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Original Article

Intermittently Increased Repetitive Work Intensity and Neuromuscular Function in the Cold

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Abstract: This study evaluated whether cold-induced deterioration in neuromuscular function can be restored by intermittently increasing the workload. We examined the level of muscular strain, agonist-antagonist co-activation, the occurrence of EMG gaps and neuromuscular efficiency in wrist flexor and extensor muscles at 21°C (TN) and 4°C (C_{10}) with a 10%MVC workload. During second exposure to 4°C (C_{50}) the workload was increased every fourth minute to 50%MVC. The results indicated that muscular strain and co-activation was the highest and the amount of EMG gaps and neuromuscular efficiency the lowest at C_{10}. By intermittently increasing the workload at C_{50} we were able to reduce muscular strain and co-activation (p<0.05) and induce a trend like increase in EMG gaps and enhance neuromuscular efficiency in relation to C_{10} (NS). It may be concluded that intermittently increasing the workload, i.e. breaking the monotonous work cycle was able to partially restore neuromuscular function.

Key words: Cold exposure, Repetitive work, EMG, Co-activation, Neuromuscular efficiency, Intermittent work

Introduction

Overuse injuries and musculoskeletal symptoms and disorders are a worldwide problem causing individual suffering and substantial economic costs[1]. These problems are more pronounced in workplaces in which repetitive work and cold are combined than in work in which cold is absent[2–4]. For example, in food processing industry the incidence of muscular strain injuries has been reported to be 27% higher than in other professions[5].

One explanation for this difference may be that low-intensity repetitive work in the cold induces higher strain (seen as higher EMG activity) and fatigue and thus reduces the neuromuscular efficiency of the working muscles in comparison to the same work in thermo neutral conditions[6, 7]. Strain and fatigue can be as much as 30% higher in cold conditions[6] and it seems that women are more susceptible to the increased strain than men[8]. In simulated sausage packing work at 4 °C, the average muscular strain for women was 14% of maximal EMG activity (%MEMG), compared with 12%MEMG among men[8]. It has also been found that the level of agonist-antagonist co-activation during low intensity repetitive work or static work increases in cold conditions, thus increasing the strain and fatigue of the working muscles[6, 7, 9]. This is significant because fatigue has previously been considered a precursor for musculoskeletal symptoms and disorders[10].

Another potential explanation for the higher incidence of overuse injuries in the cold could be the fewer occurrences of EMG gaps (a short period, less than a second, of very low muscle activity or even rest). In the longitudinal

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study of Veiersted *et al.*[11] regarding chocolate manufacturing plant employees, future trapezius myalgia patients had a lower frequency of EMG gaps than nonpatients, and a regression analysis revealed that a low rate of EMG gaps predicted future patient status. Another study recently showed that exposing the subjects to cold air while either adequately or minimally clothed are both very effective ways of reducing the occurrence of EMG gaps[7, 12]. These two studies revealed that during low intensity repetitive work in the cold, the occurrence of EMG gaps was reduced on average by 38%. A lack of or a reduced amount of EMG gaps may reflect that the normal variation in fiber recruitment during muscle contraction has diminished and that only very low threshold fibers may be active throughout the work (the so-called Cinderella theory[13]), therefore possibly increasing the risk of overuse injuries and musculoskeletal complaints and symptoms[14].

In our previous study, we showed that occasionally increasing the intensity of repetitive work from low (10%MVC) to moderate (30%MVC) raised the amount of EMG gaps. Regardless of the higher total workload in 30%MVC condition the strain of the work was more evenly distributed, which was seen as lower EMG amplitude above the working muscles. In addition, the study indicated a reduced level of co-activation when workload was intermittently increased[12]. These results may be considered as encouraging in terms of lowering the level of fatigue and thus decreasing the risk of overuse injuries and musculoskeletal complaints and symptoms. However, it is not known whether 30%MVC is optimal or would a higher intensity induce even more beneficial effects. Therefore, the aim of this study was to evaluate whether the intermittent use of higher work intensity, 50%MVC, would induce beneficial effects on neuromuscular function. Our specific questions were: in relation to low intensity repetitive work (10%MVC) in the cold, does the intermittent use of 50%MVC work intensity:

1. lower the strain of the working muscles?
2. reduce the level of agonist-antagonist co-activation?
3. increase the amount of EMG gaps?
4. increase neuromuscular efficiency?

We hypothesize that increasing the work intensity intermittently will increase neuromuscular efficiency by distributing the work more evenly (lower strain), increasing the amount of EMG gaps and reducing the amount of co-activation so that their level and occurrence is closer to the responses observed during low intensity repetitive work in thermoneutral conditions.

Materials and Methods

Subjects

Eight female non-smoking subjects volunteered for the study. Their mean ± SD age was 30 ± 11 yr, height 165 ± 8 cm, weight 57 ± 25 kg and subcutaneous fat 30.6 ± 4.1%. All subjects were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination, each subject gave her written informed consent. The subjects were asked to abstain from exhaustive exercise and from the consumption of caffeine and alcohol for 12 h before the experimental sessions. All procedures were conducted according to the guidelines of the Declaration of Helsinki, and the experimental protocol was approved by the Ethics Committee of the Hospital district of Northern Ostrobothnia.

