Interpretation of EMG spectral alterations and alteration indexes at sustained contraction

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HÄGG, GÖRAN M. *Interpretation of EMG spectral alterations and alteration indexes at sustained contraction.* J. Appl. Physiol. 73(4): 1211–1217, 1992.—Alterations of the electromyographic power spectrum have been studied extensively to assess fatigue development in the neuromuscular system. Usually, a data reduction has been applied to create an index based on the mean power frequency or the median frequency. The physiological origin of the spectrum alterations has been (and to some extent still is) incompletely known. However, during the 1980s, substantial progress has been made in this field. The factors affecting the electromyographic power spectrum discussed in this review are action potential velocity decrease, firing statistics alterations, action potential modification, muscle temperature, additional recruitment at fatigue, and force level. Their impact on three commonly used fatigue indexes, mean power frequency, median frequency, and zero crossing rate, is also reviewed.

fatigue; recruitment; action potential velocity

THE FIRST INVESTIGATOR to notice alterations of the electromyographic (EMG) signal properties at sustained muscular contraction was Piper (67). Despite primitive equipment, he reported slower varying signals when a test subject was close to exhaustion during an endurance test ("the Piper rhythm"). The only available instrument for spectral analysis at that time was the naked eye. Little further development of frequency analysis of EMG was possible until modern electronics and computers offered new powerful tools. Kogi and Hakamada (38) demonstrated an increase of the low-frequency components at fatigue. Numerous later investigators confirmed a progressive spectral compression toward lower frequencies during sustained contraction (4, 25, 34, 36, 39, 45, 46, 66, 85). These spectral alterations have been referred to as muscle fatigue effects on the EMG signal. "Spectrum shift" has been the traditional designation for these alterations. However, "spectral compression" (15) is a better expression, because this is a more appropriate description of what is seen in a plot with linear scales.

In this work, the scope is restricted to contractions implying significant surface EMG (SEMG) power spectrum (SEMGPS) alterations. It should be noted that there are several aspects of muscular fatigue that are left out by this restriction. The alteration of the SEMGPS and some of the most common spectrum compression indexes at a sustained contraction are discussed for each relevant physiological factor. Various activity levels and temperatures are also included, inasmuch as these are important basic sources of spectral alteration. However, only isotonic isometric contractions are discussed for the following reasons. When the geometric relations between the electrode and the active muscle fibers are changed during a movement, the SEMGPS is changed (66) in a complex way. Furthermore, during dynamic contractions, the number of active motor units (MUs) is changing rapidly, which implies nonstationary spectra (62). Any frequency analysis method demands several seconds of stationary SEMG to obtain a stable estimate.

Surface EMG Power Spectrum

The SEMG represents the sum of a large number of motor unit action potential (MUAP) trains with uncorrelated times of firing at rested conditions. This kind of signal is in technical literature denoted "shot noise." When the number of firing MUs is high enough for the action potentials to overlap, the SEMG is well described as a Gaussian-distributed stochastic process with a zero average. An illustrative model is the sound of applause from a large audience. Every contributing individual corresponds to an active MU. Even the phenomenon of synchronization is illustrated by the tendency by an audience to synchronize the clapping when it is extended over time.

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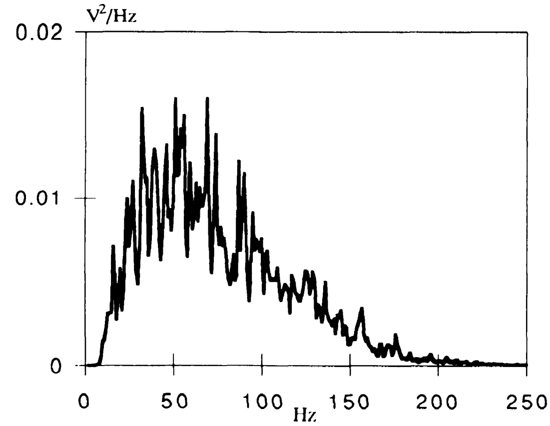

FIG. 1. Typical surface EMG spectrum based on 6 s of data. [From Hägg (29).]

The SEMGPS is estimated by sampling the SEMG signal (normally at 2 kHz) into a computer and then applying the fast Fourier transform (FFT) algorithm. A typical SEMGPS is seen in Fig. 1. The shape of the SEMGPS is essentially determined by *1)* the power spectrum of each contributing MUAP, *2)* the firing statistics of each MUAP train, *3)* correlation between firings of different MUs, and *4)* filtering properties of the electrode configuration and its geometric relation to the active MUs. These basic relations are thoroughly described elsewhere (3, 14, 46).

