Combined effect of repetitive work and cold on muscle function and fatigue

Oksa, Juha, Michel B. Ducharme, and Hannu Rintamäki. Combined effect of repetitive work and cold on muscle function and fatigue. J Appl Physiol 92: 354–361, 2002.—This study compared the effect of repetitive work in thermoneutral and cold conditions on forearm muscle electromyogram (EMG) and fatigue. We hypothesize that cold and repetitive work together cause higher EMG activity and fatigue than repetitive work only, thus creating a higher risk for overuse injuries. Eight men performed six 20-min work bouts at 25°C (W-25) and at 5°C while exposed to systemic (C-5) and local cooling (LC-5). The work was wrist flexion-extension exercise at 10% maximal voluntary contraction. The EMG activity of the forearm flexors and extensors was higher during C-5 (31 and 30%, respectively) and LC-5 (25 and 28%, respectively) than during W-25 (P < 0.05). On the basis of fatigue index (calculated from changes in maximal flexor force and flexor EMG activity), the fatigue in the forearm flexors at the end of W-25 was 15%. The corresponding values at the end of C-5 and LC-5 were 37% (P < 0.05 in relation to W-25) and 20%, respectively. Thus repetitive work in the cold causes higher EMG activity and fatigue than repetitive work in thermoneutral conditions.

THE EFFECTS OF SUBNORMAL MUSCLE temperature and fatigue on human muscle function have been found to be very much alike (6): both decrease maximal muscle force and increase time to peak tension (TPT) and relaxation time (RT) (5, 7). With subnormal muscle temperatures, more muscle fibers must be recruited to successfully perform a given work output (14). Similarly, fatiguing muscle has to recruit more fibers to maintain the required force level (18). The effect of decreased muscle temperature and fatigue may be seen as increased amplitude of surface electromyogram (EMG) (9, 27).

Literature reports that, during high-intensity dynamic work, fatigue is developed earlier when muscle temperature is lowered (4). However, literature does not report how low-intensity repetitive work and cold together affect muscle function, EMG activity, and fatigue. Because overuse injuries and musculoskeletal disorders are a worldwide problem, especially in industries where repetitive work and cold are combined [e.g., food processing industry (23)], it is important to more accurately identify the risk that the combined effect of cold and repetitive work may produce. If the combination of low-intensity repetitive work and cold accelerates the onset of fatigue, as we hypothesize on the basis of previous results with high-intensity work (4), they may increase the risk for overuse injuries and, in the long run, induce musculoskeletal disorders (8).

The possible additive effects of cold and repetitive work should be seen as increased amplitude of surface EMG. This could be caused by increased excitability of the motoneuron pool [reflected by increased amplitude of short-latency (SL) and medium-latency (ML) components of stretch reflex, i.e., reflex regulation of force production] and/or increased neural drive from the central nervous system [increased amplitude of long-latency (LL) component of stretch reflex, i.e., central force regulation]. The mechanisms underlying the effects of cold on muscle function may be many; e.g., the effect of cold air on human skin can increase the number of motor units recruited (32), motor unit recruitment pattern may be altered (14), or increased antagonist activity due to cold has to be balanced with increased agonist activity (2, 25).

We hypothesize that, compared with the thermoneutral condition, during local and systemic cold conditions, EMG activity in the forearm muscles is higher for a given level of work. During local cooling, this is due to increased reflex activity; however, during systemic cooling, increased neural drive from the central nervous system will also be required.

Our specific questions are as follows: 1) In relation to the thermoneutral condition, what is the level of EMG activity and fatigue in the forearm muscles during repetitive work during exposure to systemic and local cooling? 2) Are the possible changes in forearm EMG activity and fatigue associated with changes in peripheral or central force regulation?

MATERIALS AND METHODS

Subjects. Eight healthy, nonsmoking men volunteered as test subjects for the study. Their (mean ± SD) age was 31 ± 6 yr, mean body height was 176 ± 6 cm, mean body mass was
72 ± 9 kg, and mean skinfold thickness of biceps, triceps, subscapularis, and crista iliaca was 31.2 ± 6.7 mm (mean body fat 14 ± 3%). All subjects were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination, each subject gave written informed consent. The experimental protocol was approved by the Human Ethics Committee of the Defence and Civil Institute of Environmental Medicine. The subjects were asked to abstain from exhaustive exercise and the consumption of caffeine and alcohol for 12 h before the experimental sessions.

