Spectral properties of the surface EMG can characterize/do not provide information about motor unit recruitment strategies and muscle fiber type

**Definitions**

**Fiber types.** Human muscles have different fiber types such as fast- and slow-twitch (1, 10) or type I and II fibers. The different fibers have different force-generating capacities (5) and are task specific. Since shortening speed does not always reflect the ATPase activity, the discrimination between type I and II fibers is based on the rate of myofibrillar ATPase reaction. Human MHC isoforms are considered as types I, IIa, and IIx (12, 13). A refined subdivision of fibers was proposed correlating fiber types with EMG spectral properties (4).

**Recruitment pattern.**

A pulse train in the motoneurons is generated by the central nervous system activating the muscle fibers through the neuromuscular end plates. The fibers belonging to one motoneuron form a motor unit (MU). Different MUs can have different number of fibers usually of the same type. The recruitment pattern indicates which MUs are selected and by what pulse train they are activated. Modern technologies allow detecting the rate coding pattern of a pulse train (9). Rate-coding patterns indicate which MUs are selected and by what pulse train they are activated. Modern technologies allow detecting the rate coding pattern of a pulse train (9). Rate-coding patterns controlling the intensity of the EMG do not coincide in time with the selection of MUs (17). The recruitment strategy changes the recruitment pattern over time and controls force and timing of MUs required to perform the task at hand.

**Muscle tasks.** Not all muscle fibers will be involved in every task. Specific muscle fibers will be used for specific tasks like lock and hold, lock and release, pull and release (length change), and reflex tasks. The task-specific MU groups will most likely show different power spectra indicating when a different group has been recruited.

**The EMG Spectrum**

An understanding of how the EMG signal is generated and which properties are reflected in the power spectrum obtained by the Fourier transform is essential for this discussion (6, 20). Stegeman et al. (14) modeled the motor unit action potential (MUAP) as a convolution of individual muscle fiber action potentials with a window encompassing the end plate zone. We obtained a modeled EMG by convolving these MUAPs with a pulse train of 8-pulses. Our model computations and results from other publications show the following.

1) A temporal MUAP reflects a spatial MUAP rescaled by the conduction velocity.
2) The power spectrum depends on the shape of the MUAP (7).
3) The shape of a MUAP is determined by the size of the end plate zone and the end plate distribution. The fine structure of the MUAP is mainly contained at higher frequencies.
4) The energy of the power spectrum is equal to the integrated EMG squared.
5) The energy increases linearly with the number of identical MUAPs. There is no amplitude cancellation by overlapping MUAPs (3).
6) The pulse train, whether repetitive or random, adds noise to the MUAP’s power spectrum.

7) The filtered power spectrum represents a weighted overlay of the power spectra of the selected MUs (11).
8) Synchronization downshifts the power spectrum.
9) Time resolution limits frequency resolution (6).

Because of 6, a power spectrum reflecting the superimposed spectra of selected MUs requires averaging or filtering. The wavelet analysis represents an optimized filter bank for smoothing the power spectrum considering the time resolution required for observing muscle activation (16). The results can be displayed as a pattern encoding the intensity by a grayscale for each time point (abscissa) and frequency band (ordinate). The patterns represent the filtered power spectra at each time point during a task.

**Tasks and Power Spectra**

Power spectra of EMG signals depend primarily on the task and are subsequently modulated by factors such as length change, lactate accumulation, and volume conduction. Results of a study with EMG measurements on 80 subjects running at 4 m/s (17–19) are used to illustrate the relationship between task and power spectra. The EMG activities of the five muscles (gastrocnemius medialis, tibialis anterior, hamstring, rectus femoris, and vastus medialis) are illustrated with intensity patterns (Fig. 1).