Because of the stochastic nature of the SEMG signal, a considerable variation is seen when spectra from different muscles and/or individuals are compared. Certainly, a large stochastic variation is seen also between two consecutive spectral estimates from the same muscle.

Physiological Phenomena Related to Spectral Alteration

Muscle activity level. When the muscle activity is increased, a general increase of the SEMGPS is noted. The total area of the SEMGPS is equal to the total power of the SEMG, which is proportional to the mean square of the SEMG signal. The close relation between any amplitude measure of the SEMG and the force development of the muscle is another aspect of this phenomenon. However, it has been claimed that the SEMGPS shape (as reflected by, e.g., the mean power frequency, see below) would be insensitive to varying contraction intensity (45). However, later investigators have refuted this claim (21, 23, 24, 26, 57). This dependence of contraction intensity is most pronounced at low load levels, with an increasing frequency content of the spectrum (increasing mean power frequency) when the load is increased from low levels up to maximum voluntary contraction (MVC). This effect seems to be of different magnitude in different muscles (24). Probably, as the force is increased, additional MUs with larger fibers and higher action potential velocity (APV) are successively recruited, yielding higher frequency content of the SEMGPS (3, 50, 88).

An additional effect when the activity level is increased from low contraction levels is related to the increasing range of firing frequencies. It is seen in the SEMGPS as decreasing peak amplitudes in the low-frequency range (3). This phenomenon is discussed separately below. Still another factor at increasing activity level is increasing firing frequencies. This is also discussed separately below.

APV decrease. A decrease of the average APV has been claimed to be the major factor causing the spectrum alterations at sustained contractions (45, 46). This velocity decrease has been attributed to the accumulation of lactic acid due to impaired circulation (59). There is experimental evidence of a relation between spectrum compression and lactate concentration (31, 83) and muscle pH (7, 70). However, the role of lactate is questioned by investigators studying subjects unable to produce lactate (McArdle's disease) (47, 54). Also other metabolites such as extracellular K^+ have been suggested to decrease the APV (5, 60).

Lindström et al. (45) gave a mathematical model describing the effect of the average APV on the SEMGPS [$S(f)$]

$$S(f) = v^{-2} \cdot G(f/v) \tag{1}$$

where f is the frequency and v is the average APV. The function G is given by the geometry of the electrodes in relation to the active MUs and includes all other contributing factors. The v^{-2} factor expresses the relationship between amplitude and average APV. The factor f/v indicates that a decrease of the average APV is equivalent to a linear scaling of the frequency axis of a SEMGPS plot. It should be noted that the contributions from the firing statistics are included in the G function. It is quite obvious that these contributions are not a function of f/v. This issue is discussed further below.

If the spectrum is plotted with a logarithmic frequency axis, an average APV decrease according to *Eq. 1* would show as a parallel shift of the spectrum. Experimental data (28) (Fig. 2) indicate such a shift. In this plot, the spectra have been normalized to unity power, which implies that the general amplitude increase corresponding to the v^{-2} factor is not seen. The parallel shift is most distinct in the high-frequency band (for reasons discussed below), and the average relative APV decrease could actually be calculated as the frequency displace-

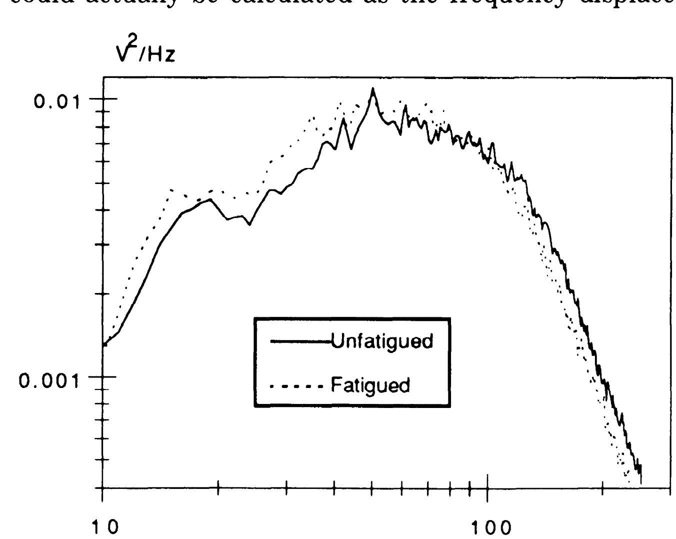

FIG. 2. Average spectra from 39 muscle registrations (m. infraspinatus and m. trapezius). Surface EMG was recorded during a 6-s test contraction of ~15% maximum voluntary contraction before and directly after 2 h of occupational assembly work. Spectra were normalized to unity power. [From Hägg (29).]