Thermal exposures and temperature measurements. Each subject was exposed once to 25°C (thermoneutral control) and twice to 5°C. During each exposure, the subjects performed six 20-min work bouts. In the control condition at 25°C, the subjects were dressed with a T-shirt, shorts, and jogging shoes. In this trial, the body and arms of the subjects were maintained at thermoneutrality (W-25). The first exposure at 5°C aimed at having the whole body cooled to an average skin temperature 5–8°C lower than in the W-25 condition, in addition to subnormal muscle and skin temperatures from 14 different sites (forehead, chest, scapula, abdomen, lower back, upper arm, flexor and extensor side of the lower arm, hand, wrist joint flexor (flexor carpi radialis muscle) and skin on the face (cheek, forehead, nose), and on the trunk (front thigh, back thigh, calf, shin, and foot; model 400, Yellow Springs Instrument, Yellow Springs, OH) capable of measuring the force produced by the maximal flexion of the wrist. The strain gauge was fixed to the floor and connected to a printer (model TA 2000, Gould, Duluth, MN). The forearm was fixed to the armrest of the chair, so that only the motion of the wrist joint was allowed. The maximal force level, TPT (the rise of force from resting level to maximum value), and RT (restoring the force from maximum to resting level) were analyzed from the MVC data. A decrease in the MVC was considered a sign of muscle fatigue. During each condition, the subjects performed 10% MVC wrist flexion-extension repetitive work in the same position in which the MVC was measured. This workload was chosen because it is recommended that during dynamic work, which lasts ≥1 h, the load corresponding to 10% MVC should not be exceeded (16). The subjects performed six 20-min work bouts for a total work period of 120 min in each condition. Between each work bout, there was a period of ~1 min during which the MVC and reflex (see Stretch reflex) measurements were performed. The proper load corresponding to 10% MVC was applied to the wrist joint with the same pulley system used for the MVC measurements. Starting with their wrist fully extended, the subjects flexed their wrist every 3rd s to the full free range of joint motion and returned their hand to the starting position. These dynamic concentric- eccentric contractions were paced with a light that flashed every 3rd s. At the beginning of the first and at the end of each work bout, EMG activity from the four forearm muscles was measured for 30 s.

Electromyography and fatigue index. To evaluate the level of muscle activity during work, surface EMG activity (model ME3000P8, Mega Electronics, Kuopio, Finland) was measured from the wrist flexors (flexor carpi radialis and flexor digitorum superficialis muscles) and wrist extensors (brachioradialis and extensor carpi radialis muscles). The EMG signals from the skin above the working muscles were acquired with a sample rate of 2,000 Hz with the use of pregelled bipolar surface electrodes (M-OO-S, Medicotest, Ølstykke, Denmark). The electrodes were placed over the belly of the muscle, and the distance between recording contacts was 2 cm. Ground electrodes were attached above inactive tissue. To ensure the constant location of the electrodes on the skin over the three conditions, their initial locations were carefully marked on the skin with permanent waterproof drawing ink. The markings were clearly visible throughout the experiments. The measured EMG signal was amplified 2,000 times (preamplifier situated 6 cm from the measuring electrodes), and the signal band between 20 and 500 Hz was full-wave rectified and averaged with a 10-ms time constant. To assess the frequency component of the EMG, the power spectrum was estimated by moving fast Fourier transform (FFT window, 512 points). From the power spectra, mean power frequency, median frequency, and zero crossing rate were calculated to describe changes in the frequency component. The EMG data were analyzed separately for concentric (wrist flexion) and eccentric (wrist extension) muscle contraction, these two phases being clearly distinct from each other (Fig. 1A). In RESULTS, EMG data from the two flexor and two extensor muscles are presented as means. The second variable used to define the level of fatigue was the fatigue index (FI), which consisted of changes in wrist flexion MVC and the amplitude of surface EMG from wrist flexion MVC.
where MVC0 min is MVC at the beginning of the exposure (N), MVC120 min is MVC at the end of the exposure (N), EMG0 min is the average EMG of wrist flexors at the beginning of exposure (µV), and EMG120 min is the average EMG of wrist flexors at the end of exposure (µV) (24). When FI = 1.0, fatigue is not apparent. The higher FI is above 1.0, the greater is the fatigue. The fatigue in this study is expressed as a percentage. At W-25, the FI is the difference between 1.0 (no fatigue) and the FI calculated from the results obtained at W-25. The FIs calculated from the results obtained at C-5 and LC-5 are compared with the FI obtained at W-25.

