The Relationship between Muscle Temperature, MUAP Conduction Velocity and the Amplitude and Frequency Components of the Surface EMG During Isometric Contractions

Jerrold Petrofsky and Michael Laymon

Department of Physical Therapy, Loma Linda University, Loma Linda, California and Department of Physical Therapy, Azusa Pacific University, Azusa, California

Abstract

The relationship between the tension developed during brief isometric contractions and the frequency and amplitude components of the surface EMG were recorded in 5 male subjects after immersion of their arms and legs in water at 24, 27, 34 and 37 deg. C. for 20 min. The muscles examined were the handgrip, biceps, quadriceps, and gastrocnemius muscles. For the three warmest water temperatures, the muscle strength was unaffected by the water bath temperature. Muscle strength was lower for all muscles examined at the coldest muscle temperature. For all temperatures, the relationship between EMG amplitude and tension for brief isometric contractions was nearly linear. The frequency components of the EMG as assessed by Fourier Analysis of the raw EMG and MUAP conduction velocity, were largely unaffected by muscle tension but was dramatically affected by muscle temperature. During fatiguing contractions at a tension of 40% MVC, the shift in frequency was similar for the warmest three muscle temperatures while for the coldest temperature, the shift in center frequency was much less. The results show the feasibility of use of EMG amplitude to assess muscle use in most physiological conditions but draws doubt on using the frequency components of the EMG as a measure of fatigue under circumstances where muscle temperature may vary.

Key words: conduction velocity, EMG, exercise, exertion, frequency analysis, isometric exercise, temperature.

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The surface EMG is an interference pattern that reflects the action potentials in the underlying muscle [4, 8, 9, 40, 47]. Many attempts have been made to use either the amplitude or frequency components of the surface EMG as a means of assessing the tension developed in muscle or the degree of fatigue in muscle during either isometric or dynamic exercise [22, 25, 32, 40, 46]. Given the premise that the amplitude of the surface EMG is related to force, investigators have used the surface EMG in industry to quantify activity of muscles (e.g. 23). But different investigators have published sometimes contradictory results. Concerning the amplitude of the EMG, some investigators point to a linear relationship between the amplitude of the EMG and the tension in muscle during brief isometric contractions [4, 25, 44]. If true, the EMG amplitude would be a good non-invasive measure of the tension exerted in a muscle. But other investigators, even in the same studies, report non-linear relationships between the surface EMG and the tension exerted by muscle [5, 28]. While some of the variation has been attributed to the type of electrode (needle or surface) or the size or position of the electrodes [54], much of the difference in various studies is unexplained. Certainly, if the muscle begins to fatigue, the power produced by the individual muscle fibers is reduced [17]. This results in more muscle fibers being recruited, thereby increasing the amplitude of the EMG [22]. Many investigators point to a linear increase in the amplitude of the surface or needle EMG as a muscle fatigues (e.g. 46) while others report a non-linear increase in the amplitude of the EMG as fatigue progresses (e.g. 11). Even if the increase in the amplitude of the EMG was perfectly and linearly related to fatigue, in assessing the tension generated by muscle through the amplitude of the surface EMG, the exact degree of fatigue in the muscle would be needed to assess the activity of the muscle. For this reason, many investigators have examined the frequency components of the EMG as a means of assessing fatigue in the muscle to correct EMG analysis for weakened motor units in an analysis of muscle activity (e.g. 46).

The EMG is predominantly composed of a fundamental frequency of about 60 Hertz [32, 37]. There are, however, both low and high frequency components of the EMG. For example, muscle tremor occurs at frequencies of between 8-25 Hertz [3, 16]. High frequency components of the EMG occur at up to or sometimes above 500 Hertz [1, 2]. One method that has gained increasing popularity to analyze these frequency components is the Fast Fourier Transform (FFT). The FFT is a mathematical means of analyzing the individual frequency components of the EMG. The average frequency and amplitude of the Fourier Spectrum or Power Spectrum is called the center frequency and gives a realistic estimate of the average of all of the frequencies of the EMG [8, 9, 32, 33 46]. The center frequency has been used to not only provide the average frequency, but has been linked as a measure of the conduction velocity of action potentials across the sarcolemma [22, 29, 31, 32, 33, 34]. It has been used to quantify fatigue in both the laboratory [29, 42, 46] and industrial settings [22].

The center frequency of the EMG power spectrum has been reported to be unrelated to muscle tension in some studies [44, 45, 46, 52], changes with tension in others [1, 2, 6], was only higher at maximal tension sin some studies [8, 9], and in some conditions goes up and down with tension in the muscle [25]. Like the amplitude of the EMG, the center frequency seems to vary with muscle fatigue and shows a great deal of variation between different studies. As muscles fatigue, there is a decrease in the frequency components of the surface EMG above the underlying muscle [22, 25, 32, 46]. The change in frequency of the EMG has been attributed to a reduction in the conduction velocity of action potentials on the sarcolemma of the underlying muscle [32, 33]. Some investigators argue that the changes in conduction velocity are far out of proportion to the change in the center frequency of the EMG while others dispute this finding [8, 9].

A number of factors have been identified to understand some of the differences in the amplitude and frequency components of the EMG in relation to tension or fatigue. Some of the variation in EMG amplitude and frequency have been attributed to the proportion of fast and slow fibers in the underlying muscle [19, 50], the placement of the electrodes [18, 19] and thickness of fat under the skin [6], and age [36]. Gerdle et al [18, 19] showed that if the mean power of the EMG was used instead of the mean frequency, there was no variation in mean power frequency with tension.

One variable that has not been well accounted for is muscle temperature. Muscle temperature varies a great deal among different muscles and in the same muscle. The resting muscle temperature of the bracheoradialis muscle for example, has been reported to be about 30 deg C in the bare armed individual in a thermally neutral environment [41, 48]. This temperature is about 7 degrees centigrade below that of the core temperatures. This is due to the fact that muscles are in the shell tissues of the body and work as a physiological radiator to control central body temperature. Muscles more proximal to the core are somewhat warmer than muscles more distal to the central axis of the body [57]. This resting temperature is closer to the core in people with high body fat contents and cooler in thin people [41]. Previous light exercise warms muscle since warm blood enters the muscle during post exercise hyperemias [10]. Thus deep muscle temperature, due to clothing, previous exercise, body fat and other conditions may vary greatly.

The conduction velocity of nerve and muscle action potentials is a function of tissue temperature [27, 30, 34, 58]. Since much of the variation in the EMG center frequency has been attributed to changes in the conduction velocity of action potentials on the muscle fiber membrane, some of the variation in EMG amplitude and frequency seen by different investigators and in different subjects may be due to differences in the temperature of the muscles. In a previous study, we looked at the effect of temperature on the amplitude and frequency components of the EMG measured above the handgrip muscles in man. While the bath temperatures were limited and the data was limited to one muscle group, there was only a negligible effect of bath temperature on the amplitude of the surface EMG but a large reduction in the center frequency of the EMG power spectrum in the cooler bath temperatures. These findings were later confirmed by Merletti et al (1984) and Krause et al (2001). But these later studies did not actually measure muscle temperature or motor unit action potential conduction velocity. These studies simply used hot or cold packs above the muscle for a brief period of time and examined the effect on the surface EMG. Further, not all possible tensions were examined, only intermediate isometric tensions.