The pattern of the tibialis anterior showed 300 ms before heel contact EMG activities with relatively high frequencies, a result of activities of high frequency-generating groups (HFG) of MUs. Toward heel strike, the spectrum shifted toward higher frequencies. This muscle preactivation before landing represented a lock and release task. In the air, the foot was locked in a certain position. At heel strike, the release occurred. The frequency was high because the release occurred quickly and fast fibers were used to accommodate this. After heel strike a new hold and lock task started. The frequencies were low, because this new hold and lock function did not require high action speeds. Thus the task could be performed with activity from low-frequency groups (LFG) of MUs.

![Intensity pattern resulting from the wavelet analysis of the EMGs for five muscles.](http://jap.physiology.org/doi/abs/10.1152/japplphysiol.90598.2008)
A similar hold and lock task could be observed for the gastrocnemius muscle used during cocontraction before landing (hold and lock corresponding to low frequencies). However, during initial ground contact, the gastrocnemius muscle activated MUs of LFG and HFG, resulting in low and high frequencies.

The pattern of the quadriceps muscles showed a pull and release task, related to the changes in knee angle during ground contact, which corresponded to a primarily slow muscle action, resulting in relatively low frequencies.

Thus the multi-muscle intensity pattern reflected the recruitment strategy used during the different muscle tasks performed while running. The recruitment strategies were highly reproducible for men and women. Details of the interplay of LFG and HFG were reported earlier (19). The generating spectra represented was most likely a mix of the spectra of the selected group of fiber types. However, the generating spectra were similar to those expected for slow- and fast-twitch fibers, indicating that the LFG most likely contained slow-twitch fibers, whereas the HFG most likely contained fast-twitch fibers.

Actual measurements of spectra relating to fiber types were performed in fish, where the two types of fibers are anatomically separated and the individual power spectra were measured (22). In rats, a procedure similar to the one used by Solomonow et al. (11) was applied using a stimulating pulse train activating the motoneurons and a second signal blocking the pulse propagation (23). When the amplitude of the block was reduced to just below threshold, only the action potentials of the slowest motor units reached the muscle.

Thus it was possible to measure the spectra of the isolated slowest MU and then observe the higher frequency components generated by the faster MUs. The observation produced different frequency bands for these two types of MUs.

Conclusion

The major statements of this publication are that 1) muscle activities are task dependent, 2) task-dependent spectral changes can be observed if the tasks actually change, and 3) power-spectral changes are associated with changes in the selected muscle fiber types.

Examples for experiments where task-dependent changes occurred include long-distance running and paw shaking of cats (21, 22). Examples where MU composition changes also generate large-frequency shifts, e.g., in atrophic muscles caused by osteoarthritis (15). In these experiments, substantial changes in the power spectra were observed. However, one should not expect to see substantial changes in power spectra when studying single-task experiments such as an isometric ramped increase in force (4), selective recruitment of fast-twitch muscle fibers during lengthening contractions (2), and/or EMG activity during an explosive contraction (8). In such experiments, the power spectrum is determined by the single task studied and substantial changes in the power spectra should not be expected.

Furthermore, one should expect controversial results in the power spectra when studying activities where synergistic activation of MUs is produced (8) because synergistic activities will downshift the power spectrum. Thus single tasks and synergistic experiments are not suited to reveal or reject changes in spectral properties resulting from changes in recruitment pattern. Single-task and synergistic experiments do provide insight in the modulations affecting spectra during individual muscle tasks.

REFERENCES

validity of two assumptions: conduction velocity (28), the crucial issue in this debate is the old (and type I) motor units. Larger relative energy at higher frequencies than lower threshold is based on the rationale that higher threshold and information about motor unit recruitment or the proportion of type II fibers (20, 21) and changes in EMG spectral variables of the muscle fiber conduction velocity (19) or in the profile of the intracellular action potential (6). In addition to these applications, the spectral characteristics of the surface EMG have been used to infer motor unit recruitment strategies and the fiber-type composition of a muscle. Higher characteristic spectral frequencies are associated with a greater proportion of type II fibers (20, 21) and changes in EMG spectral variables are used to infer the recruitment of faster or slower motor units (3, 26).

