out without prior information to the subject concerning the objectives of the study. None of the subjects had a past history of neurological disorders.

The first dorsal interosseous (FDI) muscle was tested during isometric, constant-force abduction of the index finger. Recording methods were similar to those reported by Merletti et al. (1984). The force output was measured with a specially constructed device that immobilized the subject's hand, with the index finger isolated between a rigid support and a pad attached to a force gauge of negligible compliance (0.27 μm/N). The pad made contact with the index finger at the proximal interphalangeal joint. See Fig. 1 for details.

The subjects were provided with visual feedback of their force output (via an oscilloscope) during all contractions. Initially, the level of each subject's maximal voluntary contraction (MVC) was obtained by choosing the highest value of three consecutive attempts at generating a maximal contraction. These maximal contractions lasted 5 s each and were spaced 2 min apart. The 20%, 40%, and 80% MVC levels were then computed and appropriate targets were set on the oscilloscope screen. Subjects were asked not to overshoot the target on the oscilloscope screen, especially at the beginning of each contraction level.

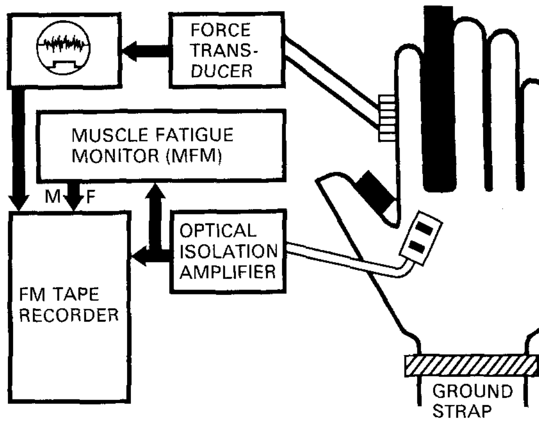

Fig. 1. The experimental arrangement for detecting and recording force and myoelectric signal from the first dorsal interosseous muscle (FDI)

Right and left hands were tested separately, and in a random order. Each subject was asked to perform three isometric abductions of the FDI muscle at 20% MVC with 30 s intervals between contractions. The first two contractions were maintained for 10 s, the third contraction for 60 s. After a rest period of 3 min, three 40% MVC contractions were performed in a similar fashion. After a rest period of an additional 3 min, three 80% MVC contractions were produced with 3 min intervals between contractions. After 5 more min, one 100% MVC was performed and sustained until the force level diminished below the 90% MVC level. After a 15 min rest period, the FDI of the contralateral hand was tested in a similar fashion during the same recording session.

The surface ME signal was detected from the FDI muscle via an active electrode probe consisting of two silver bars (10 mm long, 1 mm wide) spaced 10 mm apart and fixed on a small epoxy block. The two silver bars were connected to electronic circuitry embedded in the epoxy block. The electrode design was similar, but not identical, to that described by De Luca et al. (1979). The recording electrode was attached with tape to the skin on top of the muscle with the bars aligned perpendicularly to the direction of the muscle fibers. A saline-soaked metal strap located around the wrist provided a ground reference. The ME signal was processed with an analog device called the Muscle Fatigue Monitor, which has been described in detail by Stulen and De Luca (1982) and Gilmore and De Luca (1985). This device computes the median frequency of the ME signal with a bandwidth of 3 dB at 30 Hz and 550 Hz. The median frequency, along with the amplified ME signal and the voltage output of the force gauge, were recorded on an FM tape recorder. Fig. 1 presents the details of the experimental arrangement.

