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ORIGINAL ARTICLE

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# Motor unit action potential rate and motor unit action potential shape properties in subjects with work-related chronic pain

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**Abstract** The objective of this study was to investigate differences in motor control of the trapezius muscle in cases with work-related chronic pain, compared to healthy controls. Ten cases with chronic pain and 13 controls participated in the study. Electromyographic (EMG) signals were recorded from the upper trapezius during five computer work-related tasks. Motor control was assessed using global root-mean-square value ($RMS_G$), motor unit action potential (MUAP) rate (number of MUAPs per second, MR) and two MUAP shape parameters, i.e. root-mean-square ($RMS_{MUAP}$) and median frequency ($FMED_{MUAP}$). MR and $FMED_{MUAP}$ were higher for the cases than for the controls ($P < 0.05$). $RMS_{MUAP}$ showed a trend for higher values in the chronic pain group ($P < 0.13$), whereas $RMS_G$ did not show a significant difference between the groups. The higher MR, $FMED_{MUAP}$ and the trend for higher $RMS_{MUAP}$ suggest that more high-threshold MUs contribute to low-level computer work-related tasks in chronic pain cases. Additionally, the results suggest that the input of the central nervous system to the muscle is higher in the cases with chronic pain.

**Keywords** Chronic pain · Motor unit action potential rate · Surface EMG · Motor control

## Introduction

The prevalence of work-related disorders (WRD) has increased significantly during the last few decades. Since the majority of people with WRD are limited in their working abilities by chronic pain, this results in high costs for health care and society.

The mechanisms behind the development of chronic pain are poorly understood (Bongers et al. 2002b). The Cinderella hypothesis, which states that low-threshold motor units (MUs) are damaged due to lack of sufficient muscle rest (Hägg 1991), is a commonly used model related to work at low force levels. Some evidence for this hypothesis has been found. So-called Cinderella MUs (defined as MUs that stay active for periods of over 30 min without rest) have been reported by different authors (e.g. Thorn et al. 2002; Forsman et al. 2002; Zennaro et al. 2003; Søgaard 1995). Other authors found a decreased percentage of muscle rest, measured as gaps in the electromyogram (EMG), in chronic pain patients (Veiersted 1994; Hägg and Åström 1997). In another study, Veiersted showed that lack of gaps was a weak but significant predictor for the development of pain (Veiersted et al. 1993).

However, the Cinderella hypothesis does not explain *how* the low-threshold MUs are getting damaged. It can be hypothesised that the development of damaged MUs is either caused by, or at least accompanied by, changes in motor control. Assuming this, it is desirable to assess motor control in chronic pain cases in a direct and detailed way.

Usually, bipolar surface EMG is used for investigating motor control. However, extraction of motor control aspects from bipolar EMG is not straightforward since the EMG signal, which is measured with relatively large electrodes, consists of the summed activity of many MUs. More detailed information about single MUs can be obtained using needle electrodes. For example, Linnamo et al. (2003) used an index based on the number of motor unit action potentials (MUAPs) within different amplitude bands for describing the motor neuron pools during different contraction types. However, measuring EMG with needles is invasive, and only a few MUs contribute to the recorded signal, which limits the use of this method for assessing motor control.

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Recently, we have proposed the assessment of the number of MUAPs per second, or MUAP rate (MR), for investigating motor control (Kallenberg and Hermens 2004), since this parameter is directly related to the input of the central nervous system to the muscle. In addition to information about motor control, MUAP shape properties are provided by this method. The MUAP rate and MUAP shape properties can be assessed non-invasively with this method using multi-channel electrode arrays in combination with advanced signal processing methods (e.g. continuous wavelet transform).

The aim of the present work was to investigate differences in motor control between chronic pain cases and healthy controls during computer work-related tasks, using the MR and MUAP shape properties.

## Methods

### Subjects

This study was approved by the local medical ethics committee. All subjects gave their written informed consent.

