Surface myoelectric signal cross-talk among muscles of the leg [1]

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Summary   Surface myoelectric signals were detected from the skin surface above the tibialis anterior muscle, the peroneus brevis muscle, the soleus muscle and the tibial bone during selective maximal electrical stimulation of the tibialis anterior muscle in 12 normal subjects. The double differential technique developed by Broman et al. (1985) was used to determine if the detected signal was due to volume conduction from the tibialis anterior fibers. The peak-to-peak (PP), average rectified (ARV) and root mean square (RMS) amplitudes of the M waves were computed for each detection location. The values detected on the tibial bone, on the peroneus and on the soleus muscles were normalized with respect to those detected on the tibialis anterior and ranged from 4.8% to 33.0% (PP), 4.7% to 36.0% (ARV), and 7.7% to 37.4% (RMS) for the tibial bone area; from 4.0% to 20.0% (PP), 3.5% to 10.0% (ARV), and 3.0% to 10.0% (RMS) for the peroneus brevis muscle area; and from 3.0% to 8.0% (PP), 3.4% to 9.1% (ARV), and 2.0% to 9.8% (RMS) for the soleus muscle area. Neither peak-to-peak values, average rectified values nor root mean square values appeared to be correlated with leg size.

It is concluded that a surface myoelectric signal detected on the skin above a leg muscle and having a peak-to-peak amplitude of up to 16.6% of a signal detected above a neighboring muscle may be due to cross-talk rather than to activation of the muscle below the electrode.

Key words: Human muscles; Myoelectric signal; Surface electromyography; Cross-talk; Volume conduction; Electrical stimulation

Myoelectric signals are generated by active muscle fibers. Associated with the action potentials carried by active fibers are action currents which flow throughout the volume conductor. The action currents reflect the presence of an electrical potential field which pervades the volume conductor and which may generate a signal detected by electrodes placed at some distance from the source, near or above other fibers. Such a signal, which may be erroneously interpreted as generated by fibers near the detection electrode, is usually referred to as 'cross-talk' and its importance is often underestimated, especially in surface electromyography.

Myoelectric activity detected with surface electrodes above a given muscle may be considered as a summation of filtered signals due to a number of concurrently active motor units generating volume conducted currents and associated potential fields. Surface detection is preferred to needle detection when 'global' information is desired about the time and/or intensity of muscle activation such as during gait analysis, biofeedback therapy, fatigue studies, prosthetics control, or other applications.

Unlike indwelling electrode techniques, surface detection may lack selectivity. Furthermore, the current distribution and transfer function between

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signal source and detection point are poorly defined. As a consequence, cross-talk between nearby muscles may be substantial and in some cases may lead to paradoxical results, as reported by Morrenhof and Abbink (1985) and Nielsen et al. (1986).

Morrenhof and Abbink (1985) measured the amplitude of signals detected with surface and wire electrodes respectively placed above and in the biceps femoris, the semitendinosus and the adductor magnus muscles in the human thigh. Eight pairs of surface electrodes equally spaced along an arc over the 3 muscles provided correlated signals, showing a signal spreading over a surface area much larger than that associated with the individual muscles. We note, however, that during the voluntary contractions in these experiments the 3 muscles were simultaneously active, albeit to different degrees. This condition would be less than ideal for cross-talk measurements. The correlation coefficient does not provide reliable information about the amplitude of the volume conducted signal for at least 2 reasons. As shown by Broman et al. (1985), tissue anisotropy and inhomogeneity may alter the phase relationship of the volume conducted signal components, therefore changing the signal wave form and affecting the value of the correlation coefficient. Also, the common-drive control of synergistic or of antagonist muscles, which has been shown by De Luca and Mambrito (1987), may lead to a falsely high value of correlation.

In a recent report Etnyre and Abraham (1985) have shown that during voluntary contractions of the tibialis anterior muscle a myoelectric signal could be detected with surface electrodes located above the soleus muscle, whereas no signals were detected with wires inserted in the same muscle. This is consistent with the volume conduction theory; that is, if a source were modeled as a dipole, the potential would be inversely related to the square of the distance from the source. The differential potential between 2 closely spaced intramuscular electrodes may therefore be much smaller than that between 2 widely spaced electrodes on the skin.