Two parameters were measured: the initial median frequency (IMF) and the rate of decrease (slope) of the median frequency of the ME signal. The IMF was obtained by noting the highest value of the median frequency of the ME signal after the force stabilized at the beginning of the muscle contraction. This criterion was usually achieved during the initial 1 s of each contraction. The slope of the median frequency was calculated for the initial 5 s of each contraction. The values from the three contractions at each of the three force levels

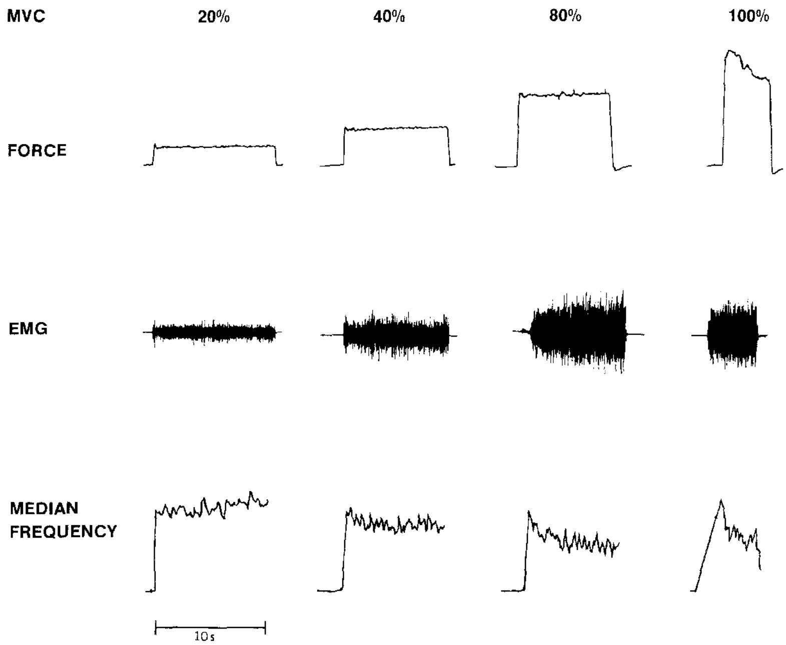

Fig. 2. Examples of the force, myoelectric signal and median frequency from one set of contractions performed by a subject

(20%, 40%, and 80% MVC) were averaged; and the mean and standard deviations of the IMF and slope were obtained across subjects. The value of the IMF and slope was also measured for a 100% MVC. *T*-test statistics for repeated measures were used to obtain the significance of the difference in the recorded parameters between the right and left hand in (R) handed and (L) handed subjects as well as between males and females.

Results

In this study, hand dominance was designated by the subjects' predominant use of a preferred hand in writing skills, manipulation, sport and leisure activities. Our interview with and observations of subjects revealed that all subjects who claimed to be (R) handed were "purely" (R) hand dominant having little or no consistent functional daily use of the left hand except to assist the right hand. However, those who claimed to be (L) handed were found to be ambidexterous. When questioned in detail, they revealed that they in fact used the (R) hand in several essential daily activities. The type and amount of (R) hand usage varied in each (L) hand designated subject.

In both hands of (R) and (L) handed subjects, the median frequency of the ME signal decreased monotonically during sustained isometric contractions of the FDI muscle. This decrease in the median frequency was more pronounced at relatively high force levels of contraction. Fig. 2 demonstrates this behavior in one sequence of contractions performed by a subject. The IMF and the slope of the median frequency were found to differ in some cases and not in others. This may be seen in Fig. 3 which displays the median frequency as a function of time at two different force levels for both FDI muscles of (R) and (L) handed subjects.

The values of the IMF and slope of the median frequency for all of the contractions are plotted in Figs. 4 and 5. In these figures, the value from the (R) hand is plotted versus the corresponding value (obtained from a contraction performed at the same level) from the (L) hand. The data are plotted separately for the (R) handed and (L) handed subjects, and in each case the data from males and females are identified separately. By presenting the data in this fashion, it is possible to study distinctions between males and females as well as hand dominance. Least square linear regressions on the data indicate that the IMF and the median frequency slopes of the two FDI muscles do not differ between males and females, as is indicated by the similarity of the regression lines and all but one of the *t*-tests presented in Table 1. Figures 4 and 5 also indicate that the IMF and the slope have a similar range of values in both (R) handed and (L) handed subjects. This observation is supported by most of the *t*-tests presented in Tables 2a, b. However, Fig. 5 and Table 2b do present one striking distinction in the behavior of the slopes of the median frequency. In (R) handed subjects, the slopes from the (R) hand FDI in a statistical sense are less than the slopes from the (L) hand FDI. Note that regres-