Thermal exposures and temperature measurements

The subjects were exposed once to 21 °C thermo neutral temperature (TN) and twice to 4 °C for two hours in each occasion. The 4 °C ambient temperature was chosen to represent actual circumstances in the food processing industry in Finland. The exposure to TN and the first exposure to 4°C consisted of wrist flexion − extension work performed at 10%MVC workload (C_{10}) (see *wrist flexion-extension work* below). During the second exposure to 4°C a 10%MVC workload was increased every four minutes to a 50%MVC workload (C_{50}). The exposures were separated by at least two days and performed in a random order. At TN the clothing used was t-shirt, trousers, socks and shoes with estimated thermal insulation of 0.8 clo[15]. At C_{10} and C_{50} the subjects were dressed in socks, shorts, jogging shoes, long-legged underpants, t-shirt and winter jacket (with right experimental hand sleeve cut off to keep the forearm exposed and available for measurements / all subjects were right-handed) mimicking the clothing used in the food processing industry, with the exception of the cut-off sleeve. The estimated thermal insulation of the clothing was 1.6 clo[15].

Rectal temperature (T_{re}, 10 cm depth) and skin temperatures from 10 different sites (forehead, chest, upper arm, extensor and flexor side of the forearm, back, palm, thigh, calf and foot) were continuously measured from the right side of the body by thermistor probes (YSI 400 Series, Yellow Springs Instruments, CO., Inc., Yellow Springs, USA) at one-minute intervals and recorded onto a data logger (Squirrel 1200, Grant, UK). Temperature probes were fixed to the skin with surgical tape. Mean skin temperature (T_{sk}) was calculated by weighing the local skin temperatures by representative areas according to Hardy and Dubois[16].We also analyzed local forearm skin temperature over flexor (T_{flexor}) and extensor ($T_{extensor}$) muscles.

Wrist flexion-extension work

The wrist flexion-extension work consisted of six 20-min work bouts with a two to three minute measurement break in between. The subject was seated with the hip and elbow angle adjusted to 90°. The armrest of the seat supported the relaxed forearm (alongside the torso). The subject held a handle in her hand (the handle and the palm of the hand were in a vertical position) and a metal wire running through a pulley system was attached to the handle. A load was fixed to the other end of the wire corresponding to either 10%MVC (maximal voluntary contraction force of the wrist flexors, see force measurement) or 50%MVC (Fig. 1). Starting with their wrist fully extended, the subjects flexed their wrist every third second to the full free range of joint motion and returned their hand back to the starting position. These dynamic concentric-eccentric contractions were paced by a metronome to a rate of 20 contractions per minute (contraction lasting for ca. 1 s every three seconds).

During the exposure to TN and C_{10}, the subjects performed continuous 10%MVC wrist flexion-extension repetitive work. This workload was chosen because it is recommended that during dynamic work lasting for one hour or more a load corresponding to 10%MVC should not be exceeded[17]. In the exposure to C_{50} the same work was performed with the exception that every fourth minute the workload was intermittently increased to 50%MVC and the subjects performed a double contraction (two consecutive wrist flexions to recruit higher threshold muscle fibers) in one second. The loads corresponding to 10% or 50%MVC were 2.1 ± 0.5 kg and 10.5 ± 0.7 kg, respectively.

EMG measurements

At the beginning of the first and at the end of each work bout, EMG activity from the four forearm muscles, wrist flexors (*m. flexor carpi radialis*, FCR and *m. flexor digitorum superficialis,* FDS) and wrist extensors (*m. brachioradialis*, BR and *m. extensor carpi radialis*, ECR), was measured for 30 s. The pre-gelled bipolar surface electrodes (Medicotest, M-OO-S, Denmark) were placed over the belly of the muscle, and the distance between recording contacts was 2 cm in accordance with recommendations of SENIAM[18]. Ground electrodes were attached

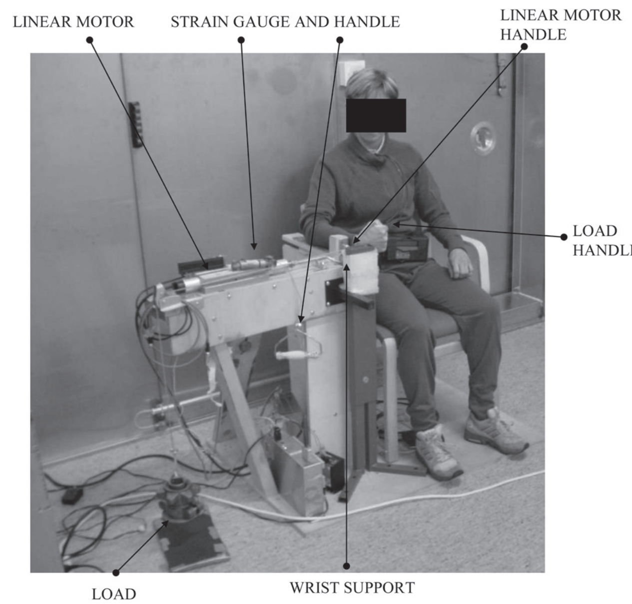

Fig. 1. Experimental setup.

above inactive tissue. To ensure proper attachment of the electrodes, skin hair was shaved and the skin was cleaned with alcohol. To assure the constant relocation of the electrodes in different exposures, their initial locations were carefully marked on the skin with permanent waterproof drawing ink. The markings were clearly visible throughout the experiments.