Another related study by Perry et al. (1981) compared myoelectric signals obtained with surface electrodes to those obtained with intramuscular wire electrodes. Their results suggested that the surface myoelectric signal on the soleus or gastrocnemius muscles could be expressed as a weighted sum of the intramuscular signals from these 2 muscles plus that from the tibialis posterior muscle. Again, the 3 muscles were simultaneously active during the tests and the previously expressed concern also applies to their work.

The aim of this work is to provide quantitative information about cross-talk between muscles of the human leg, without the limitations and ambiguity of previous studies.

Materials and methods

An ideal condition for cross-talk assessment consists of the selective activation of one muscle and the detection of volume conducted signals on neighboring muscles. Since selective activation of only one muscle cannot be easily or convincingly obtained under voluntary control, it was chosen to induce it by electrical stimulation of a muscle motor point in completely relaxed muscles. Relaxation was indicated by absence of surface electrical activity before stimulation and between M waves.

Twelve subjects (4 females and 8 males) with no history of orthopedic or neurological disorders participated in the experiments. Their ages ranged from 21 to 41 years with an average of 29 years. The subjects were comfortably seated in a dental chair with hip, knee and ankle joints at approximately 90°. The foot was bound in a specially designed brace constraining the ankle to ensure isometric conditions and reduce movement artifacts. The motor points of the tibialis anterior muscle were identified by electrical stimulation. The number of motor points ranged from 1 to 3, the main one usually in the upper third of the muscle. The tibialis anterior was stimulated using a monopolar technique with a 3×4 cm sponge electrode placed on the main motor point and 8×12 cm sponge electrode placed on the gastrocnemius muscle.

Preliminary trials indicated that measurements performed during tetanic contractions were prefer-

able to single twitch reading. The M wave response undergoes a transient during the first 5–10 pulses of a train and then stabilizes. Such a transient is probably due to muscle movement below the stimulation and detection electrodes at the beginning of the contraction. The stimulation frequency was chosen at 20 Hz as being high enough to ensure stable (tetanic) contractions and low enough to avoid short-term electrical changes due to fatigue. The pulse duration was not critical and it was chosen to be 0.2 msec. Stimulation was maintained for about 5 sec. Data were read during a 3 sec interval.

A cross-talk measurement requires the ability to discriminate between a volume conducted signal and a signal propagating along the muscle fiber below the detection electrode. The necessary discrimination was obtained with the double differential technique described by Broman et al. (1985). Such a technique allows the cancellation, from the double differential outputs, of signals simultaneously present on every electrode couple and due to relatively far sources. On the contrary, current sources traveling below the electrode generate 2 similar and time delayed double differential myoelectric signals (DDMES) with amplitudes of the same order of magnitude as of the single differential myoelectric signals (SDMES). The 4-bar electrode (Figs. 1 and 2) was placed on the lower part of the tibialis anterior muscle below the lowest motor point, to ensure the detection of a well-defined M wave generated by motor unit action potentials traveling in the same direction. The 4 bars were perpendicular to the muscle fiber direction, and were 10 mm long, 1 mm thick and spaced 10 mm apart. A single differential myoelectric signal was detected between the 2 central bars. Double differential signals were obtained as indicated in Fig. 2.