**Stretch reflex.** To evaluate whether the possible changes in muscle activity (changes in amplitude of surface EMG) were peripherally or centrally mediated, stretch reflex responses from the forearm flexors were measured at the beginning of the first and at the end of each work bout.

A stretch reflex was evoked by inducing a sudden displacement of the wrist joint (a pull to the handle the subjects were holding in their hand by a solenoid-driven motor; Gjardian Electric, Chicago, IL) with the forearm supported in the position described above. The pull was 1.6 cm, and the distance was covered in 0.3 s. The reflex was elicited 10 times within 30 s during each measurement session, with the last 7 being analyzed. Every time the solenoid motor started its displacement, a signal was simultaneously sent to the EMG device to mark the starting point of the pull for determination of the latency of the SL, ML, and LL components of the reflex response. In addition to reflex latencies, the maximum amplitudes (from baseline to peak, baseline being the activity before the stretch, see example in Fig. 1B) of SL, ML, and LL responses were analyzed.

SL and ML components are thought to reflect changes in the reflex regulation (peripheral) of force production. An LL component is thought to travel through a supraspinal pathway and to reflect changes in the neural drive from the central nervous system (12, 21). An increase in the amplitude of the SL or ML component is considered to reflect increased excitability of the motoneuron pool (3). Similarly, an increase in the amplitude of the LL component is thought to reflect an increased neural drive from the central nervous system (12, 21).

**Forearm blood flow.** At the beginning of the first, in the middle of the fourth, and at the end of the last work bout, forearm blood flow was measured using venous occlusion plethysmography (Totalab 400, Hokanson, Bellevue, WA) according to the method of Whitney (31).

**Statistics.** Analysis of variance with repeated measures was used. When a significant F ratio was observed, one-way analysis of variance with a Duncan’s post hoc test was applied, and significance was accepted at P < 0.05. The results obtained from the two cold conditions were tested against the thermoneutral reference value (value at 0 min in the beginning of the 1st work bout at W-25) and against thermoneutral data at the same time of exposure. Values are means ± SE.

**RESULTS**

**Thermal responses.** Tsk was only slightly affected by the thermal exposures, the highest value being 37.2 ± 0.1°C at the beginning of W-25 and the lowest 36.8 ± 0.2°C (P < 0.05) at the end of C-5. Despite a significant decrement, rectal temperature during the three exposures were considered to be at thermoneutrality (20). Tsk was 33.2 ± 0.2°C during W-25 and did not change significantly over the duration of the exposure. Exposure to C-5 decreased Tsk from a starting value of 32.2 ± 0.2°C to 30.3 ± 0.3°C (P < 0.05) after the first 20-min work period. Tsk continued to steadily decrease and reached its lowest value of 27.8 ± 0.3°C at the end of C-5. This final value at C-5 is 5.4°C lower than during W-25, and thus the aim of having the whole body cooled to an average skin temperature 5–8°C lower (than at W-25) was achieved. However, it is probably more appropriate to compare the final C-5 value with the initial C-5 value, and then the difference in Tsk is 4.4°C, which is slightly less than the aim (5–8°C).

During LC-5, the initial Tsk of 33.3 ± 0.3°C significantly decreased to 32.5 ± 0.3°C (P < 0.05) after the fifth work bout at 100 min and to 32.2 ± 0.3°C by the end of LC-5. Tsk during LC-5 differed significantly from that during C-5, but not from that at W-25.

The local skin temperature (average during each exposure) at the forearm flexor side was significantly
different \((P < 0.05)\) between each exposure: 34.3 ± 0.2, 27.8 ± 0.2, and 29.3 ± 0.1°C at W-25, C-5, and LC-5, respectively. At the extensor side, the corresponding values were 33.2 ± 0.2, 25.6 ± 0.5, and 25.0 ± 0.4°C. The values at C-5 and LC-5 were significantly lower than at W-25 \((P < 0.05)\) but did not differ from each other.