ment divided by the absolute frequency on the chosen level (28). This is a simplified version of the technique for estimating average APV decrease suggested by Lindström et al. (46) identifying certain "spectrum dips" and their shift toward lower frequencies at fatigue. Similar parallel shifts when logarithmic scales are applied can be seen in Ref. 4.

Action potential modification. The action potential shape is likely to be modified at fatigue. The effect of this modification on the SEMGPS is discussed by Merletti et al. (52) and Brody et al. (7). If this modification can be seen as a linear time scaling of the action potential, the effect on the SEMGPS is equivalent to an APV decrease. However, the modification may include a relative lengthening of the hyperpolarization zone (22). The effect on the SEMGPS of such an action potential alteration is a slight nonspecific displacement toward lower frequencies.

Firing rate and synchronization. In the unfatigued muscle, the firing of each MU is regulated independently by the corresponding motoneuron. Close to exhaustion, indications of a synchronization of the firings in different MUs have been reported by several investigators (4, 12, 42, 48), and it has been claimed to cause increasing spectral components in the low-frequency range of the SEMGPS.

Data describing the firing frequencies and interpulse intervals of the active MUs are usually denoted firing statistics. The firing statistics affect the spectrum mainly between 10 and 40 Hz. If MUs fire at one regular frequency, this is seen in the spectrum as a peak at this frequency and its harmonics (3). Experimental work shows the existence of such peaks in SEMG spectra (6, 40–42, 81). It has also been demonstrated by computer simulations (64, 76). At low contraction levels, when few MUs are active, these peaks tend to be more dominant (3). Several investigators (8, 44, 64) have contributed to the understanding of the theoretical background of firing statistics effects on the SEMGPS.

Comparisons of various SEMGPS alteration indexes (see below) and direct APV measurements during fatiguing static contractions indicate that the SEMGPS is affected by other factors in addition to APV decrease (4, 9, 41, 42, 63, 89). Broman et al. (9) and Linssen et al. (47) suggest an increase in the low-frequency region of the SEMGPS because of alterations in firing statistics. Hägg (28) and Krogh-Lund and Jørgenssen (41, 42) showed an additional increase of the SEMGPS in the 20- to 40-Hz region at fatigue.

A common misunderstanding is that a general increase of the firing rates would cause a substantial shift of the SEMGPS toward higher frequencies. At very low contraction levels, this is certainly true. However, when a sufficiently large number of MUs are active to cause overlap between the action potentials, the effect on the relative spectral density of the SEMG is small even if the total power of the signal is increased. This is demonstrated by simulations (64, 69) and by stimulation experiments (77). The decrease of the firing frequency attributed to fatigue (16, 65) has correspondingly little effect on the SEMGPS as long as synchronization does not occur.

Several investigators (55, 71, 73) demonstrated an increase of the APV at increasing firing frequency that will affect the SEMGPS, as described above. However, this spectrum alteration is not primarily caused by the increasing firing rate itself.

Temperature. A positive linear relationship between single-fiber APV and temperature has been demonstrated in frog muscle (11, 87). A similar relationship has been shown for human MUs (56, 73). Further indirect evidence of a linear relationship can be found in studies of spectral alteration indexes (see below). However, the range above 35°C is not satisfactorily investigated. There are indications (61) that the linearity is not valid when the temperature approaches 40°C. The close relation among SEMGPS, temperature, and APV is further demonstrated by Bigland-Ritchie et al. (4), who showed a SEMGPS alteration of the same type as in Fig. 2 at decreasing temperature. In conclusion, the influence on the SEMGPS of temperature variation is, to large extent, a matter of APV variation (see above).

Additional recruitment at fatigue. The hypothesis of successive additional recruitment of new unfatigued MUs to maintain a constant force output is old (18, 20, 41, 42, 51, 58). The possibility of alternating recruitment of MUs has also been suggested (75). However, so far no one has been able to show convincing EMG evidence for the existence of this phenomenon. Hypothetically, additionally recruited unfatigued MUs have a higher APV than the initially recruited MUs for two reasons: *1*) they are not fatigued and *2*) their fibers are likely larger (3, 50, 88). This implies a broader range of APV of the contributing MUs and subsequently a broader SEMGPS.