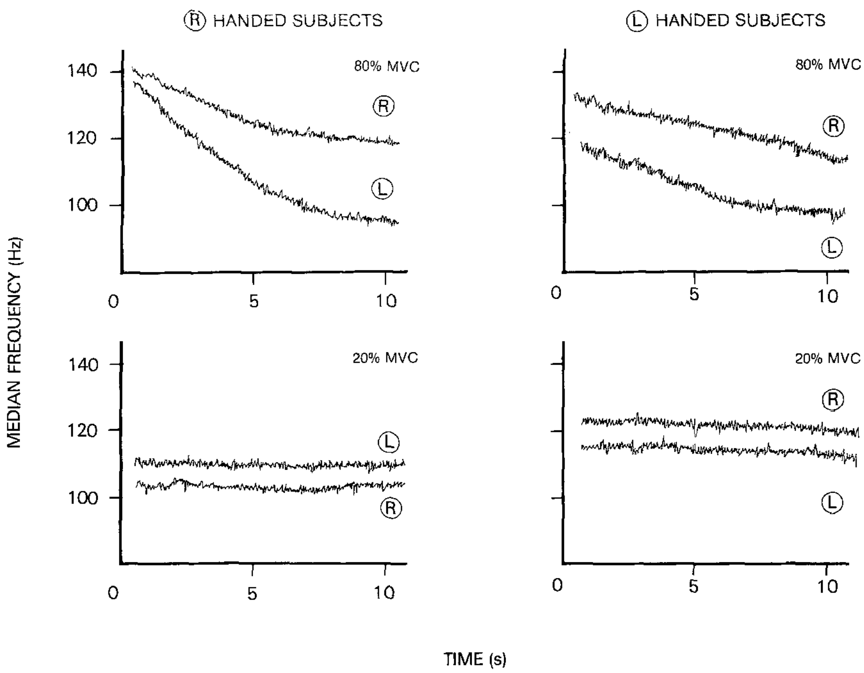

Fig. 3. Examples of the typical behavior of the median frequency decrease in the right and left first dorsal interosseous muscle for a right handed and a left handed subject. The contractions were performed at 20% and 80% of the maximal voluntary contraction (MVC) level

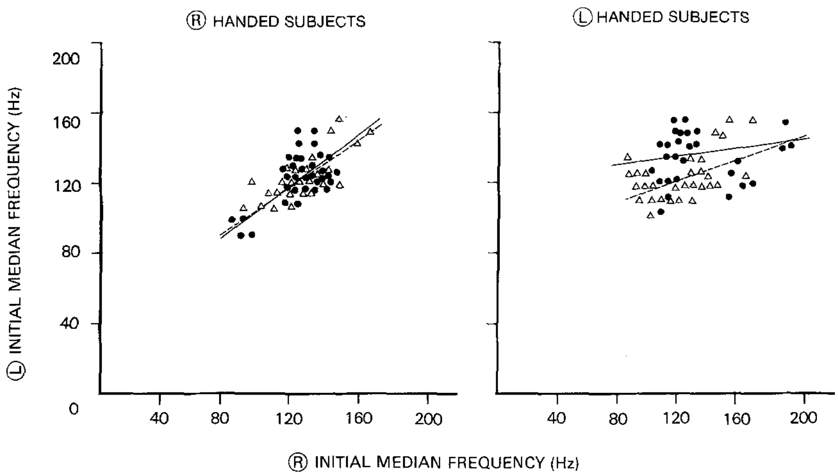

Fig. 4. Initial median frequency (IMF) data from the right and left first dorsal interosseous muscle plotted separately for all right-handed and left-handed subjects. Each datum point represents the average value for three trials at a specified force level. Separate regression lines for right-handed males [--●--] ($Y=0.73X+0.37$, $r=0.71$) and females [--△--] ($Y=0.67X+0.41$, $r=0.82$) as well as for left-handed males ($Y=0.13X+120$, $r=0.22$) and females ($Y=0.35X+81$, $r=0.55$)