The EMG signals from the skin above the working muscles were acquired with a sample rate of 1,000 Hz. The measured signal was amplified 2,000 times (preamplifier situated 10 cm from the measuring electrodes) and the signal was band passed filtered between 20–500 Hz, full-wave rectified and averaged with a 0.1-s time constant. EMG gaps were analyzed according to the following criteria: EMG activity less than 10 µV (the resting muscle tension usually being in the order of 5 µV) for at least 300 ms. In addition, 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, we calculated mean power frequency (MPF) to describe changes in the spectral frequency component.

The EMG data was analyzed separately for concentric (wrist flexion) and eccentric (wrist extension) muscle contraction for amplitude (aEMG). These two phases have been found to be distinct from each other, the concentric phase showing clearly higher EMG activity in wrist flexors than the eccentric phase, thus making the differentiation and analyses of these phases possible already with visual inspection[6]. For other EMG parameters, the analysis was performed for the whole flexion-extension contraction. Only intraindividual comparison of EMG parameters was performed and therefore no normalization procedure was required. Since the results from the two flexor and extensor muscles were similar, their results are presented as mean in the results section.

With the aid of EMG data we were able to answer the first three specific research questions:

1. The less EMG activity there is during work in either the flexor or extensor muscle the less is the strain of that particular muscle.
2. This study regarded the wrist flexor as an agonist muscle and the extensor as an antagonist muscle. Co-activation is the EMG activity relation of these muscles. If the EMG activity of the antagonist muscle increased this was considered an increase in co-activation.
3. When the EMG activity in the wrist flexor or extensor muscle fell below 10 μV and lasted at least 300 ms, this was considered an EMG gap. The more frequent the occurrence of the gaps, the better it is for the muscle.

Stretch reflex

In order to evaluate whether the possible changes in muscle function are locally or centrally mediated, stretch reflex was measured from the wrist flexor muscles at time points 0, 60 and 120 min. These time points were chosen to interfere as little as possible with the effects of intermittently increased workload at C_{50}. The measurement was performed in the same posture as that in which the external work was carried out (Fig. 1). The reflex was evoked by inducing a sudden displacement of the wrist joint by a linear motor (LinMot P, Sulzer Electronics AG, Switzerland). The subjects held a handle in their relaxed hand and the wire leading from the handle was attached to the linear motor. The displacement, 4 cm in length and 40 ms in duration, was induced 12 times, the time lag between consecutive displacements varying from 0.5 s to 4.0 s. Every time the linear motor started its displacement a marker signal was simultaneously sent to the EMG device to mark the start of the stretch. The 12 responses were plotted over each other and averaged. From the average response we analyzed short latency stretch reflex amplitude and latency. The reflex was considered to have started when EMG activity deviated from baseline (constant around 5 μV) to above 10 μV. Latency was defined as time between the marker and onset of reflex response, and amplitude was measured from the lowest to the highest peak. To reduce sensory information and to enhance motor drive the sight and vision of the subjects were occluded and they had to hold a 2-kg weight in their free hand in a horizontal position.

Maximal isometric wrist flexion force

Before the start of the first work bout and at time points 45, 90 and 120 min, we measured maximal voluntary contraction (MVC) of the wrist flexors in the same posture as that in which external work was performed. These time points were chosen to interfere as little as possible with the effects of intermittently increased workload at C_{50}. Another handle was attached to a strain gauge (Newtest Inc, Oulu, Finland) capable of measuring the force produced by the maximal isometric flexion of the wrist. The strain gauge was fixed to a level placed at a right angle to the armrest (Fig. 1) and connected to a computer for further analysis. The forearm was fixed to the armrest of the chair and the wrist joint was supported by a vertical wooden support softened with rubber insulation. On request, the subjects performed a maximal isometric wrist flexion, and maximal force level was analyzed from the MVC data. A decrease in the MVC value was considered a sign of muscle fatigue.

Neuromuscular efficiency

To answer the fourth specific research question we assessed neuromuscular efficiency in the following way: The total workload (how many kilos each subject moved during each exposure) was divided by total EMG activity measured from the wrist flexors during the concentric phases of muscle contraction (altogether seven 30-s bouts).

This efficiency reflects the alteration in the neural drive required from the central nervous system in order to be able to perform the given amount of work in different conditions. The result is expressed as a mean of the whole exposure in arbitrary units. A high value indicates better neuromuscular efficiency i.e. less neural drive required.

Statistics

We used analysis of variance with repeated measures. When a significant F ratio was obtained, we applied one-way analysis of variance with Duncan's post hoc test, and significance was accepted at the $p<0.05$ level. The results obtained from the two cold conditions were tested against thermo neutral value at the same time point and between both cold conditions. Results are expressed as mean ± SE.