This electrode was then moved around the leg on the soleus and peroneus brevis muscles and on the flat face of the tibial bone as described in Fig. 1. Single differential (SDMES) and double differential (DDMES) myoelectric signals were recorded on FM magnetic tape during supramaximal stimulation of tibialis anterior. A moist floating ground strap was applied between the stimulation and the detection electrodes.
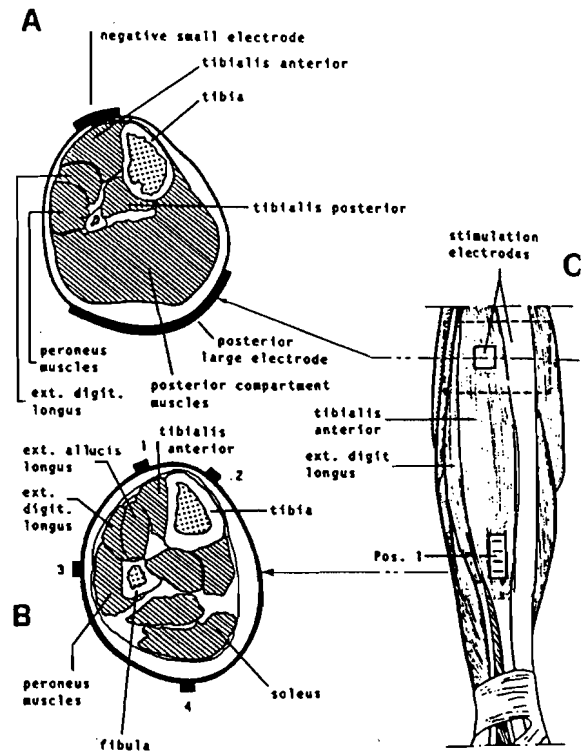

Fig. 1. Location of stimulation and detection electrodes. A: leg section at the stimulation electrode level. B: leg section at the detection level (1, 2, 3, 4 are the detection locations). C: front view of the leg.

Avoiding or removing the stimulus artifact is a common problem in this type of measurement. Voltage output stages provide a virtual short circuit to the