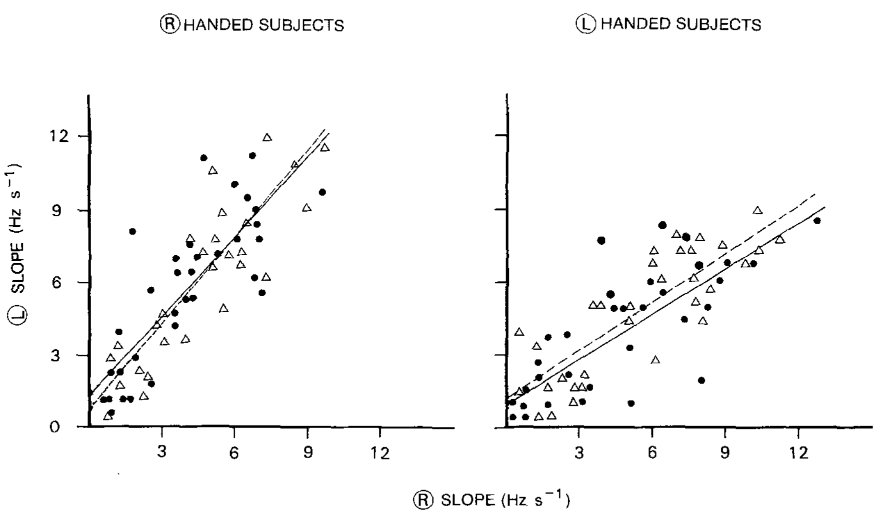

Fig. 5. Median frequency slope values from right and left first dorsal interosseous muscles plotted separately for all right and left-handed subjects. Each datum point from males and females represents the average of three trials at a specified force level. Separate regression lines for right-handed males [--●--] ($Y=1.15X+1.31$, $r=0.83$) and females [--△--] ($Y=1.20X+0.82$, $r=0.88$) as well as for left handed males ($Y=0.71X+0.99$, $r=0.74$) and females ($Y=0.82X+0.94$, $r=0.83$)

Table 1. *t*-tests of the Initial Median Frequency (IMF) and slope of the median frequency values from the first dorsal interosseous muscle comparing the data from males and females

	Males vs females	
	IMF	Slope
(R) hand of (R) dominant	$p<0.503$	$p<0.571$
(L) hand of (R) dominant	$p<0.225$	$p<0.543$
(R) hand of (L) dominant	$p<0.153$	$p<0.322$
(L) hand of (L) dominant	$p<0.008$	$p<0.146$

Table 2a. Mean values, standard deviation and *t*-test of the Initial Median Frequency (IMF) of the first dorsal interosseous (FDI) muscle, comparing the data of the right and left hand as a function of handedness. N.S. indicates $p>0.05$

	(R) FDI	(L) FDI	*p* Value
(R) Handedness	129±18 Hz	130±17 Hz	N.S.
(L) Handedness	129±24 Hz	131±15 Hz	N.S.
p Value	N.S.	N.S.	

Table 2b. Mean values, standard deviation and *t*-tests of the slope of the median frequency of the first dorsal interosseous muscle, comparing the data of the right and left hand as a function of handedness. N.S. indicates $p>0.05$

	(R) FDI	(L) FDI	*p* Value
(R) Handedness	3.6±2.4 Hz/s	5.1±3.0 Hz/s	<0.001
(L) Handedness	4.3±2.8 Hz/s	4.2±2.8 Hz/s	N.S.
p Value	N.S.	N.S.	

sion lines are shifted above the diagonal line. Such is not the case in the (L) handed subjects.