Results

All exposures induced similar reductions in rectal tem-

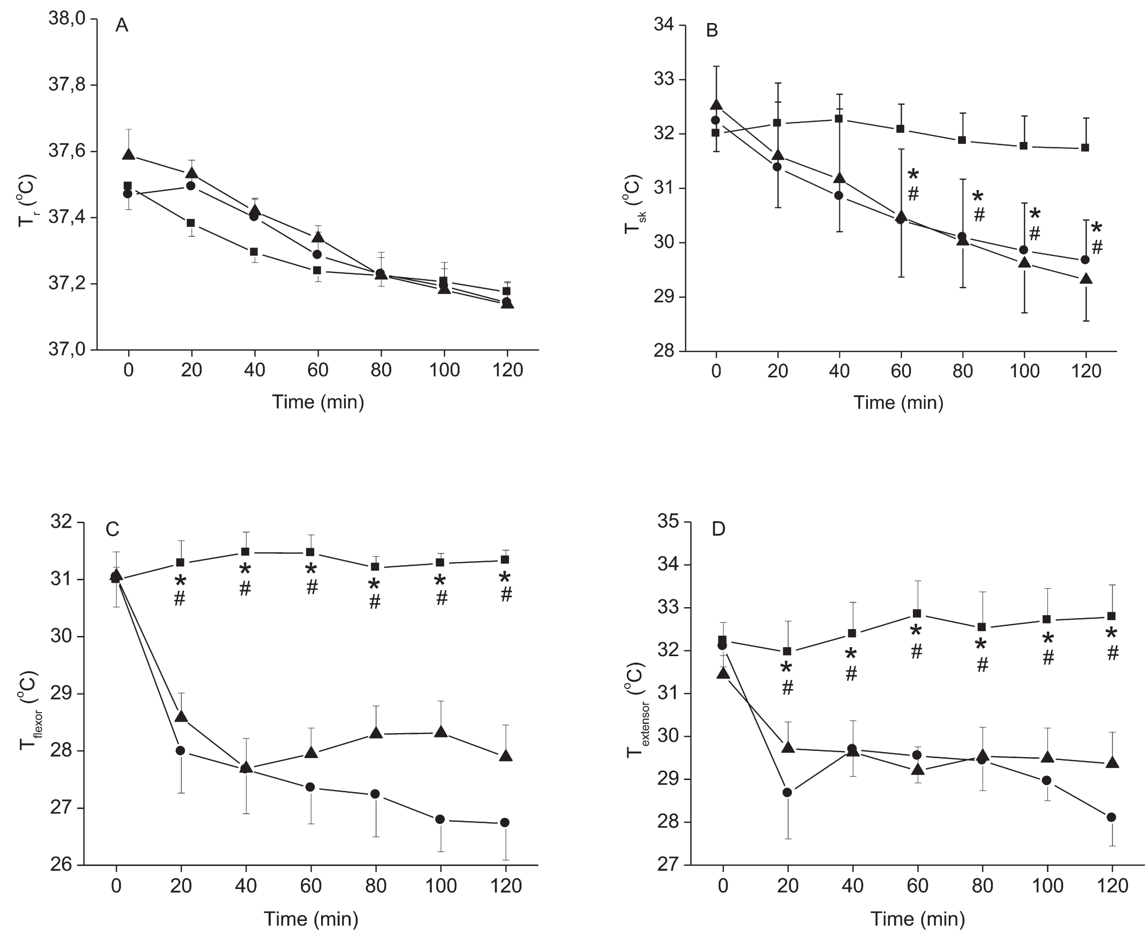

Fig. 2. Rectal temperature (A), mean skin temperature (B), local wrist flexor (C) and extensor skin temperature (D). Filled squares denote TN, triangles C_{50} and balls C_{10}. Significant difference ($p<0.05$) between TN and C_{10} is denoted by *, between TN and C_{50} by #.

perature, however T_r still remained at thermo neutral level. Mean and local skin temperatures decreased significantly during both cold exposures (Fig. 2).

The average total amount of work done at C_{50} was 11% higher than at TN and C_{10}, the absolute values being 4,950 ± 930 kg at TN and C_{10} and 5,508 ± 1,033 kg at C_{50} (NS).

In the wrist flexors the aEMG during the concentric phase was lowest at TN and equally high at C_{10} and C_{50}. In the wrist extensors, the aEMG was equally low at TN and C_{50} and the highest at C_{10} (Fig. 3A and B). During the eccentric phase there was no significant difference in the wrist flexor aEMG activity. However, the highest activity was found in wrist extensors at C_{10} (Fig. 3C and D). These results suggest smaller strain and increased co-activation of the agonist-antagonist muscle pair during wrist flexion-extension work at TN and C_{50} compared to that at C_{10}.

In the wrist flexors, the highest amount of EMG gaps was found at TN and the lowest at C_{10}. The difference was significant between TN and both C_{50} and C_{10} ($p<0.05$). In the wrist extensors the only significant difference was found between TN and C_{10} at the 20-min time point (Fig. 4A and B).