EMG of the dominant upper trapezius from a control group ($n = 13$; 2 males, 11 females, mean age 38.9, range 20–54 years, mean body mass 67.5, range 55–80 kg, mean height 173.1, range 158–183 cm, mean body mass index 23.0, range 18.2–27.1 kg/m$^2$) and a case group ($n = 10$; 4 males, 6 females, mean age 36.1, range 24–51 years, mean body mass 71.2, range 57–86 kg, mean height 176.2, range 164–195 cm, mean body mass index 23.0, range 19.4–28.3 kg/m$^2$) was recorded during computer work-related tasks. All subjects were computer workers. Subjects were recruited from a local university and a local library. Their history of neck-shoulder complaints was assessed by means of a questionnaire (an adapted version of the Standardized Nordic Questionnaire, Kuorinka et al. 1987). Subjects were included in the control group if they did not have any self-reported complaints in the neck or shoulder region for at least 3 years. Subjects were included in the case group if they reported neck or shoulder complaints for more than 30 days during the last year. Furthermore, to be included, cases had to report that their complaints restricted their ability to work.

### General procedures

Five visual analogue scales (VAS) were used to measure the levels of stress and discomfort experienced in the arms, shoulders, neck and upper back before the experiment started. The protocol consisted of a unilateral dynamic hand task (referred to as the dots task), a typing task, an editing task, a mouse task and a stress task. The duration of each task was set to 5 min. During the dots task, subjects were asked to continuously move the dominant arm between three target areas by putting marks in circles with a diameter of 12 mm with a pencil (see Fig. 1). The pace was kept constant at 88 marks/min by a metronome.

The typing task consisted of re-typing a standard text. During the editing task, subjects had to make the first word with five characters or more bold and capitalise the first character of the next word with five characters or more. This had to be repeated throughout the whole text or until the time was finished. The mouse task was performed using a drawing program on the PC, where subjects had to draw a pattern by clicking on small circles (7 mm diameter). During the stress task (the STROOP test, Faucett and Rempel 1994), the Dutch words for 'blue', 'yellow', 'green' and 'red' were shown in different colours. Subjects had to point the mouse to an icon with the colour of the word in black characters as quickly as possible. If a mistake was made or if a time limit was passed, a beep sounded.

### EMG recordings

EMG recordings were made with linear eight-channel electrode arrays (LISiN-SPES Medica, S. Pedrino di Vignate, Milan, Italy) with a 5-mm inter-electrode distance. The arrays were placed on the upper trapezius muscle, on the line from the spinous process of the seventh cervical vertebra to the acromion, with the most medial electrode 5–10 mm lateral from the midpoint, such that unidirectionally propagating signals were recorded (Farina et al. 2003). The part of the skin where the electrodes were placed was cleaned with alcohol. Conductive gel (20–30 µl for each electrode of the array) was used to assure proper electrode–skin contact and was inserted with a gel dispenser (model Eppendorf AG-Multipette plus, Hamburg, Germany) into the cavities of the adhesive electrode array (see Farina et al. 2003). A ground electrode was wrapped around the wrist. The signals were bipolarly amplified 3,500 times, analogue band-pass filtered (cut-off frequencies 6–500 Hz) and sampled at 2,048 Hz. The signals were digitised using a 12 bit A/D-converter and stored on a data logger (LISiN-Sirio Automazione, Rivoli, Turin, Italy). Before the

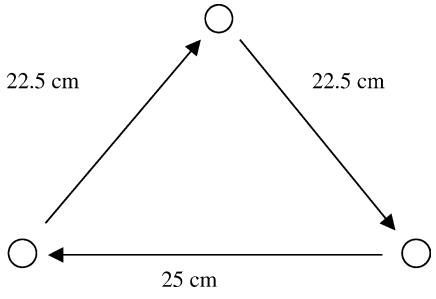


**Fig. 1** Dots task. *Circles* indicate the target areas (diameter 12 mm). The subject had to mark the target areas with a pencil at a pace of 88 marks/min. The *arrows* indicate the direction for right-handed subjects

measurement started and in between the recordings, the signal quality was inspected visually and adjustments were made when necessary.

## Signal processing

Root-mean-square (RMS) values were calculated for adjacent non-overlapping epochs of 1 s from a bipolar signal with an inter-electrode distance of 2 cm, according to the recommendations of Mathiassen et al. (1995) and Hermens et al. (2000). The four channels that were used to construct this bipolar signal were selected from all available channels according to a previously described method that minimises the sensitivity to changes in electrode position (Farina et al. 2002). In order to identify possible fatigue-related changes during the tasks, a linear regression line was fitted through the RMS values of the 1 s epochs, and its intercept and slope were calculated (Farina and Merletti 2000). The global RMS ($RMS_G$) was defined as the intercept of the regression line.