When the same data are plotted as a function of the force level at which the contractions were performed, no distinction in the IMF is seen as a function of force (Fig. 6). In contrast, the slopes of the median frequency do show a distinction. The linear regression line in the data from the right hand of (R) handed subjects has a slope value which is lower than those of the other three sets of data in Fig. 7. More importantly, in the (R) handed subjects, the values of the slope of the median frequency from the right FDI are lower in a statistical sense than the corresponding values from the left FDI. This indicates that the median frequency of the dominant FDI muscle in (R) handed subjects decreases more slowly than that of the non-dominant muscle. This fact is obvious when reviewing the data of the individual subject presented in Figure 3.

Discussion

The use of the myoelectric (ME) signal to compare the performance of corresponding contralateral muscles has been meager. The few existing publications generally report no measurable distinction. A typical example can be found in the recent report of Coogler (1983), who showed no measurable difference in the ME signal in contralateral muscles of the lower limb in (R) hand and (L) hand dominant subjects. Coogler's study, like all others before, analyzed the amplitude of the ME signal which we now understand to be influenced by many factors not associated with the

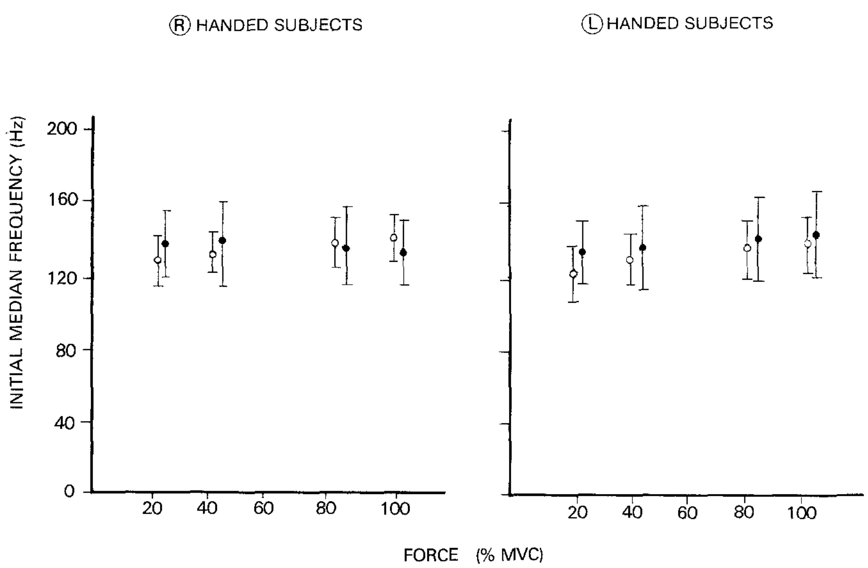

Fig. 6. Mean value and standard deviation of the initial median frequency (IMF) of all the trials as a function of contraction force level. Data from the right (●) and left (○) first dorsal interosseous are compared for right and left-handed subjects