Arendt-Nielsen et al. (2) reported an increasing mean power frequency (MPF) (see below) and APV at 10 and 20% MVC and interpret this as a sign of additional recruitment of new MUs. The phenomenon of an increasing frequency content of the SEMGPS was also investigated by Hägg (28) reanalyzing data from an earlier vocational EMG study (82). He also suggested additional recruitment of unfatigued MUs with higher APV as a feasible interpretation. This is based on indications of a widening of the SEMGPS with tendencies of a double peak in the middle range in accordance with the hypothesized spectrum alterations related above. However, the evidence presented for this interpretation is still insufficient, and this phenomenon needs to be further elucidated.

Other effects. Several other physiological factors influence the SEMGPS. However, they are secondary factors whose influence can be derived via the basic phenomena discussed here. It should also be pointed out that, depending on the chosen definition of fatigue, there are states of local muscular fatigue (e.g., decreased MVC) that do not affect the SEMGPS whatsoever.

Spectral Compression Indexes

Traditionally, spectral alterations of the SEMGPS have been studied by reducing the spectral data to a single index, such as the median frequency (MF) (80) or the MPF (43). The MF is defined as the frequency that divides the power spectrum into two parts with equal areas. The MPF is defined according to the standard definition of a mean in statistics, on the basis of a continuous distribution, in this case, the power spectrum. Conventionally, the power spectrum is calculated and thereafter the MF or the MPF. However, hardware implementations have also been suggested (10, 79).

Another much simpler method for monitoring SEMGPS compression, i.e., counting the number of zero crossings (ZCs) of the SEMG signal per time unit, has been proposed (27, 32). Willison (86) used a kindred method, i.e., counting the number of turns in the EMG, for clinical purposes. Even if the ZC method is not based on the SEMGPS, the number of expected ZCs per time unit can be expressed in terms of the power spectrum (27, 29, 32, 68). It is shown below that the relative ZC response is close to the relative MF and MPF response.

Some other methods, such as the mode frequency (frequency at the highest spectrum peak) (74) or the power ratio between a high-frequency band and a low-frequency band (4, 38, 60), have been suggested. The mode estimate is unstable (74) and shows a poor relationship with APV decrease (72). The high-to-low ratio technique is not related to any specific fatigue phenomenon by any known model. Furthermore the limits for the high and low bands are arbitrarily set without standardization.

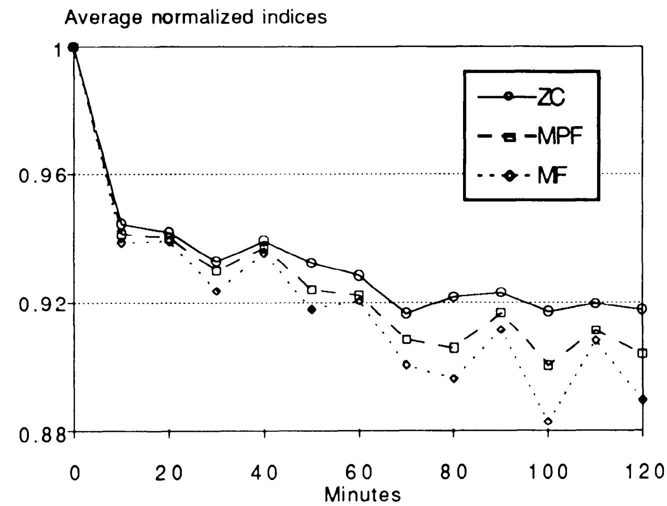

FIG. 3. Comparison of average relative median frequency (MF), mean power frequency (MPF), and zero crossing (ZC) decrease in surface EMG from 39 muscle registrations (m. infraspinatus and m. trapezius) during a 6-s test contraction of ~15% maximum voluntary contraction performed at 10-min intervals during occupational assembly work. [From Hägg (29).]

Index Response to Different Physiological Phenomena

Muscle activity level. As mentioned earlier, an increase of the muscle activity is associated with several different effects, such as average APV increase, firing statistics alterations, and firing frequency increase. These phenomena are discussed separately below.