Neuromuscular efficiency was the lowest at C_{10}, intermediate at C_{50} and the highest at TN, the absolute values being 5.8 ± 0.3, 6.4 ± 0.4 and 8.0 ± 0.9, respectively, suggesting more economic muscle functioning at TN and C_{50}. We found a significant difference between the C_{10} and TN exposures ($p<0.05$).

Mean power frequency of the wrist flexor muscles was the lowest at C_{10} and equally high at C_{50} and TN. In the extensor muscles, MPF was again the lowest at C_{10} but highest at C_{50} while intermediate at TN (Fig. 5A and B).

Maximal wrist flexion force declined in a fairly similar manner regardless of exposure, in a trend-like fashion. However, it was the lowest at C_{10} at the end of the exposure (NS, Fig. 6).

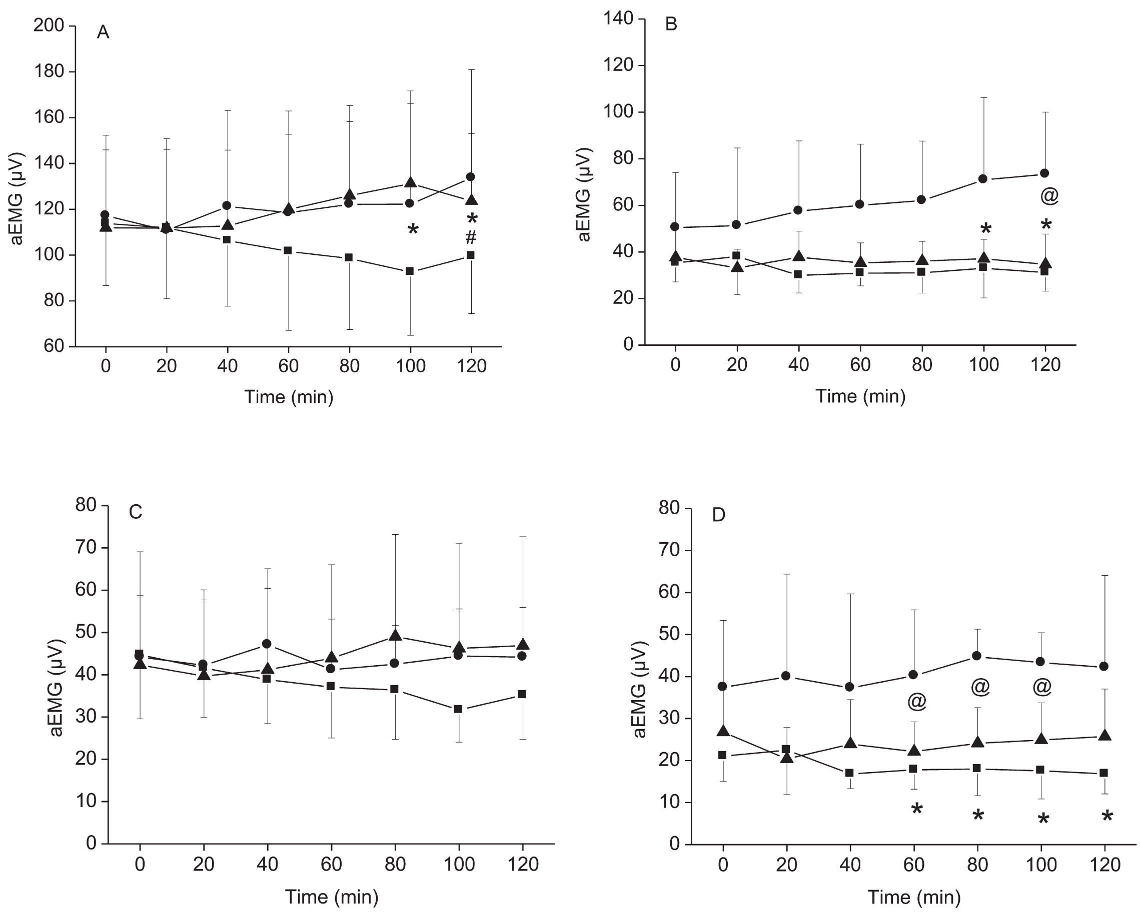

Fig. 3. Average EMG (aEMG) activity during concentric phase in wrist flexors (A) and extensors (B) and during eccentric phase in wrist flexors (C) and extensors (D). Filled squares denote TN, triangles C_{50} and balls C_{10}. Significant difference (p<0.05) between TN and C_{10} is denoted by *, between TN and C_{50} by # and between C_{10} and C_{50} by @.

The amplitude of the short latency stretch reflex response had the tendency to be lower at TN in comparison to C_{10} and C_{50} (Fig. 7). However, we observed no significant differences. Stretch reflex latency did not differ between the exposures.

Discussion

The results of this study point towards the possibility that, in relation to 10%MVC repetitive work only, intermittently increasing work intensity from 10%MVC to 50%MVC may enhance muscle function due to smaller muscle strain, cause a trend-like increase in neuromuscular efficiency and the amount of EMG gaps, and result in a reduced agonist-antagonist co-activation. Though the differences did not always reach statistical significance they may have beneficial physiological effects.