Therefore, the present investigation was conducted to examine the variation in the amplitude and frequency components of the EMG that occur in 2 upper and 2 lower body muscles in relationship to the temperature of the muscle during brief isometric contractions. Muscles were isolated using EMG of muscles that could be substituted to confirm proper muscle isolation. Further, fatiguing isometric contractions at 40% of the muscles maximal strength were used to see the impact of temperature of the muscle and fatigue together on the properties of the surface EMG.

Subjects

The characteristics of the subjects is shown in Table 1. Five male subjects participated in these experiments. Their ages ranged between 22 and 27 years old. Their weights ranged from 55.3 to 69.2 kg. Their heights ranged between 155 and 180 cm.

Table 1. General Characteristics of subjects

Subject	Sex	Height (cm)	Weight (kg)	Age (years)
1	M	168.2	59.9	25
2	M	155.7	57.7	27
3	M	180.1	69.2	21
4	M	170.8	55.3	22
5	M	168.4	59.4	26

All subjects were free of any neuromuscular deficits. The Institutional Review Board approved all protocols and all experimental procedures were explained to all subjects who signed statements of informed consent.

Methods

EMG

The electromyogram (EMG) was recorded through two bipolar vinyl foam adhesive EMG electrodes (silver-silver chloride) with an active surface area of 0.5 sq cm. One electrode was placed over the belly of the active muscle. The second electrode was placed 2 cm distal to the active electrode. The EMG was amplified using a 4-channel EMG amplifier whose frequency response was flat from DC to 1000 Hz. The common mode rejection ratio of the amplifiers was greater than 120 DB. The EMG was then digitized at 2000 samples per sec and displayed and saved on an IBM computer for later analysis. To waterproof the electrodes, a layer of collodion was applied around and on top of the electrodes so that the electrodes would stick to the skin under water and the water would not seep under the electrodes and change electrode impedance. This technique has been used by us previously and over a period of as long as 4 hours. Throughout this period, there was no variation in EMG amplitude or electrode impedance [41, 42]. Others, who have not used a waterproofing agent, have shown a significant difference in EMG amplitude in water and land for a given strength of muscle contraction [5]. For electrical safety, the EMG lead wires were extended to 10 meters in length and the amplifiers and computers were operated by battery.

The amplitude of the EMG was assessed by half wave rectifying and calculating the RMS voltage from the raw EMG. The frequency components of the EMG were analyzed by using the raw EMG and then performing a Fast Fourier Transform (FFT) on the digitized data. The Fourier analysis involved a 1024 point Fourier Transform for each 0.5 sec EMG sample. The average frequency of the power spectrum was then calculated and is given throughout this paper. From the frequency spectrum, which was calculated from DC to 2000 Hz, the average (center) frequency pf the spectrum was calculated to represent the average frequency of the EMG. This technique has been published in detail elsewhere [40, 41, 42, 44, 45].

Measurement of conduction velocity

Conduction velocity was measured during the brief isometric contractions described below under procedures. Motor unit conduction velocity was measured by the method described by Arendt- Nielsen and Mills (1988). Briefly, three additional self adhesive electrodes were placed on the distal end of the muscles being studied. The electrodes were placed parallel to the muscles fibers and 15 mm apart in a bipolar array. The third electrode in the center was the common and the 2 EMG signals were amplified and compared to determine the conduction velocity across the array. The handgrip muscles were too complex to measure conduction velocity and only the other three muscle groups were used for these studies (see 1).

Measurement of muscle strength and endurance

Isometric strength and endurance were measured in 4 muscles or muscle groups. These were the handgrip group, biceps, quadriceps and medial gastrocnemius. For each muscle or muscle group the muscles were placed in a position to minimize the use of other muscles by substitution. This was verified by EMG on other muscles that might be used during the contractions. Subjects were initially trained not to substitute other muscles. All measuring devices were waterproofed and battery operated so that they could be sued safely in the water baths used in these studies.

Handgrip

The strength and endurance of the handgrip muscles was measured through a portable handgrip dynamometer. The handgrip was constructed from an aluminum C frame with a palm bar. A square aluminum frame was in the center and was connected through a universal joint to a stainless steel bar. By placing the hand in the device with the fingers curled around the inner bar, any contraction of the muscle would bend the stainless steel bar and cause an electrical output from 4 strain gauges, which could then be amplified and displayed. This device has been described elsewhere [41].

Biceps

The device used to measure isometric contraction of the biceps consisted of a similar isometric strain gauge device. The subjects sat with their arm dependant and at an angle of 90 degrees. A strap was applied at the wrist and connected to an isometric stain gauge transducer bar. Tension exerted by the biceps could then be monitored through the electrical output of the strain gauges.

Quadriceps

Similarly, the subject was in the sitting position with the leg held dependant. The knee was bent at 90 degrees and an ankle strap connected to a stainless steel transducer bar. Extension of the knee could then be recorded.

Gastrocnemius

The strength of the medial gastrocnemius muscles was assessed with the subject in a seated position and the knee at 90 degrees. A modified ankle foot Orthosis (AFO) was applied with a movable ankle joint. A cable, under the first metatarsal head connected to a strain gauge mounted about 1 meter cephalic and on the surface of the tibia but to the plastic of the brace. The cable was connected in series with a load cell (strain gauge), which produced an electrical output upon extension of the ankle joint. Since the leg was dependant, only the angle extensors could participate in generating tension in the load cell. Only the EMG from the medial gastrocnemius was studied; it was not possible to isolate this muscle in generating strength form the lateral gastrocnemius.

Measurement of muscle temperature

Muscle temperature was measured through a needle thermistor probe. The probes were constructed from 25-gauge needle stock, which was sharpened on one end. A thermistor (Fendwall) was inserted through the needle along with a Teflon coated platinum wire. The wires were epoxied in place so that the thermistor was just behind the needle tip and the platinum wire was exposed on the end. In this manner, the single wire could be used for electrical stimulation to verify the position of the needle (see procedures below).

Statistical Analysis

Statistical analysis involved the calculation of means, standard deviations, and related and unrelated t tests, and ANOVA. The level of significance was chosen as $p<0.05$.

Procedures

Training

All subjects were first trained to exert isometric contractions and to carry these to fatigue. Training involved, on a different experimental day, sessions on each muscle group to be tested. For the handgrip, biceps, quadriceps or gastrocnemius muscles, three maximum voluntary efforts were conducted (3 sec each); 1 minute was allowed between contractions. After 5 min, a series of contractions at 20,40,60, and 80% MVC were conducted while the subject watched the EMG monitors to assure that muscle use, as assessed from surface electrodes, only involved the muscles being studied. After a 5 min rest period, a sustained contraction at a tension of 40% MVC was conducted in the handgrip and quadriceps muscles. Training was conducted on Monday, Wednesday and Friday of successive weeks until the coefficient of variation in strength and endurance for each muscle group (standard deviation/mean) reached 5% or less from day to day.