The capacity of surface EMG spectral properties to provide information about motor unit recruitment or the proportion of fiber types is based on the rationale that higher threshold and type II motor units produce surface action potentials with larger relative energy at higher frequencies than lower threshold (and type I) motor units. Because in these applications the main determinant of the frequency content of an action potential is assumed to be its conduction velocity (28), the crucial issue in this debate is the validity of two assumptions: 1) average conduction velocity of the active motor units is related to fiber-type proportions, and 2) changes in the spectral properties of the surface EMG are associated with changes in average conduction velocity.

Fiber-type composition and average muscle fiber conduction velocity. There are several physiological details that confound this association. First, the two main fiber types do not have distinct conduction velocities in humans, but rather conduction velocity has a continuous distribution with a single peak (25). Second, average conduction velocity of muscle fiber action potentials can differ among populations of motor units due to differences in fiber diameter and independent of changes in fiber-type proportions (4). Third, the number of muscle fibers innervated by a motor unit has a skewed distribution. For example, the first dorsal interosseous muscle comprises an equal number of type I and II fibers, but ~84% of the motor units have slow contraction times and are fatigue resistant (7). Fourth, the conduction velocity of muscle fiber action potentials can change by ~20% with variation in discharge rate (24) and the range of discharge rates varies with recruitment threshold in a population of motor units (2). Fifth, the conduction velocity of muscle fiber action potentials varies with fiber length (15).

Experimental evidence: fiber-type composition vs. muscle fiber conduction velocity. The significance of the physiological limitations discussed in the preceding paragraph can be underestimated due to observations of an association between fiber-type composition and muscle fiber conduction velocity (22). However, the weight of evidence argues against generalization of this association. For example, we observed a direct relation between the proportion of type I fibers identified by myosin heavy chain composition and average muscle fiber conduction velocity (9), which was contrary to the results reported by Sadoyama et al. (22). Moreover, average muscle fiber conduction velocity often does not differentiate among groups of subjects or muscles with expected differences in fiber-type proportions (e.g., 21).

Surface EMG spectral properties and muscle fiber conduction velocity. There are several biophysical details that mask this association. First, the power spectrum of a surface motor unit action potential depends on the distance between the fibers and the recording electrodes, in addition to the conduction velocity of muscle fiber action potentials (18). The power spectra of the action potentials of motor units with identical fiber membrane properties but located in different parts of the muscle may differ substantially (8). Furthermore, the spectral properties of the surface EMG are influenced by the thickness of the subcutaneous layers. Second, the power spectrum of the EMG signal depend on anatomical properties of the muscle fibers, such as length, position of the end plate, and fiber inclination (5), and on the profile of the intracellular action potential (6). Third, the spectral properties of the surface EMG also depend on the distribution of discharge rates of the active motor units and on their degree of synchronization (10, 30). These reasons indicate that the surface EMG power spectrum is influenced by factors other than the average conduction velocity of the action potentials and that these factors are independent of the method used to estimate the power spectrum.

Experimental evidence: surface EMG power spectrum vs. muscle fiber conduction velocity. The limitations discussed in the preceding paragraph are sometimes considered to be negligible (26). A study often cited to support this assertion is the observation by Solomonow et al. (23) that orderly stimulation of motor units in the cat gastrocnemius muscle via nerve electrodes gave rise to linearly increasing median frequency of the intramuscular EMG signal. As noted by the authors, however, “attempts to extend the findings . . . to data obtained from voluntary contractions require the consideration of several secondary but not unimportant factors” (23). These factors, which are common to other animal studies (17, 28), include differences between electrically evoked EMG signals and those detected during voluntary contractions, intramuscular (or over the muscle fascia) and surface recordings, and recordings of activity by discrete and mixed populations of muscle fiber types.

The orderly recruitment of motor units during a voluntary contraction in which force increases progressively (13) is accompanied by a gradual increase in average muscle fiber conduction velocity (1). Under these conditions, however, EMG characteristic spectral frequencies can either not change (12) or even decrease (29). For example, the mean frequency of