For calculation of the MR, at least five consecutive bipolar signals that showed propagating MUAPs with high quality were selected manually. MUAPs were detected with a method that uses the continuous wavelet transform to identify shapes that were similar to a mother wavelet (i.e. the first order Hermite-Rodriguez function, depicted in Fig. 2). The algorithm separated the MUAPs from the surrounding background activity. The algorithm searched for candidate MUAPs on all channels. A candidate had to occur in at least three channels before being called a MUAP. The outcomes of the detection algorithm were the times of occurrence of the MUAPs detected, and the MUAP shapes on all channels (See Fig. 2). An example of 400 ms of a recorded signal is shown in Fig. 2. The triangles indicate the MUAPs that were detected and correspond to the time instances where the detected MUAPs occurred in the second channel. The times of occurrence in all channels were stored. The extracted MUAP shapes are shown for a few examples. For more details about the method, see Farina et al. (2000) and Gazzoni et al. (2004).

The detected MUAPs were not classified into single MU firing trains. MR was calculated from *all* detected MUAPs. Thus, MR reflects the product of the number of MUs and their average firing rate. MR was calculated for adjacent, non-overlapping epochs of 1 s throughout the duration of the tasks as the number of detected MUAPs

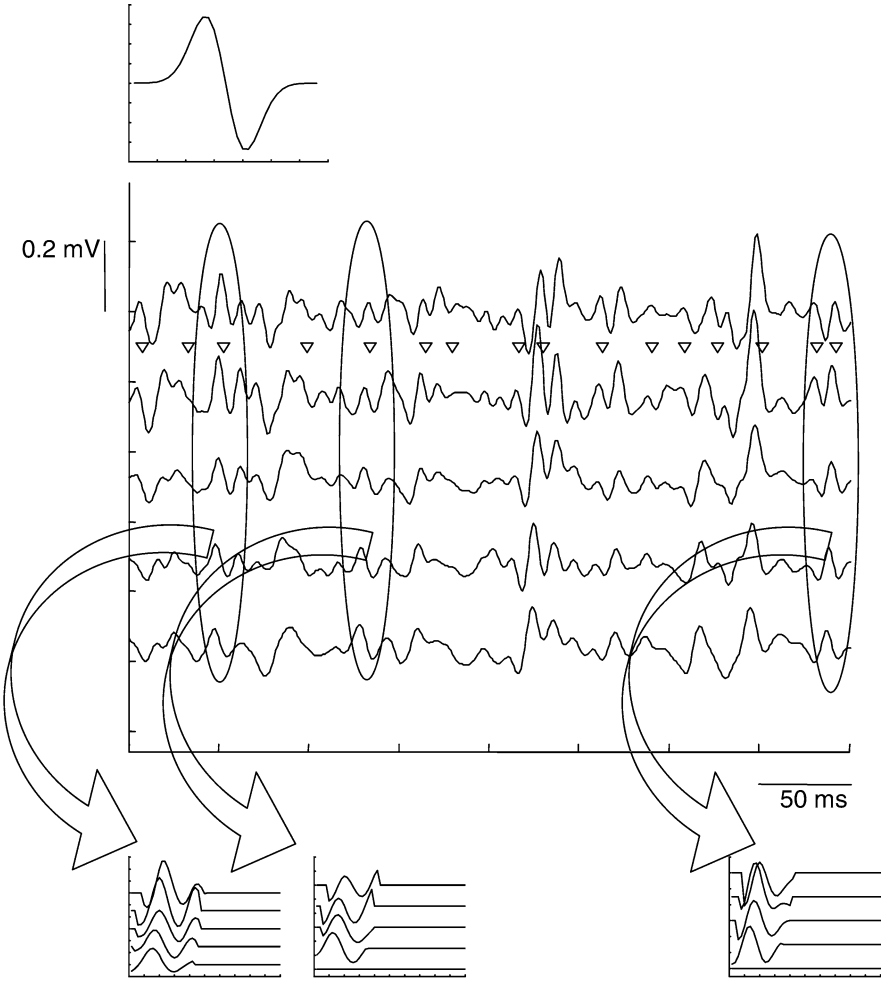


**Fig. 2** *Top* First-order Hermite-Rodriguez function, used as mother wavelet for the detection of MUAPs. *Bottom* Recorded signal (400 ms) with detected MUAPs (indicated with *triangles*) and some examples of extracted MUAP shapes (the *zeros* surrounding the MUAP shapes are not included in the analysis)

per second from the middle one of the signals selected for MUAP detection. The mean and standard deviation of MR within each subject (across seconds) were calculated. In addition, root-mean-square value ($RMS_{MUAP}$) and median power frequency ($FMED_{MUAP}$) of all detected MUAP shapes were calculated from the same signal. Subsequently, $RMS_{MUAP}$ and $FMED_{MUAP}$ were averaged per subject.