Experiment

Each subject participated under 4 experimental conditions. On each of 4 separate days for each of 4 muscle groups (2 upper body and 2 lower body), each subject first came into the laboratory and rested in a thermally neutral environment (70-74 deg. C.) in shorts and short sleeve shirts for 30 min. Within the first few minutes, a thermistor probe was inserted into the belly of the muscle being studied. A fine platinum wire was co-located with the thermistor probe in the tip of the needle. This wire was used as a stimulating electrode to assure that the thermistor was in the belly of the correct muscle. Once the belly was found as the first twitch of the muscle with a small electrical stimulus, the probe was inserted 0.5 cm deeper. The needle was then protected with a coat of collodian as a water-proofing agent. After the initial rest period, the subjects put either their arm or leg in a water bath above the muscle group being studied. The arm or leg was immersed for 20 min. and muscle temperature was monitored. Three maximum efforts were then exerted (MVC) as a brief (3 sec) maximal effort. Subjects then exerted 3 sec contracts for 3 sec at 20, 40, 60, and 80 % MVC. Three minutes was allowed between contractions and all tensions were done in replicate and randomly selected by statistical tables. The EMG and conduction velocity were recorded during these efforts. In addition to the EMG of the active muscles, antagonist muscle EMG and muscles that could be used to substitute for the muscle being studied were recorded and displayed for the subject to provide feedback and minimize the contraction of other muscles. After 10 min, a fatiguing contraction was accomplished at 40% MVC. The only muscles undergoing a fatiguing isometric contraction were the handgrip and quadriceps muscles. The contraction was sustained isometrically and subjects were exhorted to hold the tension until, although they exerted a maximum effort, the tension dropped to less than 35% MVC. The EMG was also recorded during this effort. The muscles examined were the biceps, handgrip muscles, quadriceps and medical gastrocnemius muscles.

Results

The results of the first series of experiments are shown in figures 1-13.

Change in muscle temperature after immersion

The resting muscle temperature of the biceps, bracheoradialis, quadriceps, and gastrocnemius muscles was 33+/-0.8, 29+/-1.3, 34+/-2.1, 29+/-1.8 deg. C respectively. The muscles more proximal to the body had the highest resting muscle temperature, averaging about 4 deg C greater than the more distal muscles. However, for all four muscle groups, once the limb had been submerged in the water, the muscle temperature rapidly came to equilibrium with the water bath, coming to the temperature of the bath within 15 min of immersion. As

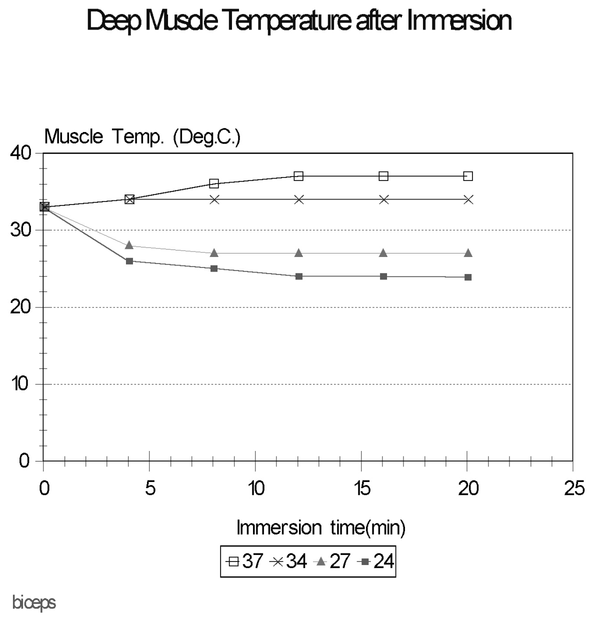

Figure 1. The temperature in the belly of the biceps muscle measured by needle thermistor probe during immersion in water baths at 24, 27, 34 and 37 deg. C for a period of 20 min.

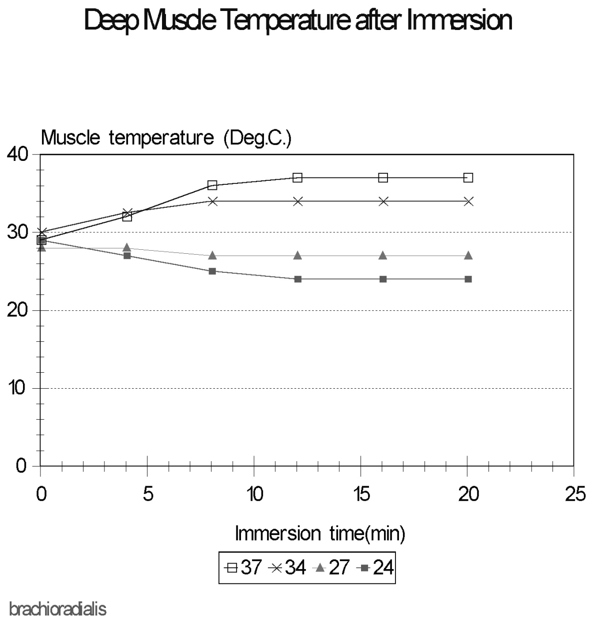

Figure 2. The temperature in the belly of the brachioradialis muscle measured by needle thermistor probe during immersion in water baths at 24, 27, 34 and 37 deg. C for a period of 20 min.

shown in figures 1-4, for the first 5 minutes, muscle temperature changed rapidly toward that of the bath. The change in muscle temperature was greatest after immersion in the coolest water temperature examined.

Muscle strength vs. muscle temperature

The maximum strength of the muscles was dependant to some extent on the temperature of the water. For ex-

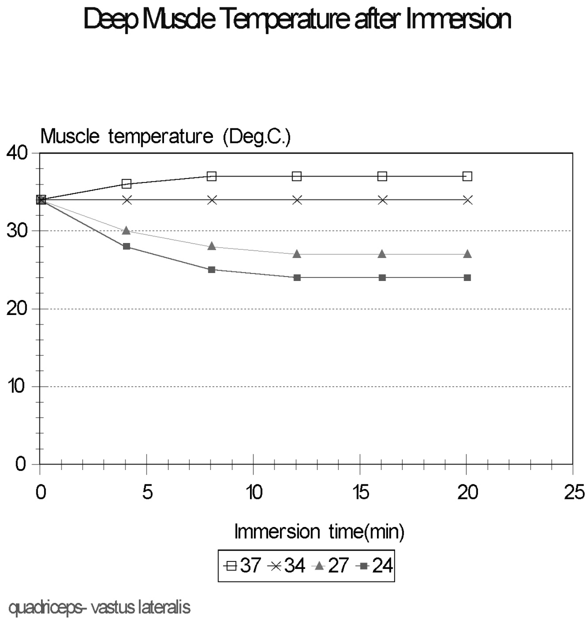

Figure 3. The temperature in the belly of the vastus lateralis muscle measured by needle thermistor probe during immersion in water baths at 24, 27, 34 and 37 deg. C for a period of 20 min.