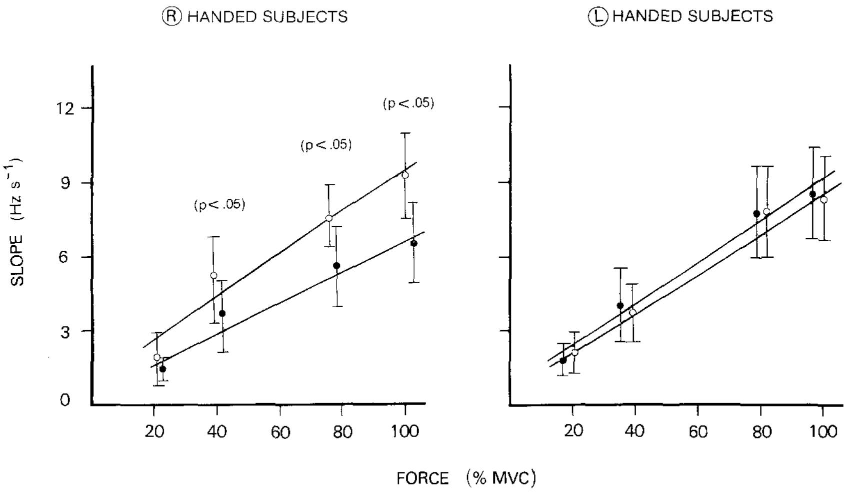

Fig. 7. Mean value and standard deviation of the slope of the median frequency of all the trials as a function of contraction force level. Data from the left and right first dorsal interosseous muscles are compared for right and left handed subjects. Separate regression lines for data from the left [○] and right [●] hand are represented for right handed subjects ($Y = 0.08X + 0.57$, $r = 0.78$ and $Y = 0.05X + 0.19$, $r = 0.77$) and left-handed subjects ($Y = 0.08X - 0.34$, $r = 0.87$ and $Y = 0.07X - 0.05$, $r = 0.77$). A t-test was used to calculate the statistical significance of the difference between mean values at each of the four force levels

performance of the contracting muscle. For details concerning this point, see Chapter 2 in *Muscles Alive* (5th Ed.) by Basmajian and De Luca (1985). In fact, in some of our previous work (Lawrence and De Luca 1983), we have shown that if the amplitude of the ME signal is normalized to the MVC, the relationship of the ME signal amplitude and force of normal sedentary subjects is statistically indistinguishable from that of endurance trained subjects.

In this study, we have chosen to use a spectral parameter of the ME signal, that is the median frequency of the power density spectrum of the ME signal. This parameter has been shown to be affected by the firing statistics of the motor units and the conduction velocity of muscle fibers. See De Luca (1985) for a detailed review of this relationship. In this discussion, we will focus on the effect of the conduction velocity which has been substantiated both mathematically (Lindström 1970) and empirically (Merletti et al. 1984; Broman et al. 1985; Arendt-Nielsen and Mills 1985).

It is widely accepted that the conduction velocity of the muscle fibers is directly related to the diameter of the muscle fibers. Thus, the median frequency at the beginning of a contraction, i. e., the initial median frequency (IMF), will reflect the size of the muscle fibers. The validity of this statement must be qualified by the proviso that the ME signal should not be effected by disturbing influences from the innervation zone and tendons.

It has been speculated by Jones et al. (1979) that during a sustained contraction, the augmentation of potassium ions in the extracellular fluid will cause the conduction velocity to decrease as a function of time. This hypothesis requires substantiation. However, it is widely accepted that the conduction velocity of the muscle fibers is directly related to the pH of the extracellular fluid surrounding the fiber membrane; see Bass and Moore (1973); Tasaki et al. (1967), and Orchardson (1978), among others. During a sustained contraction, the muscle fibers produce lactate as a metabolic byproduct. The lactate in the extracellular fluid will decrease the pH and in turn, decrease the conduction velocity of the muscle fibers. Furthermore, Tesch and Karlsson (1977) have presented data indicating that more lactate is accumulated in muscles that consist mostly of fast-twitch fibers than those that consist mostly of slow-twitch fibers. This observation is consistent with the suggestion that higher activities of glycolytic enzymes, such as LDH and M-LDH, would favor a rapid lactate formation in fast-twitch fibers (Sjodin 1976; Tesch et al. 1978).

The above series of events provides the following scenario which is useful for interpreting the results. During sustained muscle contractions, the conduction velocity of the muscle fibers, and therefore the median frequency of the ME signal, decrease. This effect will be more noticeable as more lactate remains in the extracellular fluid. This occurrance will happen if; a) more muscle fibers contract, b) the blood flow is occluded, and c) there is a proportionally greater presence of fast-twitch fibers. The examples provided in Fig. 2 demonstrate this behavior at different force levels. These observations are consistent with our previous reports (Stulen and De Luca 1981; Sabbahi et al. 1981; and others).