Muscle temperature increased due to the work bouts but remained \(\sim 2.0–4.5°C\) lower during C-5 and LC-5 (Fig. 2). The mean temperature gradient between 1.5- and 0.5-cm depths was greatest \((2.9 \pm 0.1°C)\) at C-5. The respective gradients for W-25 and LC-5 were 0.8 ± 0.2 and 2.3 ± 0.1°C, respectively. The average muscle temperatures at 1.5 cm were 35.3 ± 0.8, 32.8 ± 0.6, and 32.6 ± 0.8°C during W-25, C-5, and LC-5, respectively. The corresponding values for average muscle temperatures at 1.0 cm were 35.0 ± 0.8, 31.8 ± 0.5, and 31.9 ± 0.8°C. The average values at 0.5 cm were 34.5 ± 0.8, 30.0 ± 0.6, and 30.3 ± 0.8°C. The average muscle temperatures at C-5 and LC-5 did not differ from each other but were significantly \((P < 0.05)\) lower than at W-25.

MVC, TPT, and RT. The maximal isometric wrist flexion force decreased significantly after the first 20-min work bout during C-5 and LC-5 in relation to the thermoneutral reference value (Table 1). The MVC values during C-5 and LC-5 did not differ significantly from each other.

TPT varied between 150 and 240 ms and RT between 120 and 230 ms, but no significant differences were found between the conditions.

FI and electromyography. The FI was 1.15, 1.82, and 1.44 at the end of W-25, C-5, and LC-5, respectively. Expressed as a percentage, repetitive work at W-25 caused 15% fatigue of the forearm flexors (FI = 1.15 is related to the time point at the beginning of W-25; where there is no fatigue, FI = 1.0). In relation to FI at W-25 (1.15), the FIs at C-5 and LC-5 were 37% \((P < 0.05)\) and 20% higher, respectively. The difference between C-5 and LC-5 is not significant.

During the concentric contraction, the EMG activity of the forearm flexors and extensors was significantly higher (i.e., increased coactivation) during C-5 and LC-5 in relation to thermoneutral activity (Fig. 3). During the eccentric contraction, the EMG activity of the forearm flexors was significantly higher in C-5, and the activity of the extensors was higher at the beginning of the first work bout in relation to thermoneutral activity (Fig. 4). There were no significant differences between C-5 and LC-5. No significant changes in the frequency components of the EMG were observed.

Stretch reflex. The latencies of SL, ML, and LL responses were slightly higher (not significant) during C-5 and LC-5 than during W-25. The average SL values were 31.6 ± 0.5, 32.8 ± 0.8, and 33.1 ± 0.8 ms during W-25, C-5, and LC-5, respectively. The corresponding ML values were 65.7 ± 0.6, 69.2 ± 0.9, and 68.1 ± 1.3 ms. For average LL latencies, the values were 103.5 ± 0.6, 106.0 ± 1.1, and 106.4 ± 1.3 ms.

The amplitude of the SL and ML responses was higher or had a tendency to be higher during C-5 and LC-5 than during W-25. However, the amplitude of the LL response was higher or had a tendency to be higher only during C-5 (Fig. 5). There were no significant differences between C-5 and LC-5. The average SL amplitudes were 418 ± 15, 516 ± 16, and 434 ± 15 μV during W-25, C-5, and LC-5, respectively. The corresponding values for the average ML amplitudes were 418 ± 15, 516 ± 16, and 434 ± 15 μV and for average LL 136 ± 5, 188 ± 8, and 138 ± 7 μV, respectively.
Forearm blood flow. In relation to W-25, forearm blood flow during C-5 was significantly lower throughout the experiment. During LC-5, blood flow was significantly lower after 65 min of exposure (Table 2). There were no significant differences between C-5 and LC-5.

DISCUSSION

This study focused on comparing the force-generating capability, EMG activity, and fatigue of the forearm muscles during low-intensity repetitive work in thermoneutral and cold conditions. The main results indicate that, compared with repetitive work in the thermoneutral condition, repetitive work in the cold causes enhanced muscle EMG activity, increased level of coactivation of the agonist-antagonist muscle pairs, and enhanced fatigue of the forearm muscles.