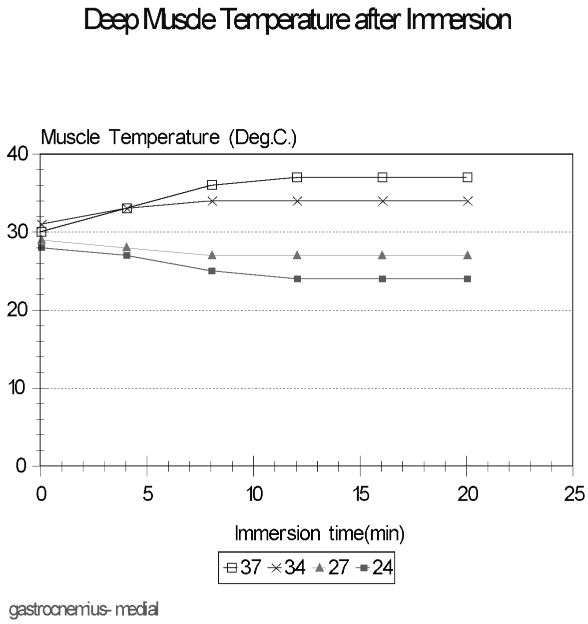

Figure 4. The temperature in the belly of the medial gastrocnemius muscle measured by needle thermistor probe during immersion in water baths at 24, 27, 34 and 37 deg. C for a period of 20 min.

ample, for the coldest temperatures, for all 4 muscles examined, there was a reduction in the maximum muscle strength. The strength of the muscles for the 5 subjects averaged 55 +/- 9.3, 57 +/- 11.2, 49 +/- 5.9 and 48 +/- 11.3 % of the strength at the warmest muscle temperature for the five subjects and for the biceps, handgrip, quadriceps and gastrocnemius groups respectively.

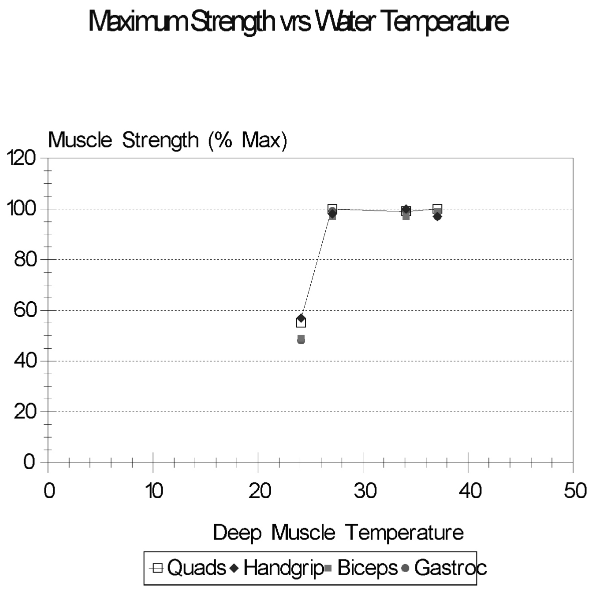

Figure 5. The strength during maximal isometric contraction fo the quadriceps, biceps, gastrocnemius and triceps muscles after 20 min of immersion in water baths at 24, 27, 34 and 37 Deg. C. Each point represents the mean of all subjects for each of the four muscle groups.

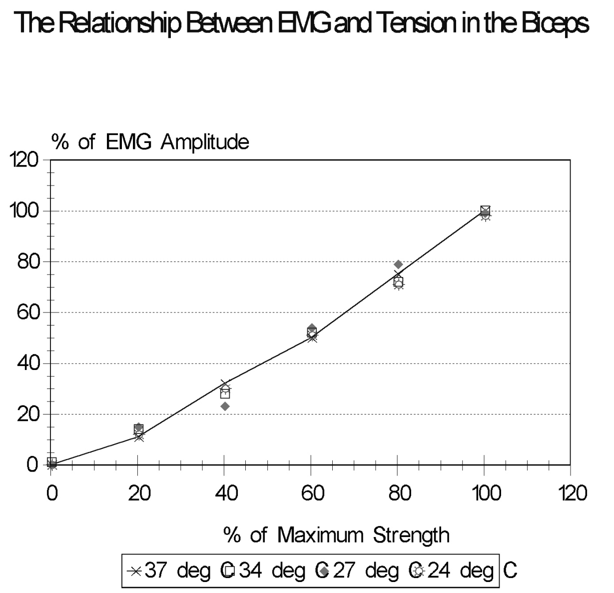

Figure 6. The average half wave rectified EMG recorded in the biceps muscle after 20 min of immersion in a water baths at either 24, 27, 34 or 37 deg. C. in relation to the tension during brief and maximal isometric contractions.

These differences in strength between the coldest and other muscle temperatures was statistically significant ($p<0.01$). There was no statistical difference between the strengths measured at the other temperatures (27, 34, and 37 deg C) for each muscle group when compared to the same group at different temperatures. ($p>0.05$) Figure 5 shows this data graphically. The strength is expressed as a % of the strength in the 37 deg. C water top between compare one muscles response to the next since the strength of the different groups was drastically different.

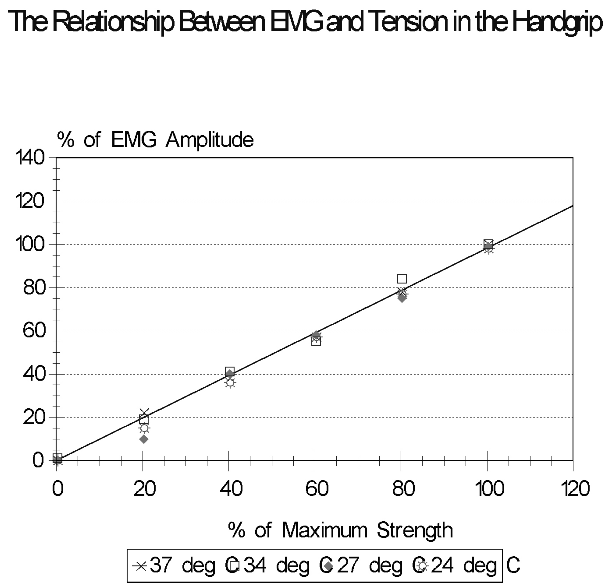

Figure 7. The average half wave rectified EMG recorded in the handgrip muscles after 20 min of immersion in a water baths at either 24, 27, 34 or 37 deg. C. in relation to the tension during brief and maximal isometric contractions.

EMG and tension

The relationship between EMG amplitude and tension for brief isometric contractions of the biceps, gastrocnemius, handgrip and quadriceps muscles is shown in figures 6-9. In these figures, the EMG amplitude during a maximum effort in the warmest bath (37 deg C) was used as a control and all EMG RMS amplitudes were expressed as a fraction of this value to normalize EMG amplitudes for each of the 5 subjects. In this manner, even if there were different EMG amplitudes from day to day due to electrode placement and other factors, the data could be compared in the same subjects and between different subjects. The relationship between tension and EMG amplitude was not effected by the water temperature. For all 4 muscle groups ANOVA analysis showed no statitistical difference in the relative amplitude of the EMG at any sub maximal tension at any muscle temperature. For the biceps (Figure 6) and gastrocnemius (Fig 9) muscles, the relationship between tension and the relative amplitude of the EMG was slightly nonlinear. However, the best fit curve was a linear regression and not a polynomial fit. There were some tensions where the EMG amplitude, for example fell below that expected for a linear relationship. For the biceps for example, the EMG amplitude at 60 % MVC in 24 deg water was only 51 +/- 11.9 % that of the MVC. The predicted value was 60% MVC. But there was no consistency related to temperature and muscle