The lack of distinction between the performance of contralateral FDI muscles in (L) handed subjects is to be expected, given that these subjects were indeed ambidextrous. This observation in our subjects is consistent with previously published information. For example, Beukelaar and Krônenberg (1983) found that in a random group of subjects examined for writing skills, 80% were (R) handed and 20% were (L) handed. However, 56% of the (L) handed subjects were able to write and perform other manual tasks with their right hand; whereas, only 0.6% of the (R) handed subjects were able to perform comparably with their non-dominant hand. Hence, the lack of preferential usage of a muscle is consistent with the lack of distinguishability in the behavior of the median frequency.

The clearly noticeable and statistically significant distinction in the behavior of the median frequency in the contralateral FDIs of (R) handed subjects suggests that the accumulated preferential usage of the dominant hand during the course of a lifetime might have altered the fiber type composition. In these subjects, the dominant FDI displayed a lower rate of decrease of the median frequency than the corresponding contralateral FDI during a sustained contraction. This may indicate a decreased rate of lactate production which, according to the results of Tesch and Karlsson (1977), suggests that there are relatively more Type I, slow-twitch, aerobic fibers in the FDI of the dominant hand. This deduction is in agreement with the recent observation of Tanaka et al. (1984), who found that when electrically stimulated, the dominant FDI displayed a statistically significant ($p < 0.01$) slower rise time in the twitch response. The fact that Fig. 7 demonstrates that the distinction in the behavior of the median-frequency slope becomes more pronounced at higher force levels is consistent with the following argument. As the force increases, the internal pressure in the muscle occludes the arterioles, shutting off the blood return. Thus, the greater amount of lactic acid generated in the non-dominant FDI would accumulate and have a greater effect on the median frequency of that muscle.

Histological modifications in fiber types of the forearm muscles of the dominant (R) hand have been reported by Fugl-Meyer et al. (1982). They noted a 25% increase in the Type I fiber composition as well as an increase in the mean net weight of the extensor carpi radialis brevis muscle when comparing contralateral muscles. They also suggested that the noted disparity might be caused by sustained preferential usage.

Considerable support may be found in the literature to sustain the argument that prolonged exercise has the potential of augmenting the number of slow twitch (Type I) muscle fibers. This has been demonstrated by Barnard et al. (1971), Morgan et al. (1971), and others by using oxidative staining techniques. Gollnick et al. (1972) further demonstrated an increase in the mitochondrial concentration with no change in the anaerobic metabolism enzymes in endurance-trained individuals. Even more relevant to our results is the work of Kiessling et al. (1973) who confirmed the observations of Gollnick et al. (1972) in a longitudinal study.

The surprising observations that no consistent statistically significant distinction was noted in the values of the IMF as a function of either gender or hand dominance would appear to conflict with the implication of available information in the literature. The only exception was found when comparing the (L) hand of (L) hand dominant males and females ($p < 0.008$). This result should be interpreted with extreme caution and with little meaning in light of the seven other non-significant comparisons presented in Table I. Change in muscle fiber size with training has been reported since the turn of the century (Morpurgo 1897). This has been consistently noted in strength-trained men and weight lifters (Gollnick et al. 1972; Edstrom and Ekblom 1972) and even in sedentary subjects after a five month period of strength training (Gollnick et al. 1973). Corresponding observations were reported by Muller (1970) who found that males possess statistically significant larger muscle fibers than females. Larger muscle fibers should theoretically have larger conduction velocities, and according to the arguments presented at the beginning of this section, the IMF should be correspondingly increased. In fact, this concept is supported by other observations made in our laboratory. Broman et al. (1985) have reported that in the tibialis anterior muscle, the value of the median frequency consistently increases as the force output of the muscle increases and larger muscle fibers are recruited. However, in that study it was noted that the direct relationship between force and median frequency was only evident when the surface electrode was located in specific locations. Subsequent work performed in our laboratory has revealed that the electrode location should not be near the tendonous portion or the innervation zone of the muscle. The FDI muscle used in this study has dimensions that are too small for the 1 cm electrode; hence, the conditions of not being near the innervation zones and tendons are always violated. This results in ambiguous measurements of the IMF which may yield conflicting data, such as these in Table 1. This argument has been supported by previous work in our laboratory (Rosenthal et al. 1981).

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