electrodes between pulses, hence electrical transients due to tissue and electrode capacitances are quickly terminated. However, the output current may be greatly affected by tissue impedance variations. Current output stages, on the other hand, present an open circuit to the electrodes between pulses, hence electrical transients in the tissue may last several milliseconds after each stimulus.

To avoid the problems associated with either technique, a switched output stage was designed to obtain a constant current output during stimulation and a constant (zero) voltage output between stimuli. The resulting current wave form was not exactly monophasic (see Fig. 2). The sharp negative peak was caused by the sudden
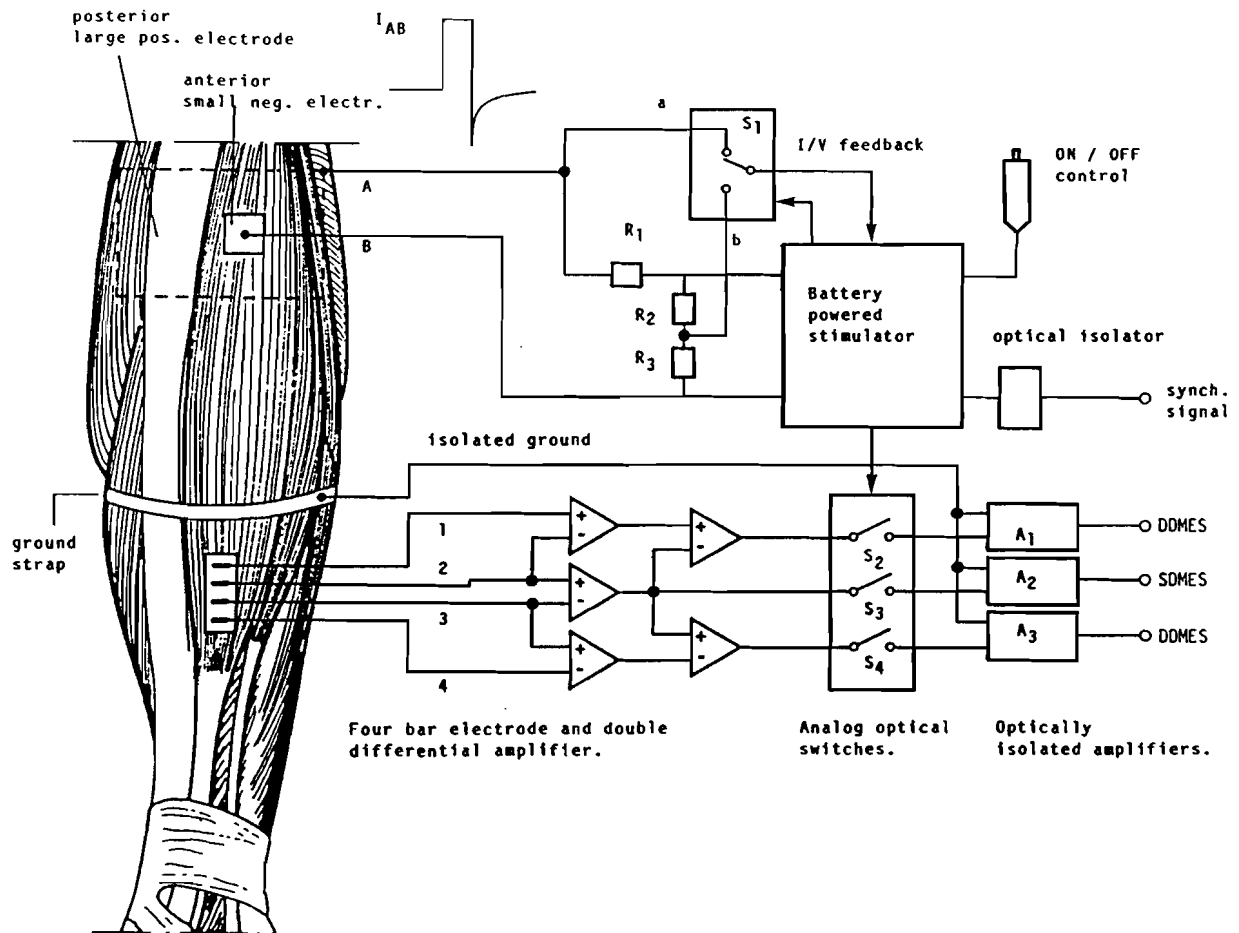
Fig. 2. Block diagram of the stimulation and detection instrumentation.