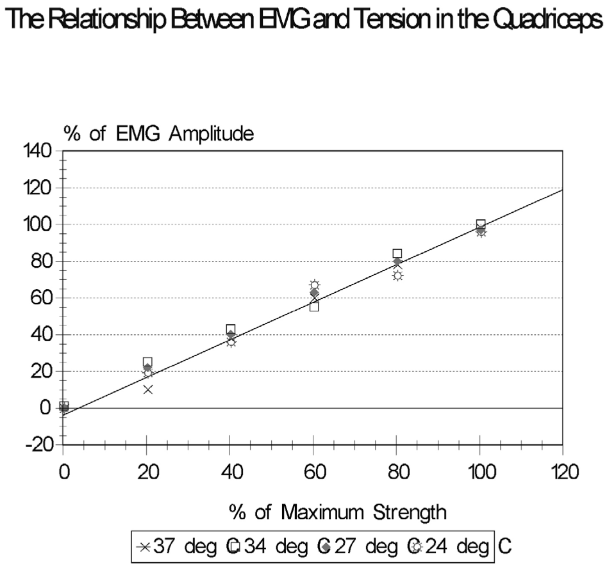

Figure 8. The average half wave rectified EMG recorded in the quadriceps muscle after 20 min of immersion in a water baths at either 24, 27, 34 or 37 deg. C. in relation to the tension during brief and maximal isometric contractions. Each point represents the mean response of the group.

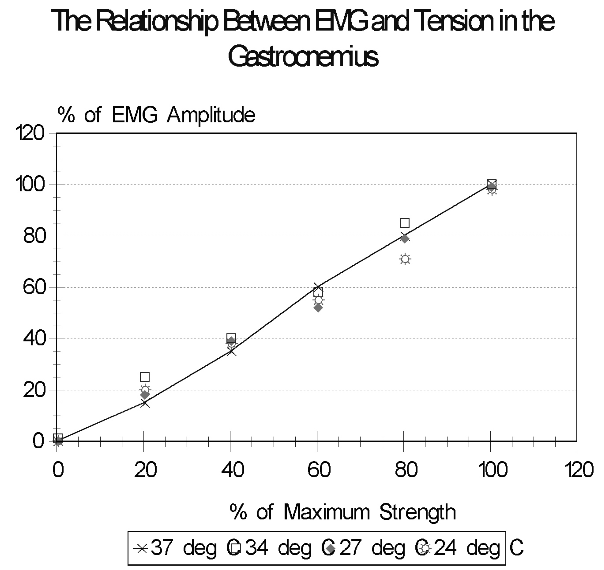

Figure 9. The average half wave rectified EMG recorded in the gastrocnemius muscle after 20 min of immersion in a water baths at either 24, 27, 34 or 37 deg. C. in relation to the tension during brief and maximal isometric contractions. Each point represents the mean response of the group.

group in these deviations in linearity. The absolute magnitude of the EMG during an MVC was quite variable. While there was a trend toward a lower maximum EMG amplitude in the coldest water in absolute terms, the large standard deviation left no statistical difference here. ($p<0.05$).

The center frequency of the EMG during the brief contractions and at the 4 bath temperatures and 4 mus-

Center Frequency vrs Tension

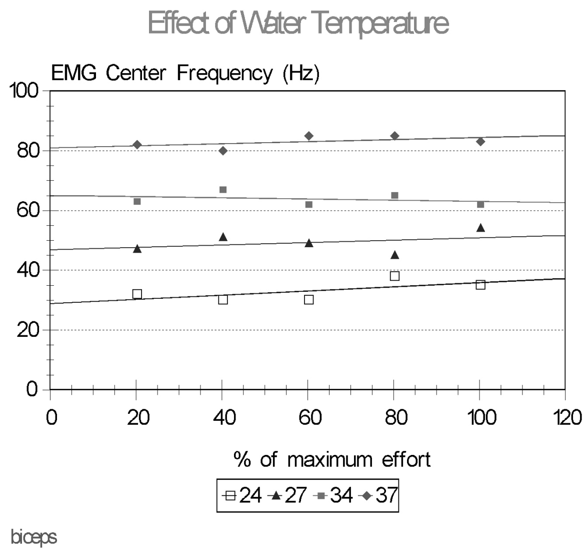

Figure 10. The relationship between the center frequency of the EMG power spectrum and tension for brief sub maximal and maximal isometric contractions for exercise after 20 min of immersion in water at 4 different bath temperatures, 24, 27, 34 and 37 deg C. The muscle examined here was the biceps muscle.

Center Frequency vrs Tension

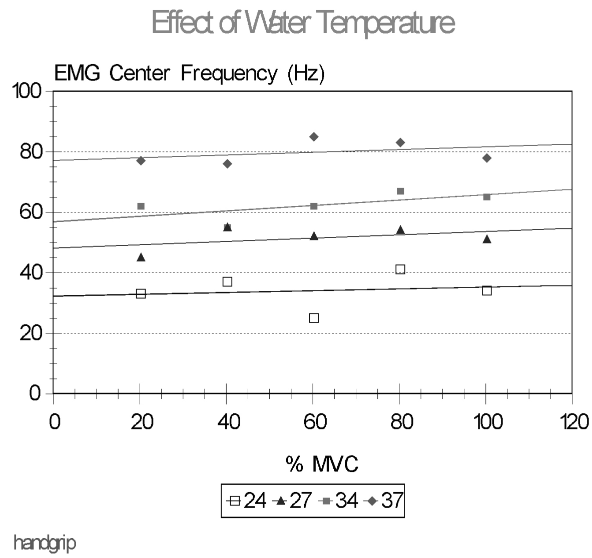

Figure 11. The relationship between the center frequency of the EMG power spectrum and tension for brief sub maximal and maximal isometric contractions for exercise after 20 min of immersion in water at 4 different bath temperatures, 24, 27, 34 and 37 deg C. The muscle examined here was the handgrip muscles.

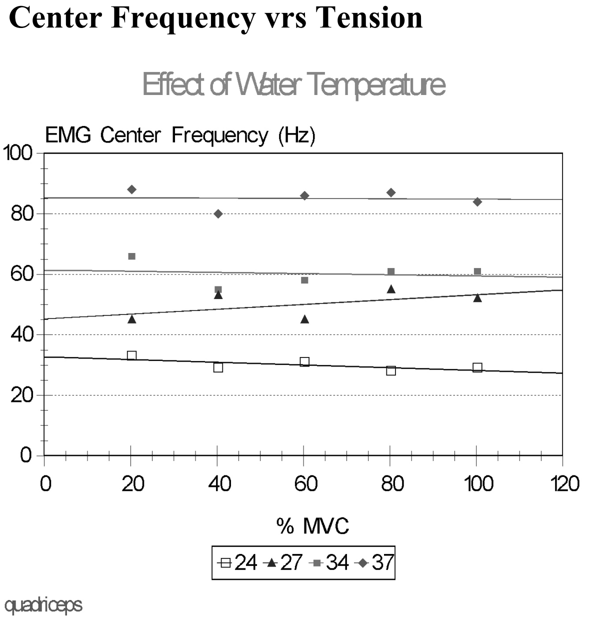

Figure 12. The relationship between the center frequency fo the EMG power spectrum and tension for brief sub maximal and maximal isometric contractions for exercise after 20 min of immersion in water at 4 different bath temperatures, 24, 27, 34 and 37 deg C. The muscle examined here was the quadriceps muscles.