The data were analyzed using two-way (task, group) analysis of variance (ANOVA), followed by post hoc Bonferroni tests, when required. When means between the two groups were compared, the normality of the distributions of the data was assessed with a Kolmogorov-Smirnov test prior to statistical testing. If the data were non-normally distributed, the Mann-Whitney test for independent samples was used. If the data were normally distributed, the Student *t*-test for independent samples was used. Differences in variance between the groups were tested with Levene's test for equality of variance. Statistical significance was set to $P < 0.05$.

## Results

The VAS scores for the overall stress level and discomfort experienced in the arms, shoulders, neck and upper back of both groups are presented in Table 1. The VAS scores in the case group are much higher than those of the control group for all items ($P < 0.05$, Mann-Whitney test).

The mean MR and the inter-subject standard deviation of both groups during the tasks is shown in Fig. 3. A two-way (task, group) ANOVA revealed a statistically significant dependency for both variables (task: $F = 3.92$, $P < 0.005$, group: $F = 6.67$, $P < 0.02$). As can be seen from the figure, the difference between the two groups is most pronounced for the stress task. Mann-Whitney tests for each task analysed separately revealed a significant difference between the groups for the stress task ($P < 0.05$).

The $RMS_G$ is presented in Fig. 4. The differences between the groups are rather small. A two-way (task, group) ANOVA revealed a dependency only on task, not on group (task: $F = 10.7$, $P < 0.000$, group: $F = 0.972$, $P > 0.32$). A post hoc Bonferroni test revealed significant differences between the dots task and all other tasks

**Table 1** Visual analogue scores of the two groups (*SD* standard deviation)

| | Healthy controls | | Chronic pain cases | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| Stress level | 0.3 | 0.4 | 3.8 | 1.8 |
| Experienced discomfort in arms | 0.3 | 0.6 | 1.7 | 1.8 |
| Experienced discomfort in shoulders | 0.1 | 0.4 | 4.6 | 2.7 |
| Experienced discomfort in neck | 0.2 | 0.4 | 4.4 | 3.0 |
| Experienced discomfort in upper back | 0.2 | 0.4 | 3.8 | 3.0 |

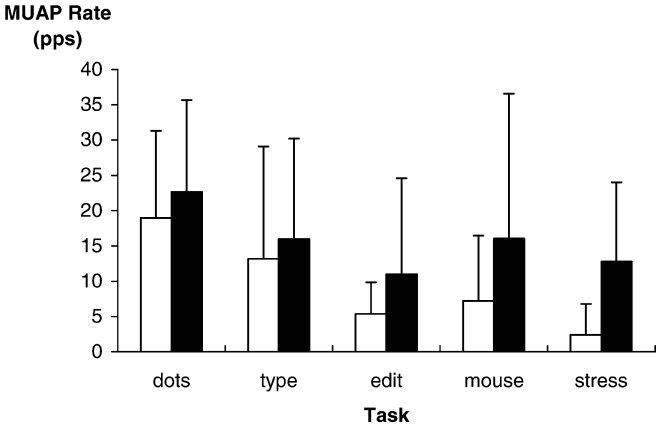


**Fig. 3** MR for the control group (*white bars*, $n = 13$) and the chronic pain group (*black bars*, $n = 10$) for all tasks. The *error bars* show inter-subject standard deviations. MR is significantly higher for chronic pain cases than for controls

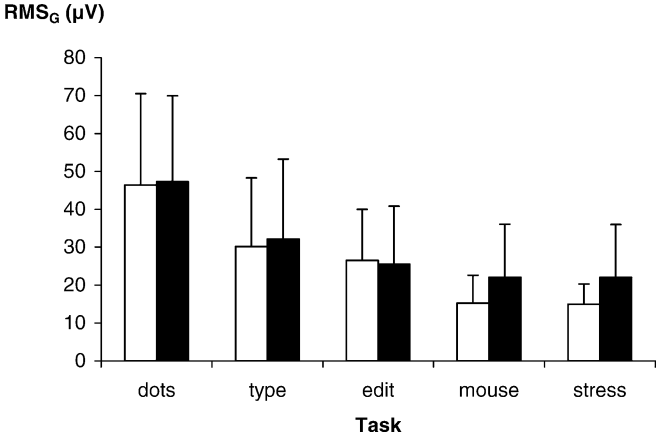


**Fig. 4** $RMS_G$ for the control group (*white bars*, $n = 13$) and the chronic pain group (*black bars*, $n = 10$) for all tasks. The *error bars* show inter-subject standard deviations. No significant differences were found between the groups

($P < 0.02$). The rates of change of the $RMS_G$ during the tasks (slopes of the regression lines) were not significantly different from zero for both groups.