The cold exposures used in this study induced fairly similar thermal responses in rectal, mean skin and local skin temperatures. The only tendency for difference was observed in local skin temperature above the wrist flexor muscles, where slightly (NS) higher skin temperature was found at C_{50} (Fig. 2C). This may have been due to less severe vasoconstriction at C_{50}.

Regardless of higher absolute workload in C_{50} the aEMG activity in wrist flexors during the concentric and eccentric phases of muscle contraction (Fig. 3A and C) was similar between the cold exposures. This indicates that the neural drive needed to perform the given work was the same in both conditions and therefore, due to higher absolute workload, the neuromuscular efficiency had a tendency to be higher at C_{50} (6.4 ± 0.4) than at C_{10} (5.8 ± 0.3). This is supported by the findings that a decrease in maximal wrist flexion force and stretch reflex responses were also similar between the cold exposures (Figs. 5 and 6). If the use of higher workload at C_{50} exposure had induced more strain and fatigue to the wrist flexor muscles this would have been seen as higher aEMG[19, 20], a more

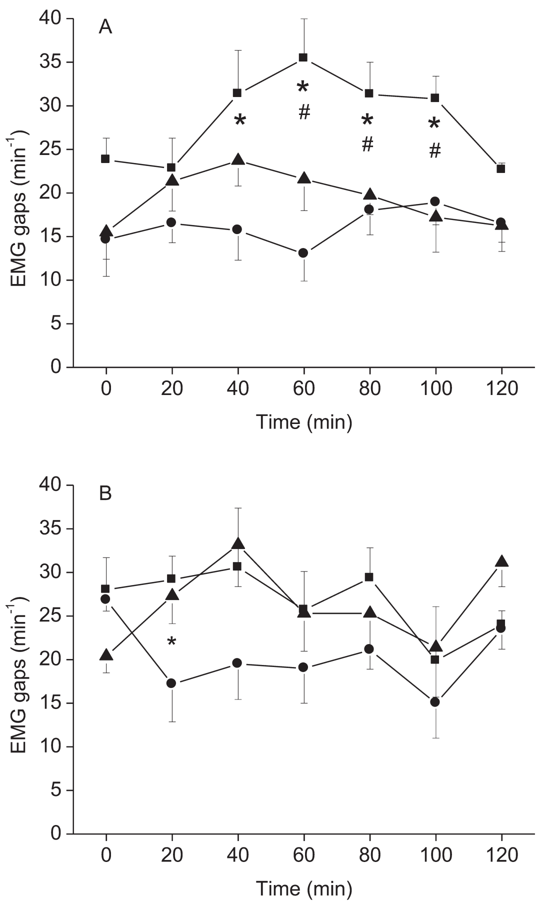

Fig. 4. Number of EMG gaps during flexion-extension contraction in wrist flexors (A) and extensors (B). Filled squares denote TN, triangles C_{50} and balls C_{10}. Significant difference (p<0.05) between TN and C_{10} is denoted by *, between TN and C_{50} by #.

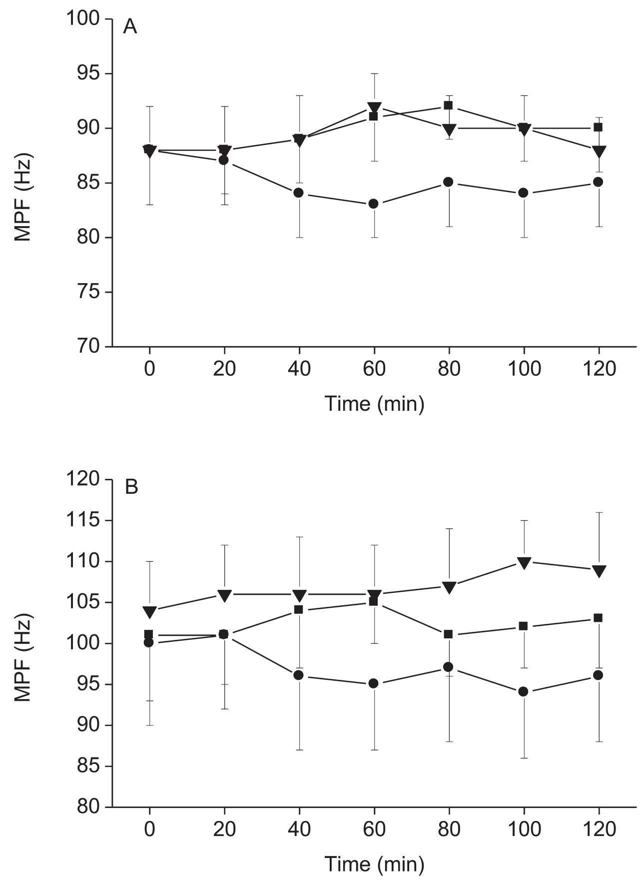

Fig. 5. Mean power frequency in wrist flexors (A) and extensors (B) during flexion-extension contraction. Filled squares denote TN, triangles C_{50} and balls C_{10}.