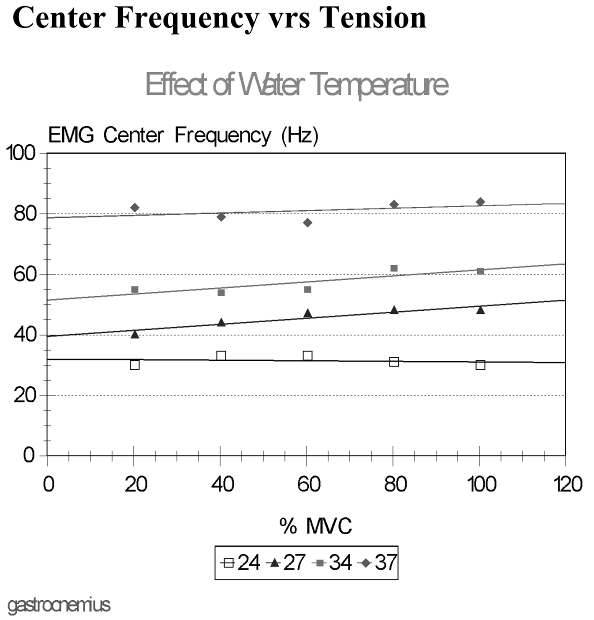

Figure 13. The relationship between the center frequency of the EMG power spectrum and tension for brief sub maximal and maximal isometric contractions for exercise after 20 min of immersion in water at 4 different bath temperatures, 24, 27, 34 and 37 deg C. The muscle examined here was the medial gastrocnemius muscles.

cle groups is shown in figures 10-13. Each figure shows the center frequency of the EMG during a brief isometric contraction measured at tensions of 20,40, 60 80 and 100 %MVC in each bath temperature. Each figure represents the results on the biceps, handgrip, quadriceps and medical gastrocnemius muscle respectively for figures 10-13. Whereas the amplitude of the emg was similar at all bath temperatures, this was not true of the frequency components of the EMG. In general, visual observation of the EMG showed that for all 4 muscles, the EMG changed shape in the cooler baths. As the bath temperature was reduced, the small wavelets that form the high frequency components of the EMG were eliminated and the large waves slowed. The result was that in the coolest bath, the waves were slow and without high frequency components. This translated numerically to a reduction in the center frequency of the EMG in relation to bath temperature. For example, simply looking at the bath temperature in relation to the center frequency during the MVC, the biceps muscle center frequency at MVC was 83+/- 9.5, 62+/- 7.3, 54+/- 5.9 and 35+/-7.1 Hertz after immersion in the baths at 37, 34, 27 and 24 deg C. as shown in figure 10. The response of the handgrip muscles was similar averaging 78+/-10.3, 65+/-9.3, 51+/-5.8 and 34+/-4.6 Hertz for these same water bath temperatures and as shown in figure 11. The quadriceps (figure 12) and gastrocnemius muscles (figure 13) showed similar responses. There was no statistical difference between the frequency of the EMG at the same muscle temperature for any of the 4 muscles ($p>0.05$) but the differences in center frequency between each muscle temperature were significantly different ($p<0.01$). The relationship between tension exerted by, and center frequency of the EMG showed no change in center frequency with tension for any muscle and at any temperature examined ($p<0.05$).

Series 2 experiments- For the handgrip and quadriceps muscles, fatiguing isometric contractions were exerted at 40% MVC at each of the bath temperatures as shown in figures 14-17. For the handgrip muscles (figures 14,15) there was a linear rise in EMG amplitude throughout the duration of the contraction. EMG was measured here at 20,40,60,80 and 100 % of the duration of the contraction by analysis of the recorded data to normalize the data between subjects since the actual endurance varied. The endurance of the handgrip muscles increased with a reduction in temperature until the coldest temperature where endurance was less. The endurance in the 37 deg water was 121 +/- 23 sec whereas in the 34 deg water the endurance increased to 152+/- 21 sec. After immersion in the 27 deg water, endurance increased to 231 +/- 35 sec and in the coolest water it dropped to 133 +/- 19 sec. These endurance were all significantly different form each other ($p<0.01$). The amplitude of the EMG in the 3 warmest temperatures when normalized as a % of the MVC were not different form each other ($p>0.05$) but the EMG amplitude of the muscle in the coolest bath temperature only rose about 50 % of the total change as the other temperatures. The

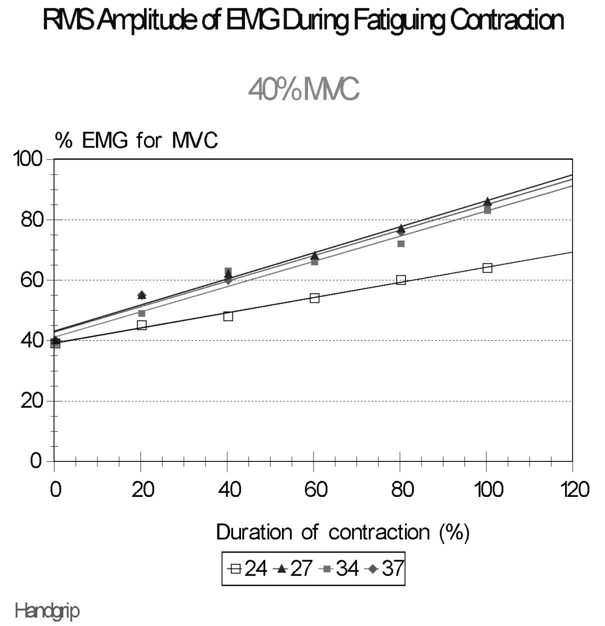

Figure 14. The RMS amplitude of the EMG recorded from the handgrip muscles during a fatiguing isometric contraction exerted at a tension of 40% MVC in the 5 subjects. Each data point shows the mean of all subjects for EMG at 20, 40, 60, 80 and 100 % duration of the contractions. The contractions were accomplished on 4 separate days under 4 different bath temperatures of 24, 27, 34 and 37 deg. C.

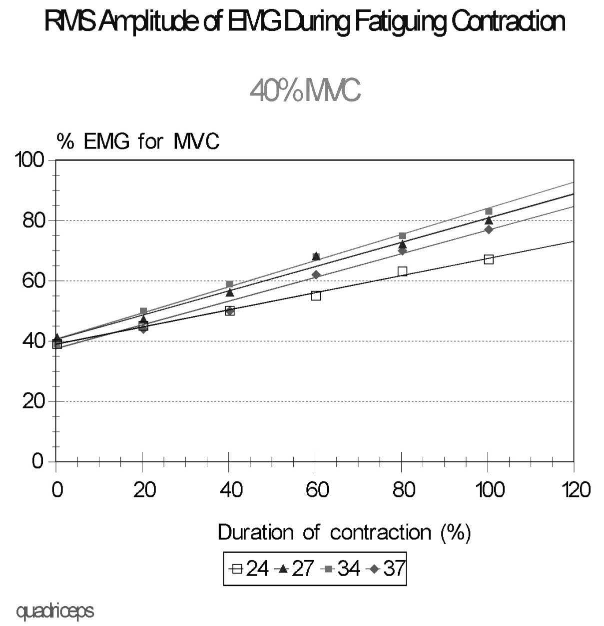

Figure 15. The Center Frequency of the EMG recorded from the handgrip muscles during a fatiguing isometric contraction exerted at a tension of 40% MVC in the 5 subjects. Each data point shows the mean of all subjects for EMG at 20, 40, 60, 80 and 100 % duration of the contractions. The contractions were accomplished on 4 separate days under 4 different bath temperatures of 24, 27, 34 and 37 deg. C.

same results were seen for the quadriceps muscle in figure 15.