During all exposures, the work done by the forearm muscles increased the muscle temperature during the first 20–40 min of work, to reach a plateau that was maintained until the end of each condition. For all measuring depths, the plateau level was significantly higher for W-25 than for C-5 and LC-5. It has been suggested that if muscle temperature is below normal, the muscle perfusion for a given workload will be reduced (26). The present study supports this observation, since the blood flow was significantly lower during the two cold conditions than during the thermoneutral condition.

Changes in MVC force have conventionally been used as an indicator of muscle fatigue (17). It was observed in the present study that by the end of W-25 the MVC had decreased by 15%, while the same variable decreased by 26% and 17% for C-5 and LC-5, respectively. The other indicator of muscle fatigue, FI

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<th>Table 1. MVC of wrist flexion</th>
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<td>Time of Exposure, min</td>
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<td>0</td>
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Values are means ± SE in N; n = 8. MVC, maximal voluntary contraction; W-25, thermoneutrality (i.e., 25°C); C-5, systemic cooling at 5°C; LC-5, local cooling at 5°C. *Significantly different (P < 0.05) from W-25; †significantly different (P < 0.05) from W-25 at the same time of exposure.

Fig. 3. EMG activity of forearm flexors (A) and extensors (B) during concentric contractions. *Significant difference in relation to thermoneutral reference value (0 min at W-25). †Significant difference in relation to thermoneutral value at the same time of exposure. Values are means ± SE; n = 8.

Fig. 4. EMG activity of forearm flexors (A) and extensors (B) during eccentric contractions. *Significant difference in relation to thermoneutral reference value (0 min at W-25). †Significant difference in relation to thermoneutral value at the same time of exposure. Values are means ± SE; n = 8.
used in this study, showed changes similar to MVC: 37% and 20% higher (in relation to W-25) in C-5 and LC-5, respectively. The larger change in FI than in MVC could be attributed to the fact that the calculation of FI also takes into account the changes in the EMG activity of the working muscles. This is because increased EMG activity for a given work performance can also be considered an indicator of muscle fatigue (13). Because FI combines the changes in MVC and EMG activity of the muscles during work, it may be considered a more “true” indicator of muscle fatigue. However, regardless of which variable is used to indicate fatigue, the results show that the combination of repetitive work and cold is more harmful when the ability of the muscles to function is considered. Together, they clearly induce a higher level of fatigue and affect the force-generating capability and EMG activity to a greater degree than repetitive work only. If it is considered that the greater effort required to maintain a given level of work is a risk factor for musculoskeletal disorders, then these results clearly show that work and cold exposure together create a substantially higher risk than either creates alone.

It is also important to note that, according to the FI, at the end of C-5 the amount of fatigue was more than twice that during W-25. At the end of LC-5, the amount of fatigue was also much higher than at W-25, but the effect of local cooling in increasing the amount of fatigue was less than the effect of systemic cooling. This emphasizes the importance of keeping the whole body in a thermoneutral state during work in cold conditions.

An increase in the duration of TPT and RT after muscle cooling has been related to slowed ATP hydrolysis (15), slowed Ca$^{2+}$ release and uptake from the sarcoplasmic reticulum (19), and decreased Ca$^{2+}$ sensitivity of actomyosin (30). Because TPT and RT showed no change in this study, it may be possible that muscle biochemistry was not substantially altered during repeated muscle contractions in the cold. However, it is also possible that the decrease in muscle temperature induced by exposures to C-5 and LC-5 simply was not large enough to produce measurable changes in TPT or RT or that the measuring system was not sensitive enough.

In comparison to the thermoneutral condition, both cold conditions caused significantly higher levels of EMG activity in the forearm flexor muscles, thus reflecting significantly higher muscular effort. When only the forearm is exposed to cold (while the rest of the body was thermoneutral), the EMG activity in the forearm had a tendency to be lower than when the whole body was thermoneutral. It has been reported that reducing muscle temperature can increase the EMG activity of the working muscles (25, 28). However, because the muscle temperature was approximately the same between C-5 and LC-5, factors other than muscle temperature are responsible for the higher EMG activity during C-5 than during LC-5.