The $RMS_{MUAP}$, mean per subject, is presented in Fig. 5. A two-way (task, group) ANOVA revealed a trend ($P < 0.13$) for higher $RMS_{MUAP}$ values in the case group. Mann-Whitney tests for each task analysed separately revealed a significant difference between the groups for the mouse task ($P < 0.03$). The distribution of $RMS_{MUAP}$ seems to be shifted to higher values for the case group, compared to the controls. The variance in the two groups did not differ (Levene's test for equality of variance, $P > 0.77$).

$FMED_{MUAP}$, mean per subject, is presented in Fig. 6. It can be seen that the distribution of $FMED_{MUAP}$ is shifted to higher values for the case group. In addition, the variability is larger in the case group. A two-way (task, group) ANOVA revealed a dependency only for group ($F = 22.1$, $P < 0.001$). Mann-Whitney tests for each task analysed separately revealed significant dif-

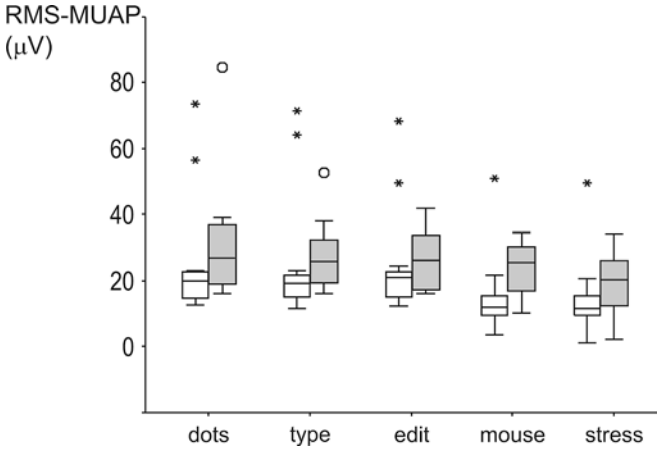


**Fig. 5** Mean RMS (per subject) of the detected MUAPs ($RMS_{MUAP}$) per subject group (*white bars* control group, $n=13$; *grey bars* chronic pain group, $n=10$) for all tasks. There is a trend for higher values in the chronic pain group (ANOVA, $P<0.13$). The *bar length* is the interquartile range. *Asterisks* indicate outliers (values between 1.5 and 3 bar lengths from the upper or lower edge of the bar). *Circles* indicate extremes (values more than 3 bar lengths from the upper or lower edge of the bar)

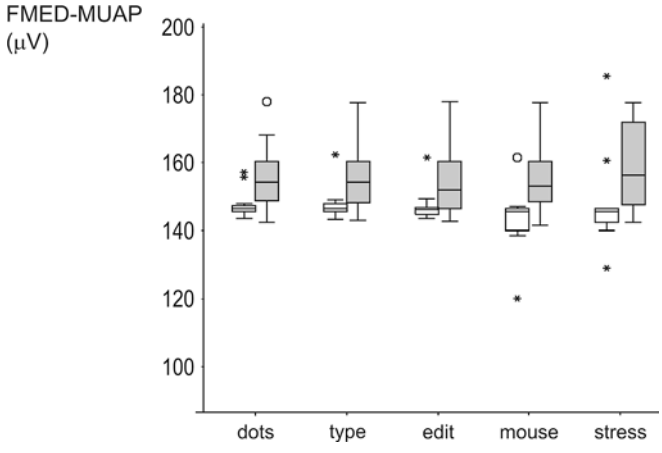


**Fig. 6** Mean FMED (per subject) of the detected MUAPs ($FMED_{MUAP}$), per subject group (*white bars* control group, $n=13$; *grey bars* chronic pain group, $n=10$) for all tasks. There is a significant difference between the two groups (ANOVA, $P<0.001$). The *bar length* is the interquartile range. *Asterisks* indicate outliers (values between 1.5 and 3 bar lengths from the upper or lower edge of the bar). *Circles* indicate extremes (values more than 3 bar lengths from the upper or lower edge of the bar)

ferences between the groups for all tasks except for the editing task ($P<0.05$). Levene's test for equality of variance revealed a significantly higher variance in the case group than in the control group ($P<0.02$).