The frequency components of the EMG (figures 16,17) during the fatiguing contractions, showed a similar response. The EMG frequency here was normalized in both figures in terms of the EMG center frequency during the MVC at that bath temperature,. In this manner relative changes in EMG center frequency could be tracked and compared from one bath temperature to the next since the baseline frequency started lower in the cooler baths as shown above in the series one experiments. The change in center frequency for the 3 warmest baths for both the handgrip (figure 16) and quadriceps muscle (figure 17) was similar, being reduced linearly during the fatiguing contractions by an average of about 25%. There was no difference between the response at different temperatures except for the coolest bath temperature for both the quadriceps and handgrip muscles. Here, after immersion in the 24 deg water, the center frequency was only reduced by 18%. The difference at the end of the contraction between the coolest and other three bath temperatures was significant ($p<0.05$).

The conduction velocity of the muscle action potentials was only calculated for the brief isometric contractions of all groups except the handgrip muscles. Here the arrangement of the muscle fiber sin the forearm made the assessment too difficult with surface electrodes. There was no statistical difference for the subjects between the MUAP conduction velocity and tension for any of the contraction tensions examined here when looking at a single temperature of immersion ($p>0.05$). However, the difference between the different baths was significant for all muscle groups ($p<0.01$). Figure 18 therefore only shows the mean conduction velocity for the biceps, gastrocnemius and quadriceps groups as an average for all tensions and after immersion at the 4 bath temperatures. As illustrated here, conduction velocity was highest after immersion in the warmest bath, averaging about 5 m/sec. The conduction velocity was linearly reduced after immersion in successively colder baths until, for the coldest bath it was reduced to about 2 meters/sec.

Discussion

The electromyogram has been extensively investigated in the last 30 years as a potential tool to determine the tension exerted by, and fatigue induced in skeletal muscle. However, while the EMG can be used successfully in many applications, there are a number of variables that influence the ability to use the EMG with reliability. Some of these have been identified and include electrode type, separation distance, size of the electrodes [54] , thickness of the subcutaneous fat layer [6, 34] and electrode placement in general.

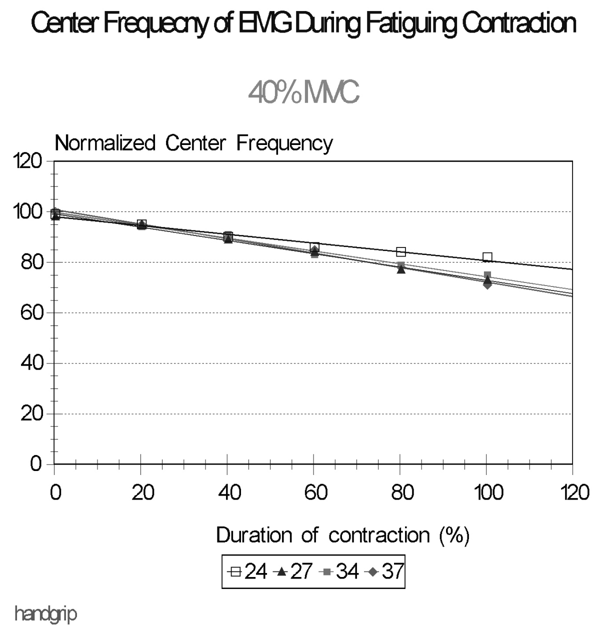

Figure 16. The RMS amplitude of the EMG recorded from the quadriceps muscles during a fatiguing isometric contraction exerted at a tension of 40% MVC in the 5 subjects. Each data point shows the mean of all subjects for EMG at 20, 40, 60, 80 and 100 % duration of the contractions. The contractions were accomplished on 4 separate days under 4 different bath temperatures of 24, 27, 34 and 37 deg. C.

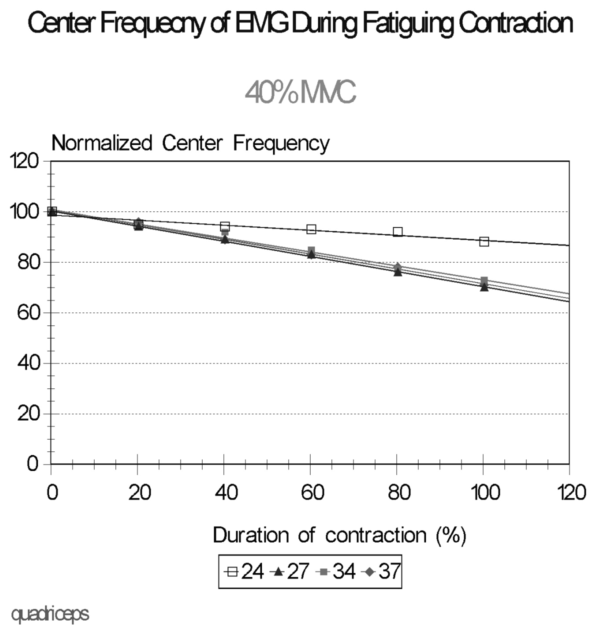

Figure 17. The Center Frequency of the EMG recorded from the quadriceps muscles during a fatiguing isometric contraction exerted at a tension of 40% MVC in the 5 subjects. Each data point shows the mean of all subjects for EMG at 20, 40, 60, 80 and 100 % duration of the contractions. The contractions were accomplished on 4 separate days under 4 different bath temperatures of 24, 27, 34 and 37 deg. C.

Other factors also have been identified such as motor unit recruitment strategies [19, 50] and age [35]. Clearly, three types of muscle contractions have been assessed using the surface EMG, isometric contractions, isotonic or phasic contractions and dynamic exercise. Each create a unique problems in terms of the analysis of the EMG. But unfortunately, irrespective of the type of exercise, the analysis is done the same in many cases and by many investigators.

EMG during dynamic exercise is the most difficult since the muscle is continually moving under the electrodes. EMG has been used to quantify muscle movement in activity such as snow skiing [55], roller skating [39], swimming [38], an activities such as bicycling [42] or walking [49]. This movement of the muscle under the electrodes, will in turn, alter the amplitude and frequency components of the EMG irrespective of tension and fatigue [6, 18, 19]. But in addition, these sports are all associated with sharp changes in muscle temperature. For example, during bicycling, the resting muscle temperature of the quadriceps muscles increases from 32 deg C at rest [57, 10] to as high as several degrees above core temperature (e.g. 39-40 deg. C). This increase in temperature will in turn have its own effect on the surface EMG irrespective of fatigue. Kiernan et al (2001) studied the effect of temperature at the wrist after immersion in water baths at various temperatures on the excitability of nerves and found that cooling increased the relative refractory period by 7.8% per degree C. The rate of accommodation to a stimulus was inversely related to the temperature of the motor nerve as was conduction velocity. In animal skeletal muscle, Gossen et al (2001), found that the amplitude of the motor unit action potential was constant or decreased slightly in 28-37 deg C muscle but increased at cooler temperatures (10 deg C). The rise and fall time fo the action potentials was increased in the cooler temperatures. Herve et al (1992) showed that cardiac action potentials in squirrels slowed in conduction and the plateau widened from 38 to 24 deg C and then became lower in amplitude and shorter in duration below this temperature. They concluded from voltage clamp studies in the guinea pig and squirrel cardiac cells that the temperature dependence was due to a temperature sensitive Ca^{++} release in the sarcoplasmic reticulum and not the Na^{+} or K^{+} channel activity. This same reduction in conduction velocity of action potentials with temperature has been observed in man [36]. Since the amplitude of the surface EMG is largely unaffected by muscle temperature, the large changes in muscle temperature that occur during dynamic exercise are not a major problem in using the amplitude of the EMG to analyze muscle function; assuming other variables can be controlled. But using the frequency components of the EMG as a predicator of fatigue certainly suffers from temperature related reliability issues. A typical scenario