It has been shown that cooling of the skin could increase the recruitment of motor units (32) and in-

![Fig. 5. Peak to peak (PTP) amplitude of SL (A), ML (B), and LL (C) stretch reflex responses. *Significant difference in relation to thermoneutral reference value (0 min at W-25). †Significant difference in relation to thermoneutral value at the same time of exposure. Values are means ± SE; n = 8.](image)

<table>
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<tr>
<th>Table 2. Forearm blood flow</th>
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<th>65 min</th>
<th>115 min</th>
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<td>W-25</td>
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<td>10.1 ± 1.6</td>
<td>10.0 ± 1.1</td>
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<tr>
<td>C-5</td>
<td>6.5 ± 1.0*</td>
<td>5.2 ± 0.7†</td>
<td>4.6 ± 0.6††</td>
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<tr>
<td>LC-5</td>
<td>7.5 ± 0.8</td>
<td>8.2 ± 0.9*</td>
<td>7.4 ± 0.5*</td>
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Values are means ± SE in %/min; n = 8. *Significantly different (P < 0.05) from W-25; †significantly different (P < 0.05) from W-25 at the same time of exposure.
increase the excitability of the motoneuron pool (1). In the present study, the local skin temperatures in the forearm, in addition to $T_{sk}$, were lowest during C-5. It could be possible that the cutaneous afferent input to the spinal cord was more intense during C-5 than during LC-5, causing an increased recruitment of motor units (higher level of EMG), therefore being one mechanism causing the increased muscular effort. This assumption is supported by the stretch reflex results, where somewhat higher reflex activity was detected during C-5 than during LC-5, especially toward the end of the exposure. The same mechanism could be responsible for the higher EMG activity observed at LC-5 than at W-25.

The EMG results very clearly indicate that, during concentric contractions, the level of coactivation (i.e., increased EMG activity of flexor and extensor muscles) increases significantly during both cold conditions and remains elevated throughout the exposures. In the study of Rissanen et al. (29), a similar cooling-induced increase in the level coactivation of lower leg muscles was observed at the beginning of exercise. However, along with increasing the temperature of the working muscles (due to work), the coactivation gradually disappeared. This was not the case in this study, possibly because the muscle temperature during the cold conditions did not rise to a high enough level. It may be concluded that the increased efforts of the flexor muscles and the increased coactivation of the agonist-antagonist muscle pairs (induced by the increase in EMG activity of the extensor muscles during concentric contraction, the activity that has to be “overcome” by flexor activity) are mechanisms causing the enhanced fatigue of the forearm observed during both cold conditions.

The increases in latency of SL, ML, and LL responses have been related to slowed nerve and muscle conduction velocity (10). Slowed conduction velocity may result in an increased temporal summation leading to an increased EMG amplitude response of the following muscle contraction. The results of this study show that there is no statistically significant difference in the latencies of different components during W-25, C-5, and LC-5 exposures. Therefore, it may be assumed that slowed nerve and/or muscle conduction velocity was not responsible for the increased EMG activity during the cold exposures.

In the cooled condition, the amplitude of EMG may be affected by many other factors: cooling may modify the shape of the action potential, and cold skin and muscle may act as a low-pass filter. In this study, during both cold conditions the muscle and skin temperatures remained stable after the first 20-min work bout and the work was the same throughout the exposures. Still, a rising tendency during C-5 and LC-5 can be seen in the EMG activity of the forearm flexor muscles, especially during the concentric contraction. Because ambient temperature, muscle temperature, local flexor skin temperature, and work remain constant, it may be assumed that physiological, rather than methodological, factors are causing the increasing tendency of EMG in the cold conditions.

The peak amplitudes of SL and ML were higher or had a tendency to be higher during C-5 and LC-5 than during W-25. Because the constant stimulus (stretch) was able to induce an increased response in relation to W-25 (although not always statistically significant), it may be considered that these changes reflect increased excitability of the motoneuron pool and/or increased sensitivity of the muscle spindles due to the cold exposure (3). It may be considered that, to meet the cold-induced increased effect of the repetitive work, the EMG activity of the working forearm muscles is increased via reflex pathways.

The amplitude of the LL component during LC-5 remained at a thermoneutral level, indicating that the increased effort required by the working muscles during that exposure was met just by increasing the reflex activity of the forearm flexors. However, during C-5, the amplitude of LL was significantly higher by the end of the exposure. This indicates that, during C-5, increasing the reflex activity was not sufficient; additional increased drive from the central nervous system was required to maintain the level of work required by the experiment in the cold.

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