## Discussion

The objective of this study was to investigate differences in motor control in chronic pain cases compared to healthy controls. The results show a higher mean MR for cases with chronic pain than for controls during computer work-related tasks. This finding would suggest a higher input from the central nervous system in the cases, due to increased recruitment and/or a higher average firing rate. The higher $FMED_{MUAP}$ and the trend for higher $RMS_{MUAP}$ in the chronic pain cases suggest that more high-threshold MUs contribute to the contractions. According to the Henneman principle (Henneman et al. 1965), this would suggest that the motor unit recruitment during an imposed task is increased in chronic pain cases compared to controls, although the biomechanical demand is the same. This is in agreement with the pain-spasm-pain model (Turk and Flor 1984; Gentry and Bernal 1977) that suggests a stiffening of the painful area through contraction of the painful muscle to prevent further muscle damage caused by movement.

Another explanation of the higher MR and higher $FMED_{MUAP}$ and $RMS_{MUAP}$ values would be a lower force output of the low-threshold MUs in chronic pain cases, thereby necessitating additional recruitment. To the authors' knowledge, information about force output per MU at low contraction levels is not available in relation to chronic pain. Some evidence pointing to a decreased force output in cases with chronic pain has been found by Schulte et al. (manuscript in preparation), who reported a decrease in maximal voluntary contraction force in cases.

The higher MR in combination with the trend for higher $RMS_{MUAP}$ values in chronic pain cases is expected to result in higher global RMS values. However, no significant difference was found between the two groups for $RMS_G$. $RMS_G$ is an estimate of the variance of the EMG signal, and therefore more sensitive to noise and background activity than MR. In addition, $RMS_G$ is highly influenced by the detection system parameters (e.g. inter-electrode distance), thickness of the subcutaneous layer etc. Differences in MR and $RMS_{MUAP}$ between the two groups might be masked by these factors. A possible confounding influence on the present results could be the body mass index as this would especially affect the $RMS_G$ and $RMS_{MUAP}$. However, the body mass index was very similar in the two groups.

The observed differences in MR were most pronounced in the stress task. The stress task requires a low biomechanical demand, as can be seen from the MR values of the control group. In spite of this low demand, the chronic pain cases showed much higher MR values than controls, suggesting that they are more sensitive to stress than controls. This is in agreement with reports of increased sensitivity to stress in chronic pain cases (Bansevicius et al. 2001; Bongers et al. 2002a; Huang et al. 2002) and the finding that stress can keep low-threshold MUs active, even when there is no biomechanical demand (Lundberg 2002).

Contrary to the present results, Birch et al. (2000) found a decreased EMG activity in relation to pain. They inserted hypertonic saline in the extensor carpi ulnaris (ECR) before starting a mouse task with either high or low precision. For the low precision task, the EMG amplitude of the ECR was less in the pain

condition than in the control condition. The contradiction between these results and the present results is most likely related to the type of pain. In the study of Birch et al. (2000) experimental pain was induced in healthy subjects, resulting in acute pain, while the present study investigated chronic pain.

Other authors (Moffroid 1997) have suggested that chronic pain is accompanied by muscle deconditioning. Deconditioning leads to a decrease in fibre diameter, thereby decreasing conduction velocity. This would in turn result in a decreased $FMED_{MUAP.}$ In contrast, we found a higher $FMED_{MUAP}$. No evidence for deconditioning was found in the cases in our study.

## Conclusion

The aim of the present work was to investigate differences in motor control of cases with chronic pain compared to healthy controls. The results show that MR is higher for chronic pain cases than for controls in computer work-related tasks. Furthermore, the higher $FMED_{MUAP}$ and the trend for higher $RMS_{MUAP}$ suggest that more high-threshold MUs contribute to the contractions in cases with chronic pain. This indicates that the input of the central nervous system to the muscle is higher in chronic pain cases, while the biomechanical demand is the same. MR seems to be a promising way to assess motor control of a muscle in a non-invasive way.

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