short circuit of the electrodes after each pulse and the consequent rapid discharge of the electrode and tissue capacitances. It was necessary to pass the detected signal through a time window in order to cancel the residual short stimulation artifacts. This was accomplished with optical isolated switches (photo FETS). The switches were open during each stimulus and for 0.5–5 msec afterward to allow post-stimulus transients to die out.

Despite the precautionary expedients, stimulus artifacts (mostly due to stray capacitances) of 100–200 μV peak-to-peak could not be eliminated. As may be seen in Fig. 3, although very small, the artifacts cannot be neglected. They were later removed by time-windowing the playback signal

before processing. An improved version of the stimulation-detection system with 25 μV peak-to-peak artifact is described in another paper (Merletti and Knaflitz 1987).

Volume conducted signals were identified as those generating output on the SDMES channel and no output on the DDMES channels. Three amplitude parameters were defined for the SDMES channels and employed as cross-talk indices; they were: normalized peak-to-peak amplitude, normalized average rectified values, and normalized root mean square values.

All of the values were computed over 60 M waves detected in a 3 sec interval. Such an interval appeared to be long enough to reduce the effects of occasional signal fluctuations and short enough
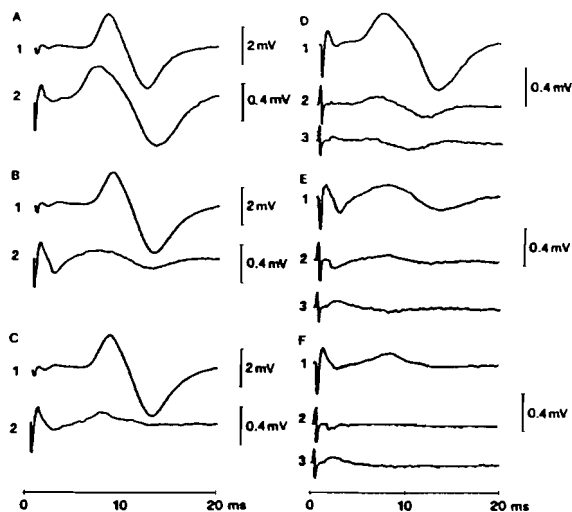
Fig. 3. Responses to supramaximal stimulation of the main motor point of the tibialis anterior muscle (0.2 msec and 20 Hz). A1, B1, C1: maximal single differential M wave elicited on the tibialis anterior muscle (repeated for comparison with A2, B2, C2). A2, B2, C2: single differential signals (volume conducted) on the tibial bone, on the peroneus brevis and soleus muscles. D1, E1, F1: single differential signals detected on the tibial bone, on the peroneus brevis and soleus muscles. D2, D3: double differential signals on the tibial bone. E2, E3: double differential signals on the peroneus brevis muscle. F2, F3: double differential signals on the soleus muscle. The absence of a double differential signal on the peroneus and soleus muscles shows that the single differential signal is volume conducted.

to avoid electrical manifestations of muscle fatigue. The values recorded on the tibial bone, on the peroneus brevis and soleus muscles were divided by the values corresponding to the maximal M wave recorded on the tibialis anterior muscle.

Results

The force obtained during supramaximal stimulation of the main motor point of the tibialis anterior was 16.3% +/− 4.3% (average +/− S.D.) of the maximal voluntary force. Obviously, during maximal voluntary contractions the entire anterior loge was contracting while during stimulated contractions only part of the tibialis anterior muscle was activated. The M wave amplitude re-

TABLE I

Cross-talk indices (average values and standard deviation of 12 subjects).

Detection electrode location	Peak-to-peak ratio (PP)	Average rectified value ratio (ARV)	Root mean square value ratio (RMS)
Tibialis anterior muscle	100.0%	100.0%	100.0%
Tibial bone area	19.4% (9.4)	19.9% (8.8)	18.4% (9.0)
Peroneus brevis muscle	7.0% (4.2)	6.5% (2.0)	6.2% (2.1)
Soleus muscle	5.0% (1.5)	5.4% (1.9)	5.0% (2.1)

corded on the tibialis anterior was 3.1 +/− 1.1 mV peak-to-peak.

Fig. 3A, B, C shows samples of SDMES recorded above the tibial bone, the peroneus brevis muscle and the soleus muscle. The residual artifact (removed before processing) is evident. Fig. 3D, E, F shows the single and the 2 double differential myoelectric signals present on the 3 detection sites. A low voltage DDMES is evident only on the tibial bone site due to its nearness to the source.