APV decrease. It has been shown theoretically by applying the model of Lindström (*Eq. 1*) that the MF, the MPF, and the ZC methods show the same relative response to an average APV decrease (28, 45, 79). This can be mathematically expressed as

$$MF/MF_0 = MPF/MPF_0 = ZC/ZC_0 = v/v_0 \qquad (2)$$

where the zero index refers to a reference value taken when the muscle is well rested and v is the average APV. Figure 2 demonstrates a parallel shift at fatigue according to this model.

Synchronization. The three indexes, MF, MPF, and ZC, were compared (28) by applying them on SEMG from short test contractions during fatiguing occupational work. The average results, presented normalized to an initial reference, are shown in Fig. 3. There is a small but systematic difference among the three indexes. When comparing average spectra (see Fig. 2), there is an increase in the 20- to 40-Hz band in addition to the parallel shift related to the average APV decrease. It is demonstrated theoretically that the three indexes show different sensitivity to alterations in the 20- to 40-Hz band (28, 29). MF is the most sensitive, ZC is the least sensitive, and MPF is intermediate. Thus a likely interpretation of the systematic differences in Fig. 3 is that they are due to the varying sensitivity to the 20- to 40-Hz increase, which probably should be interpreted as firing statistics alterations, possibly synchronization. These results are in accordance with data presented by Broman et al. (9) and Merletti et al. (52), who report a somewhat larger response in the MF than in the MPF.

Firing rate. As stated above, firing rate alterations primarily have little effect on the SEMGPS if the number of active MUs is high enough. Consequently, the influence on spectral indexes is minor, as shown for the MF (64, 77) and for the MPF (69). As mentioned earlier, there is a likely relation between firing rate and APV. However, this is a secondary effect.

Temperature. The temperature mainly affects the average APV, and these two quantities seem to be linearly related, as stated above. Further support has been provided by studies of the temperature dependence of the MF (53) and the MPF (61) but with some reservation for temperatures >35°C (61). As we have already seen, there are no systematic differences between the relative responses to APV decrease of the discussed indexes. Hence, no systematic differences could be expected in the response to temperature alterations either.

Additional recruitment at fatigue. Studies of SEMGPS alterations have traditionally been focused on decreasing spectral indexes. Some sparse reports in the literature show increasing spectrum indexes, usually in occupational studies (30, 35, 49, 82) but also in the laboratory at low contraction levels (2). The traditional explanation of this effect has been recovery (APV increase) or muscle temperature increase, without any closer scrutiny. Hägg (28) found no evidence for a general increase of the APV in the recruited MUs, because there were no signs of a general shift of the SEMGPS toward higher frequencies (opposite effect to the one in Fig. 2). Instead he interpreted this as a sign of additional recruitment in accordance with Arendt-Nielsen et al. (2). The response of MF, MPF, and ZC rate to this phenomenon, whatever the origin might be, does not show any clear systematic differences (28).

Other effects. The impact of other physiological effects on spectral alteration indexes depends on their type of influence on the SEMGPS. An effect that causes a general compression of the SEMGPS, such as APV decrease, will give the same relative response of the discussed indexes. An alteration in the low-frequency band (e.g., firing statistics alteration) will have the greatest impact on the MF and the smallest on the ZC rate with an intermediate affect on MPF. The sensitivity rank to a specific alteration in the high-frequency band (if there are any) will be the opposite. This was also noticed by Lindström et al. (45). These principles refer to the order of the spectral moments involved in the analytic expression for the corresponding index where MF involves spectral moments of order zero, MPF of the first order, and ZC rate of the second order (28).

Spectral compression indexes as indicators of fatigue. Chaffin (13) was the first to suggest SEMGPS alteration as an indicator of local muscular fatigue. The well-documented decrease of any spectrum index at a sustained contraction (17, 27, 45) has been suggested as an indicator of local muscular fatigue (27, 45, 80). These authors have emphasized the linear relation to APV, thereby reducing the complex phenomenon of muscular fatigue to a matter of APV decrease. The use of a spectrum index as a fatigue indicator has been further justified by the findings that these indexes decrease exponentially with time at sustained contraction with decreasing time constants at increased static load levels (17, 25, 37, 45).

In laboratory studies comparing MF and/or MPF with directly measured APV, a substantially greater relative decrease is found in the MPF (63, 89), in the MF (47, 41, 42), and in both the MF and MPF (9, 52). Similar discrepancies are reported during occupational work (28). Obviously, these indexes are sensitive to physiological phenomena other than APV reduction, as discussed above.