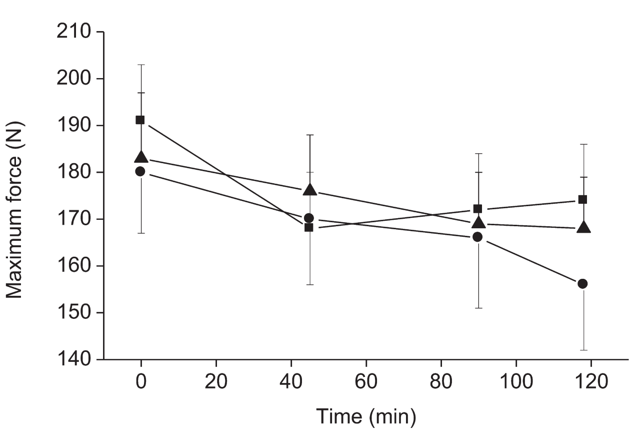

Fig. 6. Maximal isometric wrist flexion force. Filled squares denote TN, triangles C_{50} and balls C_{10}.

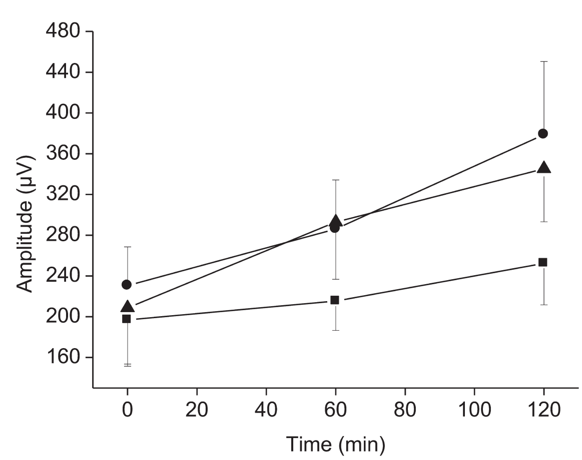

Fig. 7. Amplitude of short latency stretch reflex response of wrist flexor muscles. Filled squares denote TN, triangles C_{50} and balls C_{10}.

pronounced decrease in wrist flexion force[6], and eventually enhanced stretch reflex responses (indicating enhanced neural drive) as found in the previous study by Oksa *et al*.[6]. However, this not being the case, we suggest that the use of intermittent workload enhances the neuromuscular efficiency of the wrist flexor muscles.

Another important finding of this study is that the increased co-activation of the agonist-antagonist muscle pair observed during C_{10} exposure can be restored close to a thermo neutral level by using intermittently increased workload. Figures 3B and D show that the aEMG activity of the wrist extensors is the highest at C_{10} during the concentric and eccentric phases of muscle contraction, inducing a higher level of co-activation than that at C_{50} and TN. A clear-cut explanation for the increased co-activation in C_{10} may be difficult to find. One possible explanation could be the tendency for a lower occurrence of EMG gaps at C_{10}. This could indicate that the variation in fiber recruitment was less[21] and/or that the same fibers underneath the measuring electrodes were active more continuously at C_{10} than at C_{50} and TN, therefore, inducing higher aEMG amplitude at C_{10} and resulting in higher co-activation than at C_{50} and TN exposures. The assumption that at C_{10} there is less variation in the fiber recruitment may be supported by the finding that MPF in both the wrist flexor and extensor muscles was the lowest at C_{10}. The tendency for higher frequency at C_{50} and TN could indicate that fibers with higher firing frequency were recruited, but at C_{10} fibers with slower firing frequency were recruited and this was reflected as a smaller amount of EMG gaps.

Work in the cold may reduce the temperature of the working muscle tissue and slow nerve conduction velocity which in turn could be seen as a shift to lower frequencies in the frequency component of EMG[22]. The cold exposures used in this study induced similar thermal responses indicating that the intensity of the exposures was the same. Consequently, the level of cooling and the changes induced by this would be the same and therefore, the higher frequency response observed in C_{50} in relation to C_{10} may be due to the different recruitment pattern, as discussed above.

Increased co-activation during repetitive work in the cold has been found also previously during wrist flexion-extension work[6, 12] and simulated packing work[7]. In their study Oksa *et al*.[12] used similar intermittent work protocol in the cold (workload increased to 30%MVC every fourth minute) and the level of co-activation was also reduced due to the use intermittent work protocol. Based on their results and the results of the present study we may argue that in terms of reducing agonist-antagonist co-activation and therefore fatigue, it is beneficial to intermittently increase the workload to 30–50%MVC.

The occurrence of EMG gaps may be regarded as beneficial in terms of muscle function since it has been shown that the reduced amount of gaps may predict future patient status[11]. At both C_{50} and C_{10} exposures there were less EMG gaps than at TN. However, at C_{50} there was a tendency during both the concentric (Fig. 4A) and eccentric (Fig. 4B) phases of muscle contraction to exhibit a larger amount of EMG gaps (NS). The occurrence of EMG gaps in the study by Oksa *et al*.[12] while using 30%MVC intermittent workload was significantly more than those of this study. The difference may be due to the higher intermittent workload used in the present study and therefore, it may be concluded that in terms of EMG gap occurrence it is potentially more beneficial to use intermittent workload less than 50%MVC.