The average values and the S.D.s of the 3 cross-talk indices for the 12 subjects are presented in Table I. The values detected on the tibial bone, on the peroneus and on the soleus muscles (normalized with respect to those detected on the tibialis anterior) ranged from 4.8% to 33.0% (PP), 4.7% to 36.0% (ARV), and 7.7% to 37.4% (RMS) for the tibial bone area; from 4.0% to 20.0% (PP), 3.5% to 10.0% (ARV), and 3.0% to 10.0% (RMS) for the peroneus brevis muscle area; and from 3.0% to 8.0% (PP), 3.4% to 9.1% (ARV), and 2.0% to 9.8% (RMS) for the soleus muscle area. The relationship between each cross-talk index and the leg circumference for the 3 detection locations is presented in Fig. 4. The slopes of the regression lines for the soleus and peroneus muscles are not significantly different from zero. The slopes of the regression lines for the tibial bone are significantly different from zero ($P < 0.05$). The relationship between the cross-talk indices and the detection location are presented in Fig. 5, where they are
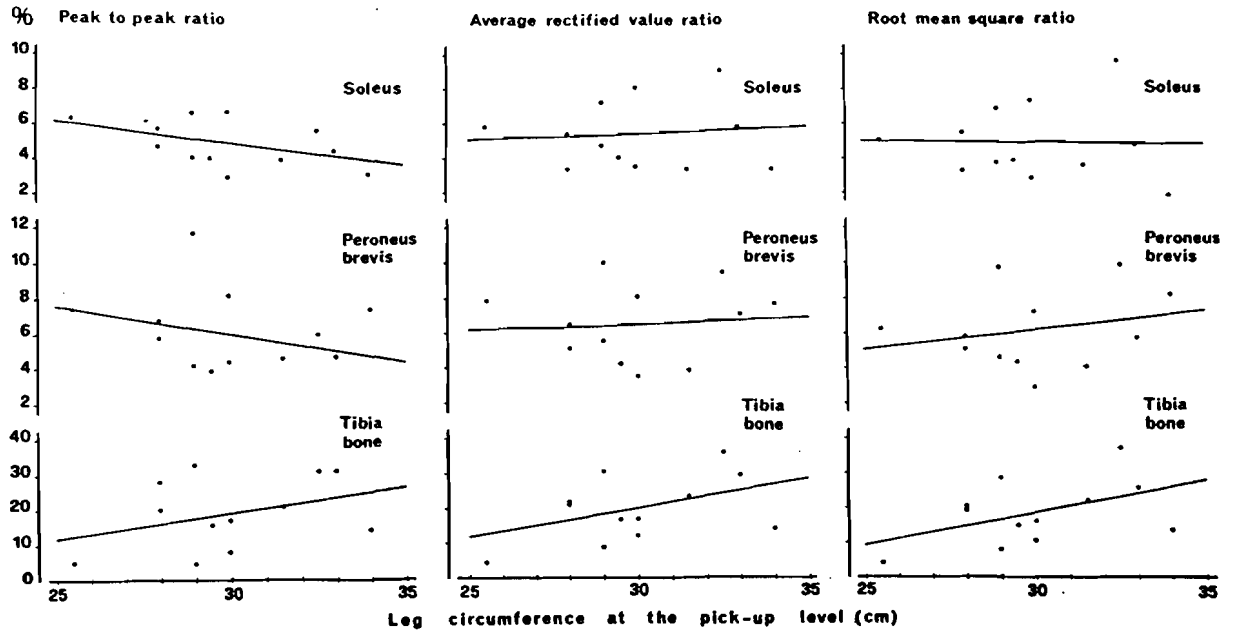
Fig. 4. Correlation between each cross-talk index and leg circumference at the detection level. Ordinates are the PP, ARV, RMS values of the signals detected on each location divided by the PP, ARV, RMS values detected on the tibialis anterior muscle during supramaximal stimulation of its main motor point.
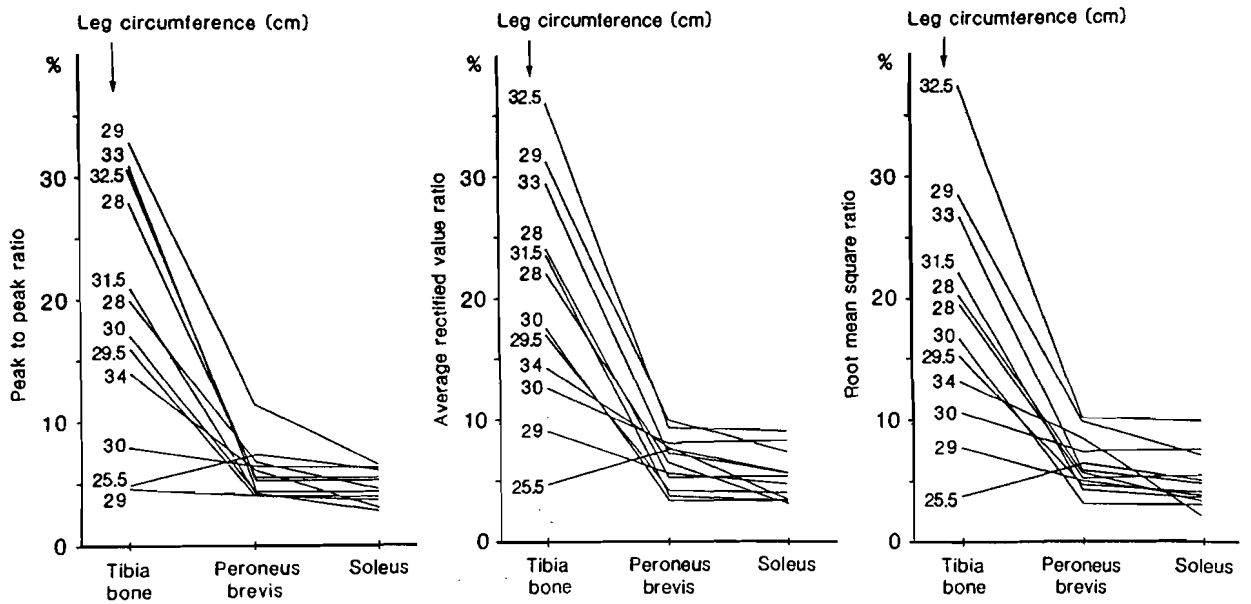