Some investigators (1, 19) did not find any signs of divergence from a linear relationship between MPF and APV at load levels above 50% MVC. Sadoyama et al. (72) reported a linear relationship at a load level of 50% MVC but weaker correlation at lower load levels. Other groups (4, 9, 41, 42, 47, 63, 89) questioned a linear relationship on the basis of experiments at varying load regimens. These conflicting results may be partly due to a varying proportion of active fast-fatigable type II fibers. A large proportion of active type II fibers likely implies a fast and dominating APV decrease. Another explanation might be that synchronization does not necessarily occur in all fatiguing situations. Arendt-Nielsen et al. (2) and Hägg (28) suggested that additional recruitment effects more or less counteract the decrease of spectral indexes at fatiguing contraction.

The multifactorial nature of SEMGPS compression indexes is perhaps even more important to notice in occupationally related studies where the load usually is <20% MVC. Even at these load levels, an APV decrease is likely to occur (78), but the expected exponential decrease is obscured by intermittent influences of various recruitment effects. These fluctuations are cancelled when averages over several individuals are calculated, yielding exponentially falling traces (33, 82). Data collected during occupational work during short test contractions (28) (Fig. 3) show that the average relative ZC decrease almost exactly mirrors the estimated average relative APV decrease, whereas the relative MPF and MF decreases are ~15 and 30% greater, respectively. Krogh-Lundh and Jørgensen (41) presented data with a relative MF decrease over 300% greater than the relative APV decrease close to exhaustion in the triceps at 25% MVC. In a recent study they reported a 35% decrease of the MF

TABLE 1. *Response of different spectrum compression indexes to different physiological factors*

Physiological Effect	Effect on Spectrum Compression Index: Median frequency	Mean power frequency	Zero crossing rate
Average APV	Proportional		
Firing statistics alteration* (10- to 40-Hz increase)		−−	−
Additional recruitment	+	+	+
Muscle temperature alteration	Approx linear, 3–3.5%/°C†		
Action potential modification	−	−	−

* No. of negative signs indicates mutual magnitude of effect. † According to Ref. 53.

with no alteration of the APV at exhaustion in the biceps brachii loaded at 15% MVC. After ~75% of the endurance time, they even noted a slight increase of the APV. They speculated that minor reductions of APV in MUs activated from the beginning of the experiment are balanced by higher APV in newly recruited MUs. Hägg (28) applied a similar reasoning to explain the almost exact resemblance between relative ZC decrease and the estimated relative APV decrease. The expected minor effect of the 20- to 40-Hz alteration (firing statistics) on the ZC rate is balanced by additional recruitment.

A conclusion is that any investigator applying spectral indexes as indicators of local muscular fatigue should be aware of these multifactorial influences.

General Discussion

The knowledge about physiological factors that influence the SEMGPS has grown substantially over the last decade. Today we have strong evidence for the hypothesis that the SEMGPS is generally compressed as a result of APV decrease (1, 9, 19, 28, 41, 52, 63, 72) but also increased in the 20- to 40-Hz band as a result of firing statistics alterations (3, 6, 29, 40, 41, 64, 76, 84), presumably synchronization. The theoretically complicated relations between firing statistics and SEMGPS shape are still not known in detail and need further elucidation. The related physiological phenomenon of synchronization is also insufficiently described and understood. Other issues that have been brought up recently are AP shape modification (52), additional recruitment (2, 28), and alternating recruitment (75). More experiments are needed to confirm the existence of these phenomena and to assess their impact on the SEMGPS.

The choice of MPF or MF as "fatigue index" is based on mathematical convention and the assumption that APV decrease is the dominating fatigue effect. As shown above, there obviously are other effects as well. It should be possible to develop tailored spectral indexes to reflect various physiological phenomena.

Generally, effects on the muscle at load levels ≥25% MVC are well documented in comparison to lower load levels, which are more common in occupational work.

Conclusions

APV decrease causes a compression of EMG spectra at sustained contraction. Another effect is an additional increase in the low-frequency part of the spectrum, most likely related to firing statistics alterations. Both of these effects decrease EMG spectral indexes. Additional recruitment of unfatigued motor units is likely to occur and is possibly seen as a widening of the spectrum with a concomitant increase of spectral indexes. The response of spectral indexes at sustained contraction is a compound effect of several physiological phenomena. Different indexes show different sensitivity to different phenomena. The effect of different physiological factors is summarized in Table 1.

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