The study by Oksa *et al*.[12] indicated that intermittently increasing the repetitive work intensity to 30%MVC had beneficial effects on neuromuscular function. The present study with its 50%MVC intermittent work showed slightly different but also beneficial effects on neuromuscular function. It may be difficult to draw a final conclusion regarding how much the work intensity should be elevated in order to gain the most beneficial effects on neuromuscular function. However, based on both the previous[12] and the present study, it may be recommended that during low intensity repetitive work, the monotonous work cycle should occasionally be broken by increasing the work intensity for short periods, and that the change in intensity could be in the range of 30–50%MVC. In addition, it could also be beneficial for muscle functioning to increase the frequency or the duration of the change in intensity. However, this cannot be based on the present results and therefore remains speculation.

In conclusion, as regards to 10%MVC repetitive work only, the results of this study suggest that it may be beneficial to intermittently increase workload to 50%MVC.

References

1) Second European Survey on Working Conditions European Foundation for the Improvement of Living and Working Conditions 1996. Cat. No. SX-05–97-414-EN-Y, ISBN No. 92–828-0552–2. Office for Official publications of the European Communities, Luxembourg.
2) Chen F, Li T, Huang H, Holmer I (1991) A field study of cold effects among cold store workers in China. Arctic Med

Res **50**, 99–103.
3) Chiang HC, Ko YC, Chen SS, Yu HS, Wu TN, Chang PY (1993) Prevalence of shoulder and upper-limb disorders among workers in the fish-processing industry. Scand J Work Environ Health **19**, 126–31.
4) Yassi A, Sprout J, Tate R (1996) Upper limb repetitive strain injuries in Manitoba. Am J Ind Med **30**, 461–72.
5) Karjalainen A, Palo L, Saalo A, Jolanki R, Mäkinen I, Kauppinen T (2009) Recognised and suspected occupational diseases in Finland 2007. New cases in the Finnish Register of Occupational Diseases. Finnish Institute of Occupational Health, Helsinki (in Finnish).
6) Oksa J, Ducharme MB, Rintamäki H (2002) Combined effect of repetitive work and cold on muscle function and fatigue. J Appl Physiol **92**, 354–61.
7) Piedrahita H, Oksa J, Malm C, Sormunen E, Rintamäki H (2008) Effects of cooling and clothing on vertical trajectories of the upper arm and muscle functions during repetitive light work. Eur J Appl Physiol **104**, 183–91.
8) Sormunen E, Rissanen S, Oksa J, Pienimäki T, Remes J, Rintamäki H (2009) Muscular activity and thermal responses in men and women during repetitive work in cold environments. Ergonomics **52**, 964–76.
9) Bawa P, Matthews PBC, Mekjavic IBC (1987) Electromyographic activity during shivering of muscle acting at the human elbow. J Therm Biol **12**, 1–4.
10) Buckle P, Devereaux J (1999) Work-related neck and upper limb musculoskeletal disorders. Report of European Agency for Safety and Health at Work. Office for Official publications of the European Communities, Luxembourg.
11) Veiersted KB, Westgaard RH, Andersen P (1993) Electromyographic evaluation of muscular work pattern as a predictor of trapezius myalgia. Scand J Work Environ Health **19**, 284–90.
12) Oksa J, Sormunen E, Koivukangas U, Rissanen S, Rintamäki H (2006) Changes in neuromuscular function due to intermittently increased workload during repetitive work cold conditions. Scand J Work Environ Health **32**, 300–9.
13) Hägg G (1991) Static work and occupational myalgia − a new explanation model. In: Electromyographical Kinesiology, Andersson PA, Hobart DJ and Danoff JF (Eds.), Elsevier Science, Amsterdam.
14) Sjögaard G, Sögaard K (1998) Muscle injury in repetitive motion disorders. Clin Orthop Relat Res **351**, 21–31.
15) ISO 9920 (1995) Ergonomics of the thermal environment − Estimation of the thermal insulation and evaporative resistance of a clothing ensemble. International Standards Organisation, Geneva.
16) Hardy JD, DuBois EF (1938) The technic of measuring radiation and convection. J Nutr **15**, 461–75.
17) Jonsson B (1982) Measurement and evaluation of local muscular load in the shoulder during constrained work. J Hum Ergol (Tokyo) **11**, 73–88.
18) Hermens HJ, Freriks B, Merletti R, Stegeman DF, Blok J, Rau G, Disselhorst-Klug C, Hägg G (1999) European recommendations for surface electromyography. SENIAM 8, Roessingh Research and Development, Enshede (NL).
19) DeLuca CJ (1984) Myoelectrical manifestations of localized muscular fatigue in humans. CRC Crit Rev Biomed Eng **11**, 251–79.
20) Edwards RHT (1981) Human muscle function and fatigue. In: Human muscle fatigue: physiological mechanisms, Porter R and Whelan J (Eds.), Pitman, London.
21) Westgaard RH, De Luca CJ (1999) Motor unit substitution in long-duration contractions of the human trapezius muscle. J Neurophysiol **82**, 501–4.
22) Petrofsky J, Laymon M (2005) Muscle temperature and EMG amplitude and frequency during isometric exercise. Aviat Space Environ Med **76**, 1024–30.