Fig. 5. Correlation between each cross-talk index and the detection location. Ordinates are the PP, ARV, RMS values of the signals detected on each location divided by the PP, ARV, RMS values detected on the tibialis anterior muscle during supramaximal stimulation of its main motor point.

plotted in order of increasing distance from the tibialis anterior muscle area.

The signals detected above the tibial bone are not cross-talk signals in the usual sense since myoelectric signal detection over the bone would serve no clinical purpose. In this location volume conducted currents are probably mostly due to the subcutaneous tissue layer which has higher conductivity than the bone. The large spread and the correlation of values obtained in the tibial bone region (see Figs. 4 and 5) are probably due to the greater thickness of this layer in subjects with larger legs.

The absence of correlation between muscle cross-talk indices and leg size indicates that the standard deviation of the values presented in Table I reflects only random factors rather than a relationship with leg size. The 95% confidence limits for the indices are: 11% for the ARV and RMS indices for the soleus and peroneus muscles; 16.6% for the PP index for the peroneus muscle and 8.4% for the soleus muscle.

Discussion

The lack of correlation between cross-talk indices and leg size indicates the existence of a compensatory relationship between the source intensity and the tissue filter attenuation. Such compensation is less evident in the tibial bone area due to the proximity of the source and the relatively low conductivity of the bone. Predictably, larger legs with greater amounts of tissue over the bone yield higher signals in the tibial bone area. The smallest leg, with only skin over the bone, shows a tibial signal even smaller than that on the peroneus brevis area (plot corresponding to 25.5 cm leg circumference in Fig. 5).

The SDMES on the tibial bone was approximately 5 times smaller than the one on the tibialis anterior muscle (Table I) while the DDMES was more than 15 times smaller. On the peroneus brevis and soleus muscles the DDMES was at noise level (Fig. 3). As expected, the DDMES decreased with distance much faster than the SDMES since the 3 SDMES obtained from the first set of amplifiers (Fig. 2) became more similar

and less delayed as the source became more distant. As shown by Reucher et al. (1987), the DDMES has a smaller detection volume.

The low-pass filtering properties of the volume conductor and the wave shape distorting effect of tissue anisotropy and inhomogeneity is amply evident in Fig. 3. The wave form of the single differential cross-talk signals are low-pass filtered and distorted with respect to the signal detected on the tibialis anterior. The behavior of the propagating signal supports our initial comment that cross-correlation measurements cannot provide reliable indices of cross-talk.

In conclusion, it is emphasized that particular caution should be exercised in interpreting surface myoelectric signal when nearby muscles may be active. Our data indicate that a signal detected above a particular muscle cannot be assumed to originate exclusively from that muscle. Specifically, in our case the signal amplitude detected above the peroneus brevis and soleus muscles undeniably originated in the tibialis anterior muscle. It is suggested that whenever there is reason to suspect the coactivation of other muscles, the surface myoelectric signals should be detected with the double differential technique, thereby reducing the susceptibility to cross-talk.

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