Conduction Velocity of MUAP

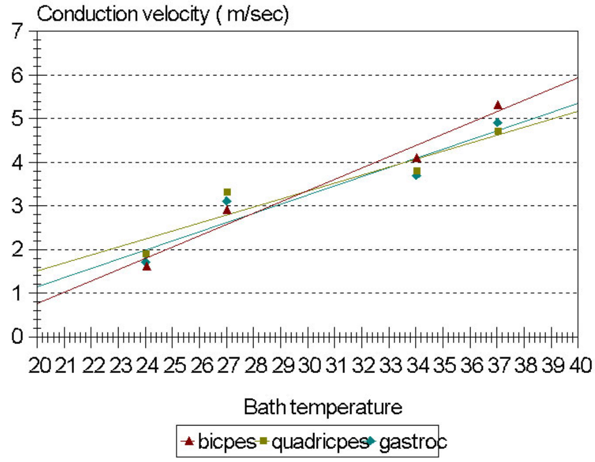

Figure 18. The Motor Unit Action potential conduction velocity measured in the handgrip, biceps, quadriceps and gastrocnemius muscles during brief isometric contractions at 4 different bath temperatures.

would be for muscle to start work at a temperature of at 30 deg. C and then to warm to 37 deg C during the first few minutes of exercise; here the center frequency would increase due to temperature and decrease if there was any fatigue. The result may be an actual increase in center frequency in particularly fatigued muscle. During very heavy work, while the center frequency should decline, much of that decline would be masked by a further increase in muscle temperature due to the additional warming of the muscle above that of core temperature from the muscle contraction itself.

For phasic contractions or isokinetic contractions many of the same arguments would follow. Here the muscle would still be changing length but in between the contractions muscles would warm, although perhaps not as much, due to the perfusion of blood in between the contractions.

For isometric exercise, the change in flow and temperature during the exercise is modest (less than .2 deg C) [10]. But the initial temperature of muscle may range from 28 deg C to 37 deg C depending on prior activity and the clothing won on the arms or legs. If the actual frequency of the EMG was used as an index of fatigue, there would be no way of knowing how fatigued the muscle was. But using a change in the center frequency as done here, would be reliable since the center frequency decreases by about the same relative amount as fatigue ensues. Kiernan et al (2000) cooled and heated muscle with hot packs and, while the actual muscle temperature was not determined, found no change in EMG amplitude for a given force of contraction irrespective of the temperature of the muscle. They did, however, show that the small high frequency components of the EMG disappeared after cold pack application.

Of interest was the relationship between the center frequency change in relation to muscle temperature vs. the change in conduction velocity. For all three muscles here, the reduction in conduction velocity with temperature paralleled the reduction in the center frequency of the EMG, again pointing to the argument that the reduction in the EMG center frequency really reflects a change in MUAP conduction velocity.

One difference between this and other studies is the linearity at each temperature between the tension exerted in the muscle and the amplitude of the surface EMG. But here, EMG was used to control muscle substitution. If other muscles are substituted and used to help the contractile forces at a joint, then the tension exerted would not be reflected in the EMG from one muscle alone. This may account for the non linearity's seen between EMG and tension in many studies. The same hold's for the relationship between frequency and tension.

Many studies have reported that the center frequency of the EMG spectrum or power spectrum was the same at all tensions during contractions of the underlying muscle. Others report increased in the center frequency at either low or high tensions. This may be due to substitution of other muscles. The frequency of the surface EMG has been related to be affected by recruitment properties of the motor units as well as the percent of fats and slow twitch motor units under the electrodes. By substituting in other muscle groups, there may be an effect on the alpha motor neuron pool through reflex inhibition that alters the recruitment properties and hence the frequency components of the EMG.

The lack of effect of temperature on muscle strength throughout the physiological range of temperatures is not new. It has been reported previously by others [10] and by ourselves [41]. In isolated tissue studies in animals strength in both fast and slow twitch muscle in the cat was unaffected by temperature within this same range of temperatures [43]. While muscle studies do report an increase in twitch tension as muscle is cooled from 37 to 31 deg C [58], even in cardiac muscle, the total titanic tension is constant over a wide range of temperatures. In cardiac muscle, the reduction in temperature had no effect on the strength of actin and myosin cross bridges, it only caused the bridges to be in place longer, increasing twitch tension [58]. There was no increase in Ca^{++} content of muscle as temperature was reduced.

The adductor pollicis muscle in man, when cooled from 38 to 28 deg C and stimulate with electrical stimulation also showed little effect of titanic strength by temperature. Below this temperature maximum strength was rapidly reduced [14]. The same results were seen in the human quadriceps by Gerrits et al (2000) while half relaxation time was inversely related to muscle temperature.

One final comment lies in the linearity observed here in the relationship between the amplitude of the EMG for brief and linear changes in center frequency and EMG amplitude for sustained isometric contractions. Here, care was taken to assure no muscle substitution could occur. This in itself may account for the differences in many studies which do report non linearity's. It is easy to substitute other muscle groups in exercise [26]. Therefore, EMG may not accurately reflect muscle use when muscle can be substituted.

What this study does support is the use of the amplitude of the EMG during brief dynamic or isometric exercise to assess the degree of muscle involvement even over a wide range of environmental conditions. For a study of muscle fatigue, for isometric contractions, the center frequency of the EMG is still a powerful tool. But for phasic or dynamic exercise where muscle temperature changes a great deal, it is hard to quantify fatigue without first warming the muscle to core temperature and then starting the study. Caution should be taken especially in cold environments. At the coolest muscle temperatures, the change in center frequency in fatiguing work was less than that reported for warmer temperatures. This may be due to neuromuscular junction failure at the cooler temperatures as suggested by Clarke et al (1958) or simply a lack of energy supply to sustain the exercise due to cooling of aerobic enzymes in the cell. Whatever the cause, these temperatures (24 deg C) are normally below normal physiological temperatures but could occur when a person is exposed to cold environments. Here the use of EMG for quantifying fatigue or muscle use may be in question; for most physiological conditions, EMG amplitude bears as a good measure of muscle use given restrictions on electrode placement and other considerations given above.

Address correspondence to:

Dr. Jerrold Petrofsky, Professor and Director of Research, Department of Physical Therapy, Loma Linda University, Loma Linda California, tel. 909 798 4240, Email jerry-petrofsky@sahp.llu.edu

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